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Comparing Aboveground Biomass Predictions for an Uneven-Aged Pine-Dominated Stand Using Local, Regional, and National Models

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Running Title: Aboveground Biomass Predictions for an Uneven-Aged Pine-Dominated Stand

Abstract

Sequestration by Arkansas forests removes carbon dioxide from the atmosphere, storing this carbon in biomass that fills a number of critical ecological and socioeconomic functions. We need a better understanding of the contribution of forests to the carbon cycle, including the accurate quantification of tree biomass. Models have long been developed to predict aboveground live tree biomass, but few of these have been derived from Arkansas forests. Since there is geographic variability in the growth and yield of pine as a function of genetics, site conditions, growth rate, stand stocking, and other factors, we decided to compare aboveground tree biomass estimates for a naturally regenerated, uneven-aged loblolly pine (*Pinus taeda*)-dominated stand on the Crossett Experimental Forest (CEF) in southeastern Arkansas. These predictions were made using a new locally derived biomass equation, five regional biomass equations, and the pine model from the National Biomass Estimators. With the local model as the baseline, considerable biomass variation appeared across a range of diameters—at the greatest diameter considered, the minimum value was only 69% of the maximum. Using a recent inventory from the CEF's Good Farm Forty to compare each model, stand-level biomass estimates ranged from a low of 76.9 Mg/ha (a different Arkansas model) to as much as 96.1 Mg/ha (an Alabama model); the local CEF equation predicted 82.5 Mg/ha. A number of different factors contributed to this variability, including differences in model form and derivation procedures, geographic origins, and utilization standards. Regardless of the source of the departures, their magnitude suggests that care be used when making large-scale biomass estimates.

Introduction

One of the primary ecosystem services of forests in Arkansas is their sequestration of carbon dioxide (CO_2). Statewide, it is estimated that tree biomass (in terms of oven dry weight for all species) stood at 709 Tg in 2011, an increase of 12.3 Tg from 2010 (Rosson 2012)—a gain equivalent to 22.6 million metric tons of atmospheric CO_2 sequestered in one year.[1] Not only do forests remove this greenhouse gas from the atmosphere, but they also store carbon in biomass which fills a number of critical ecological and socioeconomic roles. For example, forest biomass supports over 27,000 Arkansas jobs in timber and timber-related industries, contributing an estimated $2.6 billion dollars to the state's economy (University of Arkansas Division of Agriculture 2012). In addition, a significant portion of the $5.7 billion spent annually by tourists comes from forest-based recreational experiences (Arkansas Department of Parks and Tourism 2011). Forest biomass also directly and indirectly contributes to a range of ecosystem services such as air and water purification, pollination, nutrient cycling, wildlife habitat, and soil stabilization, among many others (e.g., Malmsheimer et al. 2011).

To better understand the contribution of forests to the carbon cycle, it is imperative that we estimate the quantity of biomass as accurately as possible. Research has repeatedly shown that model choice and application impacts the estimates of biomass accumulation (e.g., Payadeh 1981, Ruark et al. 1987, Crow and Schlaegel 1988, Parresol 1999, Chave et al.

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[1] Rosson (2012) estimated the 2011 oven-dry forest biomass from trees in Arkansas at 1.56345×10^{12} pounds, an increase of 2.708×10^{10} pounds over the 2010 estimate. Since 2.2046 billion pounds = 1 billion kilograms (kg) or 1 teragram (Tg), 1.56345×10^{12} pounds = 709.2 Tg and 2.708×10^{10} pounds = 12.3 Tg. Conversion from pounds of oven-dry biomass to millions of tons of CO_2 equivalents (CO_2e) assumed a conversion factor of 0.5 between oven-dry biomass and C content, a multiplier of 3.67 to produce CO_2e from the C estimate, and that 1 Tg = 1 million metric tons.

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2005, Zianis et al. 2005, Bragg 2011, Melson et al. 2011) and, hence, projections of carbon sequestration. Therefore, care should be taken when selecting a particular equation to predict tree biomass, especially when results are to be extrapolated (projected beyond the range of derivation, over a large geographic area, or across a long time scale). Over the years, a series of models have been developed to predict aboveground live tree biomass, but few of these were actually derived from Arkansas forests. The primary objective of this paper is to provide a preliminary evaluation of the influence of model choice on biomass predictions using the limited suite of models available for this region, and to make some recommendations regarding future efforts to study biomass accumulation.

Materials and Methods

Study area and stand description

The focus of the biomass component of this research project is the nearly 680-ha Crossett Experimental Forest (CEF) located 11 km south of the city of Crossett (Ashley County, Arkansas). Established in 1934 by the U.S. Forest Service, the CEF has long been managed for research and demonstration purposes and contains some of the oldest examples of uneven-aged silviculture in North America (Reynolds et al. 1984).

Most of the CEF is covered by naturally regenerated loblolly (*Pinus taeda*) and shortleaf (*Pinus echinata*) pine-dominated forest, with various hardwood species most frequently found along the small ephemeral streams that cross the property. The rolling terrain of the CEF has limited vertical relief (between 36 and 48 m above sea level, with local differences rarely more than 3 m) and the soils are primarily silt loams with a loblolly pine site index of 25 to 30 m (50 year base age) (Gill et al. 1979).

Our study location is the 16-ha Good Farm Forestry Demonstration Area (hereafter, the "Good Forty"), an uneven-aged loblolly pine-dominated stand in the southeastern corner of the CEF. The Good Forty was named in 1937 when a demonstration project looking at uneven-aged silviculture was established on the CEF, and refers to its initial pine stocking level of approximately 126 m^3/ha (in more conventional English units: 5,074 board feet (Doyle log rule) per acre) of merchantable timber, which was considered well stocked (Reynolds et al. 1984). We used a 100% inventory of all pine at least 10 cm in diameter at breast height (DBH) collected in 2008 on the Good Forty as the basis for our later model comparisons.

Figure 1 provides a diameter distribution of this stand by 5-cm DBH classes for pines only (loblolly and shortleaf are combined, with loblolly comprising over 90% of the pines in the Good Forty).
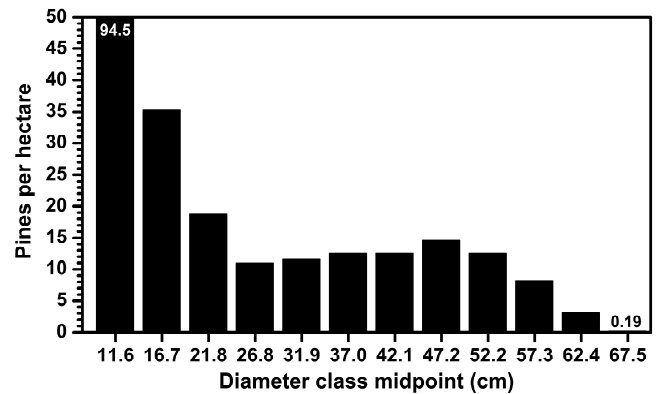

Figure 1. Current (2008) size class distribution for merchantable-sized pines in the CEF's Good Forty Demonstration Area.

Models for comparison

These predictions were made using a locally derived biomass equation, five regional biomass equations, and the pine model from the National Biomass Estimator (Jenkins et al. 2003). The locally derived equation was based on 62 destructively sampled, oven-dried loblolly pines from 0.9 to 15 cm DBH (McElligott and Bragg 2013):

$$B_D = 0.36099 + 0.047168(DBH^2 \times HT)^{0.901992} \quad (1)$$

where aboveground pine biomass (B_D) is oven dry weight (kg) and *DBH* is in centimeters. Note that equation (1) was fit to data only to 15 cm DBH, yet the Good Forty is predominantly a sawtimber-sized stand with individual pines to 70 cm DBH (Figure 1). The rationale and process for extrapolation of this equation beyond the data range it was derived for is explained in detail in McElligott and Bragg (2013). Total tree height (*HT*, in m) in equation (1) was predicted from a Chapman-Richards-based model for loblolly and shortleaf pines on the CEF (Bragg 2008):

$$HT = 1.37 + 41.964(1 - e^{-0.0247 \times DBH})^{1.1496} \quad (2)$$

Figure 2 demonstrates the relationship between height and DBH of loblolly pines on the CEF.

The regional and national models were selected from a number of designs that have been used to predict loblolly pine biomass for various locations across the southeastern United States. For consistency, we converted the results of these models to metric units and applied the same height function (equation (2)) to all models that required it. Stand-level biomass was

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derived from the sum of all individual tree predictions using the different models (stand table in Figure 1).
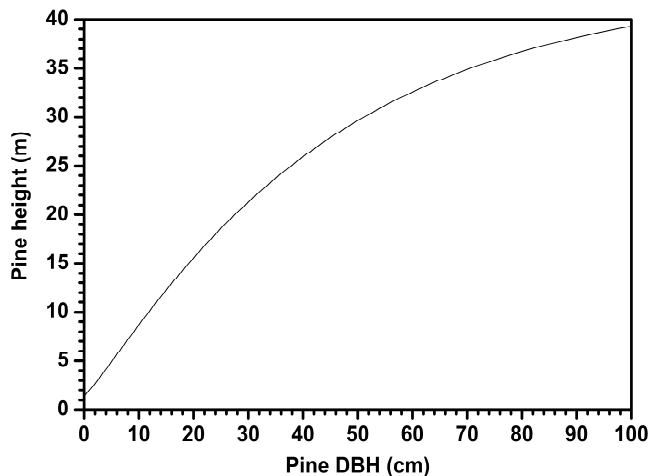

Figure 2. Equation (2) predicts total height as a function of DBH for loblolly pines on the CEF (adapted from Bragg 2008).

Likewise, in all instances when these models predicted green biomass, we converted to oven-dry values by multiplying green weights by 0.5 ($B_D = B_G \times 0.5$) (Patterson et al. 2004). The extrapolation of a number of these other models beyond the range of data they were derived for can be problematic, but highlights the unfortunate reality that sometimes the need for specific predictive ability exceeds the proper statistical bounds of the models being used.

A set of models to predict loblolly pine green weight were developed by Doruska and Patterson (2006) and Posey et al. (2005) using felled trees from southeastern Arkansas. Assuming summer conditions (100% moisture content), the following equations calculated green biomass (B_G) for pulpwood-sized trees (stems < 25 cm DBH; Doruska and Patterson 2006):

$$B_G = -26.23697 + 0.1431(DBH^2 \times HT) + 0.00481(DBH^2 \times HT) \qquad (3)$$

and sawtimber (stems 25-75 cm; Posey et al. 2005):

$$B_G = e^{-0.1341 + 2.0178\ln(DBH) + 0.5726\ln(HT)} \qquad (4)$$

These two equations used English units of measure (biomass in pounds, DBH in inches, height in feet).

In addition to the Doruska and Patterson models, four other regional biomass models were used in this comparison. Van Lear et al. (1986) developed a regression model for a naturally regenerated, uneven-aged loblolly pine stand in Alabama that was approximately 40 years old. Their sample included pines from 15 to 50 cm DBH, and their data yielded

the following relationship:

$$B_D = 194.04(DBH^2 \times HT)^{0.99} \qquad (5)$$

where all variables are as previously defined, except both DBH and HT are in terms of meters. Clark and Saucier (1990) presented a different model for green biomass from naturally regenerated loblolly pine stands in the coastal plains of Alabama, Georgia, and South Carolina. Their field data included trees from 2 to over 60 cm DBH, and their equation for larger (DBH > 12.5 cm) stems was:

$$B_G = 0.19821[(DBH^2)^{1.06419} \times HT^{0.9133}] \qquad (6)$$

Newbold et al. (2001) published the following equation to predict the green weights of planted loblolly pines in northern Louisiana:

$$B_G = e^{-1.90705 + 2.0023\ln(DBH) + 0.99208\ln(HT)} \qquad (7)$$

Bullock and Burkhart (2003) developed the following equation to predict the green weight of loblolly pine (origin unspecified) using samples from Georgia, Texas, and Virginia:

$$B_G = -4.3238 + 0.1397(DBH^2 \times HT) \qquad (8)$$

Equations (7) and (8) both use English units of measure, and were taken from pines up to 53 cm DBH.

Note that all of the local and regional models used both DBH and total tree height to predict biomass. The final equation in this comparison, the one used to forecast biomass for North America (the national model), was developed by Jenkins et al. (2003) and included only DBH (in cm) as a predictor. This model, known as the National Biomass Estimator, predicts total aboveground tree oven-dry biomass for pine using the following equation:

$$B_D = e^{-2.5356 + 2.4349(\ln(DBH))} \qquad (9)$$

Equation (9) was not derived specifically for loblolly pine, but rather developed from "pseudodata" generated by 43 different equations using 14 different species of *Pinus*, of which only four equations were *Pinus taeda*. This differs from the other models in this paper that were directly derived from destructively sampled loblolly pines.

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Comparative approach

The models used in this equation were selected for their potential applicability to the question of determining pine biomass in this stand. However, direct statistical comparisons were not possible between these equations because we did not have their independent measures of variation—our results are too deterministic. However, we could provide descriptive comparisons between predicted oven-dry biomass as a function of pine DBH, and then compare the stand-level outcomes of each model using the same stand of timber partitioned into different timber product classes (in this case, the Good Forty, Figure 1). The difference in stand-level predictions can then be used to inform future efforts to assess the amount of biomass solely as a function of model choice.

Results

Individual tree predictions

Each of the models compared followed a very similar trajectory for pines less than 50 cm DBH (Figure 3). However, the modest differences between the subset of models (Van Lear et al. 1986, Newbold et al. 2001, Bullock and Burkhart 2003) that forecast the greatest biomass per unit stem diameter in smaller pines quickly escalated with increasing tree size.
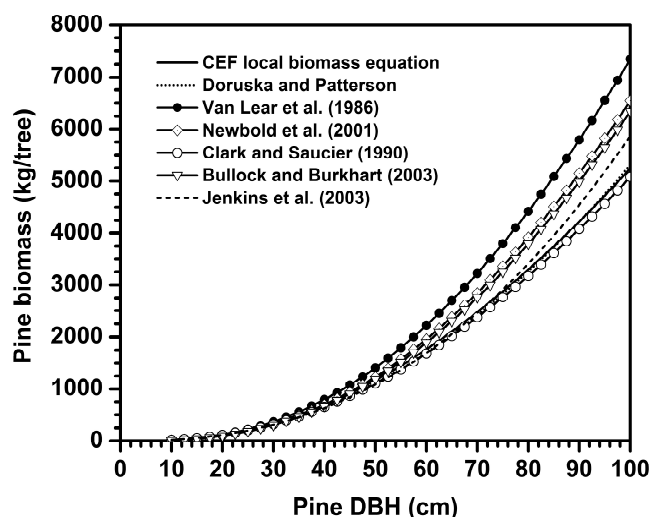

Figure 3. Biomass for loblolly pine on the CEF as a function of DBH using the different equations.

For large pines, three models (the CEF biomass equation, Doruska and Patterson's (2006) model, and Clark and Saucier's model) projected very similar and conservative biomass to the maximum value extrapolated (100 cm DBH). The Jenkins et al. (2003)

equation differed little from these three conservative models until about 75 cm DBH, after which it predicted a level of biomass intermediate between the more aggressive and more conservative designs (Figure 3). These differences are not trivial—at 100 cm DBH, the minimum value (5,076 kg) is only about 69% of the maximum prediction (7,347 kg).

Because of how the CEF biomass model was derived (McElligott and Bragg, this volume), it should not be surprising that the predictions are similar to those of the National Biomass Estimator. More remarkable is the parity of equation (1) and the two models developed by Doruska and Patterson. These equations produce values that are virtually indistinguishable from each other to at least 100 cm DBH—a satisfying result, given that all of the trees used to produce these equations were harvested from pine stands in southeastern Arkansas. Close correspondence to the Clark and Saucier (1990) model across this same range was not anticipated, especially since the stands they sampled were from central Alabama eastward, and included plantations as well as natural-origin stands.

Stand level predictions

Using the CEF biomass model, the Good Forty is predicted to currently yield 82.5 Mg/ha of biomass, roughly in the middle of the range of predicted biomass from all models (Table 1). At 96.1 Mg/ha, the Van Lear et al. (1986) model projected the greatest quantity of biomass, with most of the difference coming from the various sawtimber size classes. Another group of models clustered around 82 Mg/ha (including the CEF biomass model), followed by several that predict about 77 Mg/ha (Table 1).

When extrapolated to very large diameters, the Van Lear et al. (1986) equation was predicted to yield a much higher quantity of biomass than any of the other designs. However, this tendency seemed to have had very little impact on overall stand biomass fraction. This is not surprising, given the relative rarity of pines of this size in modern landscapes; hence, this difference produced little deviation in the biomass in the very large sawtimber size class (Table 1).

Even though all of the different models predicted only subtle individual tree differences in biomass at small diameters (Figure 3), the number of small stems per hectare is considerably greater in uneven-aged stands, and therefore the biomass variation between the model types when sorted by product classes becomes apparent, especially when scaled to the total predicted yield as a function of model (Table 1, Figure 4). For

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Table 1. Predicted biomass for the Good Forty Demonstration Area on the CEF as a function of timber product size classes and equation.

Timber product class [a]	CEF biomass (Eq. 1)	Doruska & Patterson (Eqs. 3&4)	Van Lear et al. (Eq. 5)	Newbold et al. (Eq. 7)	Clark & Saucier (Eq. 6)	Bullock & Burkhart (Eq. 8)	Jenkins et al.[b] (Eq. 9)
	-- Biomass (Mg/ha) --						
Pulpwood	6.7	4.4	6.1	5.2	6.1	4.7	6.5
Chip-and-saw	8.8	8.3	9.4	8.1	8.2	7.8	8.1
Small sawtimber	23.6	22.6	27.4	23.9	22.3	23.1	21.6
Large sawtimber	37.2	35.7	45.5	40.0	35.4	38.6	34.9
Very large sawtimber	6.1	5.9	7.8	6.8	5.9	6.6	5.9
All product classes	82.5	76.9	96.1	84.0	77.9	80.8	77.0

[a] Pulpwood size class DBH range = 10.2-22.8 cm (midpoint = 15.2 cm); chip-and-saw DBH range = 22.9-35.5 cm (midpoint = 27.9 cm); small sawtimber DBH range = 35.6-48.2 cm (midpoint = 40.6 cm); large sawtimber DBH range = 48.3-60.9 cm (midpoint = 53.3 cm); and very large sawtimber DBH range = 61.0-68.6 cm (midpoint = 64.8 cm).

[b] National Biomass Estimator.

example, the pulpwood (PW) size class was disproportionately higher for the CEF (local), Clark and Saucier (1990) (regional), and Jenkins et al. (2003) (national) models when compared to the others, which tended to have a larger fraction of their biomass in the large sawtimber (LS) class (Figure 4). Most of the cumulative differences between equations (1) and (9) came from the consistently lower predictions of the National Biomass Estimator (Table 1).

Discussion

Since there is 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 such as the scale of model derivation (Mitchell and Wheeler 1959, Schultz 1997, Jordan et al. 2008), there is good evidence that biomass models developed for other regions or silvicultural origins will yield predictions that differ from local equations (e.g., Bragg 2011). Variation of wood density (and, hence, carbon content) in any given species has long been recognized. For example, samples of natural-origin loblolly pine have wide bell-shaped curves for specific gravity when sampled both within and across populations (Davis 1927, Mitchell and Wheeler 1959, Jordan et al. 2008), although a fixed value of between 0.47 and 0.51 is often assumed (e.g., Jenkins et al. 2004, Miles and Smith 2009).

Though not as pronounced, there is also a range of specific gravities in planted loblolly pine (Jordan et al. 2008). For years, tree improvement programs in the southeastern United States have bred their planting stock, with the strong relationship between specific gravity and wood strength in mind, to increase this attribute (Bendtsen 1978, Aspinwall et al. 2012), thereby affecting the biomass as well. Variation in the specific gravity (and, hence, biomass) in planted pine can be largely explained by silvicultural and ecological influences such as density management, genetics, and/or site-specific conditions (e.g., Megraw 1985).

One should not be surprised, then, that a biomass model developed for naturally regenerated pine in Alabama (e.g., Van Lear et al. 1986) or Arkansas (this
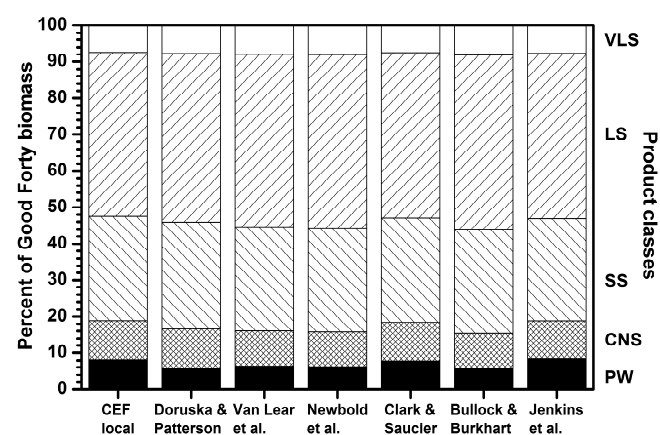

Figure 4. Proportioning of Good Forty biomass between different size classes ranging from pulpwood only (PW; DBH class midpoint 15.2 cm), to chip-and-saw (CNS; DBH class midpoint 27.9 cm), small sawtimber (SS; DBH class midpoint 40.6 cm), large sawtimber (LS; DBH class midpoint 53.3 cm), and very large sawtimber (VLS; DBH class midpoint 64.8 cm).

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paper) differs from those derived from loblolly pine plantations from Georgia (e.g., Bullock and Burkhart 2003) or Louisiana (Newbold et al. 2001). Model choice will increasingly concern those managing specifically for carbon storage, as research continues to demonstrate the influence of wood density on biomass estimation (e.g., Chave et al. 2005, Aspinwall et al. 2012). For example, a local model will be more useful for applications such as a specific carbon project while a regional model may be more useful at a larger scale, such as state-wide predictions of carbon storage.

Recognizing the sensitivity of predictions to model choice is critical because the most commonly applied design used across the United States, the National Biomass Estimator, incorporates multiple individual species into broad species groups (Jenkins et al. 2003). While this makes the simulation process easier while permitting a reasonable estimate of biomass for many species with little to no information on biomass, it can obscure significant differences with potentially major consequences. For example, the National Biomass Estimator pine equation incorporates all *Pinus* in North America (Jenkins et al. 2004), from eastern white pine (*Pinus strobus*, specific gravity = 0.35) to longleaf pine (*Pinus palustris*, specific gravity = 0.59). Given the range of specific gravity in the wood of these different pines (Miles and Smith 2009), we expected the National Biomass Estimator to underestimate other biomass models specifically fit to loblolly pine in Arkansas.

In addition to these issues, we also chose to develop a new model to specifically address the need for determining pine biomass for southeastern Arkansas because existing options were either untested for our forest conditions (e.g., the National Biomass Estimator) or were developed for a different type of purpose, such as weight-scaling for the timber trade (e.g., the Doruska and Patterson models) and hence applied different utilization standards (e.g., green weight to a 10 cm top diameter). Though our individual tree results did not differ appreciably from either of these efforts, their lack of specificity and differing design could cause some to rightly question their applicability to carbon storage assessment in this region.

Conclusions

A number of different factors contributed to the variability in predicted pine biomass at both the individual tree and stand scales, including differences in model form and derivation procedures, geographic origins, and utilization standards incorporated in the original biomass model designs. Given the increasing use of biomass models in carbon accounting procedures being applied locally by various trading markets and regulatory agencies (e.g., California ARB 2009), it behooves those documenting stand-level biomass to use the most reliable model permissible.

For this reason alone it would seem to be advantageous for more site- and stand-specific biomass models to be developed. Under new carbon markets or regulations, Arkansas landowners will increasingly be asked to accurately account for the carbon stored in their forests. The inappropriate application of certain model designs may produce inadequate predictions that could cost the forest owner money (in the case when the model predicts less biomass than actually occurs) or misstate the amount of carbon sequestered (in the case when more stored biomass is predicted than actually stored in reality).

Regardless of the source of the departures, their magnitude suggests that more care be used when developing large-scale biomass estimates. After all, how biomass quantities are determined and carbon-driven management may have large-scale impacts on forest policy across a range of scales (Galik et al. 2013). To date, the initial assessments have provided mixed results. Some have reported that certain intensive silvicultural practices have significantly increased carbon sequestration (e.g., Aspinwall et al. 2012). Other results indicate that loblolly pine plantations have lower average wood specific gravity than naturally regenerated pines (Jordan et al. 2008), implying that increased wood production accounts for the increased sequestration of Aspinwall et al. (2012).

This may suggest that further gains in carbon sequestration could be realized from retaining slower-growing and/or mixed species stands and avoidance of large-scale conversions of such stands in favor of monospecific plantations (Sohngen and Brown 2006, Woodall et al. 2011, Gamfeldt et al. 2013). However, given current markets and carbon accounting designs, such storage gains would only occur if timber harvest from these stands is diminished, thereby reducing economic incentives to manage primarily for sequestration. Given the stakes of carbon sequestration and related ecosystem service-based issues, unreliable biomass predictions should not be allowed contribute to the problem.

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