ADVANCING INDIVIDUAL TREE BIOMASS PREDICTION: ASSESSMENT AND ALTERNATIVES TO THE COMPONENT RATIO METHOD

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Abstract—Prediction of forest biomass and carbon is becoming important issues in the United States. However, estimating forest biomass and carbon is difficult and relies on empirically-derived regression equations. Based on recent findings from a national gap analysis and comprehensive assessment of the USDA Forest Service Forest Inventory and Analysis (USFS-FIA) component ratio method (CRM) for estimating both biomass and carbon using historical individual tree biomass data, alternative approaches for predicting forest biomass and carbon were evaluated. The different CRM approaches tested included: 1) development and use of a unified stem taper equation to estimate stem volume; 2) updated model forms and parameters for predicting biomass components; and 3) comparison of alternative wood density values. Overall, these modifications show the potential to improve estimates of forest biomass and carbon, but additional testing is required before implementation.

Estimation of national forest biomass and carbon in the United States is increasingly desirable for many reasons. Recent studies evaluated nationally-prominent (Domke et al. 2012) and regionally-prominent (Westfall 2012) biomass estimation methods and found significantly disparate results, instigating research into current estimation methods. However, assessing biomass estimation methods and developing new methods are difficult due to the requisite for independent empirical data. A national biomass estimation research project currently is acquiring the necessary data for improving biomass estimation.

Currently, the USDA Forest Service Forest Inventory and Analysis (USFS-FIA) uses the component ratio method (CRM) to estimate biomass. This method relies on sound wood volume estimates, component ratio estimators (Jenkins et al. 2003), and bark and wood density values (Miles and Smith 2009). These ratio estimators are generalized across the United States into two broad groups (hardwoods and softwoods) and a fixed species-level value is assumed for bark ratios and densities. In contrast, over 25 different species-level volume forms are used across over 20 different regions. These models are largely delineated across state lines (see Fig. 1 in Woodall et al, 2011), though it may be more appropriate to group across ecologically delineated spatial units.

Estimation of different components at different taxonomic and geographic levels may be appropriate because of large observed variation in these relationships. However, to our knowledge this assumption has not been formally examined. For instance, using hardwood and softwood ratio estimators at the national level may lead to errors when estimating at a regional or state level. With regard to bole estimation, separate volume equations of varying form may be overly complex, whereas a single model form could simplify implementation while improving estimation at varying scales. In this analysis, we evaluate alternative approaches to volume and component estimation within the context of the CRM method.

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The primary objectives are:

1. Develop and test a unified bole volume model
2. Examine variation in wood specific gravity
3. Provide an improved component ratio model
4. Compare these modifications to the current CRM method on trees with observed biomass

Considering that one objective is to estimate volume at varying scales (nationally, regionally, and perhaps statewide), a formal examination of these factors at the national level warrants a unified approach, while allowing for methods to examine how different taxonomic groupings and geographical specifications influence estimates. Mixed-effects modeling allows for such an approach. Using all available tree data across the United States and incorporating taxonomic and regional random effects provide a flexible framework to formally examine what groupings are most appropriate.

METHODS

We compiled a volume and biomass "legacy" data set of over 100,000 trees with stem taper profiles and over 3,000 trees with aboveground biomass (AGB), bole, top, and foliage biomass observations. For each component we estimated biomass using 1) the original component ratio method (CRM); 2) a refit CRM where we generated new coefficients using CRM/Jenkins model forms and species groupings (CRM1); and 3) a modified CRM using species-specific parameters derived from non-linear mixed-effects models (CRM2). The Jenkins model and CRM impose a merchantability limit from 1-foot stump to a 4-inch top. For the modified CRM, we remove these limits and estimate bole biomass from ground line to a 0 inch top. Aside from merchantability limits and how parameters were estimated, the methods follow Woodall et al. (2011).

We chose the Kozak (2004) taper model form and incorporated a mixed-effects structure (Li et al. 2012). While results from previous work (Li and Weiskittel 2010) suggest that a segmented taper model (e.g., Clark et al. 1991) may offer small gains in estimation accuracy, we thought that the variable exponent equation of Kozak (2004) offered a more flexible model form that can ease the estimation and updating of parameters with minimal reduction in accuracy.

The form of the Kozak (2004) model with random effects is:

$$dob = (\propto_0 + \ Gp_0/\boldsymbol{Sp_0})\, D^{\propto_1} H^{\propto_2} X^{\left(\mathrm{B}_1 z^4 + \mathrm{B}_2\left(1/e^{D/H}\right) + (\beta_3 + Gp_0/\boldsymbol{Sp_0})X^{0.1} + \beta_4(1/D) + \beta_5 \mathrm{H}^{\mathrm{Q}} + \beta_6 \mathrm{X}\right)}$$

where $X = 1 - z^{1/3} / 1 - p^{1/3}$, $Q = 1 - z^{1/3}$, dob = diameter outside bark, H = total tree height, D = diameter at breast height (d.b.h.), h = section height from ground, p = 1.3/H (relative breast height), and z = h/H (relative height from ground). We generated models separately for hardwoods and softwoods and modified the original Kozak (2004) function by adding nested random effects coefficients for Jenkins species groups and species (Gp_0/Sp_0 and Gp_3/Sp_3). For the modified CRM, rather than generate new coefficients using existing species-level-regional volume models, we estimate volume using the Jenkins species groups (CRM1), while we used species as the random effect for the modified estimate (CRM2). To convert from outside bark diameter to inside bark diameter (dib), we used the following equation: dib = (a + Spa) * $dob^{(b+Spb)}$.

We derived new coefficients for AGB and ratio estimators (CRM1) using equation forms and broad species groupings (Jenkins et al. 2003). In the second formulation (CRM2) for AGB, we used a simple non-linear model form: $(a + Spa) * DBH^{(b+Spb)}$. We also estimated parameters using a mixed-effects Chapman-Richards formulation with species as a random effect on all parameters (CRM2). The Jenkins et al. (2003) ratio model is below:

$$component\ ratio = e^{\left(\beta_0 + \frac{\beta_1}{DBH}\right)}.$$

The mixed-effects Chapman-Richards model is specified as follows:

$$CR\ component\ ratio = (a + Spa)\left[1 - e^{-(b+Spb)*DBH}\right]^{(C+Spc)}$$

Using data from the legacy database, we calculated mean wood specific gravity and 95percent confidence interval for 12 species that had a sample size of at least 30 observations. We compared this to the value presented in Miles and Smith (2009).

RESULTS

Model performance was strong with no clear trend in the residuals for any given species (Fig. 1). By species, whole tree volume percent root mean square error ranged from 8.6 to 24.4 percent (Table 1), which was comparable and in some cases better than the regional volume equations.

There was considerable regional variation in wood specific gravity for a given species and these values were generally significantly different than the value reported by Miles and Smith (2009) (Fig. 2). For example, mean specific gravity values for sugar maple (*Acer saccharum* Marsh.) ranged from 0.61 inches the northeast to 0.65 inches the north-central region, while Miles and Smith (2009) reports 0.56 inches.

CRM underestimated stem biomass by 5.0 ± 20.2 percent (mean ± SD) overall, while top biomass was underestimated by 43.3 ± 108.2 percent. Using the unified taper function for species groups (CRM1) and species-specific (CRM2), we found stem biomass error estimates of 1.5 ± 19.0 percent and 0.8 ± 19.3 percent, respectively. Since the Miles and Smith (2009) specific gravity values were used throughout the analysis, some improvement over the current regional volume equations was indicated. Likewise, improved accuracy with the newly generated AGB and ratio estimators (CRM1) as well as additional improvement using the mixed-effect AGB and Chapman-Richards formulation (CRM2) were observed (Table 2).

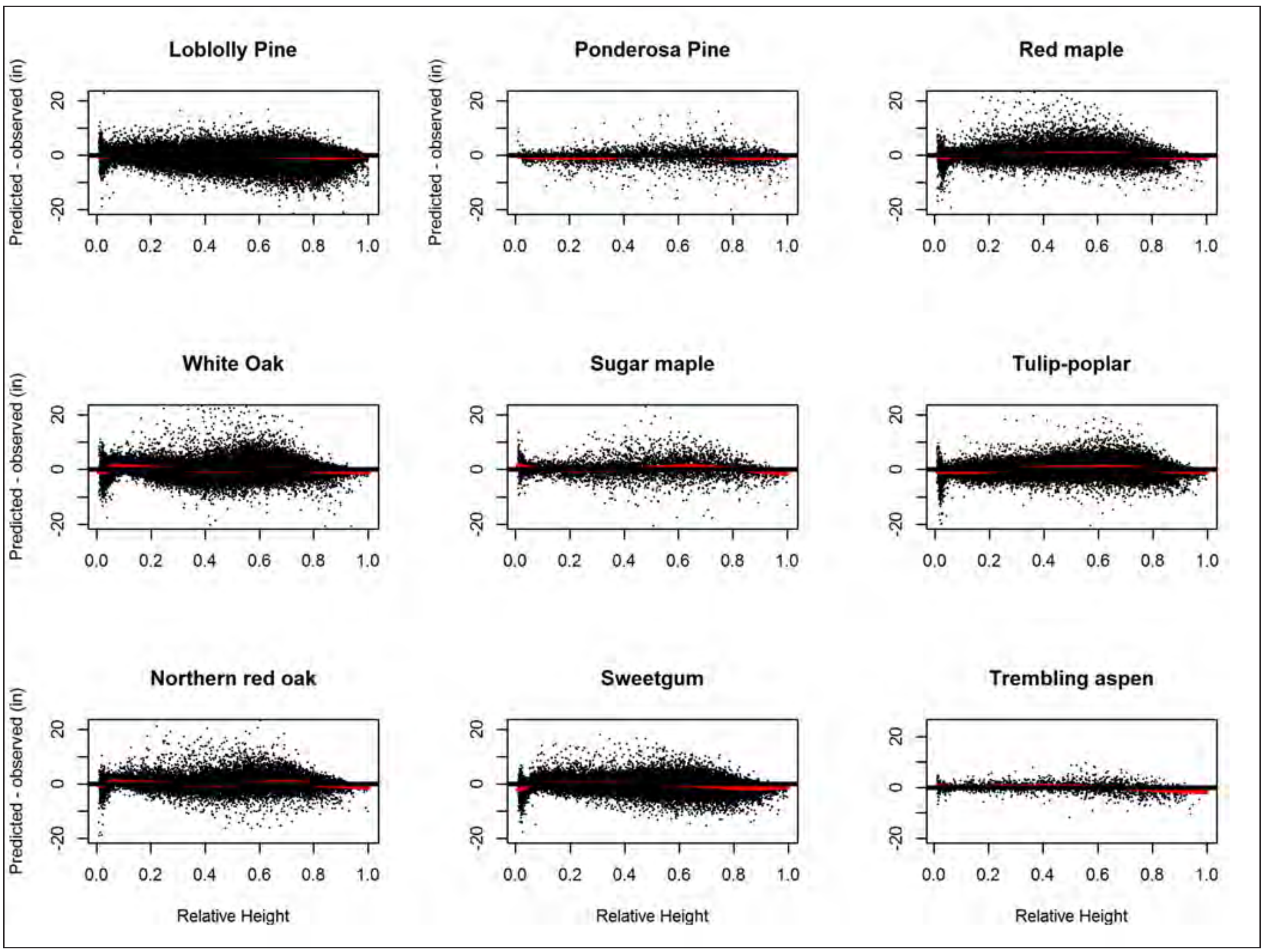

Figure 1—Prediction errors (predicted – observed) for diameter outside bark (d.o.b in inches) over relative height (disc height divided by total height) using the unified taper equation for nine prominent species with a lowess regression trend line (red).

Table 1—Summary statistics and errors associated with volume estimates for a species-level unified taper equation.

Common name	SPCD	n	Min d.b.h. (in)	Mean d.b.h. (in)	Max d.b.h. (in)	Outside bark volume (ft^3)	Outside bark volume error (ft^3)	Outside bark volume RMSE (ft^3)	Inside bark volume (ft^3)	Inside bark volume error (ft^3)	Inside bark volume RMSE (ft^3)
Loblolly pine	131	10664	5.0	11.1	38.3	27.88	-1.27	4.72	22.75	-1.27	5.01
Ponderosa pine	122	360	5.0	15.9	38.9	61.03	-6.29	14.70	48.96	-6.06	15.44
Red maple	316	1540	5.0	10.8	41.8	22.43	0.59	5.48	19.59	0.61	5.12
White oak	802	2604	5.0	12.1	44.4	30.91	0.25	6.12	25.66	0.32	5.54
Sugar maple	318	92	5.1	11.3	29.7	23.91	0.95	4.83	20.88	0.75	4.38
Yellow-poplar	621	2378	5.0	13.1	39.5	42.93	0.07	4.82	34.78	0.02	4.25
Northern red oak	833	1010	5.0	13.7	34.4	39.88	1.15	7.08	33.56	0.91	6.36
Sweetgum	611	2300	5.0	11.7	32.6	31.81	-0.57	5.14	26.41	-0.35	4.55
Quaking aspen	746	154	5.1	8.2	15.4	11.35	-0.12	1.46	9.56	-0.04	1.06
Engelmann spruce	93	100	5.0	8.1	17.8	10.77	-0.05	2.00	9.47	-0.10	1.99
Shortleaf pine	110	4435	5.0	11.0	26.1	26.82	-0.94	3.85	21.99	-0.94	4.02
White fir	15	596	5.1	17.3	48.7	68.91	-0.06	10.70	51.85	-0.45	9.83
Eastern white pine	129	1597	5.0	13.1	32.8	40.77	-0.22	5.56	35.01	-0.39	5.41
Black oak	837	1004	5.0	13.0	28.7	35.17	0.82	4.67	28.07	0.70	3.81
Chestnut oak	832	1464	5.0	12.3	34.0	30.46	0.10	4.59	24.19	-0.53	4.01
Slash pine	111	5513	5.0	9.0	23.8	16.68	-0.31	2.03	12.74	-0.50	2.24
American beech	531	402	5.1	13.6	35.0	35.73	1.57	6.41	32.36	2.08	6.53
Eastern hemlock	261	189	5.8	14.2	30.4	48.25	0.48	6.33	40.13	0.63	4.77
White ash	541	183	5.0	13.5	26.5	45.12	-0.75	5.97	37.02	-0.30	4.93
Water oak	827	691	5.0	11.8	30.1	27.38	0.12	3.57	23.67	-0.01	3.30
Black cherry	762	176	5.0	12.7	31.9	41.23	-0.50	5.94	36.66	-0.19	5.69
Hickory spp.	400	1711	5.0	12.1	33.8	31.54	0.04	5.20	25.46	-0.25	4.28
Virginia pine	132	1739	5.0	9.0	21.6	14.63	-0.50	1.82	12.77	-0.24	1.89
Post oak	835	578	5.0	11.6	25.3	23.26	0.24	2.95	18.74	0.00	2.58
Scarlet oak	806	1022	5.0	11.9	31.1	29.35	0.65	5.16	24.43	0.61	4.35
Southern red oak	812	893	5.0	12.4	48.9	29.43	0.64	5.95	23.92	0.20	4.63
Swamp tupelo	694	886	5.0	11.7	32.7	28.35	0.63	5.31	22.74	0.97	5.12
Paper birch	375	339	5.0	8.6	19.4	10.34	-0.08	1.77	9.14	-0.13	1.66
Northern white-ce	241	66	7.2	9.2	11.7	9.42	0.07	0.75	8.00	0.04	0.69
Balsam fir	12	494	5.0	8.4	18.9	11.89	0.09	1.56	10.61	0.03	1.42
All	All	61535	5.0	11.3	48.9	27.83	-0.32	4.79	22.91	-0.39	4.57

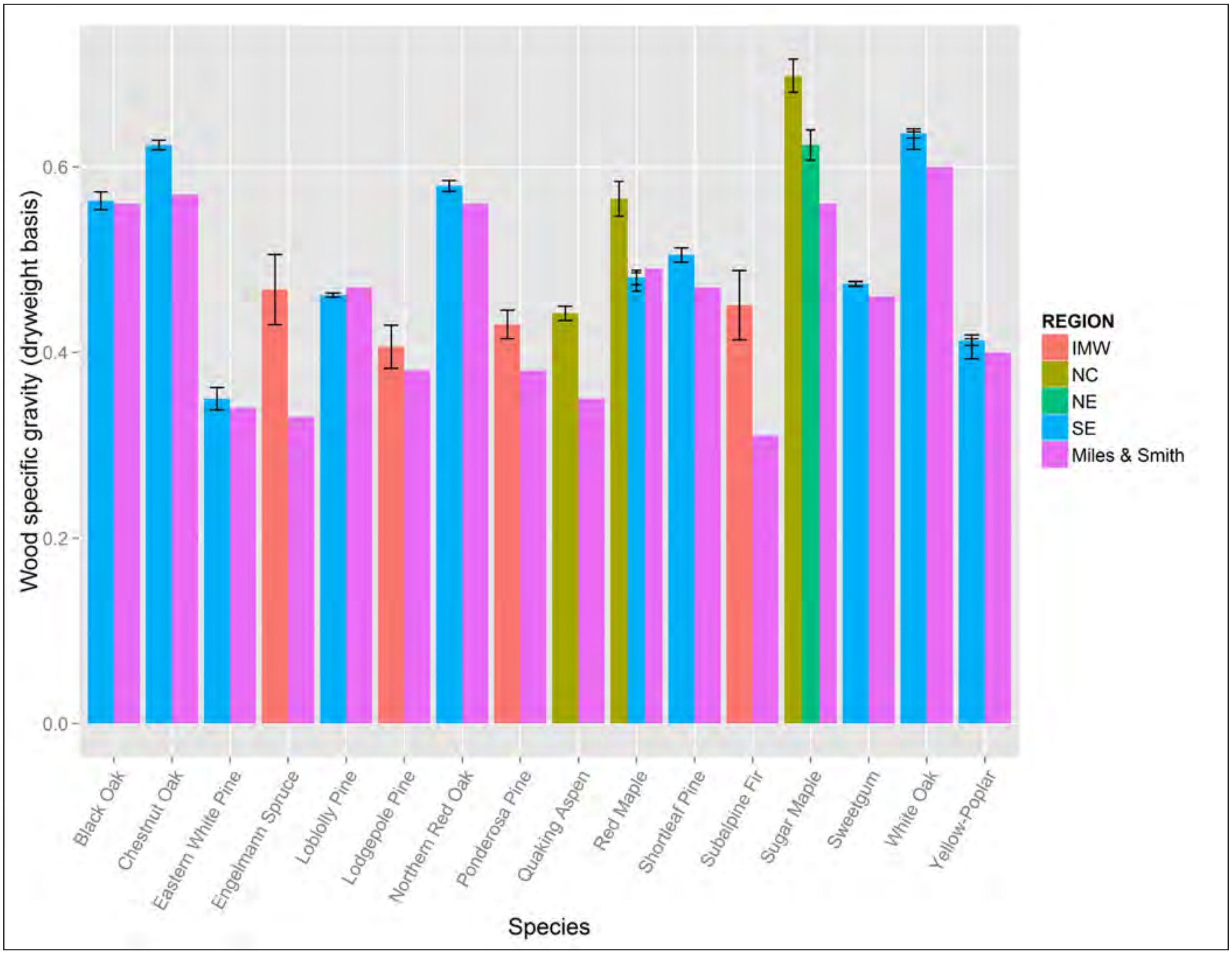

Figure 2—Comparison between average regional specific gravity and Miles and Smith (2009) reported specific gravity. Error bars are presented for the 95 percent confidence interval.

Table 2—Summary statistics and mean errors (standard deviation in parentheses) for all observations and four common eastern species between the current component ratio method (CRM), CRM with refitted parameters (CRM1) and modified CRM with species-specific parameters and updated model forms (CRM2). Error was estimated as predicted – observed. Mean CRM estimated error is derived from mean observed biomass with merchantability limits, while estimated error for CRM1 and CRM2 are derived from mean observed biomass without merchantability limits. Bole and Top are CRM estimates, while Above-ground and Foliage are Jenkins (2003) estimates.

Component	Common Name	No. of trees	Min. d.b.h. (in)	Mean d.b.h. (in)	Max. d.b.h. (in)	Mean observed biomass (lbs) (with merch. limit)	Mean observed biomass (lbs) (without merch. limit)	Mean CRM estimated error (lbs)	Mean CRM1 estimated error (lbs)	Mean CRM2 estimated error (lbs)
Above-ground	Loblolly pine	645	5.0	11.8	24.0	1088.6	1088.6	-245.4 [277.7]	58.5 [217.6]	5.2 [214.8]
Above-ground	Red maple	148	5.0	8.7	33.7	624.9	624.9	10.4 [125.0]	37.8 [115.3]	-8.6 [105.8]
Above-ground	Yellow-poplar	71	5.2	11.6	20.3	1117.2	1117.2	-68.2 [198.0]	-23.9 [196.2]	9.8 [193.1]
Above-ground	White oak	155	5.0	9.4	29.7	1011.5	1011.5	-39.8 [360.3]	0.2 [331.7]	-31 [324.9]
Above-ground	All	3154	5.0	10.5	33.7	968.7	968.7	-159.7 [326.4]	-9.3 [256.0]	1.3 [209.7]
Bole	Loblolly pine	645	5.0	11.8	24.0	849.3	916.8	-33.2 [126.5]	-7.9 [128.9]	-34 [133.0]
Bole	Red maple	148	5.0	8.7	33.7	403.8	461.4	-18.8 [128.3]	24 [211.2]	15.6 [201.6]
Bole	Yellow-poplar	71	5.2	11.6	20.3	863.8	929.4	-129.6 [167.5]	-76.4 [165.4]	-87 [168.9]
Bole	White oak	155	5.0	9.4	29.7	614.9	694.2	12.0 [89.8]	-16.8 [87.0]	7.5 [103.2]
Bole	All	3154	5.0	10.5	33.7	701.0	770.7	-34.8 [141.6]	-11.3 [146.7]	-6.5 [148.6]
Foliage	Loblolly pine	645	5.0	11.8	24.0	40.1	40.1	9.6 [15.2]	4.4 [12.4]	-6.3 [15.3]
Foliage	Red maple	148	5.0	8.7	33.7	13.8	13.8	-0.4 [11.0]	2.2 [13.9]	-1.8 [10.2]
Foliage	Yellow-poplar	71	5.2	11.6	20.3	15.3	15.3	5.6 [8.5]	10.3 [11.8]	2.2 [6.8]
Foliage	White oak	155	5.0	9.4	29.7	30.3	30.3	-10.5 [20.8]	-6.3 [20.0]	-8.5 [19.8]
Foliage	All	3154	5.0	10.5	33.7	28.2	28.2	2.8 [18.0]	2.4 [16.4]	-3.4 [15.3]
Top	Loblolly pine	645	5.0	11.8	24.0	199.2	131.7	-67.3 [86.2]	-1.3 [82.0]	4.3 [75.9]
Top	Red maple	148	5.0	8.7	33.7	213.3	155.7	-103.2 [566.2]	-54 [507.4]	-62 [506.6]
Top	Yellow-poplar	71	5.2	11.6	20.3	238.2	172.5	-60.0 [175.2]	6.3 [149.7]	-40 [161.5]
Top	White oak	155	5.0	9.4	29.7	366.4	287.1	-204.9 [522.4]	-138 [433.0]	-89 [357.7]
Top	All	3153	5.0	10.5	33.7	239.9	170.2	-104.3 [259.5]	-33.8 [220.3]	-22 [194.9]

DISCUSSION

This analysis indicates that a unified, nationally-consistent taper equation has potential to improve upon regional, species-specific volume equations. The taper equation has the advantage of estimating compatible total and merchantable volume when compared to existing approaches used by the FIA. Continuing efforts will focus on acquiring additional stem taper data.

The mixed-effects modeling framework that we propose here has the potential to examine species groupings by assessing the magnitude of the random effect and grouping by influential species traits. The similar performance between the species group volume/biomass model and the species model suggests that grouping species may be appropriate. Examining the branch component, we see improvement by first removing merchantability restraints and refitting coefficients (CRM1) and additional improvement by fitting a more flexible model form that allows for variation between species (CRM2). We present results from our most robust model with random effects on all coefficients. Future analyses will examine simplifying by species groups, removing parameters as appropriate, and grouping by geographical units to address local variability. This subject is not well understood, but recent work (Westfall 2015) suggests that local bias issues need to be addressed as part of the model development process.

Our examination of species-level wood specific gravity suggests that there can be considerable differences as regional estimates were generally statistically different than what is currently being used by the FIA CRM method. Previous efforts have suggested strong spatial patterns in wood specific gravity and this may need to be accounted for. In addition, other analyses have suggested that localized specific gravity estimates can improve stem biomass estimates.

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