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Comparison of uncertainty in per unit area estimates of aboveground biomass for two selected model sets

Michael Shettles [a], H. Temesgen [a,*], Andrew N. Gray [b], Thomas Hilker [a]

[a] Department of Forest Engineering, Resources, and Management, 237 Peavy Hall, Oregon State University, Corvallis, OR 97331 – 5703, USA
[b] Forest Analysis and Inventory Branch, USDA, Pacific Research Station, Corvallis, OR, USA

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ABSTRACT

Uncertainty in above ground forest biomass (AGB) estimates at broad-scale depends primarily on three sources of error that interact and propagate: measurement error, model error, and sampling error. Using Monte Carlo simulations, we compare the total propagated error for two sets of regional-level component equations for lodgepole pine AGB, and for two sets of high-precision instruments by accounting for all three of these sources of error. The two sets of models compared included a set of newly-developed component ratio method (CRM) equations, and a set of component AGB equations currently used by the Forest Inventory and Analysis (FIA) unit of the United States Department of Agriculture (USDA) Forest Service.

Relative contributions for measurement, model, and sampling error using the current regional equations were 5%, 2% and 93%, respectively, and 13%, 55% and 32%, respectively using the CRM equations. Relative standard error (RSE) values for the current regional and CRM equations with all three error types accounted for were 20.7% and 36.8%, respectively. Results for the model comparisons indicate that per acre estimates of AGB using the CRM equations are far less precise than those produced with the current set of regional equations. Results for the instrument comparisons indicate the terrestrial lidar scanning reduce uncertainty in broad-scale estimates of AGB attributed to measurement error.

1. Introduction

Increasingly central to the planning and monitoring-related goals of disciplines such as forestry and ecology, the production of defensibly precise broad-scale estimates of above ground biomass (AGB) but requires a thorough recognition of their primary associated sources of variability (Temesgen et al., 2007). The widespread sample-based approach of acquiring these AGB estimates for forested areas typically involves applying individual-tree regression equations to trees selected within randomly selected sample plots to obtain tree-level estimates of AGB. All individual-tree estimates are then summed to obtain plot-level estimates, with all plot values subsequently expanded up to per unit area levels of ABG. The reported precision of these per unit area estimates using this approach commonly reflect only the sampling error; the variability resulting from among-plot differences in plot-level values of ABG. In addition to sampling error, two other primary sources of error have been shown to interact and propagate during the process of scaling individual-tree estimates of AGB up to per unit area levels; namely measurement error and model error (Cunia, 1965). Measurement error is defined as the difference between a defined "true" value and the measured value of a given attribute. Model errors are sourced mainly from the residual variability around the model predictions and uncertainty in the parameter estimates. Because only sampling error is accounted for, uncertainty estimates for AGB are often an underestimation of the actual uncertainty. If uncertainty estimates for AGB are to be statistically credible, all three of these error types must be accounted for.

Measurement error is a source of uncertainty that has received broad attention in the forestry literature. A number of authors have

Abbreviations: AGB, aboveground biomass; CRM, component ratio method; CRM-FIA, component ratio method used by FIA; CV, coefficient of variation; DBH, diameter at breast height; DNF, Deschutes National Forest; DOB, diameter outside bark; FIA, Forest Inventory and Analysis; HT, total tree height; HTCB, height to the base of live crown; NFI, National Forest Inventory; RMSE, root mean square error; RRMSE, relative root mean square error; RSE, relative standard error; SE, standard error; STM, standing tree measurements; SUR, seemingly unrelated regression; TTWOF, total tree aboveground biomass without foliage; WNF, Willamette National Forest.

* Corresponding author.
E-mail addresses: michaelashettles@fs.fed.us (M. Shettles), hailemariam.temesgen@oregonstate.edu (H. Temesgen), agray01@fs.fed.us (A.N. Gray), Thomas.hilker@oregonstate.edu (T. Hilker).

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investigated the measurement error of particular instruments used in forestry applications (Behre, 1926; Bell and Gourley, 1980; McRoberts et al., 1994; Williams et al., 1994; Skovsgaard et al., 1998; Plamondon, 1999; Kalliovirta et al., 2004), while others have characterized the distributions of measurement errors for measured tree variables (McRoberts et al., 1994; Canavan and Hann, 2004). Work has also been done to investigate the effects of measurement error on the uncertainty of forest model predictions (Westfall and Patterson, 2007; Suty et al., 2013; Berger et al., 2014). Westfall and Patterson (2007) used the two stage error distribution method, also described by Canavan and Hann (2004), to model measurement variation distributions. Using quality assurance data from 682 inventory plots implemented by the Forest Inventory and Analysis (FIA) unit of the United States Department of Agriculture (USDA) Forest Service, they were able to assess the effects of measurement variability on several volume change estimates, including ingrowth, accretion, removals and mortality. Error due to measurement variability was minimal compared to the sampling variability, with accretion being the most sensitive to systematic measurement errors. Suty et al. (2013) used Taylor series expansion and empirical comparisons between two volume growth prediction methods to illustrate the effect of introduced bias from random measurement errors to inputs for non-linear volume growth models used in the Swedish National Forest Inventory (NFI). Similarly, Berger et al. (2014) used Taylor series expansion and Monte Carlo simulations to approximate the effects of measurement errors in four independent variables on the relative error of stem volume equations currently used in the Austrian NFI. None of these studies, however, investigated how measurement error affected broad-scale AGB estimates.

The effects of model errors on the variability of broad-scale forest inventory estimates are well described. Breidenbach et al. (2014) assessed how variability in models used by the Norwegian NFI affects biomass stock and change estimates for Norway spruce. A parametric bootstrap approach was employed to quantify the contributions of parameter estimate uncertainty, inflated model residual variance and within-plot correlation to the total uncertainty of biomass stock and change in Norway. McRoberts and Westfall (2014) used Monte Carlo simulations to examine how volume model-related variability influences broad-area estimates generated from 2178 FIA plots across a study area in northeastern Minnesota, USA. A comparison was made of the gains using species-specific models versus coniferous/deciduous nonspecific models, calibrated from a species-specific dataset collected from 2102 trees across 24 states of the northern and northeastern Unites States. Both of these authors found the model errors to be minimal contributors to the total uncertainty. However, neither studies investigated the effects of measurement error as well.

Unfortunately, very few studies have addressed the effects of all primary sources of error on broad-scale forestry inventory estimates (Temesgen et al., 2015). Mowrer and Frayer (1986) addressed the effects of measurement error, model error and sampling error by measuring the cumulative variance of five 10-year projections from a growth and yield model for pure even-aged clonal quaking aspen using both Taylor series expansion and Monte Carlo simulations. Gertner (1990) approximated the effect of all three sources for non-linear individual-tree volume functions used to estimate stand-level volume per acre. Chave et al. (2004) examined the effects of these different sources of error using permanent plot data from the moist forests of the canal region of Panama. In addition to the three aforementioned error sources, the magnitude of uncertainty from the specific model form chosen was assessed. This study is similar in that all three forms of error were empirically compared for two different sets of component models developed for lodgepole pine (*Pinus contorta*) for use in the Pacific Northwest region. In doing so, we were able to produce credible depictions of uncertainties useful for determining which model is the most reliable for future use.

1.1. Component ratio method

The FIA is charged with the task of providing stock and change estimates for a large number of national-scale forest-related variables, with their estimates of AGB being drawn upon and used for a wide range of applications. Regional-level equations for small to mid-level estimation in specific regions are publicly available and used by many individuals seeking species-specific localized component estimates of AGB. However, these suites of equations often source from an array of different studies, inconsistent methodologically and in sample size, often yielding AGB estimates that differ across regions for trees of identical size and species. To address consistency issues in estimation across regions, the national-level Jenkins equations were developed and used by FIA for national-scale estimation (Jenkins et al., 2003). Stemming from extensive meta-analysis of 2640 published equations for component and total-tree biomass, the resultant Jenkins equations are a group of 10 generalized component and total tree biomass equations with diameter at breast height (DBH) as the only independent variable.

Reservations about the low-level of species specificity of these generalized models arose when large variations of AGB estimates were observed when applied to smaller-scale operations. This was illustrated by Zhou and Hemstrom (2009) who observed Jenkins estimates of total AGB of softwoods in the state of Oregon to be 17% greater compared to regional species-specific equations. Hence, in 2009 a new component ratio method (CRM) was proposed as the standard for nationwide AGB reporting. This method uses a combination of the component ratios from the Jenkins equations, regional bole volume equations and percent bark estimates, so as to ensure consistency with regional tree-level volume estimates (Heath et al., 2008; Woodall et al., 2011). However, despite the conformance with regional-based estimates of bole volume, the reliance on the national-scale generalized Jenkins component ratios yields the same non-specificity for regional and finer-scale applications.

A new set of species-specific CRM component equations for lodgepole pine (*P. contorta*) are presented here for comparing total uncertainties with those produced from the current regional equations. These new CRM equations are heretofore referred to as the CRM equations; the hybrid CRM method described in the previous paragraph will be referred to as CRM-FIA. These new CRM equations originate from a pilot research study aimed at developing new regional-level models for AGB consistent across regions. Rather than rely on the component ratios from the Jenkins models and the current regional volume models, these equations directly predict the proportion of tree-level AGB for bole wood, bark, branch wood and foliage. With these new CRM equations for component AGB stemming from one study, rather than a host of different studies as with the current regional equations, and with the specificity for use in smaller, more localized operations, the prior stated issues with consistency, specificity and congruence are addressed. The three independent variables for these new models are DBH, total height (HT) and height to crown base (HTCB).

To evaluate the performance of these new equations relative to the current regional approach for estimating tree-level AGB for lodgepole pine, comparisons of the magnitude of the cumulative propagated error will be made between the two sets of equations. Using Monte Carlo simulations, and applying both sets of equations to cluster sample plot data associated with destructively sampled trees used for development of the new CRM models, we were able to quantify the effects of measurement and model error