Forest Ecology and Management 270 (2012) 108–116

Contents lists available at SciVerse ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Consequences of alternative tree-level biomass estimation procedures on U.S. forest carbon stock estimates

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ARTICLE INFO

Article history:
Received 8 December 2011
Received in revised form 11 January 2012
Accepted 12 January 2012
Available online 15 February 2012

Keywords:
Forest inventory
Carbon accounting
Tree volume
Climate change
Tree biomass

ABSTRACT

Forest ecosystems are the largest terrestrial carbon sink on earth and their management has been recognized as a relatively cost-effective strategy for offsetting greenhouse gas emissions. Forest carbon stocks in the U.S. are estimated using data from the USDA Forest Service, Forest Inventory and Analysis (FIA) program. In an attempt to balance accuracy with consistency, the FIA program recently developed the component ratio method which utilizes regional volume models to replace the existing set of generalized allometric regression models used to estimate biomass and carbon stocks. This study describes the impact of the transition from the generalized allometric regression models to the component ratio method on the National Greenhouse Gas Inventory estimates by comparing estimates of carbon stocks from both approaches by common tree species and varying spatial scales (e.g., tree to national scale). Results for the 20 most abundant tree species in the 48 conterminous states of the U.S. suggest there is a significant difference in estimates of carbon stocks at the plot and national scales for the two estimation approaches. The component ratio method decreased estimates of national carbon stocks by an average of 16% for the species in the study. The observed reductions in carbon estimates can be attributed to incorporation of tree height as a predictor variable into species-specific volume models used to estimate tree biomass and carbon stocks. While the transition from the generalized allometric regression models to the component ratio method is procedural in nature, it may have important implications for national and global forest carbon sink estimates and the perception of the role forests play in mitigating the effects of atmospheric carbon dioxide. By combining regional accuracy with a nationally consistent approach, the component ratio method reflects a critical first step in aligning estimates of forest carbon stocks in the U.S.'s National Greenhouse Gas Inventory with estimates of tree volume in the FIA database.

Published by Elsevier B.V.

1. Introduction

Forest ecosystems represent the largest terrestrial carbon (C) sink on earth (Fan et al., 1998; Pacala et al., 2001; Pan et al., 2011), such that the United Nations Framework Convention on Climate Change (UNFCCC, 2011) has recognized their management as a relatively cost-effective strategy for offsetting greenhouse gas (GHG) emissions. As part of the Convention, countries are required to submit national reports detailing estimates of emissions and removals of GHGs (UNFCCC, 2011). These UNFCCC requirements, along with interest in integrating forest C sequestration into a cap-and-trade program to reduce GHG emissions (Daniels, 2010) and the use of forest-derived biomass for energy (Domke et al., 2012), have heightened the scrutiny on forest C accounting and led to continual refinement of estimation procedures (Smith et al., 2003, 2006; Jenkins et al., 2003; Heath et al., 2009; Woodall et al., 2011).

Forest C stocks in the U.S. are estimated using data from the national forest inventory conducted by the USDA Forest Service, Forest Inventory and Analysis (FIA) program. Carbon estimates for ecosystem components such as litter, down dead wood, and soil organic matter are calculated using models based on geographic area, forest type, and in some cases, stand age (Woudenberg et al., 2010; EPA, 2011). Estimates of standing live and dead tree C stocks are based on biomass estimates obtained from inventory tree data. In the past, the FIA program used a set of generalized allometric regression models to predict oven-dry biomass in tree components for all tree species in the U.S. (Jenkins et al., 2004). This approach hereafter referred to as "Jenkins" provided a nationally consistent method for estimation of biomass and C stocks by tree component, which was useful at large scales and required a

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0378-1127/$ - see front matter Published by Elsevier B.V.
doi:10.1016/j.foreco.2012.01.022

single field-based variable – tree diameter at breast height (dbh; 1.37 m) – as a predictor variable.

The Jenkins method was developed using a modified version of a type of meta-analysis (Pastor et al., 1984) where regression predictions were refit for species and groups of species using pseudo-data rather than developing a formal statistical model for combining regression results (Jenkins et al., 2003). Species were organized by taxonomic and geographical categories into 10 tree species groups (five softwood groups, four hardwood groups, and one woodland group; Jenkins et al., 2004). While the simplicity of this approach is useful at large scales, the generalized nature of the Jenkins method may not account for tree-, site-, or region-level variation in tree attributes (e.g., basal flare) or growing conditions (e.g., site productivity). This limits the accuracy of the Jenkins approach at local and regional scales and, since Jenkins biomass predictions are based solely on dbh, they may not agree with FIA volume estimates, which incorporate tree height or site index (SI) as a proxy for tree height, cull deductions, and in some cases, basal area into predictions (Woudenberg et al., 2010).

In an attempt to balance accuracy with consistency, the FIA program developed the component ratio method (CRM) for biomass estimation (Heath et al., 2009; Woodall et al., 2011). The CRM uses sound bole volume in standing live and dead trees along with component ratios from Jenkins et al. (2004) and an adjustment factor to estimate tree component biomass (Woodall et al., 2011). The CRM maintains national consistency by standardizing the use of regional volume models which incorporate tree-, and in some cases, stand-level predictors, thereby aligning estimates of tree volume, biomass, and C at multiple spatial scales. The Jenkins and CRM tree biomass approaches result in different estimates of biomass in the FIA database which, in turn, will produce different estimates of C stocks via the Carbon Calculation Tool (CCT; Smith et al., 2007) for national reports. These differences are entirely procedural, in that the disparities in estimates are an artifact of different estimation procedures in the FIA program rather than actual forest C flux. Further, all C stock estimates in national reports are calculated using the same estimation approach over time (1990–present) such that C stock comparisons between published reports using different estimation methods are not valid. Examining the implications for C accounting between the Jenkins and CRM approaches for estimation of biomass and C stocks is paramount to improving the accuracy and transparency of the U.S.'s National Green House Gas Inventory (NGHGI).

The goal of this study is to estimate the effect that procedural changes within the FIA program will have on NGHGI estimates by comparing estimates of live tree C stocks calculated using the Jenkins and CRM tree biomass estimation approaches at multiple spatial scales. The specific objectives of the analysis are: (1) to estimate differences in live-tree C stocks calculated using the CRM and Jenkins approach at multiple spatial scales, (2) to examine tree-level factors contributing to differences in live-tree C stocks between the CRM and Jenkins approach, and (3) to describe implications of the tree-level volume model changes on national C reporting and suggest directions for future research.

2. Methods

The Jenkins approach and CRM for individual tree biomass estimation are briefly described in this section. For complete documentation, see Jenkins et al. (2004) for the Jenkins approach and Woodall et al. (2011) for the CRM.

2.1. Jenkins approach for tree biomass estimation

The Jenkins approach is based on a single model form which utilizes species group-specific model parameters and tree diameter at breast height to estimate total aboveground biomass for all tree species in the U.S. (Jenkins et al., 2003, 2004). A second model is required, along with tree dbh and component-specific hardwood and softwood model parameters, to estimate the ratio of total aboveground biomass in the foliage, coarse roots, stem bark, and stem wood of the tree. Stump biomass is estimated according to Raile (1982) where stump height aboveground is assumed to be 30.48 cm, and top and branch biomass is estimated by subtracting the total aboveground biomass estimate from the sum of all aboveground component (foliage, stem bark, stem wood, and stump) biomass estimates.

2.2. Component ratio method (CRM) for live-tree biomass estimation

The CRM was developed, in part, to facilitate estimation of tree component biomass from the central stem volume in standing live and dead trees. The CRM is a nationally consistent estimation procedure which relies on regional volume models and specific gravity information to estimate tree biomass (Heath et al., 2009; Woodall et al., 2011). Gross volume is estimated using regional models which rely on tree height or a height surrogate such as SI, dbh, and in some cases, basal area to estimate volume in the central stem of the tree. Sound volume for live trees is estimated from gross volume by incorporating deductions for rotten or missing volume in the central stem. Cull deductions for live trees $\geqslant$12.7 cm dbh include the percentage of rotten or missing volume, estimated in the field to the nearest 1%, in the merchantable bole along with any additional cull due to broken top (Woudenberg et al., 2010). Regional gross and sound volume model forms, model parameter estimates, and references can be found in Woodall et al. (2011). Sound volume estimates are multiplied by wood specific gravity to convert to merchantable stem biomass. The same steps are used to estimate bark biomass, only replacing wood specific gravity with bark specific gravity and multiplying by the percent bark volume. The sum of bark and merchantable stem biomass estimates is the merchantable bole biomass estimate. The merchantable bole biomass estimate from the CRM is divided by the merchantable bole biomass estimate from the Jenkins approach to produce an adjustment factor, which is multiplied by each Jenkins component biomass estimate to estimate tree component biomass values for the CRM. Component ratios from the Jenkins approach cannot be applied directly to CRM bole biomass estimates because the CRM and Jenkins bole biomass estimates are calculated differently. It was assumed that the component proportions were the same for both approaches so the adjustment factor is used to correct for the difference between the CRM and Jenkins bole biomass estimates (Heath et al., 2009).

2.3. Study area and tree species characteristics

The 20 most abundant (number of trees) tree species across the 48 conterminous states of the U.S. were selected to assess differences in estimates of oven-dry biomass and C stocks in the study due to difference in estimation methods (Table 1). The species selected for analysis represent more than 52% of all live trees $\geqslant$12.7 cm dbh in the FIA database. There were 11 conifers representing the five softwood species groups (cedar/larch, Douglas-fir, true fir/hemlock, pine, and spruce) identified in Jenkins et al. (2003, 2004) and nine deciduous species representing the four hardwood species groups (aspen/alder/cottonwood/willow, soft maple/birch, mixed hardwood, and hard maple/oak/hickory/beech). Note that Utah juniper (*Juniperus osteosperma* (Torr.) Little) and two-needle pinyon (*Pinus edulis* Engelm.) were excluded from the analysis because they are classified as woodland species in the FIA database.