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

Grant M. Domke [a,*], Christopher W. Woodall [a], James E. Smith [b], James A. Westfall [c], Ronald E. McRoberts [a]

[a] USDA Forest Service, Northern Research Station, 1992 Folwell Ave., St. Paul, MN 55108, USA
[b] USDA Forest Service, Northern Research Station, 271 Mast Rd., Durham, NH 03824, USA
[c] USDA Forest Service, Northern Research Station, 11 Campus Blvd., Suite 200, Newtown Square, PA 19073, USA

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

---

* Corresponding author. Tel.: +1 651 649 5138; fax: +1 651 649 5140.
E-mail addresses: gmdomke@fs.fed.us (G.M. Domke), cwoodall@fs.fed.us (C.W. Woodall), jsmith11@fs.fed.us (J.E. Smith), jameswestfall@fs.fed.us (J.A. Westfall), rmcroberts@fs.fed.us (R.E. McRoberts).

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 pseudodata 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.

Table 1
Common and scientific names for the 20 most abundant tree species in the FIA database for the 48 conterminous states of the U.S.

Common name	Scientific name	Number of trees	Percent of total trees
Balsam fir	*Abies balsamea* (L.) Mill.	42,788	1.66
Subalpine fir	*Abies lasiocarpa* (Hook.) Nutt.	37,117	1.44
Engelmann spruce	*Picea engelmannii* Parry ex Engelm.	34,948	1.36
Lodgepole pine	*Pinus contorta* Dougl. Ex. Loud.	76,697	2.98
Slash pine	*Pinus elliottii* Engelm.	46,141	1.79
Ponderosa pine	*Pinus ponderosa* Dougl. Ex Laws.	64,028	2.48
Eastern white pine	*Pinus strobus* L.	32,551	1.26
Loblolly pine	*Pinus taeda* L.	241,818	9.38
Douglas-fir	*Pseudotsuga menziesii* (Mirb.) Franco	128,311	4.98
Northern white-cedar	*Thuja occidentalis* L.	47,652	1.85
Eastern hemlock	*Tsuga canadensis* (L.) Carr.	31,518	1.22
Red maple	*Acer rubrum* L.	151,543	5.88
Sugar maple	*Acer saccharum* Marsh.	86,273	3.35
Sweetgum	*Liquidambar styraciflua* L.	58,994	2.29
Yellow-poplar	*Liriodendron tulipifera* L.	39,836	1.55
Quaking aspen	*Populus tremuloides* Michx.	79,289	3.08
Black cherry	*Prunus serotina* Ehrh.	31,841	1.24
White oak	*Quercus alba* L.	58,581	2.27
Northern red oak	*Quercus rubra* L.	38,151	1.48
Post oak	*Quercus stellata* Wangenh.	29,393	1.14

Among the study species, loblolly pine ($n = 241{,}818$), red maple ($n = 151{,}543$), Douglas-fir ($n = 128{,}311$), sugar maple ($n = 86{,}273$), and quaking aspen ($n = 79{,}289$) were the five most abundant trees in the FIA database, collectively representing more than 50% of the total sample (Table 1). Mean dbh ranged from 17.4 to 36.1 cm for species in the study with Douglas-fir having the largest mean dbh followed by ponderosa pine (31.3 cm (mean) ± 19.2 cm (±1 SD)), northern red oak (29.9 ± 13.3 cm), yellow-poplar (27.8 ± 13.3 cm), and white oak (27.0 ± 12.1 cm) (Table 2). The range of dbh values varied widely by species in the analysis, with Douglas-fir showing the largest variation across its respective range. Tree height measurements also varied substantially across all tree species in the analysis. Yellow-poplar had the largest mean height (22.3 ± 6.7 m) followed by Douglas-fir (21.7 ± 12.2 m), northern red oak (19.6 ± 5.3 m), white oak (18.8 ± 5.5 m), and sugar maple (18.6 ± 4.4 m). Douglas-fir was the tallest species in the study, and not surprisingly, had the largest variation in tree height, ranging from 1.5 to 91.4 m across its respective range (Table 2).

A mean cull ratio for each species was calculated by taking the difference between gross and sound volume estimates and dividing by gross volume to assess the proportion of volume deemed missing or rotten in the merchantable bole and tops of trees in the study. With the exception of northern white-cedar, all hardwood tree species had larger cull ratios than softwoods, with quaking aspen having the largest cull ratio at more than 5% (Table 2).

2.4. Data and analysis

Field data collected by the FIA program during the most recent inventories (1999–2010) in the 48 conterminous states of the U.S. were used in this analysis (Bechtold and Patterson, 2005). FIA plots are systematically distributed approximately every 2428 hectares across the 48 conterminous states. Each plot which contains a forest land use is comprised of a series of smaller plots (i.e., subplots) where tree- and site-level attributes – such as dbh height and tree height – are measured at regular temporal intervals (Bechtold and

Table 2
Summary statistics of mean tree diameter (DBH), height, and cull ratio (proportion of rotten and missing cull) for the 20 most abundant tree species in the FIA database for the 48 conterminous states of the U.S.

Species	DBH (cm)			Height (m)			Cull ratio	
	Mean	Minimum[a]	Maximum	Mean	Minimum	Maximum	Mean	SD
Balsam fir	17.4	12.7	53.6	12.6	1.5	29.6	0.00	0.04
Subalpine fir	21.6	12.7	136.7	14.3	2.1	44.8	0.03	0.44
Engelmann spruce	26.8	12.7	124.5	16.4	2.4	65.5	0.01	0.23
Lodgepole pine	22.0	12.7	234.2	15.6	0.9	43.9	0.01	0.17
Slash pine	20.2	12.7	106.4	16.4	4.6	39.6	0.00	0.24
Ponderosa pine	31.3	12.7	176.0	15.7	1.5	72.5	0.01	0.11
Eastern white pine	27.0	12.7	112.8	16.9	1.5	45.4	0.00	0.05
Loblolly pine	21.2	12.7	110.7	16.0	2.1	45.4	0.00	0.07
Douglas-fir	36.1	12.7	310.1	21.7	1.5	91.4	0.01	0.22
Northern white-cedar	21.1	12.7	88.4	11.4	1.5	27.1	0.05	0.23
Eastern hemlock	25.0	12.7	114.8	14.2	2.4	44.2	0.01	0.08
Red maple	22.0	12.7	123.2	17.3	1.5	43.6	0.04	0.34
Sugar maple	23.4	12.7	127.0	18.6	1.5	44.2	0.02	0.12
Sweetgum	22.1	12.7	180.3	18.4	3.0	60.7	0.04	0.42
Yellow-poplar	27.8	12.7	123.2	22.3	2.1	48.2	0.02	0.22
Quaking aspen	20.8	12.7	72.9	16.6	1.5	37.2	0.05	0.51
Black cherry	22.6	12.7	104.9	16.7	1.8	41.5	0.03	0.19
White oak	27.2	12.7	114.8	18.8	1.8	47.2	0.02	0.14
Northern red oak	29.9	12.7	122.2	19.6	1.5	42.7	0.02	0.16
Post oak	23.8	12.7	114.8	14.1	2.7	33.8	0.03	0.35

[a] The analysis was restricted to live trees with a dbh $\geqslant$12.7 cm.

Patterson, 2005). In this study, all live trees with a dbh ⩾12.7 cm were included in the analysis. Estimation methods for biomass in woodland species, standing dead trees, and live saplings (trees with dbh between 2.5 and 12.6 cm) differ from live tree methods for trees ⩾12.7 cm dbh so they were excluded from the analysis. A total of 1,357,470 live trees were sampled throughout the 48 conterminous states on 88,725 plots (Table 1, and Fig. 1). Mean differences in tree-level C stock estimates between the CRM and Jenkins model approaches were compared by first summing estimates of total oven-dry biomass (top and branches, merchantable bole, stump, and belowground) for each tree, multiplying by 0.5 (carbon content multiplier), and computing the mean difference for each species across the 48 conterminous states of the U.S. Mean differences of tree level C estimates for the two approaches were not tested for statistical significance for two reasons. First, information was not available to estimate the uncertainty of the tree level C predictions. Second, differences between estimates for individual trees on the same plot were expected to be highly correlated. Techniques for accommodating these correlations, particularly with different numbers of trees per plot, are beyond the scope of this study. However, trend analyses were conducted at the tree level by holding dbh constant (at 12.7, 22.9, and 33.0 cm) and examining the effects of tree height on estimates of bolewood C for each estimation method.

Estimates of plot-level C stocks were separated into hardwood and softwood groups for each of five U.S. regions (Fig. 1). The uncertainty of mean plot-level estimates can be attributed to two sources, the uncertainty of individual tree-level estimates and plot-to-plot sampling variability. The uncertainty of the tree-level estimates is generally regarded by national forest inventory programs as negligible relative to the sampling variability and, therefore, was ignored for these analyses. Mean differences in plot-level estimates were calculated in three steps. First, the estimate for each tree was calculated using both the Jenkins and the CRM approaches. Second, plot level differences were calculated as the difference between the Jenkins estimate of the plot total and the CRM estimate of the plot total. Mean plot-level differences were calculated as the mean over all plots of the previously calculated plot-level differences. A t-test was used to determine the statistical significance in the mean differences; in effect, the test was a paired t-test because it focused on mean differences rather than differences of means. The paired t-test is not particularly sensitive to deviations from normality; however, the data were also compared using the non-parametric Wilcoxon signed-rank test. The results from the Wilcoxon signed-rank test were consistent with the paired t-tests so paired t-test values were reported. The null hypothesis was that the mean difference between estimates of C stocks was not significantly different from zero ($\alpha = 0.01$). Spearman rank correlation analysis was also conducted at the plot-level to assess relationships between model parameter estimates and site-level factors.

Estimates of population C stocks were compared by calculating the difference between Jenkins and CRM estimates for each plot, computing the mean difference across plots within each stratum (nonoverlapping subdivision of the population into estimated "forest" and "non-forest" classifications), multiplying each stratum mean by stratum weight, summing the weighted stratum means, and then multiplying by the total land area to arrive at the population total (Cochran, 1977; Bechtold and Patterson, 2005). Stratification is an approach used by the FIA program to reduce variances of volume/biomass/C estimates and it is also appropriate to use it to assess the differences in population estimates due to the two estimation approaches. The mean differences in population estimates were compared using paired t-tests. All analyses were conducted using R statistical software (R Development Core Team, 2011).

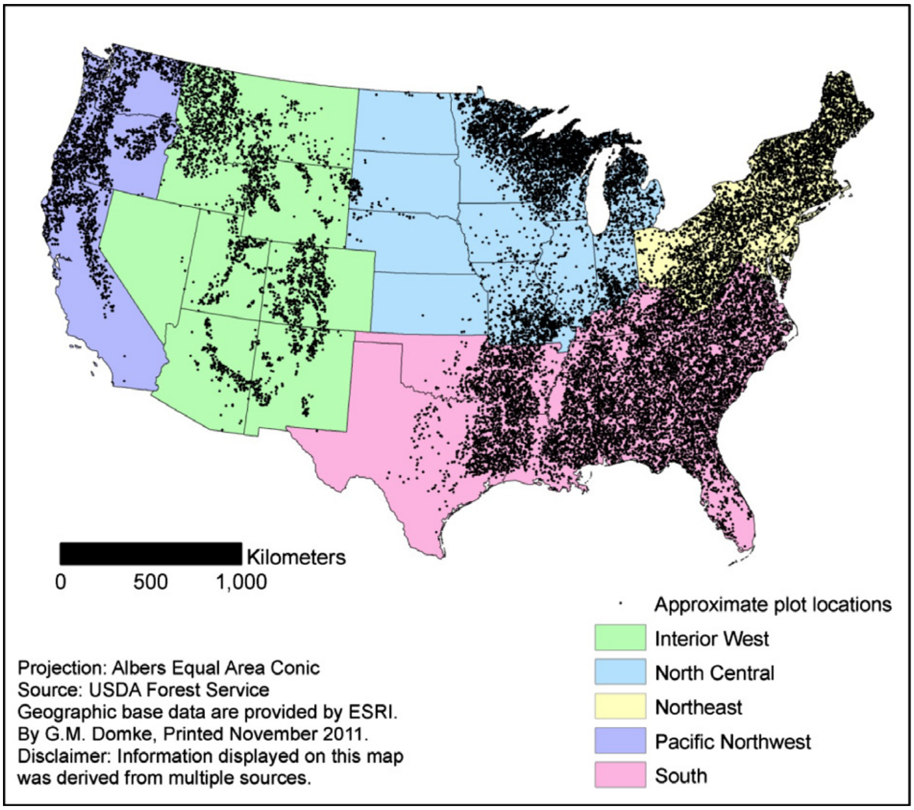

Fig. 1. Study regions and approximate plot locations of FIA plots used in this study.

3. Results

Given the large variation in tree height and dbh for the species in this study, Douglas-fir and quaking aspen were selected for regional analysis given their abundance in the database and large geographic ranges. Douglas-fir was found in all five geographic regions and had large differences between regions for both tree height and dbh. The largest Douglas-fir trees were located in the PNW (Pacific Northwest), where mean dbh was 41.6 ± 30.7 cm (±1 SD) and mean height was 25.4 m (±13.2 m). The dbh of Douglas-fir trees in the PNW were, on average, 23% larger than Douglas-fir trees in the SO (South) region, 37% larger in the IW (Interior West) region, 54% larger in the NC (North Central) region, and 61% larger in the NE (Northeast) region. Mean tree heights for Douglas-fir across the five regions showed a similar trend, although trees in the SO were 63% shorter than trees in the PNW. Quaking aspen trees were found in all but the SO region. Quaking aspen dbh was similar across the four regions in which it was found, with trees in the PNW having the largest dbh (23.4 ± 11.1 cm), on average. Mean tree heights for quaking aspen were similar in the NC and NE regions at 17.7 m (±3.8 m) and 17.7 m (±4.0 m), respectively, and nearly the same in the PNW and IW at 14.1 m (±6.4 and ±4.7 m, respectively).

The mean tree-level estimates of C stocks calculated from the Jenkins approach and CRM were substantially different for all tree species in the study (Fig. 2). Estimates of tree-level C stocks for the majority of species decreased compared to the Jenkins approach, with northern white-cedar showing the largest decrease at 41%. Tree-level C stock estimates for slash pine and loblolly pine increased by 24% and 8%, respectively. While these increases are small relative to decreases in estimates of C stocks for many species, loblolly pine is by far the most abundant tree species in the FIA database so even small changes will likely have a substantial effect on national estimates of plot- and population-level C stocks. Estimates of C stocks were further assessed at the tree level by combining species into hardwood and softwood groups and comparing by dbh class. In general, differences in the estimates of tree-level C stocks between the CRM and Jenkins decreased with increasing dbh (Fig. 3).

Mean differences in plot-level C stock estimates for the two estimation methods were assessed by hardwood and softwood species group for each region in the 48 conterminous states of the U.S. (Fig. 4). All plot-level C stock differences by region and species group were significantly different from zero ($\alpha = 0.01$). The largest absolute plot level difference was in the PNW region, where estimated softwood C stocks decreased by more than 5.7 Mg ($t = -31.01$, 8758 d.f., $p < 0.01$) for the CRM. Only two hardwood species (quaking aspen and yellow-poplar) in the study were located in the PNW, but there was still a significant decrease in estimated C stocks for the hardwood group. Mean softwood C stock estimates decreased by more than 32% (compared to the Jenkins approach) in the NC region while softwood C estimates decreased by more than 24%. Mean plot-level differences for the softwood group in the IW decreased by more than 30%, while the hardwood group, which only included quaking aspen, decreased by more than 25%. Mean C stock differences for the softwood group in the SO region increased by more than 10%. This is not surprising, given the two most common softwood species (loblolly pine and slash pine) in the region showed tree-level increases in C stock estimates. Mean plot-level C stock estimates for the hardwood species group – which is dominated by yellow-poplar and red maple – decreased approximately 17%. Mean plot-level C stock estimates in the NE region decreased by more than 24% for the softwoods group and 8% for hardwoods.

Estimated population differences, which include all species in the study by geographic region were also significantly different from zero ($\alpha = 0.01$; Fig. 5). The largest decrease was in the IW, where total estimated C stocks decreased by nearly 28% (445 ± 27Tg (95% confidence interval)). The large decrease is driven by several softwood species (lodgepole pine, Douglas-fir, subalpine fir, Engelmann spruce, and ponderosa pine) which showed large tree-level decreases. Estimated C stocks in the NC and NE regions decreased by more than 27% (268 ± 12Tg) and 11% (211 ± 12Tg), respectively. Population estimates decreased by nearly 12% (215 ± 16Tg) in the PNW, which is due in large part to Douglas-fir which was, by far, the most abundant species in the region. The SO region had the smallest decrease in total C stock estimates at 6% (119 ± 29Tg) which is due, in part, to the increases in tree-level C stock estimates in the two most abundant softwood species (loblolly pine and slash pine) in the region.

An examination of tree height effects on bolewood C stocks indicated, as expected, that Jenkins estimates did not vary by region or tree height at specific tree dbh for Douglas-fir or quaking aspen (Fig. 6). Estimates of CRM C stocks, on the other hand,

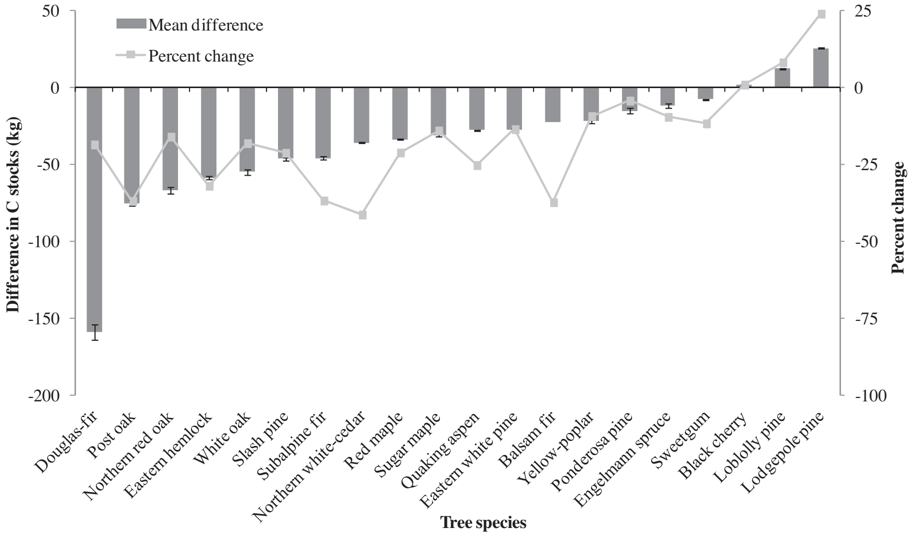

Fig. 2. Mean difference (with 95% confidence intervals) in tree-level C (kg) stocks between estimation approaches (compared to the Jenkins approach) along with percent change (compared to the Jenkins approach) for the 20 most abundant tree species in the 48 conterminous states of the U.S.

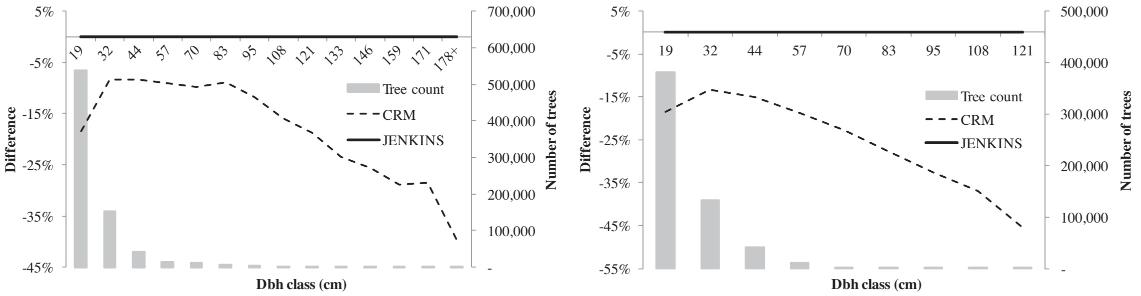

Fig. 3. Percent difference (as compared to Jenkins) in total tree-level C stocks for softwoods (left) and hardwoods (right) by dbh class for the two estimation methods along with the distribution of trees by dbh class for each group.

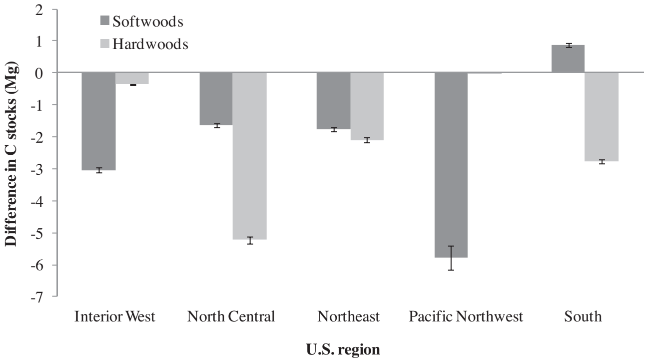

Fig. 4. Mean difference (with 95% confidence intervals) in plot-level C (Mg) stocks between estimation approaches (compared to the Jenkins approach) for the 20 most abundant hardwood and softwood species by region in the 48 conterminous states of the U.S. All differences were significantly different from zero ($\alpha = 0.01$).

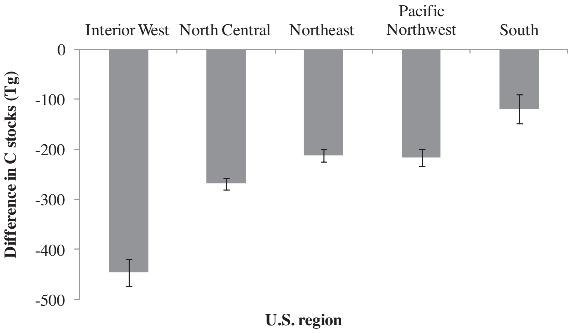

Fig. 5. Total estimated difference (with 95% confidence intervals) in C stocks (Tg) between estimation approaches (compared to the Jenkins approach) for the 20 most abundant hardwood and softwood species by region in the 48 conterminous states of the U.S.

generally increased with increasing tree height. CRM estimates for Douglas-fir at 12.7 cm dbh showed distinct linear trends over tree height, revealing localized differences in volume models – constructed using local data with the result that parameter estimates are specific to local areas – used to estimate merchantable bole biomass and C stocks (Fig. 6). The majority of CRM C stock estimates at 12.7 cm dbh fell below Jenkins estimates and intersected the Jenkins values at substantially different tree heights. CRM estimates for Douglas-fir trees at 22.9 cm dbh intersected Jenkins C stock estimates over a much narrower range of tree heights from 17 to 23 m. The trend continued at 33.0 cm dbh, where CRM estimate trend lines intersected Jenkins estimates at tree heights ranging from 22 to 28 m. While estimates of CRM bolewood C stocks intersected and, in some cases, exceeded estimates of Jenkins C stocks, the majority of CRM estimates at all three dbh values were less than estimates of Jenkins bolewood C stocks for Douglas-fir. Quaking aspen showed similar trends although the CRM-tree height relationships were much less defined, particularly at larger dbh (Fig. 6). At 12.7 cm dbh, all estimates of CRM bolewood C stocks fell below estimates of Jenkins C stocks and there were clear linear trends over tree height pointing to localized differences in volume models used to obtain bolewood C stock estimates. Estimates of CRM bolewood C stocks approached, and in some cases, exceeded estimates of Jenkins biomass at 22.9 cm dbh. However, the linear trends over tree height were much less obvious at the larger dbh value. There were far fewer quaking aspen trees at 33.0 cm dbh and the CRM estimates – the majority of which were less than Jenkins estimates – are widely scattered across tree heights.

4. Discussion

As a means of improving the national consistency, transparency, and local accuracy of the U.S.'s official NGHGI of forest C stocks, the FIA program has adopted the CRM for tree volume/biomass estimation in lieu of the Jenkins approach. The transition from the Jenkins approach to the CRM for biomass estimation results in significant differences in estimates of C stocks at the plot and national levels. In most cases, Jenkins values are larger than CRM estimates, suggesting future biomass and C stock estimates will be substantially less than those reported to date. It appears that biomass and C stock estimates will decrease, on average, by 16% for the 20 most common species across the 48 conterminous states of the U.S. Assuming the decrease in estimated C stocks holds for the majority of species and states in the FIA database, the C stock estimates produced in future NGHGI reports will be substantially less than previous reports. It is important to note that estimates of C stocks will be calculated using the same estimation approach (e.g., CRM) from base years forward (1990–present) such that future reports will reflect changes in C stocks that are unaffected by methodological differences. As the change in volume/biomass models is not a trivial exercise for the nation, the drivers of differences between the two estimation approaches and benefits of the CRM approach have been elucidated in this study.

First, it appears that across the diverse species and growing conditions of the U.S. that inclusion of tree metrics (e.g., height) that account for this variability may afford greater tree and regional volume/biomass specificity. At the individual tree level, species had substantial variation in dbh and height (as affected by site quality) throughout their respective ranges and, as a result, large variation in individual tree biomass and C stocks. While these differences may be the result of substantially different size- and/or age-class structures across the diverse biomes of the U.S., holding dbh constant by species revealed large regional differences in tree

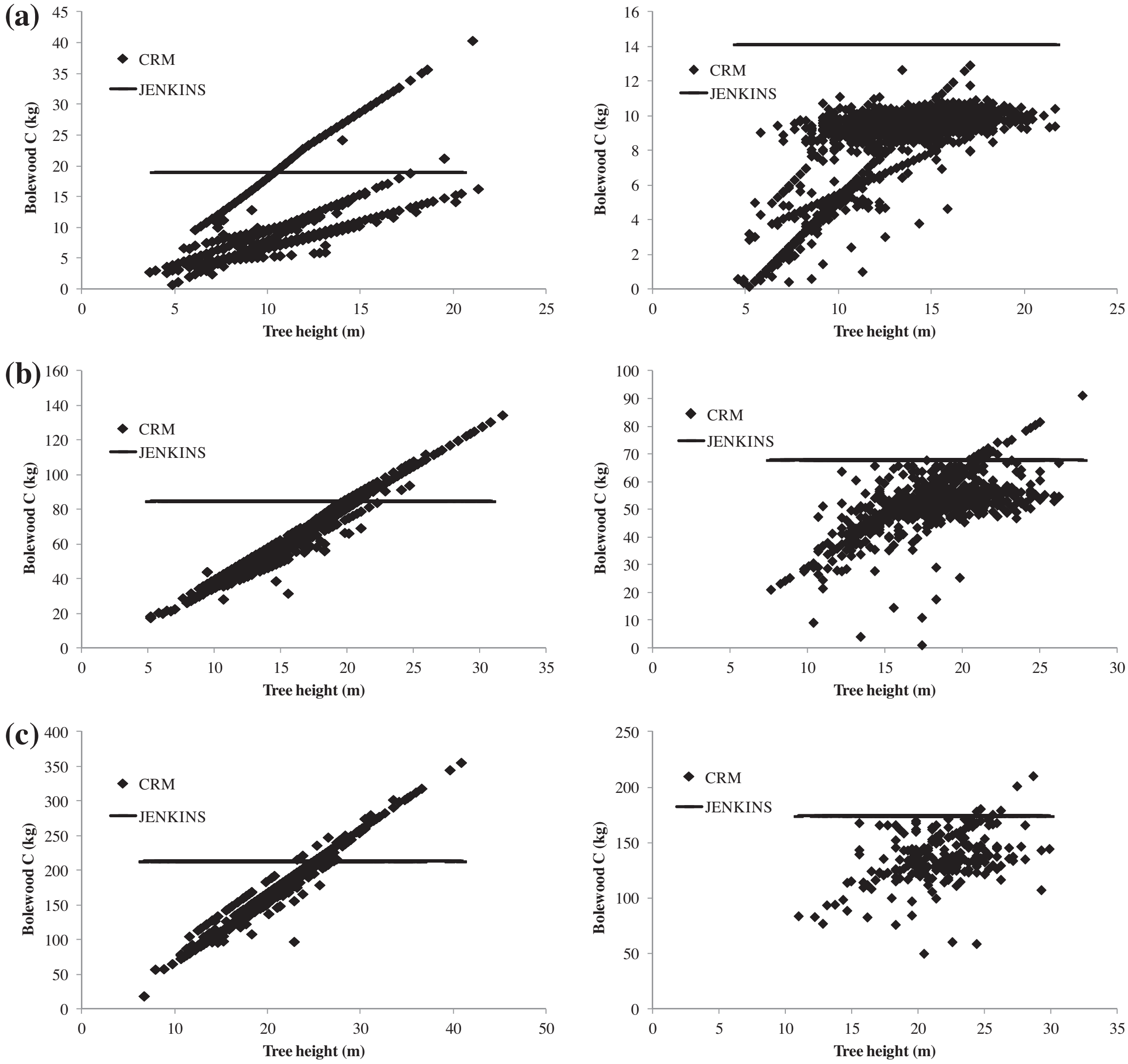

Fig. 6. Comparison of estimated bolewood C stocks (kg) for Douglas-fir (left) and quaking aspen (right) by estimation method, tree height, and diameter: (a) 12.7, (b) 22.9, and (c) 33.0 cm.

height. These differences are without question related to growing conditions across regions (Lambert et al., 2005) in conjunction with disturbance history inclusive of forest management practises (e.g., stand density control) (Woodall et al., 2006). Regional differences in growth form and habit may also be factors for species with large geographic ranges or those growing across a range of elevations. Several studies suggest that dbh alone is adequate for biomass estimation (Ter-Mikaelian and Korzukhin, 1997; Jenkins et al., 2003), particularly at local scales, while others suggest that both dbh and tree height should be included when available (Lambert et al., 2005), particularly at large scales. Statistical correlations between CRM and Jenkins bole biomass and several tree- and site-level variables suggest that estimates of biomass and C stocks, and differences between estimation methods, may be attributable to a complex of tree- and site-level factors. Among these, dbh was clearly the most important variable followed by tree height, which had substantial variability at constant dbh. The correlation between dbh and tree height (and other variables) results in confounding factors, which make it difficult to conclusively define variables leading to significant differences in estimates of C stocks between the CRM (which relies on volume models that utilize dbh and tree height, among other variables) and Jenkins approach (which relies on dbh alone). Nevertheless, there are clear differences in tree height with dbh held constant and these differences influence estimates of tree biomass and C stocks.

Second, the CRM and Jenkins approach differ in their methods of delineating regions of the U.S. The first step of the CRM approach (i.e., volume estimation) is to construct a volume model based on a tree's location (e.g., state or region) and species. In contrast, the Jenkins approach requires only the selection of a species group assignment for any given tree. These procedural and critical differences in estimation methods result in substantial variation in regional estimates of biomass and C stocks for the species in this study, with the largest differences in the western states. This may be partially due to the relatively large size of conifers in the PNW and IW regions as well as differences in geographic locations from which data were obtained for developing Jenkins biomass models and CRM volume models. The Jenkins model for Douglas-fir is based on a pool of 11 biomass regression models specific to Douglas-fir throughout the western U.S. This is unique among Jenkins biomass models in that most parameters for the models were estimated for a group of species. CRM estimates for Douglas-fir are state-specific and include dbh, height, and cull deductions, the latter of which likely contribute to differences between the two estimation methods. The Jenkins model for subalpine fir is based on two studies specific to the species and 30 studies of other true fir and hemlock species. This generalized model led to biomass estimates more than 36% larger than CRM estimates, where the volume models used to derive biomass rely on dbh and height from specific states within each region.

Combining softwoods and hardwoods at the plot level illustrated the large disparity in estimated C stocks between the two functional groups as well as the large differences between estimation methods. The difference between estimation methods is the result of the adjustment factor in the CRM, where bole biomass calculated from a set of gross and sound volume models which incorporate dbh, height, cull deductions and, in some cases, basal area and site index is divided by Jenkins bole biomass which is based on a ratio of total aboveground biomass calculated from dbh alone. This disparity scaled to the population level for all species in the study decreases estimates of national C stocks by more than 1,260Tg (±96Tg). The Jenkins approach was developed at a time when tree height estimates were not available for many regions in the FIA database so dbh alone was the most consistent and reliable metric available nationally (Jenkins et al., 2003). Most regions now measure tree height directly or have a reliable proxy for tree height so using species- and species group-specific volume models (Woudenberg et al., 2010; Woodall et al., 2011) in conjunction with nationally consistent species-specific gravity values for wood and bark (Miles and Smith, 2009) should improve regional, and thus national accuracy while maintaining national consistency.

The adoption of the CRM for estimation of tree biomass and C stocks will substantially reduce estimates of national C stocks, but will this procedural change indeed improve consistency and accuracy? As the CRM exhibits regional accuracy (e.g., height incorporation as a surrogate of regional specificity) and national consistency (e.g., ratios of biomass components using the Jenkins approach), it may improve accuracy without much sacrifice of consistency across regional boundaries. Furthermore, as the FIA database and the U.S.'s official forest inventory reports (Smith and Heath, 2008) use FIA volume models and CRM, the CRM will afford consistency across national reports whether they are for a NGHGI or national biomass assessment. Avoiding "double accounting" of forest resources is a critical objective of the NGHGI. Beyond accounting consistency and site quality incorporation it has been suggested that climate change may subject U.S. forests to more episodic disturbance events of increasing intensity (Ryan et al., 2010). Incorporation of height and cull metrics into volume/biomass models should increase their accuracy (Lambert et al., 2005).

Despite possible gains in accuracy and consistency with adoption of the CRM, the approach is not without limitations and needed improvements. The CRM relies on the Jenkins approach to estimate component biomass estimates except for stump biomass (Raile, 1982), which is inconsistent with other component calculations in the CRM. Furthermore, there are hurdles to estimating biomass and C stocks for trees lacking tree height measurements (e.g., idiosyncrasies in older, periodic inventories). This is of particular concern in the NGHGI, where estimation often begins in the 1990 baseline year. There are also some regional volume models used in the CRM which rely on total tree height estimates (rather than actual tree height) or SI as a proxy for tree height to estimate merchantable stem volume. These volume models may not capture site-level factors which affect tree height, potentially leading to over or underestimates of biomass and C stocks. Although the CRM is a step forward, future research should explore viewing trees as a continuum of biomass/C stocks replete with rotten sections, missing tops, and site-quality restricted heights as opposed to more idealized views of only one volume/biomass value for each dbh value. Furthermore, the CRM and Jenkins approaches are based on traditional volume/biomass studies conducted for merchantable tree species on sites of sufficient quality to support forest land management. A holistic approach to site and species selection is suggested that should improve volume/biomass estimation for all tree species on all forest sites benefitting industries beyond those of traditional forest management (e.g., bioenergy).

5. Conclusions

The CRM results in estimates of C stocks that are, on average, 16% less than the Jenkins approach (used previously in NGHGI reports) and, assuming these results hold for the majority of species in the FIA database, will produce substantially smaller C stock estimates via the CCT for future NGHGIs. While the transition from the Jenkins approach to the CRM is procedural in nature, it may have important implications for national and global forest C sink estimates and the perception of the role forests play in mitigating the effects of atmospheric carbon dioxide.

The CRM reflects a critical first step in improving the accuracy of the U.S.'s NGHGI by combining a nationally consistent approach to assigning biomass to individual tree components (i.e., tree tops and bark) with regional accuracy (e.g., local volume models). Beyond this near-term improvement, a more holistic approach to both modeling whole tree biomass/C and fitting said models across the diverse tree species and growing conditions throughout the U.S. is needed. Although methodological changes such as those documented in this study will substantially change the U.S. NGHGI, the potential gains in accuracy and sensitivity to climate change events will benefit not only forest monitoring, but also forest industries.

Acknowledgements

The authors thank Paul Van Deusen, Aaron Weiskittel, and John Stanovich for helpful comments and suggestions which improved this manuscript.

References

Bechtold, W.A., Patterson, P.J., 2005. The enhanced Forest Inventory and Analysis program–national sampling design and estimation procedures. USDA For. Serv. Gen. Tech. Rep. SRS-80, 85.

Cochran, W.G., 1977. Sampling Techniques, third ed. Wiley, NewYork, 428 p.

Daniels, T.L., 2010. Integrating forest carbon sequestration into a cap-and-trade program to reduce net CO_2 emissions. J. Am. Plann. Assoc. 76 (4), 463–475.

Domke, G.M., Becker, D.R., D'Amato, A.W., Ek, A.R., Woodall, C.W., 2012. Carbon emissions associated with the procurement and utilization of forest harvest residues for energy, Northern Minnesota, USA. Biomass Bioenerg. 36, 141–150.

EPA (U.S. Environmental Protection Agency), 2011. *Land use, land-use change, and forestry.* Available from <www.epa.gov/climatechange/emissions/downloads11/US-GHG-Inventory-2011-Chapter-7-LULUCF.pdf>; (accessed 31.08.2011).

Fan, S., Gloor, M., Mahlman, J., Pacala, S., Sarmiento, J., Takahashi, T., Tans, P., 1998. A large terrestrial carbon sink in North America implied by atmospheric and oceanic carbon dioxide data and models. Science 282, 442–446.

Heath, L.S., Hanson, M.H., Smith, J.E., Smith, W.B., Miles, P.D., 2009. Investigation into calculating tree biomass and C in the FIADB using a biomass expansion factor approach. 26 p. in Forest Inventory and Analysis (FIA) Symposium 2008. In: McWilliams, W., Moisen, G., Czaplewski, R. (Eds.), USDA For. Serv. Proc. RMRS-P-56CD.

Jenkins, J.C., Chojnacky, D.C., Heath, L.S., Birdsey, R.A., 2003. National scale biomass estimators for United States tree species. For. Sci. 49 (1), 12–35.

Jenkins, J.C., Chojnacky, D.C., Heath, L.S., Birdsey, R.A., 2004. Comprehensive database of diameter-based biomass regressions for North American tree species. USDA For. Serv. Gen. Tech. Rep. NE-319, 45.

Lambert, M.-C., Ung, C.-H., Raulier, F., 2005. Canadian national tree aboveground biomass models. Can. J. For. Res. 35, 1996–2018.

Miles, P.D., Smith, W.B., 2009. Specific gravity and other properties of wood and bark for 156 tree species found in North America. USDA For. Serv. Res. Note NRS-38, 35.

Pacala, S.W., Hurtt, G.C., Baker, D., Peylin, P., Houghton, R.A., Birdsey, R.A., Heath, L., Sundquist, E.T., Stallard, R.F., Ciais, P., Moorcroft, P., Caspersen, J.P., Shevliakova, E., Moore, B., Kohlmaier, G., Holland, E., Gloor, M., Harmon, M.E., Fan, S.-M., Sarmiento, J.L., Goodale, C.L., Schimel, D., Field, C.B., 2001. Consistent land- and atmosphere-based U.S. carbon sink estimates. Science 292, 2316–2320.

Pan, Y., Birdsey, R.A., Fang, J., Houghton, R., Kauppi, P.E., Kurz, W.A., Phillips, O.L., Shvidenko, A., Lewis, S.L., Canadell, J.G., Ciais, P., Jackson, R.B., Pacala, S., McGuire, A.D., Piao, S., Rautiainen, A., Sitch, S., Hayes, D., 2011. A large and persistent carbon sink in the world's forests. Science 333, 988–993.

Pastor, J., Aber, J.D., Melillo, J.M., 1984. Biomass using generalized allometric regressions for some northeast tree species. For. Eco. Manag. 7, 265–274.

R Development Core Team, 2011. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.

Raile, G.K., 1982. Estimating stump volume. USDA For. Ser. Res. Pap. NC-224, 7.

Ryan, M.G., Harmon, M.E., Birdsey, R.A., Giardina, C.P., Heath, L.S., Houghton, R.A., Jackson, R.B., McKinley, D.C., Morrison, J.F., Murray, B.C., Pataki, D.E., Skog, K.E., 2010. A synthesis of the science on forests and carbon for US forests. Issues in Ecol. 13, 1–16.

Smith, J.E., Heath, L.S., 2008. Carbon stocks and stock changes in U.S. forests, and Appendix C. In: USDA. U.S. Agriculture and Forestry Greenhouse Gas Inventory: 1990-2005. Tech. Bull. No. 1921. Office of the Chief Economist, Washington, DC.

Smith, J.E., Heath, L.S., Jenkins, J.C., 2003. Forest tree volume-to-biomass models and estimates for live and standing dead trees of U.S. forests. USDA For. Serv. Gen. Tech. Rep. NE-298, 57.

Smith, J.E., Heath, L.S., Nichols, M.C., 2007. U.S. forest carbon calculation tool: forest-land carbon stocks and net annual stock change. USDA For. Serv. Gen. Tech. Rep. NRS-13, 34.

Smith, J.E., Heath, L.S., Skog, K.E., Birdsey, R.A., 2006. Methods for calculating forest ecosystem and harvested carbon with standard estimates for forest types of the United States. USDA For. Serv. Gen. Tech. Rep. NE-343, 216.

Ter-Mikaelian, M.T., Korzukhin, M.D., 1997. Biomass models for sixty-five North American tree species. For. Ecol. Manag. 97 (1), 1–24.

UNFCCC (United Nations Framework Convention on Climate Change), 2011. Available from<www.unfccc.int/2860.php>; (accessed Aug. 31.08.2011).

Woodall, C.W., Perry, C.H., Miles, P.D., 2006. The relative density of forest in the United States. For. Eco. Manag. 226, 368–372.

Woodall C.W., Heath, L.S., Domke, G.M., Nichols, M., Oswalt, C., 2011. Methods and models for estimating volume, biomass, and C for forest trees in the U.S's national inventory, 2010. USDA For. Serv. Gen Tech. Rep. NRS-88, 30.

Woudenberg, S.W., Conkling, B.L., O'Connell, B.M., LaPoint, E.B., Turner, J.A., Waddell, K.L., 2010. The Forest Inventory and Analysis Database: Database description and users manual version 4.0 for Phase 2. USDA For Serv. Gen. Tech. Rep. RMRS-GTR-245, 336.