Forest Ecology and Management 400 (2017) 100–109

Contents lists available at ScienceDirect

Forest Ecology and Management

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

Equivalence among three alternative approaches to estimating live tree carbon stocks in the eastern United States

Coeli M. Hoover *, James E. Smith

USDA Forest Service, Northern Research Station, 271 Mast Road, Durham, NH 03824, USA

A R T I C L E I N F O

Article history:
Received 23 March 2017
Received in revised form 25 May 2017
Accepted 29 May 2017

Keywords:
Biomass equation
Biomass estimation
Allometry
Forest carbon stocks
Equivalence

A B S T R A C T

Assessments of forest carbon are available via multiple alternate tools or applications and are in use to address various regulatory and reporting requirements. The various approaches to making such estimates may or may not be entirely comparable. Knowing how the estimates produced by some commonly used approaches vary across forest types and regions allows users of carbon stock estimates to make informed comparisons. Here, we focus on equivalence of alternate estimates of aboveground live tree carbon in eastern U.S. forests derived from the carbon reports output by the Fire and Fuels Extension (FFE) to the Forest Vegetation Simulator (FVS). Three approaches to estimating individual-tree carbon are compared by FVS variant and forest type. There are two approaches available in the FVS Fire and Fuels Extension (labeled FFE and Jenkins) and a third based on the U.S. Forest Service's forest inventory (component ratio method, labeled CRM).

We found that the two volume-based approaches, CRM and FFE, are most often identified as equivalent within forest type group or whole-variant relative to the other two pairs of approaches. Equivalence is common in the Northeast and Southern variants, but relatively infrequent in the Central States and Lake States variants. The underlying volume equations of the FFE and CRM approaches influence the carbon equivalence patterns as indicated by differences in volume estimates between FVS and the U.S. Forest Service's forest inventory. Aggregation, or expanding forest estimates to include increasingly larger areas, tends to reduce apparent differences between approaches – that is, they become more equivalent. This result is most evident with the CRM-FFE pair or in softwood forest type groups.

Published by Elsevier B.V.

1. Introduction

The Forest Vegetation Simulator (FVS, Dixon, 2002) is a growth-and-yield modeling system developed and maintained by the U.S. Forest Service. This model and its carbon reports in the Fire and Fuels Extension have an established record of use among forest managers within the Forest Service but also other public and private land managers and researchers (Hoover and Rebain, 2011), and are approved for estimation in California's cap and trade system (California Environmental Protection Agency Air Resources Board, 2015). A number of alternate approaches to estimating tree carbon are in use, for example see Radtke et al. (2017). Of particular interest here are the estimations related to FVS simulations; specifically, these are: Rebain (2010), labeled here as FFE, Jenkins et al. (2003), described here as Jenkins, and Heath et al. (2009), referred to here as CRM (the component ratio method). The CRM approach to estimating carbon is not explicitly included in FFE calculations but is included here because it is the method currently used by forest carbon reports that rely on U.S. Forest Service data (e.g., U.S. EPA, 2017). Hoover and Smith (2017) investigated comparability and explicitly addressed statistical equivalence among these three alternate approaches to estimating live tree carbon for the 15 variants (FVS regions) in the western United States. That study, hereafter referred to as the western variants paper, focused on the question: where can FVS users expect results to align either within FVS across variants or with external independent forest carbon assessments? Information regarding the equivalence of estimates developed using different computational approaches is of interest to researchers, managers, and policymakers because multiple equations are in use and may produce estimates which are not strictly comparable. For example, a carbon offset registry may specify a particular method, but a regional protocol may employ another, neither of which may be congruent with other U.S. forest carbon estimation methods (e.g., U.S. EPA, 2017; USDA

* Corresponding author.
E-mail addresses: choover@fs.fed.us (C.M. Hoover), jsmith11@fs.fed.us (J.E. Smith).

http://dx.doi.org/10.1016/j.foreco.2017.05.052
0378-1127/Published by Elsevier B.V.

Forest Service, 2017a). Knowing how the estimates produced by some commonly used approaches vary across forest types and regions allows users of carbon stock estimates to better understand the comparability of such estimates. Zhou and Hemstrom (2009) and Domke et al. (2012) provide examples of such analyses.

This study addresses some questions about equivalence related to the contrasts between FVS variants and forest types of the eastern U.S. relative to those of western forests. The western variants paper focused on application of FVS in the western U.S. to predict carbon where forest carbon assessments could potentially include more than one of the multiple relatively small variants, which was one of the rationales for the focus on the West. Within the East, the FVS variants cover large areas and generally follow state boundaries, so it is less likely that FVS based forest carbon assessments will include multiple variants. Results from the western variants paper suggested that differences among the three approaches were less important at aggregate, or large extent, levels of forest carbon assessment. This appeared to be truer for the conifer forests than the hardwood groups. In addition, there was little consistency in equivalence identified among groups at the lower level of aggregation. That is, particular paired approaches were equivalent within certain forest type groups for some variants but not others, and within-variant consistency among softwood or hardwood type groups was not apparent. Again, this outcome was more pronounced in the hardwood type groups, which are a limited presence in the West.

The eastern variants are geographically large, and unlike the West, hardwood forest type groups are the majority. The purpose of this study is threefold. First, to inform users of FVS-based carbon assessments of equivalence or non-equivalence among these alternative approaches. That is, an extension to the East, following the western variants paper (Hoover and Smith, 2017). Second, to address the geographic size of the variant: is there a trend toward greater proportion of forest type groups and pairs of approaches being identified on these variants that encompass much larger forest areas? Third, to determine if patterns regarding western hardwood versus softwood forest types observed in the western variants paper continue in the East where hardwood type groups represent the majority of forests?

2. Methods

The goal here is to identify if, and possibly where, any of the three approaches to estimating live tree carbon can be considered equivalent within the four FVS eastern variants (Fig. 1). Equivalence tests applied to stand level carbon estimates obtained from both Forest Inventory and Analysis (FIA) inventory data and stands defined by FVS are pairwise comparisons; these are: Jenkins vs. CRM, Jenkins vs. FFE, and CRM vs. FFE. Methods are described in detail in Hoover and Smith (2017) and briefly outlined below.

Forest inventory data were obtained from the Forest Inventory and Analysis Data Base (FIADB), which is compiled and maintained by the FIA Program of the U.S. Forest Service (USDA Forest Service, 2017a). The specific data in use here were downloaded from <http://apps.fs.fed.us/fiadb-downloads/datamart.html> on 13 May 2016. The most recent evaluations – or cycle of the permanent inventory plots across each state – within each of the 37 states used for this analysis provided input data to FVS to establish simulations on plots identical to the FIADB plots. For consistency, only those plots representing a single forested condition were used in the FVS simulations (USDA Forest Service, 2017b). In addition, CRM carbon density (tonnes carbon per hectare, t C/ha, 1 tonne = 1 Mg) was calculated according to Appendix M of O'Connell et al. (2017) for aboveground portion of live trees in each of these FIADB plots.

We used FVS to establish stands identical to those obtained from the FIADB and provide the two FVS approaches to quantifying live tree carbon – FFE and Jenkins (see Rebain, 2010). Importing the FIADB data and establishing an FVS simulation is necessary to obtain the carbon estimates for the two alternate approaches; the model was run using default settings, since simulations were statewide. Note that the only part of the FVS simulation that is used here is the output from the initial year, which place all three approaches to carbon estimates as originating from identical data.

Equivalence tests are appropriate where the analysis addresses the question of whether the groups are effectively similar, which is in contrast to asking if they are different (Robinson et al., 2005; MacLean et al., 2014). The null hypothesis of equivalence tests states that the two populations are different (Parkhurst, 2001; Brosi and Biber, 2009), which can be viewed as the reverse of the

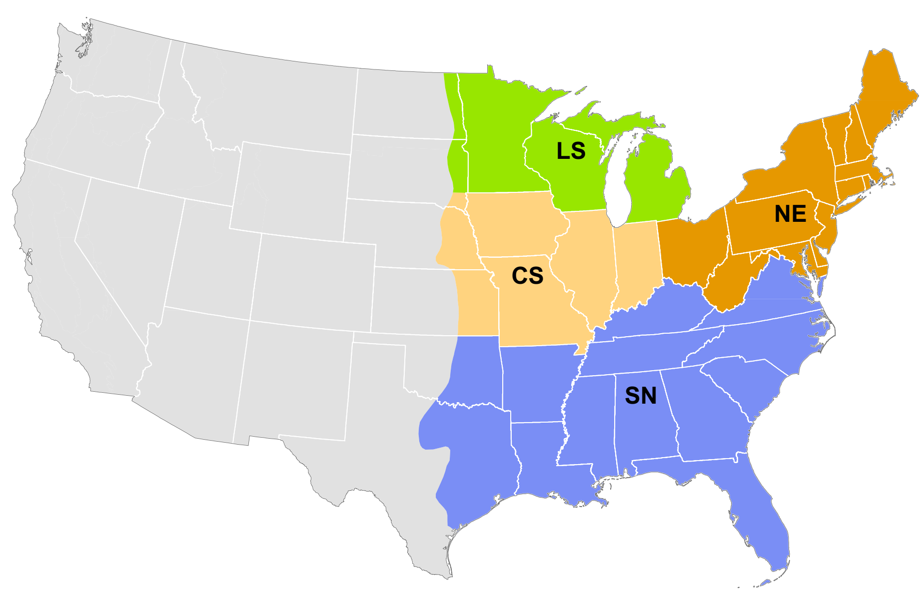

Fig. 1. Illustration showing the geographic extent of each FVS variant in the eastern U.S. Variant labels are: CS = Central States, LS = Lake States, NE = Northeast, and SN = Southern.

more common approach to hypothesis testing. The test threshold of equivalence between pairs or populations is set by analysts and rejection of the null hypothesis results in a conclusion of not-different, or equivalent.

We focused on equivalence of the mean difference between paired estimates at plot level for various levels of classification, including: FVS variant, softwood versus hardwood forest types, or forest type group (e.g., mean difference within a specific forest type within a variant). The user-defined equivalence threshold provides a range of results that are considered equivalent; here these are set at 10% (or 5%) of the mean of the two stock estimates within the pair under consideration (i.e., a percentage of tonnes per hectare). Equivalence tests presented here are paired-sample tests (Feng et al., 2006; Mara and Cribbie, 2012), with the pairs being two estimates from the same plot (e.g., CRM and FFE). A distribution of the mean difference is obtained through resampling. The test statistic is the confidence interval about the mean difference between paired estimates as applied in two one-sided tests of the null hypothesis (Berger and Hsu, 1996). Equivalence – rejection of the null hypothesis that the two approaches are different – is the conclusion where the test statistic (95% CI) falls entirely within the specified equivalence threshold.

3. Results and discussion

The overall variant-wide equivalence tests identified the three paired approaches as equivalent in the Southern variant (Fig. 2). Among the three remaining variants, only the CRM-FFE pair in the Northeast is equivalent, an outcome partially in alignment with MacLean et al. (2014) which reports equivalence within 20% of the CRM-FFE and Jenkins-FFE pairs for a subset of states in the Northeast variant. At the slightly less aggregate level of variant by softwood forest type (Fig. 3a), again all three pairs in the Southern variant are equivalent while one pair in each of the other variants are equivalent – CRM-FFE in the Northeast and Lake States, and Jenkins-FFE in the Central States. The hardwood type groups have equivalent estimates with the CRM-FFE pair in the Northeast and Southern variants (Fig. 3b). These aggregate sets include all softwood or hardwood type groups except for nonstocked or woodland types (i.e., oak-pine is classified as a hardwood type and pinyon/juniper, woodland hardwoods, and nonstocked type groups are excluded).

At the type-group level, the most conspicuous trend in the paired equivalence tests is the relatively high frequency of equivalent pairs in the Northeast and Southern variants. In contrast, there are few equivalent pairs in the Lake States, and none identified in the Central States (Table 1). The most commonly equivalent pair of estimates is CRM-FFE. All three pairs are equivalent within three of the variant by type group combinations, and each of these included pines. These are the loblolly/shortleaf pine groups in the Northeast and Southern variants and the oak/pine group in the Southern variant (Table 1). A notable contrast to the loblolly/shortleaf pine equivalence of all three approaches in the Southern variant is the longleaf/slash pine group where none of the pairs is found to be equivalent.

At all levels of aggregation, the most consistent result is equivalence between the CRM and FFE methods. This agrees with the findings of the western variants paper (Hoover and Smith, 2017), and is likely due to the volume-based nature of both methods. The remaining paired approaches both include Jenkins – Jenkins-CRM and Jenkins-FFE – and these do occur as equivalent, but less frequently. In general, the Jenkins carbon estimates are greater than those based on either the CRM or FFE approaches (Table 2). Domke et al. (2012) also found that CRM estimates were generally lower than those produced using the Jenkins equations. Similarly, in the majority of plots and in most forest type groups the FFE estimates are greater than the CRM estimates, but these differences are frequently smaller than for the other pairs (see Table 2), which is reflected in the more common equivalence between CRM and FFE approaches. However, note that overall effect of Jenkins > FFE > CRM (Table 2) also includes many stand-level exceptions.

Forest type groups common throughout eastern forests generally have different equivalence results among variants (Table 1). For example, the CRM-FFE paired approaches for oak/hickory and maple/beech/birch type groups are equivalent in the Northeast and Southern variants but not the Lake States or Central States. The underlying equations of merchantable volume of wood for both the CRM and FFE approaches vary across variants. Individual-tree carbon or volume estimates are not readily available for the stands as defined within FVS. However, we illustrate how the paired stand level equivalence results of Table 1 reflect the volume differences with examples from the oak/hickory type group (Fig. 4). Note that differences in the two separate estimates

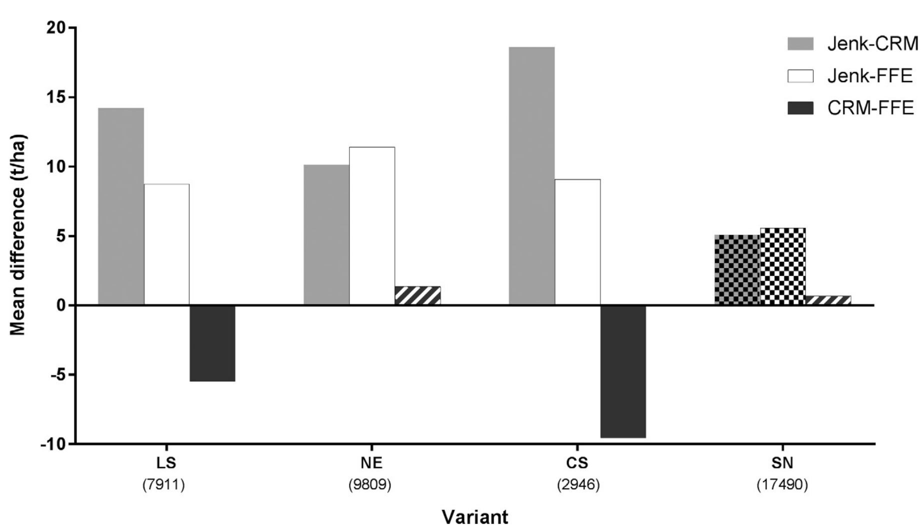

Fig. 2. Mean difference of live aboveground biomass carbon estimates (t/ha) as computed by three different methods for each eastern FVS variant. Jenk = Jenkins, FFE = Fire and Fuels Extension, CRM = FIA component ratio method. Legend indicates each comparison, e.g. Jenk minus CRM. Equivalence at the 5% bounds is indicated by a striped bar. Equivalence at the 10% bounds is indicated by a checked bar. Number of plots is in parentheses beneath the variant code; variant codes are as given in Fig. 1.

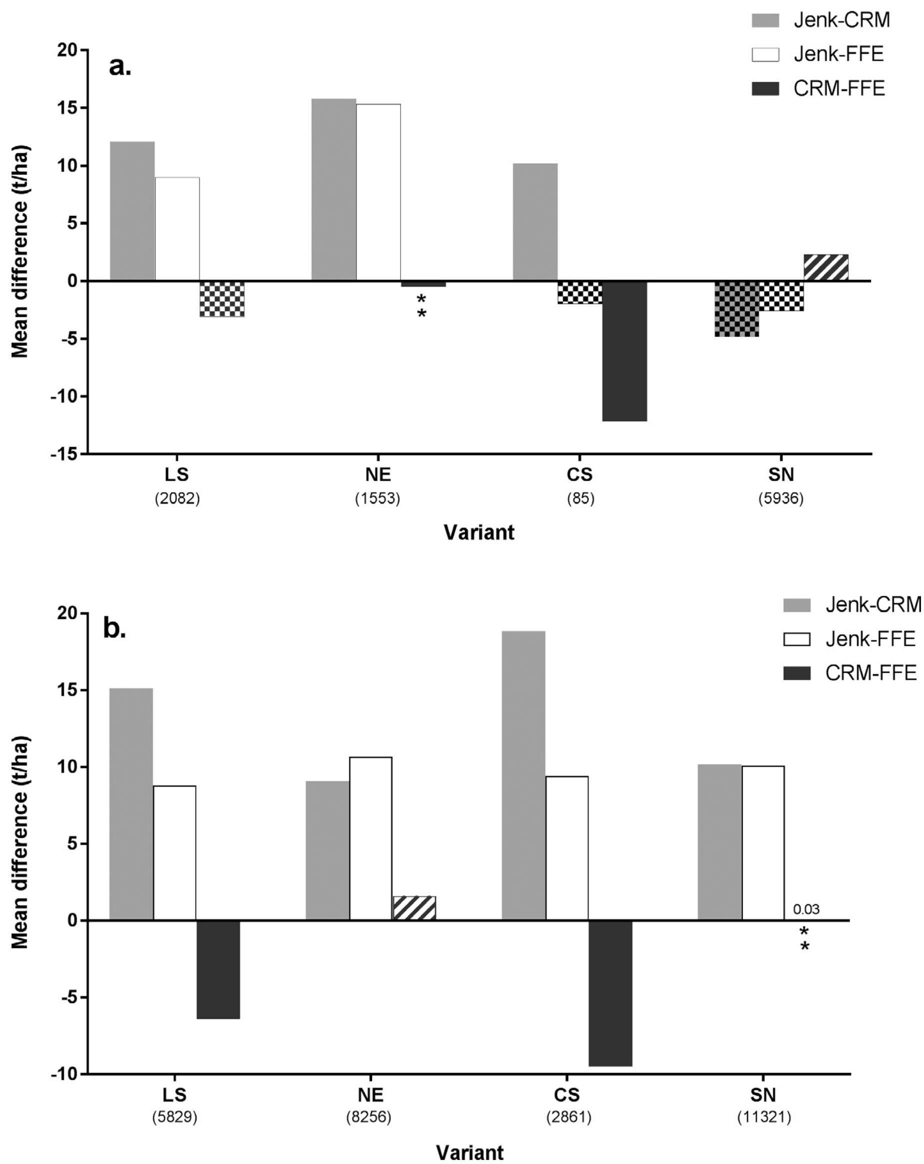

Fig. 3. Mean difference of live aboveground biomass carbon estimates (t/ha) as computed by three different methods for each eastern FVS variant for (a) softwood or (b) hardwood forest types. Comparisons are as described in Fig. 2. Equivalence at the 5% bounds is indicated by a striped bar, or double asterisk when bar height is near zero. Equivalence at the 10% bounds is indicated by a checked bar. Number of plots is in parentheses beneath the variant code; variant codes are as given in Fig. 1.

of merchantable volume are greater in Central States and Lake States, the two variants where the associated carbon stocks are not equivalent. The carbon stock differences and thus the test statistics developed for this pair (CRM-FFE) for the four variants also reflect the asymmetry in volume differences. The test statistic used for the equivalence tests expressed in the same units as the null hypothesis – namely, percentage of mean carbon stock – can provide an indication of how close a pair of estimates is to being accepted as equivalent. Recall that the test statistic based on resampling paired differences produces a conclusion of equivalence if the 95% confidence interval is within the 10% equivalence threshold set by the null hypothesis. The maximum percentage relative to equivalence bounds for the CRM-FFE carbon pairs corresponding to the groups for Fig. 4 was 0.5, 17.3, 12.5, and 3.5 for Southern, Central States, Lake States, and Northeast, respectively, indicating a clear difference in equivalence for Northeast and Southern relative to Central States and Lake States. These volume results (Fig. 4) suggest that the differences among regions are strongly influenced by differences in predicted volume and not necessarily the CRM or FFE models that expand from volume to carbon in biomass.

Southern pines also include what are apparently very different results for the loblolly/shortleaf pine and longleaf/slash pine groups. A similar analysis of the paired differences in volumes underlying the CRM and FFE approaches as we applied in Fig. 4 was developed for these southern pines, and both difference distributions are relatively symmetrical and centered near zero difference (data not shown). This non-equivalence despite lack of overt difference in volumes is partly explained by the test statistics; the maximum percentage represented by the test statistic for the two pairs is 3.5% and 10.4% for the loblolly/shortleaf pine and longleaf/slash pine groups, respectively. The longleaf/slash pine group is very close to, but outside of, the threshold set for CRM-FFE equivalence.

These two southern pine type groups also show a similar pattern for the Jenkins-CRM approaches – equivalent for the loblolly/shortleaf pine but not equivalent for the longleaf/slash pine group (Table 1). An examination of tree level differences in

Table 1
Mean difference, confidence interval, and equivalence test result for live aboveground carbon stock estimates computed by each method, by variant and forest type group.

Variant	Forest Type Group	Equation Pair[a]	Mean Diff.	CI	Equiv.
Central States (CS)	Loblolly/Shortleaf Pine	Jenk-CRM	8.25	7.0 to 9.3	
		Jenk-FFE	−10.07	−12.8 to −8.2	
		CRM-FFE	−18.33	−20.9 to −16.3	
	Other Eastern Softwoods	Jenk-CRM	11.28	9.4 to 13.3	
		Jenk-FFE	7.96	6.6 to 9.9	
		CRM-FFE	−3.30	−4.3 to −2.4	
	Oak/Pine	Jenk-CRM	13.28	12.5 to 14.1	
		Jenk-FFE	5.24	4.3 to 6.2	
		CRM-FFE	−8.04	−9.0 to −7.2	
	Oak/Hickory	Jenk-CRM	19.18	18.8 to 19.5	
		Jenk-FFE	9.29	9.0 to 9.6	
		CRM-FFE	−9.90	−10.1 to −9.7	
	Oak/Gum/Cypress	Jenk-CRM	18.73	16.0 to 21.3	
		Jenk-FFE	7.56	6.1 to 9.3	
		CRM-FFE	−11.19	−13.5 to −9.1	
	Elm/Ash/Cottonwood	Jenk-CRM	19.73	18.3 to 21.3	
		Jenk-FFE	13.90	12.7 to 15.3	
		CRM-FFE	−5.83	−6.7 to −5.0	
	Maple/Beech/Birch	Jenk-CRM	18.67	16.7 to 21.4	
		Jenk-FFE	8.34	6.8 to 10.2	
		CRM-FFE	−10.37	−11.9 to −8.9	
Lake States (LS)	White/Red/Jack Pine	Jenk-CRM	10.77	10.3 to 11.3	
		Jenk-FFE	5.40	4.9 to 5.9	
		CRM-FFE	−5.36	−5.9 to −4.9	
	Spruce/Fir	Jenk-CRM	12.83	12.3 to 13.4	
		Jenk-FFE	10.87	10.4 to 11.4	
		CRM-FFE	−1.95	−2.1 to −1.8	10%
	Oak/Pine	Jenk-CRM	12.08	11.4 to 12.8	
		Jenk-FFE	8.91	8.3 to 9.6	
		CRM-FFE	−3.17	−3.7 to −2.6	10%
	Oak/Hickory	Jenk-CRM	18.50	18.0 to 19.0	
		Jenk-FFE	11.47	11.1 to 11.9	
		CRM-FFE	−7.03	−7.3 to −6.8	
	Elm/Ash/Cottonwood	Jenk-CRM	13.05	12.4 to 13.7	
		Jenk-FFE	8.86	8.3 to 9.5	
		CRM-FFE	−4.19	−4.5 to −3.9	10%
	Maple/Beech/Birch	Jenk-CRM	18.20	17.9 to 18.6	
		Jenk-FFE	9.39	9.1 to 9.7	
		CRM-FFE	−8.82	−9.1 to −8.6	
	Aspen/Birch	Jenk-CRM	10.91	10.7 to 11.1	
		Jenk-FFE	6.51	6.3 to 6.7	
		CRM-FFE	−4.41	−4.5 to −4.3	
	Other hardwoods	Jenk-CRM	5.39	4.3 to 6.9	
		Jenk-FFE	3.90	3.0 to 5.1	
		CRM-FFE	−1.49	−2.4 to −0.9	
Northeast (NE)	White/Red/Jack Pine	Jenk-CRM	16.00	15.2 to 16.8	
		Jenk-FFE	16.61	15.9 to 17.4	
		CRM-FFE	0.63	0.2 to 1.0	5%
	Spruce/Fir	Jenk-CRM	17.34	16.9 to 17.8	
		Jenk-FFE	16.59	16.1 to 17.0	
		CRM-FFE	−0.75	−0.9 to −0.6	5%
	Loblolly/Shortleaf Pine	Jenk-CRM	3.59	3.2 to 4.0	10%
		Jenk-FFE	2.46	1.4 to 3.3	10%
		CRM-FFE	−1.12	−2.1 to −0.4	5%
	Oak/Pine	Jenk-CRM	9.25	8.7 to 9.9	
		Jenk-FFE	10.82	10.1 to 11.6	
		CRM-FFE	1.58	1.1 to 2.0	5%
	Oak/Hickory	Jenk-CRM	7.64	7.4 to 7.9	10%
		Jenk-FFE	10.17	9.9 to 10.4	
		CRM-FFE	2.53	2.4 to 2.7	5%
	Oak/Gum/Cypress	Jenk-CRM	13.52	11.9 to 15.5	
		Jenk-FFE	13.48	12.1 to 14.9	
		CRM-FFE	−0.04	−1.9 to 1.3	5%
	Elm/Ash/Cottonwood	Jenk-CRM	8.39	7.6 to 9.3	
		Jenk-FFE	8.61	7.8 to 9.5	
		CRM-FFE	0.23	−0.4 to 0.8	5%
	Maple/Beech/Birch	Jenk-CRM	9.77	9.6 to 10.0	
		Jenk-FFE	11.13	10.9 to 11.3	
		CRM-FFE	1.36	1.2 to 1.5	5%
	Aspen/Birch	Jenk-CRM	12.02	11.4 to 12.6	
		Jenk-FFE	11.64	10.9 to 12.4	
		CRM-FFE	−0.38	−0.8 to 0.0	5%
	Other hardwoods	Jenk-CRM	4.61	4.1 to 5.2	10%

Table 1 (*continued*)

Variant	Forest Type Group	Equation Pair[a]	Mean Diff.	CI	Equiv.
		Jenk-FFE	5.98	5.2 to 6.7	
		CRM-FFE	1.36	0.6 to 2.1	5%
Southern (SN)	White/Red/Jack Pine	Jenk-CRM	5.32	3.0 to 7.9	10%
		Jenk-FFE	13.45	12.1 to 15.2	
		CRM-FFE	8.13	6.4 to 10.1	
	Longleaf/Slash Pine	Jenk-CRM	−9.79	−10.4 to −9.2	
		Jenk-FFE	−5.28	−5.7 to −4.9	
		CRM-FFE	4.51	4.3 to 4.8	
	Loblolly/Shortleaf Pine	Jenk-CRM	−4.12	−4.4 to −3.8	10%
		Jenk-FFE	−2.34	−2.5 to −2.2	5%
		CRM-FFE	1.78	1.6 to 1.9	5%
	Other Eastern Softwoods	Jenk-CRM	8.32	7.1 to 9.9	
		Jenk-FFE	7.09	6.2 to 8.2	
		CRM-FFE	−1.23	−1.7 to −0.7	10%
	Pinyon/Juniper	Jenk-CRM	5.14	3.7 to 6.4	
		Jenk-FFE	−0.82	−3.8 to 0.6	
		CRM-FFE	−5.95	−7.4 to −4.9	5%
	Oak/Pine	Jenk-CRM	4.07	3.7 to 4.5	10%
		Jenk-FFE	4.80	4.5 to 5.1	10%
		CRM-FFE	0.73	0.5 to 1.0	5%
	Oak/Hickory	Jenk-CRM	11.22	10.9 to 11.5	
		Jenk-FFE	11.37	11.2 to 11.6	
		CRM-FFE	0.16	0.0 to 0.3	5%
	Oak/Gum/Cypress	Jenk-CRM	9.72	9.2 to 10.3	
		Jenk-FFE	10.03	9.6 to 10.4	
		CRM-FFE	0.31	−0.0 to 0.6	5%
	Elm/Ash/Cottonwood	Jenk-CRM	11.08	10.3 to 11.9	
		Jenk-FFE	9.38	8.9 to 9.9	
		CRM-FFE	−1.69	−2.2 to −1.3	5%
	Maple/Beech/Birch	Jenk-CRM	15.80	14.1 to 17.7	
		Jenk-FFE	13.61	12.6 to 14.8	
		CRM-FFE	−2.17	−3.3 to −1.3	5%
	Other hardwoods	Jenk-CRM	8.03	5.8 to 10.9	
		Jenk-FFE	7.05	5.5 to 9.1	
		CRM-FFE	−1.02	−2.2 to 0.3	5%
	Woodland hardwoods	Jenk-CRM	0.54	0.2 to 1.0	
		Jenk-FFE	−2.67	−3.3 to −2.2	
		CRM-FFE	−3.21	−3.6 to −2.9	
	Tropical hardwoods	Jenk-CRM	33.29	26.7 to 41.4	
		Jenk-FFE	26.80	21.2 to 33.8	
		CRM-FFE	−6.46	−8.3 to −5.2	
	Exotic hardwoods	Jenk-CRM	6.77	5.8 to 8.1	
		Jenk-FFE	3.12	2.4 to 4.0	
		CRM-FFE	−3.66	−4.6 to −3.0	

[a] Text in the equation pair column indicates the order of the comparison, e.g. Jenkins estimate *minus* CRM estimate. If equivalence column is blank, estimates were not equivalent at either 5 or 10%. Sample size is given in Table 2.

estimates is possible for Jenkins and CRM and is made here for the four component species, which are qualitatively similar for each of the four with the estimates similar at lower diameters and diverging, with CRM clearly greater than Jenkins, at larger diameters (Fig. 5). The CRM estimates are based on the same underlying volume equation form for each of the four species, which are each independently fit (i.e., each has different coefficients), and the Jenkins estimates are identical (within d.b.h.) in the four panels of Fig. 5. There are no overt differences among the tree level estimates that would likely extend to the stand level differences in equivalence. However, the test statistics for the Jenkins-CRM paired approaches suggest considerable differences in equivalence. A comparison of the maximum percentage represented by the test statistic for the two Jenkins-CRM pairs shows values of 8.2 and 24.0 for the loblolly/shortleaf pine and longleaf/slash pine groups, respectively (calculated from Tables 1 and 2). A possible mechanism for the contrast in equivalence between these two type groups is that the much wider distribution of loblolly/shortleaf pine across the South means that the whole-variant results (Table 1) include greater aggregation of parts in loblolly/shortleaf, which is consistent with the effects of aggregation seen here and in the western variants paper.

To some degree, the equivalence prevalent in Southern, a large variant, could result from aggregation of smaller areas that are themselves not necessarily equivalent. As an informal evaluation using only previously defined methods and the Southern variant as an example, we treated each state within the variant as a "small variant" and determined equivalence for a few example pairs of approaches. That is, we ask what proportion of individual states have equivalence levels identical to what is found for the entire variant? This example (Table 3) of disaggregation by state for the Southern loblolly/slash pine type group illustrates that some individual states show a different equivalence outcome (either not equivalent or equivalent at a higher percentage) for pairs that are equivalent for the whole variant. This is particularly true of the pairs with the Jenkins approach where at least half of states were identified as not equivalent (or equivalent at a higher percentage) as compared with the entire variant. Kentucky has fewer than 30 of these plots so is not included here. This is an informal step; a complete list of such results would be effectively the length of Table 1 repeated for each of the 37 eastern states involved. The maximum percentage represented by the test statistic charted over the number of plots contributing to the equivalence test showed a general, but not significant, trend toward equivalence at lower percentage

Table 2
Mean live aboveground biomass carbon stock, standard deviation, and sample size by forest type group and variant as computed by each method. Note that table structure corresponds to Table 1.

Variant	Forest Type Group	Equation	Mean tC/ha [a]	SD	N
Central States (CS)	Loblolly/Shortleaf Pine	Jenkins	74.6	22.6	46
		CRM	66.3	20.9	
		FFE	84.7	28.9	
	Other Eastern Softwoods	Jenkins	34.5	19.8	30
		CRM	23.3	13.3	
		FFE	26.6	15.3	
	Oak/Pine	Jenkins	56.7	25.4	153
		CRM	43.4	21.1	
		FFE	51.5	27.2	
	Oak/Hickory	Jenkins	72.8	32.3	2353
		CRM	53.7	23.8	
		FFE	63.6	29.0	
	Oak/Gum/Cypress	Jenkins	78.8	35.1	32
		CRM	60.1	27.3	
		FFE	71.3	34.0	
	Elm/Ash/Cottonwood	Jenkins	73.3	41.8	248
		CRM	53.6	29.4	
		FFE	59.4	34.2	
	Maple/Beech/Birch	Jenkins	77.3	33.5	60
		CRM	58.6	24.8	
		FFE	69.0	29.5	
Lake States (LS)	White/Red/Jack Pine	Jenkins	55.6	31.6	706
		CRM	44.8	27.5	
		FFE	50.2	31.0	
	Spruce/Fir	Jenkins	41.1	30.3	1359
		CRM	28.3	20.4	
		FFE	30.2	21.4	
	Oak/Pine	Jenkins	57.7	33.6	210
		CRM	45.7	29.2	
		FFE	48.8	29.8	
	Oak/Hickory	Jenkins	73.5	35.9	1339
		CRM	55.0	28.3	
		FFE	62.1	30.8	
	Elm/Ash/Cottonwood	Jenkins	56.1	35.1	651
		CRM	43.1	27.0	
		FFE	47.3	29.2	
	Maple/Beech/Birch	Jenkins	80.0	32.6	1818
		CRM	61.8	25.9	
		FFE	70.6	29.4	
	Aspen/Birch	Jenkins	44.6	24.5	1762
		CRM	33.6	20.2	
		FFE	38.0	21.1	
	Other hardwoods	Jenkins	19.6	18.7	44
		CRM	14.2	14.2	
		FFE	15.7	15.4	
Northeast (NE)	White/Red/Jack Pine	Jenkins	90.6	36.2	419
		CRM	74.6	30.1	
		FFE	74.0	31.2	
	Spruce/Fir	Jenkins	58.7	28.4	984
		CRM	41.4	21.5	
		FFE	42.1	21.1	
	Loblolly/Shortleaf Pine	Jenkins	55.5	28.9	118
		CRM	52.0	28.4	
		FFE	53.1	32.6	
	Oak/Pine	Jenkins	77.8	34.7	278
		CRM	68.5	30.8	
		FFE	67.0	30.9	
	Oak/Hickory	Jenkins	87.6	38.0	3000
		CRM	80.0	34.8	
		FFE	77.4	33.8	
	Oak/Gum/Cypress	Jenkins	92.4	35.0	54
		CRM	78.9	31.0	
		FFE	78.9	31.6	
	Elm/Ash/Cottonwood	Jenkins	63.2	37.7	255
		CRM	54.8	33.7	
		FFE	54.6	33.3	
	Maple/Beech/Birch	Jenkins	81.5	35.4	4139

Table 2 (*continued*)

Variant	Forest Type Group	Equation	Mean tC/ha [a]	SD	N
		CRM	71.8	32.7	
		FFE	70.4	31.4	
	Aspen/Birch	Jenkins	59.4	29.7	384
		CRM	47.4	24.8	
		FFE	47.7	23.2	
	Other hardwoods	Jenkins	60.4	37.0	138
		CRM	55.8	35.8	
		FFE	54.4	35.1	
Southern (SN)	White/Red/Jack Pine	Jenkins	100.9	37.3	49
		CRM	95.6	40.7	
		FFE	87.5	34.0	
	Longleaf/Slash Pine	Jenkins	38.6	21.3	1150
		CRM	48.4	30.6	
		FFE	43.9	26.1	
	Loblolly/Shortleaf Pine	Jenkins	52.1	22.4	4642
		CRM	56.2	30.3	
		FFE	54.4	26.1	
	Other Eastern Softwoods	Jenkins	36.5	22.0	92
		CRM	28.2	20.0	
		FFE	29.4	19.6	
	Pinyon/Juniper	Jenkins	19.6	10.0	41
		CRM	14.4	10.4	
		FFE	20.4	14.8	
	Oak/Pine	Jenkins	58.2	30.9	1596
		CRM	54.1	32.8	
		FFE	53.4	29.5	
	Oak/Hickory	Jenkins	73.0	38.1	6655
		CRM	61.7	35.3	
		FFE	61.6	32.5	
	Oak/Gum/Cypress	Jenkins	83.3	47.9	2045
		CRM	73.6	46.1	
		FFE	73.3	43.3	
	Elm/Ash/Cottonwood	Jenkins	57.2	37.8	707
		CRM	46.1	33.5	
		FFE	47.8	32.5	
	Maple/Beech/Birch	Jenkins	84.0	32.6	178
		CRM	68.2	26.1	
		FFE	70.3	25.9	
	Other hardwoods	Jenkins	51.7	42.0	42
		CRM	43.6	37.4	
		FFE	44.6	37.0	
	Woodland hardwoods	Jenkins	9.0	8.9	192
		CRM	8.5	8.2	
		FFE	11.7	10.5	
	Tropical hardwoods	Jenkins	59.0	54.3	49
		CRM	25.7	27.1	
		FFE	32.2	31.9	
	Exotic hardwoods	Jenkins	34.0	21.3	48
		CRM	27.2	18.9	
		FFE	30.9	20.3	

[a] tC/ha = metric tonnes of carbon per hectare.

bounds with larger sample sizes when examined for several forest type groups within the Southern variant (data not shown).

This example result (Table 3) is consistent with observations from the western variants paper, which suggested that estimates made for increasingly larger forest areas, or greater aggregation, tended to increase equivalence among the alternate approaches. Pooling softwood or hardwood type groups across all variants in the East, and a summary from the analogous data set of the western variants paper, are summarized in Table 4. The equivalence tests are weighted according to the frequency of the constituent forest type groups (e.g., Table 2) within the regions. The effect seems most apparent in the eastern softwood groups. This is consistent with the suggestion that especially for conifers, the choice of estimation approach matters for plot level or small areas but becomes increasingly less important for assessments over large land areas.

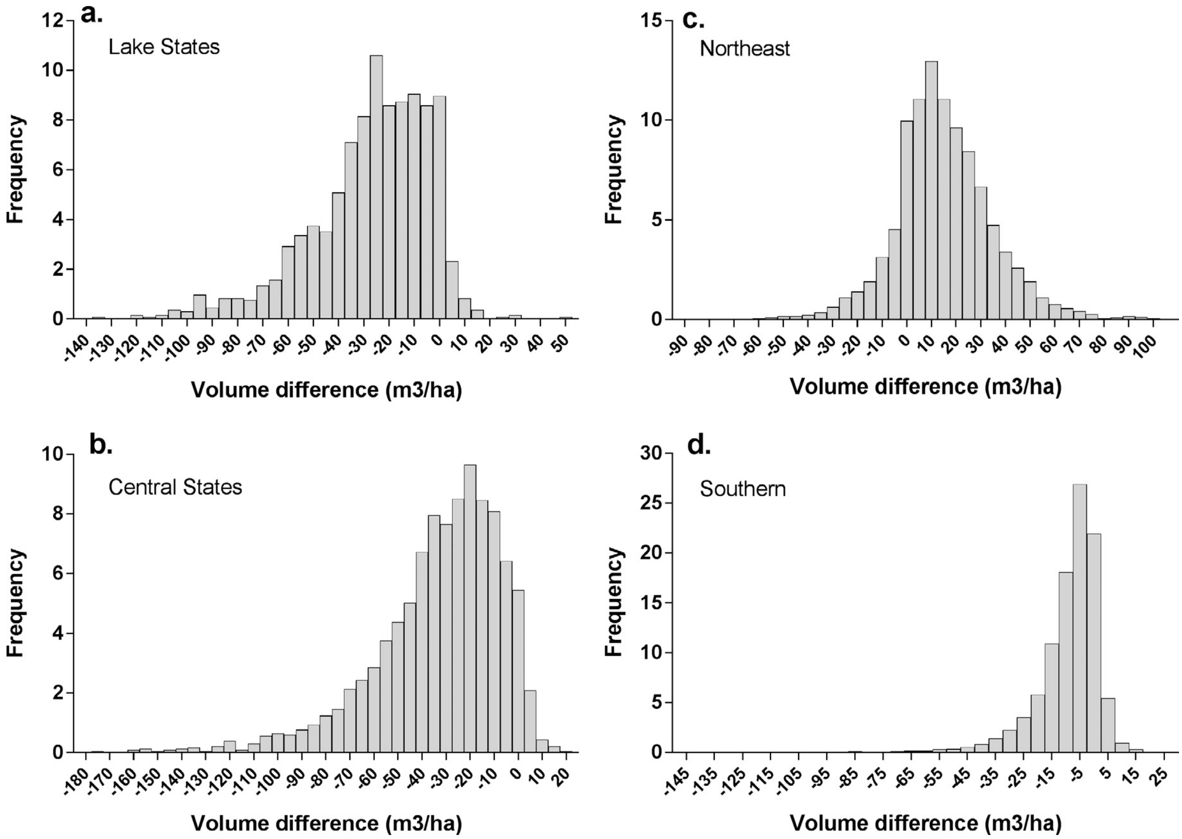

Fig. 4. Frequency of plot level difference in merchantable volume (m^3/ha) between the FIADB volumes underlying CRM and the FVS volumes underlying FFE (i.e., CRM minus FFE) for oak/hickory forests in the four eastern variants. Panels are as follows: (a) Lake States, (b) Central States, (c) Northeast, (d) Southern. Note that axis scales differ between panels.

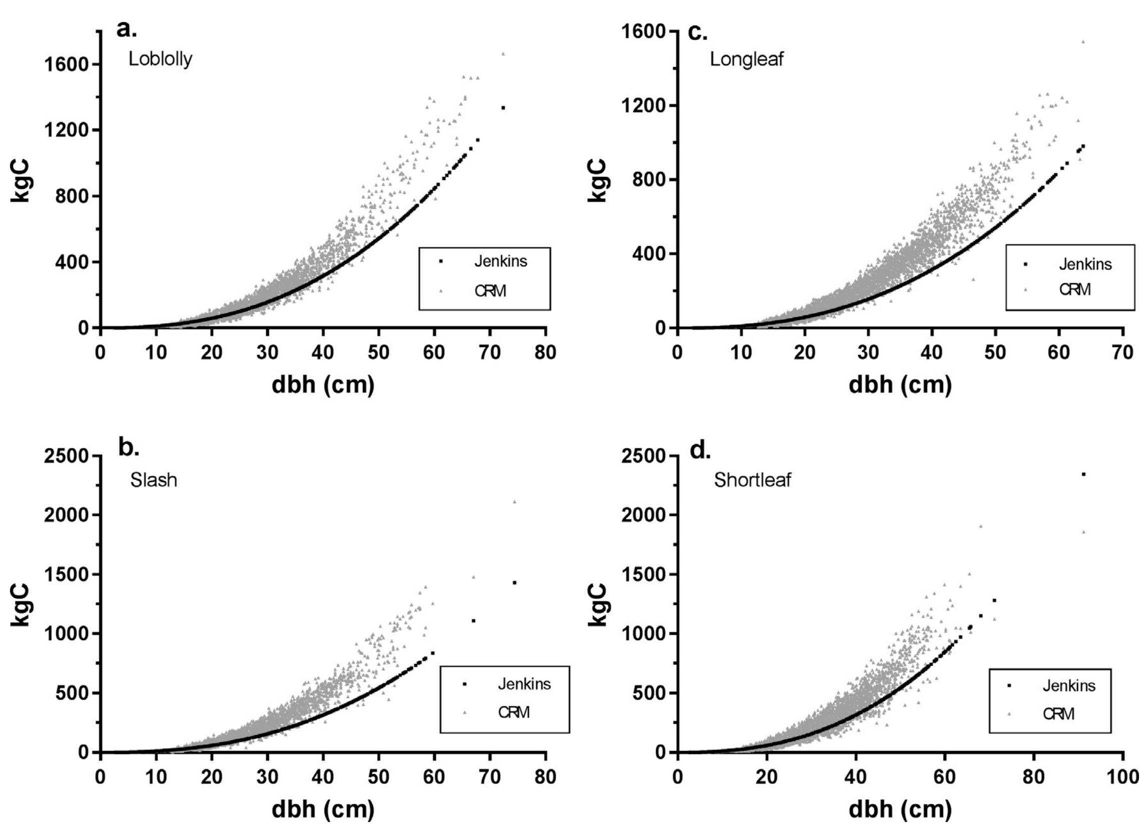

Fig. 5. Individual-tree estimates for live aboveground carbon (kg C) according to the Jenkins and CRM approaches for the four southern pine species that define the loblolly/shortleaf pine and longleaf/slash pine type groups in the Southern variant. Panels are as follows: (a) loblolly pine, (b) slash pine, (c) longleaf pine, (d) shortleaf pine. Note that axis scales differ between panels.

Table 3
Mean difference, number of plots, and equivalence test result for live aboveground carbon stock estimates in the Southern variant for the loblolly/shortleaf pine group, computed by each method, by state.

State	Equation Pair[a]	Mean Diff.	N	Equiv.	Variant-Level Equiv.
Alabama	Jenk-CRM	−3.75	735	10%	10%
	Jenk-FFE	−2.25		10%	5%
	CRM-FFE	1.50		5%	5%
Arkansas	Jenk-CRM	−3.18	463	10%	10%
	Jenk-FFE	−1.82		5%	5%
	CRM-FFE	1.36		5%	5%
Florida	Jenk-CRM	−4.54	163		10%
	Jenk-FFE	−1.51		10%	5%
	CRM-FFE	3.01		10%	5%
Georgia	Jenk-CRM	−5.11	619		10%
	Jenk-FFE	−2.76		10%	5%
	CRM-FFE	2.34		10%	5%
Louisiana	Jenk-CRM	−4.36	394		10%
	Jenk-FFE	−3.18		10%	5%
	CRM-FFE	1.19		5%	5%
Mississippi	Jenk-CRM	−5.88	642		10%
	Jenk-FFE	−3.72		10%	5%
	CRM-FFE	2.15		5%	5%
North Carolina	Jenk-CRM	−2.78	420	10%	10%
	Jenk-FFE	−1.60		5%	5%
	CRM-FFE	1.19		5%	5%
Oklahoma	Jenk-CRM	5.62	119		10%
	Jenk-FFE	4.23			5%
	CRM-FFE	−1.42		5%	5%
South Carolina	Jenk-CRM	−6.67	520		10%
	Jenk-FFE	−3.36		10%	5%
	CRM-FFE	3.31		10%	5%
Tennessee	Jenk-CRM	0.54	50	5%	10%
	Jenk-FFE	1.36		5%	5%
	CRM-FFE	0.81		5%	5%
Texas	Jenk-CRM	−2.52	261	10%	10%
	Jenk-FFE	−1.67		5%	5%
	CRM-FFE	0.85		5%	5%
Virginia	Jenk-CRM	−3.77	245	10%	10%
	Jenk-FFE	−2.09		5%	5%
	CRM-FFE	1.68		5%	5%

[a] Text in the equation pair column indicates the order of the comparison, e.g. Jenkins estimate *minus* CRM estimate. If equivalence column is blank, estimates were not equivalent at either 5 or 10%.

Table 4
Mean difference, confidence interval, sample size, and equivalence test result for live aboveground carbon stock estimates computed by each method for pooled hardwoods and softwoods[a] in the East and West.

Geographic Region	Vegetation Type	Equation Pair[b]	Mean Diff.	CI	N	Equiv.
Eastern States (NE, LS, CS, SN)	Softwoods	Jenk-CRM	2.21	1.9 to 2.5	9656	5%
		Jenk-FFE	2.86	2.6 to 3.1		10%
		CRM-FFE	0.63	0.5 to 0.8		5%
	Hardwoods	Jenk-CRM	11.70	11.5 to 12.0	28,267	
		Jenk-FFE	9.80	9.6 to 10.0		
		CRM-FFE	−1.86	−2.0 to −1.7		5%
Western States[c] (all other variants)	Softwoods	Jenk-CRM	14.34	13.8 to 14.8	18,985	
		Jenk-FFE	19.45	18.9 to 20.0		
		CRM-FFE	4.76	4.4 to 5.1		10%
	Hardwoods	Jenk-CRM	13.58	13.1 to 14.1	2809	
		Jenk-FFE	9.98	9.5 to 10.5		
		CRM-FFE	−3.60	−4.0 to −3.2		10%

[a] Hardwood groups exclude woodland hardwoods; softwood groups exclude pinyon/juniper.
[b] Text in the equation pair column indicates the order of the comparison, e.g. Jenkins estimate minus CRM estimate. If equivalence column is blank, estimates were not equivalent at either 5 or 10%.
[c] From Hoover and Smith (2017)

4. Conclusions

Our overall results are consistent with those from the western variants paper (Hoover and Smith, 2017). In particular: (1) equivalence between CRM and FFE is most common, and (2) aggregation of forest area included in an assessment tends to increase equivalence between (any pair of) approaches, more particularly in softwood forest types. In both the East and West, hardwoods were less likely to be equivalent, likely due to less regular growth form.

An influence of the equations used to estimate individual-tree merchantable volume is suggested in these results following the discussion related to Fig. 4, which indicate a greater difference between the two different volume estimates underlying CRM and FFE in the Central States and Lake States variants as compared with the smaller differences in the Northeast and Southern variants. The inconsistent equivalence results seen by forest type group between variants may also be related to volume. The number of sets of regional volume equations in the FIADB that underlie the CRM estimates used here can be quite variable; the Northeast and Southern variants each include one set while the Central States and Lake States variants each include two sets (O'Connell et al., 2017; Smith and Hoover, in press). This variability increases in the western variants, where seven of the variants include four or more sets of volume equations. This influence of volume is likely to extend to the Jenkins-CRM pair as well as CRM-FFE.

The effects of aggregation, or scale of a forest carbon assessment, where inclusion of greater forest area is associated with greater possibility of equivalence among the approaches considered here has two implications: (1) selection of tree carbon estimation approach becomes less consequential for larger areas in use, and (2) the information we have provided about equivalence of techniques, such as in Table 1, becomes less applicable for smaller areas in use. When comparing carbon stock estimates generated using different methods, scale of the assessment is important to consider. Finally, the Jenkins estimates are commonly, but not always, the largest and least likely to be equivalent among the three approaches examined.

Acknowledgements

We are grateful to Jeff Gove and Linda S. Heath for their helpful comments on this manuscript, as well as two anonymous reviewers.

References

Berger, R.L., Hsu, J.C., 1996. Bioequivalence trials, intersection-union tests and equivalence confidence sets. Stat. Sci. 11 (4), 283–319.

Brosi, B.J., Biber, E.G., 2009. Statistical inference, Type II error, and decision making under the US Endangered Species Act. Front. Ecol. Environ. 7 (9), 487–494.

California Environmental Protection Agency Air Resources Board, 2015. <https://www.arb.ca.gov/cc/capandtrade/protocols/usforest/usforestprojects_2015.htm> (23 May 2017).

Dixon, G.E. (Comp.), 2002. Essential FVS: A user's guide to the Forest Vegetation Simulator. Internal Rep. Fort Collins, CO: U. S. Department of Agriculture, Forest Service, Forest Management Service Center. 226p. (Last Revised: November 2015). Available at: <http://www.fs.fed.us/fmsc/ftp/fvs/docs/gtr/EssentialFVS.pdf>.

Domke, G.M., Woodall, C.W., Smith, J.E., Westfall, J.A., McRoberts, R.E., 2012. Consequences of alternative tree-level biomass estimation procedures on U.S. forest carbon stock estimates. For. Ecol. Manage. 270, 108–116.

Feng, S., Liang, Q., Kinser, R.D., Newland, K., Guilbaud, R.T., 2006. Testing equivalence between two laboratories or two methods using paired-sample analysis and interval hypothesis testing. Anal. Bioanal. Chem. 385, 975–981.

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

Hoover, C.M., Rebain, S.A., 2011. Forest carbon estimation using the Forest Vegetation Simulator: seven things you need to know. USDA Forest Service Gen. Tech. Rep. NRS-77. 16 p.

Hoover, C.M., Smith, J.E., 2017. Equivalence of live tree carbon stocks produced by three estimation approaches for forests of the western United States. For. Ecol. Manage. 385, 236–253.

MacLean, R.G., Ducey, M.J., Hoover, C.M., 2014. A comparison of carbon stock estimates and projections for the northeastern United States. For. Sci. 60(2), 206–213.

Mara, C.A., Cribbie, R.A., 2012. Paired-samples tests of equivalence. Commun. Stat. Simulat. 41, 1928–1943.

O'Connell, B.M., Conkling, B.L., Wilson, A.M., Burrill, E.A., Turner, J.A., Pugh, S.A., Christensen, G., Ridley, T., Menlove, J. 2017. The Forest Inventory and Analysis Database: Database description and user guide version 7.0 for Phase 2. U.S. Department of Agriculture, Forest Service. 830 p. Available: <https://www.fia.fs.fed.us/library/database-documentation/current/ver70/FIADB%20User%20Guide%20P2_7-0_ntc.final.pdf> (25 May 2017).

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.

Parkhurst, D.F., 2001. Statistical significance tests: equivalence and reverse tests should reduce misinterpretation. BioScience 51, 1051–1057.

Radtke, P., Walker, D., Frank, J., Weiskittel, A., DeYoung, C., MacFarlane, D., Domke, G., Woodall, C., Coulston, J., Westfall, J., 2017. Improved accuracy of aboveground biomass and carbon estimates for live trees in forests of the eastern United States. Forestry 90, 32–46.

Rebain, Stephanie A. comp., 2010 (revised March 23, 2015). The Fire and Fuels Extension to the Forest Vegetation Simulator: Updated Model Documentation. Internal Rep. Fort Collins, CO: U. S. Department of Agriculture, Forest Service, Forest Management Service Center. 403p. Available at: http://www.fs.fed.us/fmsc/ftp/fvs/docs/gtr/FFEguide.pdf.

Robinson, A.P., Duursma, R.A., Marshall, J.D., 2005. A regression-based equivalence test for model validation: shifting the burden of proof. Tree Phys. 25, 903–913.

Smith, J.E., Hoover, C.M., in press. Proceedings of the Fifth Forest Vegetation Simulator Conference. USDA Forest Service, Southern Research Station.

U.S. EPA, 2017. Inventory of U.S. greenhouse gas emissions and sinks: 1990–2015. EPA 430-P-17-001. U. S. Environmental Protection Agency, Office of Atmospheric Programs, Washington, D.C. Available at: <https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks> (24 May 2017).

USDA Forest Service, 2017a. FIA Datamart. Washington, DC: U.S. Department of Agriculture, Forest Service. <http://apps.fs.fed.us/fiadb-downloads/datamart.html> (25 May 2017).

USDA Forest Service, 2017b. Forest inventory and analysis national program: FIA library, database documentation. Washington, DC: U.S. Department of Agriculture, Forest Service. <http://fia.fs.fed.us/library/database-documentation/> (25 May 2017).

Zhou, Z., Hemstrom, M.A., 2009. Estimating aboveground tree biomass on forest land in the Pacific Northwest: a comparison of approaches. USDA Forest Service Res. Pap. PNW-RP-584. 18p.