Forest Ecology and Management 385 (2017) 236–253

Contents lists available at ScienceDirect

Forest Ecology and Management

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

Equivalence of live tree carbon stocks produced by three estimation approaches for forests of the western United States

Coeli M. Hoover *, James E. Smith

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

ARTICLE INFO

Article history:
Received 19 October 2016
Accepted 23 November 2016

ABSTRACT

The focus on forest carbon estimation accompanying the implementation of increased regulatory and reporting requirements is fostering the development of numerous tools and methods to facilitate carbon estimation. One such well-established mechanism is via the Forest Vegetation Simulator (FVS), a growth and yield modeling system used by public and private land managers and researchers, which provides two alternate approaches to quantifying carbon in live trees on forest land – these are known as the Jenkins and Fire and Fuels Extension (FFE) equations. A necessary consideration in developing forest carbon estimates is to address alternate, potentially different, estimates that are likely available from more than one source. A key to using such information is some understanding of where alternate estimates are expected to produce equivalent results. We address this here by focusing on potential equivalence among three commonly employed approaches to estimating individual-tree carbon, which are all applicable to inventory sampling or inventory simulation applications. Specifically, the two approaches available in FVS – Jenkins and FFE – and the third, the component ratio method (CRM) used in the U.S. Forest Service's, Forest Inventory and Analysis national DataBase (FIADB).

A key finding of this study is that the Jenkins, FFE, and CRM methods are not universally equivalent, and that equivalence varies across regions, forest types, and levels of data aggregation. No consistent alignment of approaches was identified. In general, equivalence was identified in a greater proportion of cases when forests were summarized at more aggregate levels such as all softwood type groups or entire variants. Most frequently, the FIA inventory-based CRM and FFE were determined to be equivalent.

Published by Elsevier B.V.

1. Introduction

With the implementation of offset protocols such as those included in the Regional Greenhouse Gas Initiative (RGGI, https://www.rggi.org/design/overview) and California Assembly Bill 32 (California Global Warming Solutions Act, 2016; California Environmental Protection Agency Air Resources Board, 2015), forest carbon estimation and management have become increasingly important areas of research and discussion. In addition, there is an active market in voluntary forest carbon credits (Forest Trends, 2016). The increased focus on forest carbon estimation is fostering the development of multiple tools and methods to facilitate carbon estimation. The diverse set of approaches for quantifying forest carbon can result in a range of possible values ascribed to a given subset of forest. That is, available tools produce alternate answers, largely because the underlying data and mathematical equation forms often vary among the approaches. Despite the potential for differences, the approaches addressed here all attempt to estimate the same quantity – whole tree biomass from inventory-like individual tree measurements. In this study, we assess the different estimation approaches to see if they produce carbon stock estimates that are statistically equivalent. Because alternate published routes to forest carbon are in use for carbon reporting (Heath et al., 2009; Jenkins et al., 2003; Rebain, 2010), a key to successfully using such information is some understanding of where alternate estimates are expected to produce equivalent results, or where they are not likely to be equivalent. We address this by focusing on potential equivalence among three commonly employed individual-tree carbon estimates applicable to inventory sampling or inventory simulation applications.

Methods for estimating aboveground live tree biomass, one of the two largest forest carbon stocks (soil being the other), fall into two main approaches when considering individual tree estimates: volume-based versus whole-tree based allometric relationships. In the first, the primary focus of the model estimate is on forest wood production. Bole volume is then converted to biomass or carbon, and the estimate is extended to account for the balance of the tree. This approach relies on local or regional equations for tree volume

* 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.2016.11.041
0378-1127/Published by Elsevier B.V.

(in the Forest Vegetation Simulator, known as FVS, these are generally regional equations from the National Volume Library, Dixon, 2002). With the second approach, the allometric relationships are intended to directly relate individual tree measurements, such as diameter and height, to estimates of biomass or carbon, usually through destructive sampling of a limited number of trees. These individual tree biomass equations generally are developed for local or regional applications. Choice of approach (volume-to-carbon or allometric biomass equation) depends on many factors including the type of data and equations available as well as the scale of the project and the needs of the manager or investigator. Because local and regional volume equations may be constructed quite differently from place to place, a set of ten generalized biomass equations was developed (Jenkins et al., 2003) to produce consistent national-scale estimates for U.S. reporting purposes. Due to concerns about the broad species groups used for the equations, the component ratio method (CRM) was developed in 2009 (Heath et al., 2009) and combines the Forest Inventory and Analysis (FIA) regional volume equations with component ratios from the Jenkins et al. (2003) method for calculating components of tree biomass. The CRM method (a volume-based approach) is now used to compute forest carbon estimates arising from FIA's forest inventory (USEPA, 2016).

The Forest Vegetation Simulator, or FVS (Dixon, 2002) is a growth and yield modeling system that is used by U.S. Forest Service managers for forest planning purposes, as well as other public and private land managers and researchers. FVS consists of 19 main geographic variants and can simulate a wide range of management scenarios. Simulations developed within FVS produce a series of intermediate results in the form of explicitly defined stand and tree structures, which are amenable to the inclusion of individual tree biomass equations. In 2006, carbon estimation capability was added to the Fire and Fuels Extension (FFE) of FVS (Rebain, 2010) to enable managers to assess the carbon implications of various management scenarios. The FFE includes two methods (one volume-based, one allometric) for estimating carbon in live tree biomass: the FFE default methods (FFE) based on equations from the National Volume Library, and the Jenkins et al. (2003) method described above. For more detail on carbon estimation using FFE, consult Hoover and Rebain (2011).

Each of these three approaches to estimating carbon in live tree biomass has strengths and weaknesses. For an excellent overview of the CRM and Jenkins estimates, see Zhou and Hemstrom (2009). Each method, using the same dataset, will produce a somewhat different carbon stock estimate. Chojnacky (2012) and Domke et al. (2012) reported that the CRM method generally produced lower biomass estimates than those calculated using the Jenkins et al. (2003) equations. This calls for caution when comparing studies or estimates which have been developed using different approaches since the results may not be genuinely comparable. With the advent of voluntary and compliance carbon markets, understanding these differences becomes a matter of some importance. The California Compliance Offset Protocol, for example, specifies one method for use in California, Oregon, and Washington, and another for the rest of the conterminous U.S. (California Environmental Protection Agency Air Resources Board, 2015). In addition, the Protocol allows for use of a set of approved growth and yield models (of which FVS is one) for certain purposes, and these employ still different computation methods. The FFE carbon reports have been used by a variety of investigators to examine the carbon implications of fuels reduction treatments, beetle outbreaks, and various harvesting scenarios (Hurteau and North, 2009; Caldwell et al., 2013; Kelsey et al., 2014).

MacLean et al. (2014) compared aboveground live carbon stock estimates and growth projections on a subset of states in the Northeast variant of FVS. Equivalence testing was used to compare estimates at a county level based on the biomass estimation approaches of CRM, FFE, and Jenkins. In this study, we build on that approach and compare aboveground live biomass carbon stock estimates produced from the three methods (CRM, FFE, and Jenkins) for each of the 15 major variants that cover the western U.S. We focus on the West because more variants are available, the Western variants compute total tree volume slightly differently than Eastern variants (Rebain, 2010), and west-versus-east is a common divide for forest inventories and populations.

We have three major objectives in this study where our focus is on the equivalence of alternate approaches when applied to a common set of inventory data:

(1) To test if estimates of live aboveground carbon stocks produced from the CRM, FFE, and Jenkins methods are statistically equivalent.
(2) Determine if the relative differences between the estimates are consistent across each of the geographic variants, or are variant-specific.
(3) Within variants, identify equivalence or patterns in equivalence by forest type groups (as defined by the Forest Inventory and Analysis (FIA) Program of the U.S. Forest Service, USDA Forest Service, 2016a).

2. Methods

2.1. Forest inventory data

Forest inventory data are used to provide a common input for calculations using each of the three approaches to estimating forest carbon, and these data are from the network of FIA permanent inventory plots (USDA Forest Service, 2016a). Inputs for calculating aboveground carbon vary among the Jenkins, CRM, and FFE approaches, and in some cases inputs vary from region to region (Jenkins et al., 2003; USDA Forest Service, 2016a; Hoover and Rebain, 2011). However, all necessary information for the three approaches are included in the FIA plot level data, which provides the basis for consistent comparisons.

Inventory data were obtained from the Forest Inventory and Analysis Data Base (FIADB), which is compiled and maintained by FIA (USDA Forest Service, 2016b). The data are based on continuous systematic annualized sampling of permanent plots over all land within individual states so that a portion of the survey data is collected each year on a continuous cycle, with remeasurement at 5 or 10 years depending on the state. The portion of the data used here represents U.S. forest lands of the western conterminous United States, and the approximately 12 percent of Alaska forest land of southern coastal Alaska that currently has the established permanent annual survey (Fig. 1). The specific data in use here were downloaded from http://apps.fs.fed.us/fiadb-downloads/datamart.html on 13 May 2016.

The forest inventory data were used to directly calculate stand level tree carbon and to initiate identical stands within FVS. Plot level estimates of carbon were calculated for CRM (USDA Forest Service, 2016a) directly from the FIADB. The Jenkins and FFE estimates include foliage, while the CRM estimates provided in the FIADB do not. For consistent comparison, an estimate for foliage following Jenkins et al. (2003) is added to the CRM estimate; this is consistent with the other Jenkins-based component ratios used within CRM (USDA Forest Service, 2016a). The same set of FIADB data – from the plot, condition, and tree tables (USDA Forest Service, 2016b) were input to FVS in order to establish simulations on plots identical to the FIADB's (see additional discussion of FVS in Section 2.2). Stand level estimates were resolved to carbon in the aboveground portion of all live trees greater or equal to 2.5 cm d.

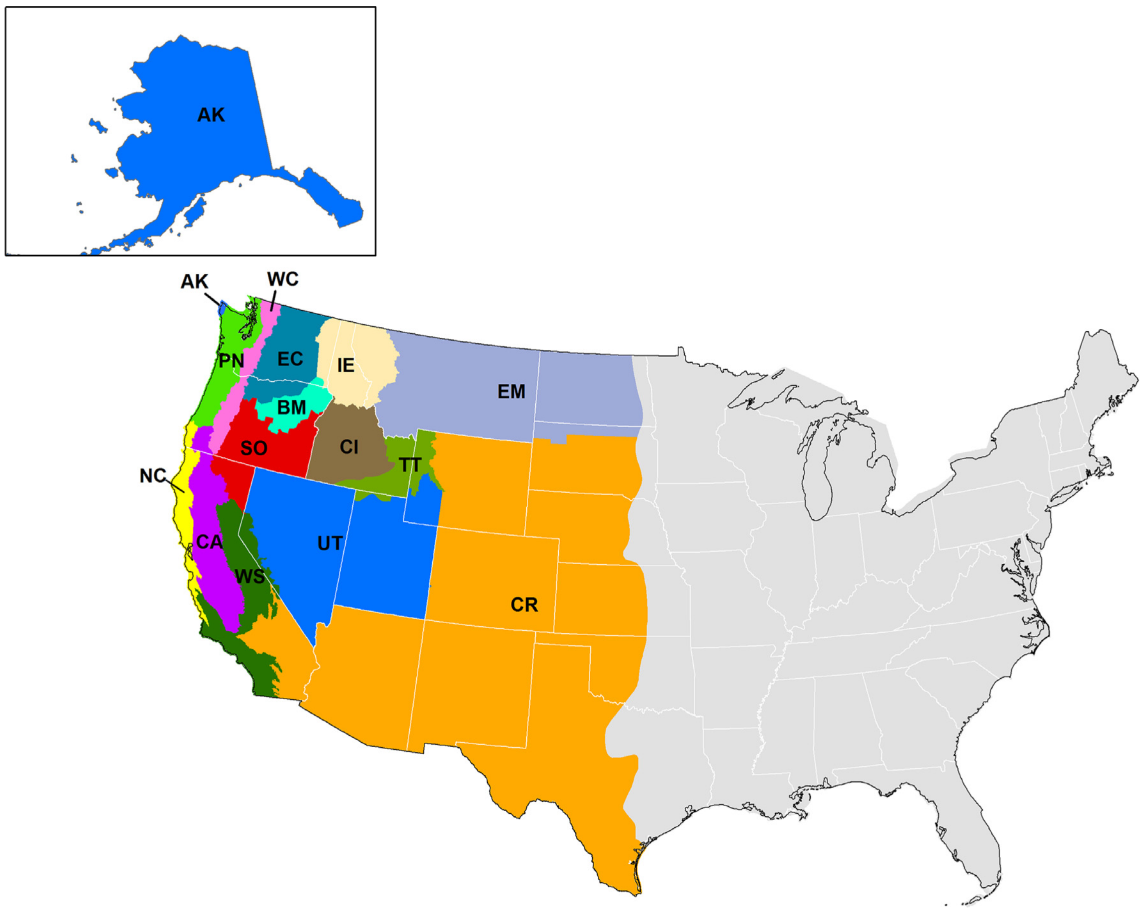

Fig. 1. Illustration showing the geographic extent of each FVS variant in the western U.S. Variant labels are as follows: AK = Southeast Alaska, PN = Pacific Northwest Coast, NC = Klamath Mountains, CA = Inland California and Southern Cascades, WS = Western Sierra Nevada, WC = Westside Cascades, EC = East Cascades, BM = Blue Mountains, SO = South Central Oregon and Northeast California, UT = Utah, IE = Inland Empire, CI = Central Idaho, EM = Eastern Montana, TT = Tetons, and CR = Central Rockies.

b.h. and expressed as carbon density or tonnes carbon per hectare (t C ha^{-1}).

The most recent evaluations – or cycle of the permanent inventory plots across each state – within each of the 18 states covered by western variants (Fig. 1) are used for this analysis, and these most-recent data include measurements obtained on plots from 2004 through 2015. For consistency, only those plots representing a single forested condition are used in the FVS simulations (USDA Forest Service, 2016a). We exclude non-stocked or very young stand-age (i.e., under 10 year) plots from the analysis because the lack of trees on these forest plots results in a zero-difference in carbon, an artifact biasing the resampling needed to develop the equivalence tests (see discussion of equivalence, below).

2.2. FVS and forest simulations

FVS simulations were used 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)). A companion of the FVS model (FIA2FVS, http://www.fs.fed.us/fmsc/ftp/fvs/docs/gtr/topics/Topic_yZ1_Fia2Fvs.pdf) provides the option of uploading FIA plot data from the FIADB. Importing the single-condition forest plots identified from the FIADB for the western variants into FVS permits us to reproduce the inventory plots and provides a means to apply the two FVS approaches to calculating stand level carbon density. From this, we obtain both FFE and Jenkins estimates for aboveground live tree carbon for trees of at least 2.5 cm d.b.h, excluding stands under 10 years or without trees.

2.3. Equivalence: Biomass equations and tests

Equivalence tests identify where estimates provided by one set of biomass equations can be considered equivalent to estimates from a different set of biomass equations (e.g., CRM vs. FFE). An essential feature of equivalence tests is that the null hypothesis states that the two populations are different (Parkhurst, 2001; Brosi and Biber, 2009) which can be viewed as the reverse of the more common approach to hypothesis testing. Equivalence tests are appropriate where the questions addressed by the analysis ask "are the groups similar, that is, effectively the same?" and not directly concerned with "are they different?" (Robinson et al., 2005; MacLean et al., 2014). This distinction follows from the idea that failure to reject a null hypothesis of no difference between populations does not necessarily indicate that the null hypothesis is true. The specific threshold of where two populations can be considered equivalent vs. different is set by researchers and a conclusion of not-different, or equivalent, results from rejecting the null hypothesis (that the two are different). We focus on equivalence tests of the mean difference between pairs of estimates – i.e., Jenkins vs. CRM, Jenkins vs. FFE, and CRM vs. FFE. These equivalence tests were applied within each FVS variant according to forest type group (USDA Forest Service, 2016a) and at additional levels of aggregation such as softwood versus hardwood forest type groups, or by entire variant. Note that the pooled softwood and hardwood aggregate groups do not include the pinyon/juniper and woodland hardwood type groups because they represent very different stand structures relative to other common western type groups.

The threshold, or bounds, of what is considered equivalent depends on the particular application and is set in advance by the researcher (Robinson et al., 2005; MacLean et al., 2014). Here, where the difference in carbon estimates is of interest, we set equivalence as an interval bounded by ±10 percent of the mean of the two stock estimates (i.e., tonnes carbon per hectare, t C ha^{-1}) within each classification. We also include tests based on a level of equivalence within ±5 percent of the mean of the two stocks. To illustrate this numerically, if two approaches (sets of equations) have mean carbon densities of 45.2 and 43.2 t C ha^{-1}, then the equivalence bounds are ±4.42 t C ha^{-1} (and ±2.21 t C ha^{-1} if the threshold is viewed as 5 percent).

Determination of equivalence is based on the data relative to these bounds, and the equivalence tests presented here are paired-sample tests (Feng et al., 2006; Mara and Cribbie, 2012). The "paired-samples" are two estimates – such as Jenkins and CRM – attained from each plot. A number of these paired estimates are calculated for the plots selected within a variant, and the differences (between pairs) are used to form the equivalence tests. The test statistic is based on the distribution of mean difference, which is obtained through resampling with replacement (Efron and Tibshirani, 1993) 10,000 times, with a mean value determined for each sample. This number of resamples is used because it is a convenient large number that produced stable distributions in all our preliminary analyses. To continue the numerical example, if a forest type group within an FVS variant includes 271 plots, then each sample is based on 271 random selections (with replacement) from that original pool of 271 paired differences. These sample random selections are repeated ten thousand times (i.e., 10,000 sets of 271), and the 10,000 means of each set of 271 samples (which are generally near 2 t C ha^{-1} for the example in use here, i.e., first stock minus second stock) form the distribution for the equivalence test. The number of plots available for resampling varied depending on the number of plots available from the FIADB-to-FVS import as well as the variant by type classification (i.e., level of aggregation within variant). To ensure statistical validity, we did not test for equivalence if fewer than 30 plots were available within a classification; however, these sparsely populated groups were included in aggregate sets. If over 5000 plots were available we randomly selected 5000 for resampling to reduce computational time because the sample size was already very large for this purpose.

The test statistic is based on the confidence interval of the distribution of mean difference between estimates, which was obtained through resampling. The confidence interval is calculated according to the bias corrected and accelerated method, which accounts for asymmetry and possible change in skewness as the mean varies; see Carpenter and Bithell (2000) and Fox (2008) for additional discussion. We use the two one-sided tests (TOST) of our null hypothesis (Berger and Hsu, 1996) that the plot-level difference exceeded the specified equivalence bounds and set $\alpha = 0.05$. So, the test statistic is the range of the 95 percent confidence interval about the mean difference between the paired plots, and this is compared with the previously set equivalence bounds.

The null hypothesis is that the two estimates are not equivalent, so this hypothesis is expressed in two parts – difference is greater than or less than the equivalence bounds. This is the basis for the two tests (TOST), which are: (1) that the mean difference interval extends to less than minus the equivalence bound, or (2) that the mean difference interval extends to greater than the equivalence bound. Within an application of the TOST where α (Type I error) is set to 0.05, a one-step approach to accomplish the TOST result is establish a 2-sided 90 percent confidence interval for the test statistic. If this falls entirely within the bounds prescribed as "equivalence" then the two populations (or carbon estimates, in this case) can be considered equivalent (Berger and Hsu, 1996). To complete the numerical example, the 2-sided 90 percent confidence interval for the example data is the interval from 1.5 to 2.6 t C ha^{-1}. This confidence interval (test statistic) is entirely within the ±4.42 t C ha^{-1} interval set for the 10 percent of mean bounds for equivalence. However, the confidence interval extends outside of the ±2.21 t C ha^{-1} interval set for the 5 percent of mean bounds so it is not considered equivalent at the narrower 5 percent level.

3. Results

We conducted equivalence tests at several levels of aggregation which may be useful to individuals developing estimates of carbon in aboveground live biomass. The West is covered by 15 different FVS variants (Fig. 1), each with different parameters and submodels. For information on each variant, see (http://www.fs.fed.us/fmsc/fvs/documents/guides.shtml). Note that in some cases a user's study area may include more than one geographic variant. Examining the mean variant-wide difference between carbon stock estimates calculated by each method (Jenkins minus CRM, Jenkins minus FFE, and CRM minus FFE), there is a general pattern of Jenkins estimates generally being higher than the CRM or FFE estimates, as noted by Domke et al. (2012), with the CRM and FFE estimates exhibiting the smallest average difference (Fig. 2a and b). This is an expected outcome, since both the CRM and FFE methods are based on the volume-to-biomass approach. The CRM and FFE approaches are equivalent at 5 percent in the Southeast Alaska, Klamath Mountains, East Cascades, Western Sierra, Blue Mountains, South Central Oregon, Central Idaho, Inland Empire, and Tetons variants, and at 10 percent in the Inland California and Eastern Montana variants. Exceptions to this general trend are found in the Pacific Northwest Coast, Westside Cascades, and Klamath Mountains variants, where Jenkins and CRM are equivalent at 5 percent in Pacific Northwest Coast and 10 percent in Westside Cascades and Klamath Mountains. In addition, Jenkins and FFE estimates are equivalent at 10 percent in the Klamath Mountains variant, the only case where all approaches produced comparable estimates.

Depending on the composition of the study area, investigators may be particularly interested in primarily hardwood or softwood forest types, so similar testing was done after classifying plots as either hardwood or softwood. The results for the mean difference between estimates for all pooled softwood plots show a similar pattern to the variant-wide results; the volume-based approaches are generally more alike (Fig. 3a and b). In most of the variants the CRM and FFE approaches are equivalent at either 5 or 10 percent, while in Pacific Northwest Coast, Westside Cascades, and Klamath Mountains the Jenkins and CRM approaches are equivalent at either 5 or 10 percent. When considering only softwoods, the Jenkins and FFE approaches are not equivalent in any variant, and in the Inland California variant, no approaches produced comparable estimates. If considering only hardwood types, estimates are equivalent in only a few cases; FFE and CRM at 10 percent in Westside Cascades, East Cascades, Inland Empire, and Central Rockies, Jenkins and FFE at 5 percent in Klamath Mountains, and Jenkins and CRM at 10 percent in Pacific Northwest Coast (Fig. 4a and b). No aggregate hardwood results are presented for Blue Mountains, South Central Oregon, and Central Idaho since equivalence was not tested when fewer than 30 plots were available. Note that in many cases the mean difference between the CRM and FFE estimates is negative, in contrast to the pooled softwoods where this difference is generally positive.

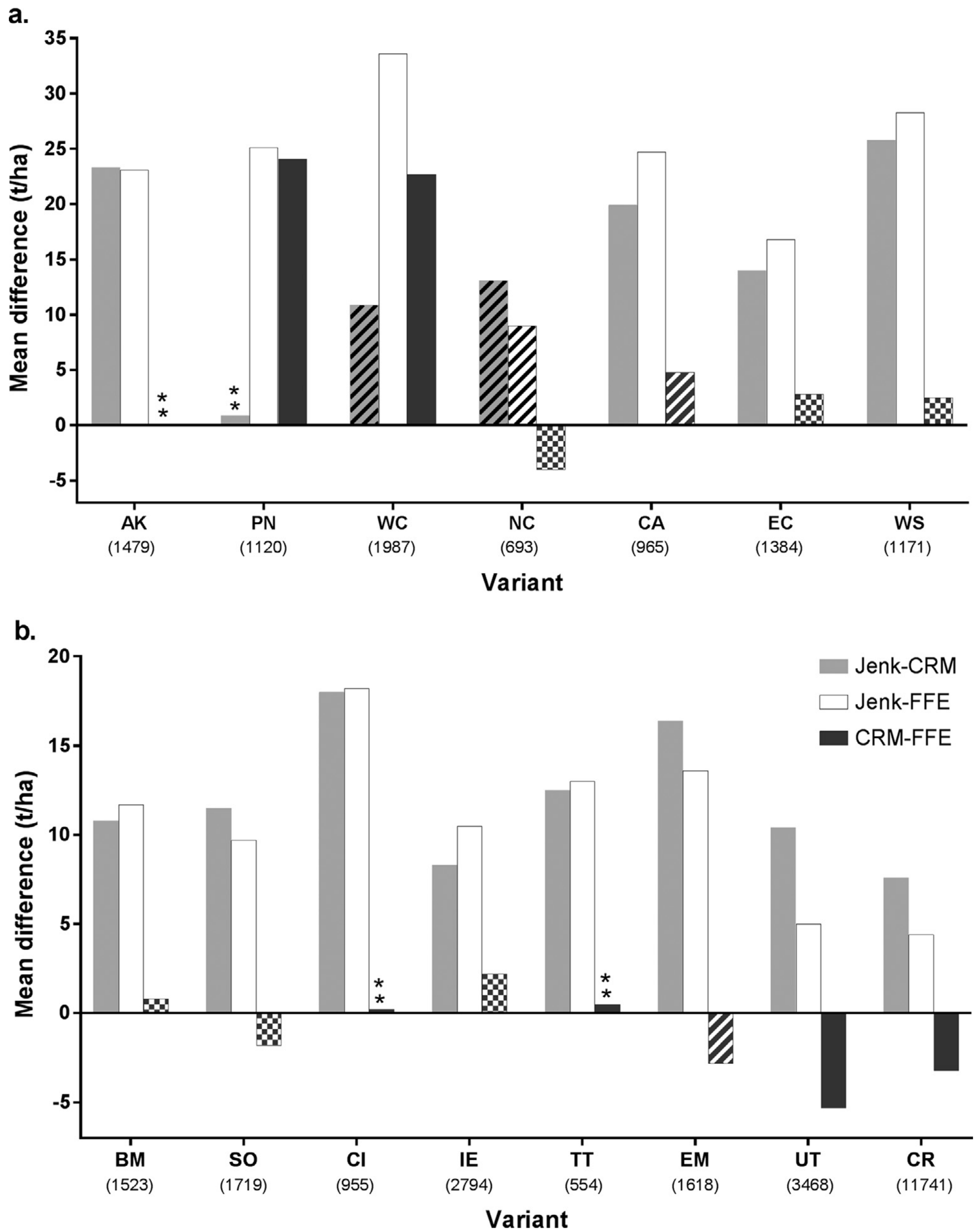

Fig. 2. (a and b) Mean difference of live aboveground biomass carbon estimates (t/ha) as computed by three different methods for each western FVS variant. Jenk = Jenkins, FFE = Fire and Fuels Extension, CRM = FIA component ratio method. Legend indicates each comparison, e.g. Jenk *minus* CRM. Equivalence at the 5 percent bounds is indicated by a striped bar, or double asterisk when bar height is near zero. Equivalence at the 10 percent bounds is indicated by a checked bar or single asterisk. Number of plots is in parentheses beneath the variant code; variant codes are as given in Fig. 1. Note that y axis scales differ.

To explore the equivalence patterns, we tested equivalence between estimates for each forest type group represented by at least 30 plots in our study dataset. Results are shown in Table 1 and are variable across type groups and variants, but a few trends are seen. Of the 12 variants in which Douglas-fir was tested, the CRM and FFE estimates are equivalent in 7; similar results hold for lodgepole pine, where CRM-FFE equivalence occurs in 10 out of 12 variants. Additionally, in the East Cascades and Inland Empire variants, carbon stock estimates are equivalent for lodgepole pine regardless of the approach, though the equivalence level varies. Finally, estimates for the fir/spruce/mountain hemlock type group are equivalent for the CRM-FFE comparison in 13 of 14 variants. As noted earlier, in the Pacific Northwest Coast and Westside Cascades variants the Jenkins and CRM estimates are often equivalent, and that is demonstrated in Table 1, with equivalence in Douglas-fir and the hemlock/Sitka spruce groups in both variants, and the alder/maple group in Westside Cascades.

For this study, all analysis is focused on testing the average difference between estimates developed using the three approaches. However, this provides little context for the magnitude of the difference relative to the stock estimate across variants and type groups. Table 2 gives the mean and standard deviation of the live aboveground biomass carbon stock for each type group and variant, along with the number of plots used. It is important to note that these stock values do not represent the overall average of all data in the FIADB for that type group and variant, but the average value for the plots included in our study sample (recalling that partial plots and multiple condition plots were excluded, as were very

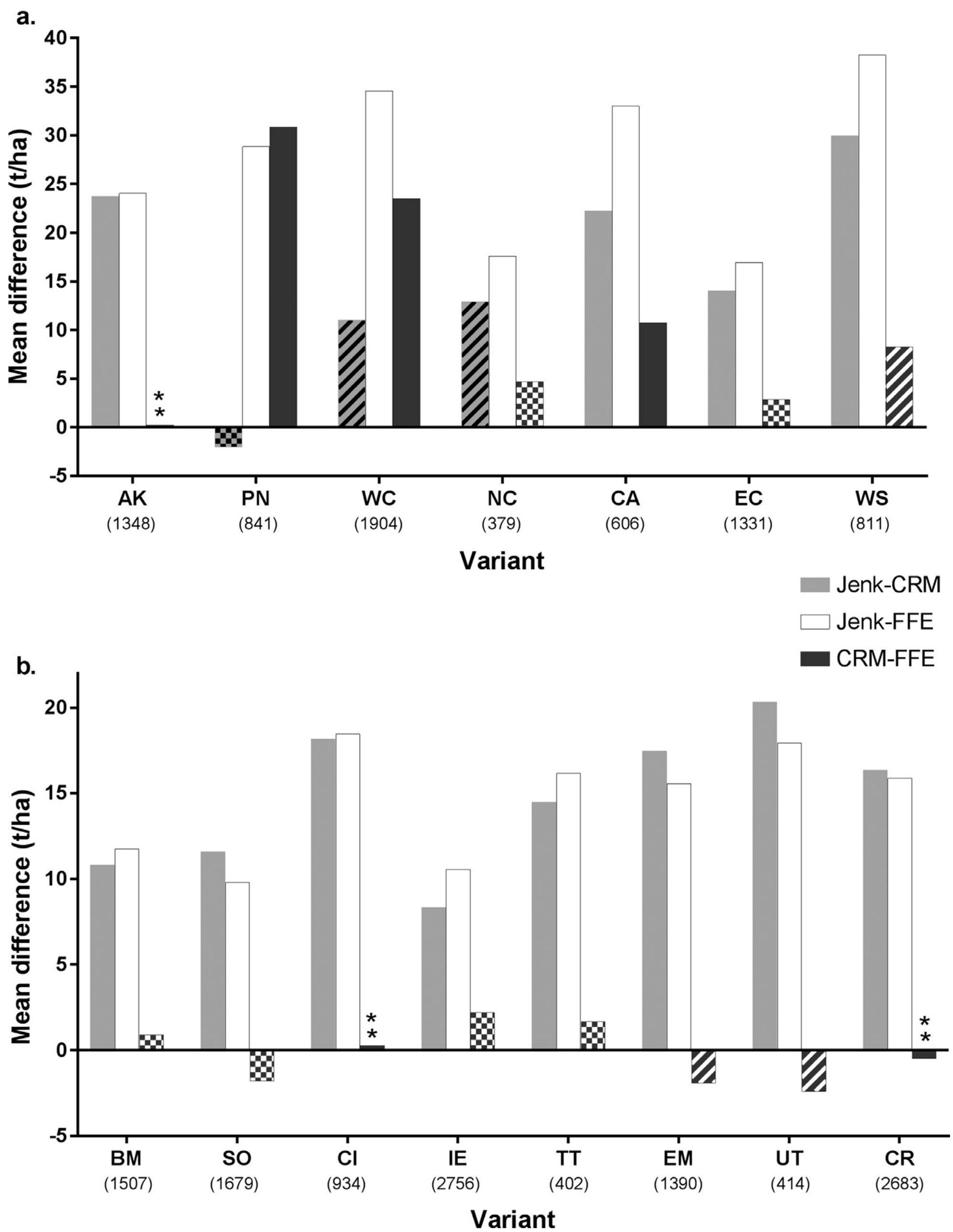

Fig. 3. (a and b) Mean difference of live aboveground biomass carbon estimates (t/ha) as computed by three different methods for each western FVS variant for softwood types only. Comparisons are as described in Fig. 2. Equivalence at the 5 percent bounds is indicated by a striped bar, or double asterisk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

young plots). The values reflect the high variability inherent in forest measurement data, but also provide concrete examples of how the calculation approach used affects the stock estimate.

4. Discussion

We identified multiple cases in which the different computation methods produced equivalent carbon stock estimates but there was no consistent alignment of approaches across all forest types or variants. In general, equivalence was identified in a greater proportion of cases when forests were summarized at more aggregated levels such as all softwood type groups or entire variants (see Figs. 2 and 3 relative to Table 1). A second generalization drawn from the summaries is that where equivalence was identified between two approaches, more often than not it was the two volume based estimates – CRM and FFE (e.g., Figs. 2–4). However, these same figures also identify exceptions to the general trend in the results.

An exception to the greater equivalence with aggregation is the Utah variant, where the CRM and FFE approaches are equivalent within the aggregate softwood type groups. However, this equivalence is not apparent for all forests over the entire variant; the mechanism for this is the large proportion of pinyon/juniper and woodland hardwood type groups within the Utah variant. These two type groups rarely included equivalent pairs (Table 1) but are part of the whole-variant analysis yet are not included in the softwood or hardwood aggregates (e.g., see differences in carbon, Table 2). A second example somewhat counter to a trend with

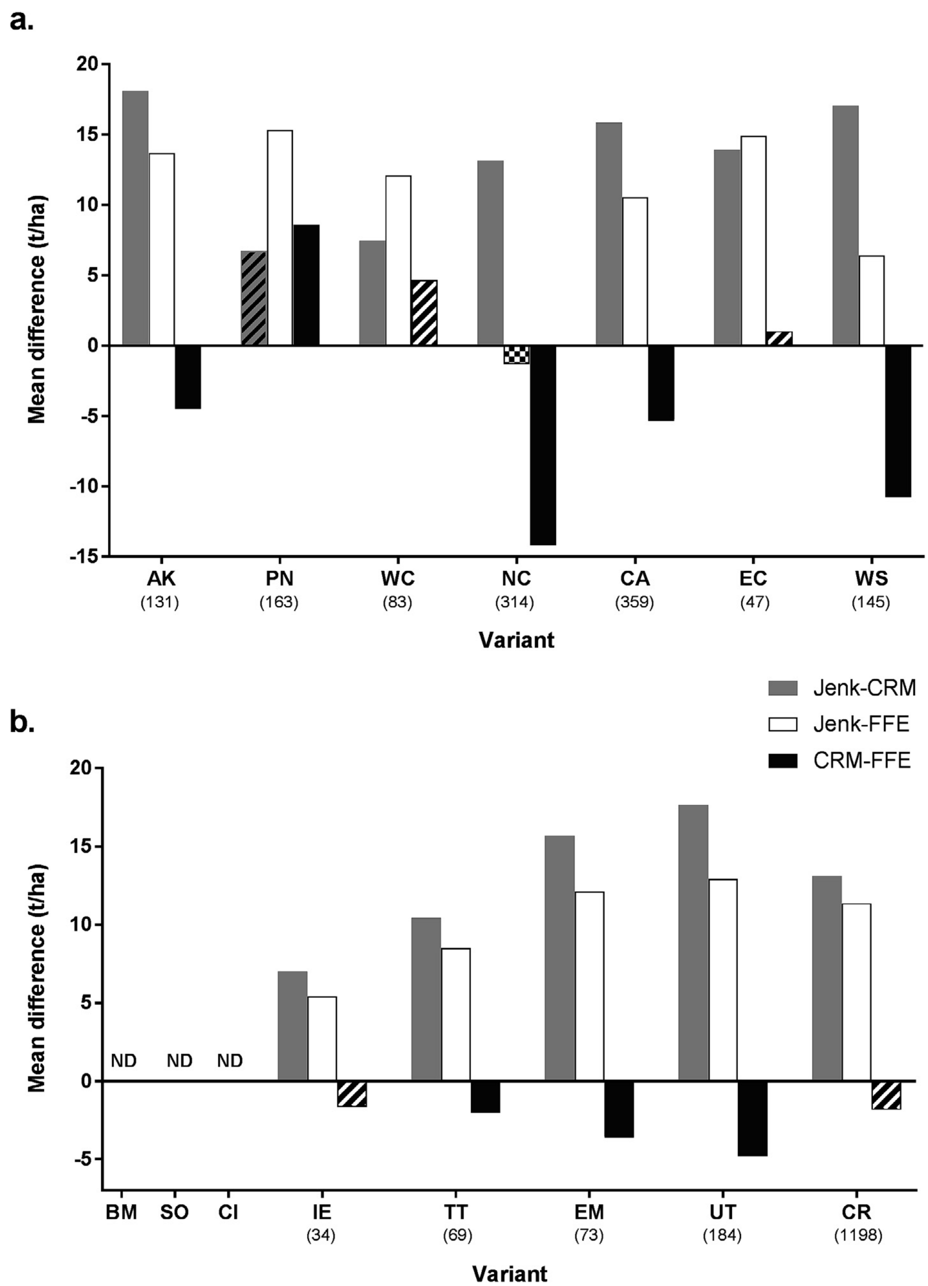

Fig. 4. (a and b) Mean difference of live aboveground biomass carbon estimates (t/ha) as computed by three different methods for each western FVS variant for hardwood types only. Comparisons are as described in Fig. 2. Equivalence at the 5 percent bounds is indicated by a striped bar, or double asterisk when bar height is near zero. Equivalence at the 10 percent bounds is indicated by a checked bar or single asterisk. Results are not shown when a category was represented by fewer than 30 plots (shown as ND). Number of plots is in parentheses beneath the variant code; variant codes are as given in Fig. 1. Note that y axis scales differ.

increased aggregation and equivalence is also with the CRM and FFE approaches in the variant Inland California. Both of the aggregate softwood and hardwood type groups are not identified as equivalent, but largely because the CRM minus FFE differences are in opposite directions (softwood vs. hardwood), the pooled whole-variant differences are small enough to be considered equivalent (i.e., intermediate aggregate is not equivalent but whole-variant is). The purpose of providing summaries at scales from whole variant to specific forest type groups is to assess outcomes relative to the three different approaches for estimating tree carbon that reflect the scale of interest for different possible applications. The observation that scale can affect equivalence only underscores the importance of identifying the use of the data before considering equivalence among approaches. Results for a particular forest type group are not a particularly useful reference if an FVS simulation addresses a landscape that includes many types.

The notable exception to the more-often general agreement between CRM and FFE and the mostly persistent differences of Jenkins from the other approaches is apparent in Fig. 2a and the Pacific Northwest Coast and Westside Cascades variants, which are on the west of the Cascade Mountains sides of Oregon and Washington. Within each of these the Jenkins and CRM approaches are equivalent for the whole-variant summaries. Effectively what has happened here is that the volume equations underlying CRM in this region produce estimates relatively closer to the Jenkins values than generally seen with other variants. Within the Pacific Northwest Coast variant, this change is most influenced by western

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. Values are metric tonnes of carbon per hectare.

Variant	Forest type group	Equation pair[a]	Mean diff.	CI	Equiv.
Southeast Alaska (AK)	Spruce/fir	Jenk-CRM	8.87	7.8–10.1	
		Jenk-FFE	1.51	0.8 to 2.3	
		CRM-FFE	−7.35	−8.5 to −6.4	
	Fir/spruce/mtn. hemlock	Jenk-CRM	28.80	27.2–30.6	
		Jenk-FFE	25.05	23.8–26.4	
		CRM-FFE	−3.75	−4.4 to −3.1	10%
	Lodgepole pine	Jenk-CRM	12.04	10.1–14.4	
		Jenk-FFE	10.48	8.9–12.4	
		CRM-FFE	−1.56	−2.2 to −1.0	
	Hemlock/Sitka spruce	Jenk-CRM	24.24	22.6–25.9	
		Jenk-FFE	28.24	27.1–29.5	
		CRM-FFE	4.01	3.1–4.9	5%
	Elm/ash/cottonwood	Jenk-CRM	29.00	24.5–34.8	
		Jenk-FFE	19.23	16.0–23.4	
		CRM-FFE	−9.81	−12.1 to −7.9	
	Aspen/birch	Jenk-CRM	14.09	12.5–15.9	
		Jenk-FFE	11.52	10.1–13.2	
		CRM-FFE	−2.56	−3.5 to −1.7	
Inland CA/S. Cascades (CA)	Douglas-fir	Jenk-CRM	23.55	20.3–26.8	
		Jenk-FFE	38.01	34.2–42.5	
		CRM-FFE	14.51	12.1–17.1	
	Ponderosa pine	Jenk-CRM	12.32	9.0–15.1	
		Jenk-FFE	17.59	15.2–20.2	
		CRM-FFE	5.28	3.2–8.3	
	Fir/spruce/mtn. hemlock	Jenk-CRM	38.84	34.8–43.6	
		Jenk-FFE	43.74	38.8–50.2	
		CRM-FFE	4.94	1.8–9.3	10%
	Calif. mixed conifer	Jenk-CRM	20.74	19.2–22.3	
		Jenk-FFE	32.60	30.9–34.5	
		CRM-FFE	11.86	10.4–13.4	
	Western oak	Jenk-CRM	16.65	15.5–18.0	
		Jenk-FFE	10.48	9.5–11.6	
		CRM-FFE	−6.17	−7.2 to −5.3	
	Other hardwoods	Jenk-CRM	9.80	5.3–15.4	
		Jenk-FFE	8.31	4.5–13.3	
		CRM-FFE	−1.45	−3.7 to 0.7	5%
Klamath Mountains (NC)	Douglas-fir	Jenk-CRM	19.23	15.4–23.2	
		Jenk-FFE	39.86	34.6–46.2	
		CRM-FFE	20.69	17.2–24.7	
	Redwood	Jenk-CRM	−28.79	−60.9 to −15.1	
		Jenk-FFE	−87.05	−126.4 to −68.0	
		CRM-FFE	−58.16	−68.8 to −51.4	
	Calif. mixed conifer	Jenk-CRM	28.01	24.1–32.4	
		Jenk-FFE	44.97	40.0–51.3	
		CRM-FFE	16.92	13.3–21.2	
	Western oak	Jenk-CRM	17.23	14.9–19.9	
		Jenk-FFE	16.85	14.1–20.0	
		CRM-FFE	−0.40	−2.0 to 2.0	5%
	Tanoak/laurel	Jenk-CRM	12.79	10.3–15.4	
		Jenk-FFE	−5.07	−8.2 to −1.9	10%
		CRM-FFE	−17.83	−20.2 to −15.6	
Pacific Northwest Coast (PN)	Douglas-fir	Jenk-CRM	2.64	0.8 to 4.6	5%
		Jenk-FFE	28.18	26.3–30.3	
		CRM-FFE	25.51	23.8–27.2	
	Fir/spruce/mtn. hemlock	Jenk-CRM	27.23	15.0–37.6	
		Jenk-FFE	30.34	21.4–40.6	
		CRM-FFE	3.05	−4.3 to 11.8	10%
	Hemlock/Sitka spruce	Jenk-CRM	−13.46	−18.0 to −9.1	10%
		Jenk-FFE	22.72	19.6–26.3	
		CRM-FFE	36.23	32.8–39.8	
	Alder/maple	Jenk-CRM	6.82	4.6–8.9	10%
		Jenk-FFE	15.49	13.7–17.9	
		CRM-FFE	8.69	6.9–10.7	

(*continued on next page*)

Table 1 (*continued*)

Variant	Forest type group	Equation pair[a]	Mean diff.	CI	Equiv.
Westside Cascades (WC)	Douglas-fir	Jenk-CRM	9.66	7.9–11.4	10%
		Jenk-FFE	41.80	40.0–43.6	
		CRM-FFE	32.15	30.9–33.5	
	Fir/spruce/mtn. hemlock	Jenk-CRM	17.13	15.2–19.2	
		Jenk-FFE	19.78	17.7–21.9	
		CRM-FFE	2.64	0.7 to 4.5	5%
	Lodgepole pine	Jenk-CRM	9.38	6.9–12.2	
		Jenk-FFE	9.18	7.1–12.1	
		CRM-FFE	−0.22	−1.9 to 1.7	5%
	Hemlock/Sitka spruce	Jenk-CRM	6.39	2.4–10.3	10%
		Jenk-FFE	34.46	31.3–38.2	
		CRM-FFE	28.08	25.4–30.9	
	Alder/maple	Jenk-CRM	6.06	2.8–9.5	
		Jenk-FFE	14.08	11.6–17.4	
		CRM-FFE	8.02	5.8–10.4	
Blue Mountains (BM)	Douglas-fir	Jenk-CRM	15.52	14.6–16.5	
		Jenk-FFE	16.63	15.6–17.7	
		CRM-FFE	1.10	0.7 to 1.6	5%
	Ponderosa pine	Jenk-CRM	9.21	8.7–9.7	
		Jenk-FFE	10.07	9.6–10.6	
		CRM-FFE	0.86	0.5 to 1.2	5%
	Fir/spruce/mtn. hemlock	Jenk-CRM	16.42	15.3–17.7	
		Jenk-FFE	18.03	16.8–19.4	
		CRM-FFE	1.59	0.9 to 2.3	5%
	Lodgepole pine	Jenk-CRM	5.72	4.6–7.0	
		Jenk-FFE	6.00	5.1–7.0	
		CRM-FFE	0.26	−0.3 to 0.8	5%
	Western larch	Jenk-CRM	−7.20	-13.2 to −3.9	
		Jenk-FFE	0.82	−2.5 to 3.0	5%
		CRM-FFE	8.02	6.2–10.7	
	Other western softwoods	Jenk-CRM	5.16	4.6 to 5.9	
		Jenk-FFE	1.82	1.3 to 2.6	
		CRM-FFE	−3.34	−3.7 to −3.0	
Central Idaho (CI)	Douglas-fir	Jenk-CRM	26.40	24.7–28.2	
		Jenk-FFE	26.49	24.9–28.2	
		CRM-FFE	0.08	−0.3 to 0.5	5%
	Ponderosa pine	Jenk-CRM	10.09	8.9–11.6	
		Jenk-FFE	9.96	8.9–11.4	
		CRM-FFE	−0.13	−0.8 to 0.7	5%
	Fir/spruce/mtn. hemlock	Jenk-CRM	17.97	16.2–20.4	
		Jenk-FFE	19.01	17.3–21.5	
		CRM-FFE	1.06	0.5 to 1.7	5%
	Lodgepole pine	Jenk-CRM	4.32	3.2–5.7	
		Jenk-FFE	5.93	5.1–7.3	
		CRM-FFE	1.63	1.1–2.2	10%
	Other western softwoods	Jenk-CRM	11.06	9.0–13.7	
		Jenk-FFE	8.59	6.8–10.8	
		CRM-FFE	−2.46	−3.1 to −1.9	
East Cascades (EC)	Douglas-fir	Jenk-CRM	17.45	16.3–18.7	
		Jenk-FFE	23.39	22.2–24.8	
		CRM-FFE	5.94	5.3–6.7	10%
	Ponderosa pine	Jenk-CRM	8.25	7.4–9.2	
		Jenk-FFE	8.44	7.6–9.4	
		CRM-FFE	0.19	−0.3 to 0.7	5%
	Fir/spruce/mtn. hemlock	Jenk-CRM	21.44	19.7–23.2	
		Jenk-FFE	20.31	18.7–22.0	
		CRM-FFE	−1.12	−2.2 to −0.0	5%
	Lodgepole pine	Jenk-CRM	1.46	−0.5 to 3.3	10%
		Jenk-FFE	1.06	−0.6 to 2.6	10%
		CRM-FFE	−0.39	−1.1 to 0.4	5%
	Hemlock/Sitka spruce	Jenk-CRM	11.81	5.2–19.7	
		Jenk-FFE	23.25	18.8–29.7	
		CRM-FFE	11.43	6.0–16.6	

Table 1 (*continued*)

Variant	Forest type group	Equation pair[a]	Mean diff.	CI	Equiv.
	Western larch	Jenk-CRM	−12.66	−16.3 to −9.2	
		Jenk-FFE	−9.60	−12.8 to −6.6	
		CRM-FFE	3.09	1.4–4.9	10%
	Other western softwoods	Jenk-CRM	9.22	6.9–12.4	
		Jenk-FFE	5.52	3.6–7.9	
		CRM-FFE	−3.75	−4.9 to −2.8	
Inland Empire (IE)	Douglas-fir	Jenk-CRM	12.14	11.5–12.8	
		Jenk-FFE	15.39	14.8–16.0	
		CRM-FFE	3.24	2.8 to 3.7	10%
	Ponderosa pine	Jenk-CRM	6.75	6.0–7.6	
		Jenk-FFE	5.31	4.7 to 6.0	
		CRM-FFE	−1.43	−1.9 to −1.0	5%
	Fir/spruce/mtn. hemlock	Jenk-CRM	11.18	10.5–11.9	
		Jenk-FFE	12.19	11.6–12.8	
		CRM-FFE	1.01	0.6 to 1.4	5%
	Lodgepole pine	Jenk-CRM	−0.61	−1.6 to 0.4	5%
		Jenk-FFE	1.01	0.3 to 1.7	5%
		CRM-FFE	1.62	1.2–2.1	5%
	Hemlock/Sitka spruce	Jenk-CRM	5.41	3.1–8.3	10%
		Jenk-FFE	11.50	9.8–13.6	
		CRM-FFE	6.11	4.5–7.5	10%
	Western larch	Jenk-CRM	−8.87	−11.1 to −6.9	
		Jenk-FFE	−3.09	−4.3 to −2.1	10%
		CRM-FFE	5.78	4.7–7.0	10%
S. Central OR/Northeast CA (SO)	Ponderosa pine	Jenk-CRM	9.83	9.3–10.4	
		Jenk-FFE	7.37	6.9 to 7.8	
		CRM-FFE	−2.46	−2.8 to −2.1	10%
	Fir/spruce/mtn. hemlock	Jenk-CRM	28.12	26.2–30.0	
		Jenk-FFE	28.87	26.9–31.1	
		CRM-FFE	0.76	−0.2 to 1.8	5%
	Lodgepole pine	Jenk-CRM	6.82	6.3–7.4	
		Jenk-FFE	5.01	4.5–5.6	
		CRM-FFE	−1.81	−2.1 to −1.6	10%
	Other western softwoods	Jenk-CRM	3.52	3.2–3.9	
		Jenk-FFE	0.21	−0.0 to 0.6	5%
		CRM-FFE	−3.31	−3.5 to −3.1	
	California mixed conifer	Jenk-CRM	20.07	18.0–22.4	
		Jenk-FFE	19.27	17.2–21.9	
		CRM-FFE	−0.83	−1.9 to 0.4	5%
Central Rockies (CR)	Other eastern softwoods	Jenk-CRM	7.60	6.0–9.7	
		Jenk-FFE	9.62	7.5–12.7	
		CRM-FFE	2.05	1.0–3.5	
	Pinyon/juniper	Jenk-CRM	5.11	5.0–5.2	
		Jenk-FFE	0.12	0.0–0.2	5%
		CRM-FFE	−4.99	−5.1 to −4.9	
	Douglas-fir	Jenk-CRM	26.09	24.9–27.4	
		Jenk-FFE	27.18	25.9–28.5	
		CRM-FFE	1.07	0.5 to 1.6	5%
	Ponderosa pine	Jenk-CRM	11.13	10.7–11.5	
		Jenk-FFE	10.93	10.6–11.3	
		CRM-FFE	−0.20	−0.5 to 0.1	5%
	Fir/spruce/mtn. hemlock	Jenk-CRM	21.66	20.9–22.4	
		Jenk-FFE	19.61	19.0–20.3	
		CRM-FFE	−2.04	−2.4 to −1.7	5%
	Lodgepole pine	Jenk-CRM	6.80	5.8 to 7.7	
		Jenk-FFE	8.81	8.1–9.5	
		CRM-FFE	2.01	1.5 to 2.6	10%
	Other western softwoods	Jenk-CRM	21.05	17.9–25.1	
		Jenk-FFE	16.90	14.2–19.5	
		CRM-FFE	−4.15	−6.3 to −2.5	
	Oak/hickory	Jenk-CRM	10.56	9.8–11.6	
		Jenk-FFE	11.35	10.5–12.5	
		CRM-FFE	0.79	0.5 to 1.2	10%

(*continued on next page*)

Table 1 (*continued*)

Variant	Forest type group	Equation pair[a]	Mean diff.	CI	Equiv.
	Elm/ash/cottonwood	Jenk-CRM	12.01	10.3–14.1	
		Jenk-FFE	15.44	12.7–18.9	
		CRM-FFE	3.39	2.0–5.3	
	Aspen/birch	Jenk-CRM	17.05	16.3–17.8	
		Jenk-FFE	10.76	10.2–11.4	
		CRM-FFE	−6.28	−6.7 to −5.9	
	Other hardwoods	Jenk-CRM	10.13	8.2–12.4	
		Jenk-FFE	7.41	5.9–9.2	
		CRM-FFE	−2.71	−3.7 to −1.9	
	Woodland hardwoods	Jenk-CRM	1.38	1.3 to 1.5	
		Jenk-FFE	−1.60	−1.7 to −1.5	
		CRM-FFE	−2.97	−3.1 to −2.9	
Eastern Montana (EM)	Pinyon/juniper	Jenk-CRM	6.68	6.0–7.5	
		Jenk-FFE	−3.52	−5.1 to −2.3	
		CRM-FFE	−10.21	−11.9 to −8.8	
	Douglas-fir	Jenk-CRM	31.38	30.0–32.9	
		Jenk-FFE	27.58	26.2–29.1	
		CRM-FFE	−3.79	−4.3 to −3.4	
	Ponderosa pine	Jenk-CRM	10.25	9.5–11.1	
		Jenk-FFE	6.37	5.8 to 7.1	
		CRM-FFE	−3.88	−4.5 to −3.4	
	Fir/spruce/mtn. hemlock	Jenk-CRM	16.67	15.5–17.9	
		Jenk-FFE	16.14	14.9–17.4	
		CRM-FFE	−0.54	−1.1 to −0.1	5%
	Lodgepole pine	Jenk-CRM	4.03	3.2–4.9	
		Jenk-FFE	4.51	3.8 to 5.2	
		CRM-FFE	0.48	−0.1 to 0.8	5%
	Other western softwoods	Jenk-CRM	16.34	14.6–18.5	
		Jenk-FFE	16.71	14.9–18.7	
		CRM-FFE	0.36	−0.5 to 1.3	5%
Tetons (TT)	Pinyon/juniper	Jenk-CRM	3.37	2.7 to 4.3	
		Jenk-FFE	2.07	1.5 to 2.7	
		CRM-FFE	−1.30	−2.2 to −0.8	
	Douglas-fir	Jenk-CRM	23.96	21.6–26.9	
		Jenk-FFE	26.12	24.1–28.9	
		CRM-FFE	2.17	1.3–3.3	10%
	Fir/spruce/mtn. hemlock	Jenk-CRM	18.21	16.3–20.4	
		Jenk-FFE	19.40	17.7–21.4	
		CRM-FFE	1.19	0.4 to 2.1	5%
	Lodgepole pine	Jenk-CRM	2.84	1.8 to 3.9	
		Jenk-FFE	4.95	4.3–5.7	
		CRM-FFE	2.10	1.5 to 2.9	10%
	Aspen/birch	Jenk-CRM	10.20	8.8–12.0	
		Jenk-FFE	8.23	7.0–9.6	
		CRM-FFE	−2.01	−2.5 to −1.5	
Utah (UT)	Pinyon/juniper	Jenk-CRM	8.56	8.3–8.8	
		Jenk-FFE	3.36	3.2–3.5	
		CRM-FFE	−5.20	−5.4 to −5.0	
	Douglas-fir	Jenk-CRM	24.32	21.7–27.7	
		Jenk-FFE	25.92	23.2–29.3	
		CRM-FFE	1.62	0.2–3.3	10%
	Ponderosa pine	Jenk-CRM	12.67	11.2–14.3	
		Jenk-FFE	9.69	8.2–11.4	
		CRM-FFE	−2.98	−3.8 to −2.2	
	Fir/spruce/mtn. hemlock	Jenk-CRM	24.22	22.6–26.0	
		Jenk-FFE	20.21	18.7–21.9	
		CRM-FFE	−4.01	−4.8 to −3.2	
	Lodgepole pine	Jenk-CRM	3.91	1.6 to 5.3	
		Jenk-FFE	7.51	6.5–8.5	
		CRM-FFE	3.61	2.6 to 5.2	
	Aspen/birch	Jenk-CRM	17.78	16.5–19.2	
		Jenk-FFE	13.03	12.0–14.2	
		CRM-FFE	−4.76	−5.2 to −4.3	

Table 1 (*continued*)

Variant	Forest type group	Equation pair[a]	Mean diff.	CI	Equiv.
	Woodland hardwoods	Jenk-CRM	7.44	6.8–8.0	
		Jenk-FFE	−3.49	−4.1 to −3.0	
		CRM-FFE	−10.94	−11.6 to −10.3	
Western Sierra Nevada (WS)	Pinyon/juniper	Jenk-CRM	15.55	14.2–17.1	
		Jenk-FFE	6.03	5.4–6.7	
		CRM-FFE	−9.53	−10.5 to −8.7	
	Ponderosa pine	Jenk-CRM	11.67	8.7–14.2	
		Jenk-FFE	21.05	18.5–24.2	
		CRM-FFE	9.42	7.2–12.2	
	Fir/spruce/mtn. hemlock	Jenk-CRM	57.25	53.2–61.8	
		Jenk-FFE	63.40	58.7–68.4	
		CRM-FFE	6.11	4.0–8.6	10%
	Lodgepole pine	Jenk-CRM	31.52	29.3–34.0	
		Jenk-FFE	31.63	29.2–34.3	
		CRM-FFE	0.09	−0.8 to 1.2	5%
	Other western softwoods	Jenk-CRM	27.40	23.1–33.6	
		Jenk-FFE	22.98	19.1–27.6	
		CRM-FFE	−4.53	−8.1 to −2.6	
	California mixed conifer	Jenk-CRM	25.69	23.6–27.7	
		Jenk-FFE	38.99	37.3–40.9	
		CRM-FFE	13.31	11.9–14.9	
	Western oak	Jenk-CRM	18.65	16.3–21.3	
		Jenk-FFE	7.49	5.6–9.5	
		CRM-FFE	−11.16	−13.7 to −9.2	

[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.

hemlock and somewhat less so by Douglas-fir, as demonstrated by the individual tree carbon estimates for these species (Figs. 5 and 6). The uppermost graph in each figure represents species level individual tree estimates for western hemlock and Douglas-fir within Pacific Northwest Coast where a large proportion of the CRM estimates are on or above the Jenkins values; this is the basis for the Jenkins minus CRM mean differences being negative for the aggregate softwood forest types. More typically, for most types in most other variants, the Jenkins minus CRM mean differences are positive. That is, the greater carbon estimate is generally but not always associated with Jenkins relative to CRM. This difference is particularly apparent in the larger diameter trees of Fig. 6, which suggests a related effect on net change, but that is not within the scope of this manuscript.

A useful feature of these summaries and tests of equivalence is that they provide a reference of expected differences between FVS carbon reports and forest carbon estimates from other sources where they are based on either Jenkins or CRM. Estimates of carbon stock or change within a particular forest, state or region, for example, are seldom the only available information on a given forest or project. Many alternate sampling or modeling systems exist to address the same quantities, and this report identifies where FVS results are likely placed relative to other inventory based (sampled or simulated) assessments.

This study was designed to assess the comparability of three commonly used approaches, not to validate the accuracy of those approaches. Validation would require the destructive sampling of trees of a range of species and diameters and is well beyond our scope. The methods that we compared are three commonly used approaches, but many more sets of local and regional volume and biomass equations, some proprietary, exist for U.S. tree species (e.g., see citations in Jenkins et al., 2003; Chojnacky et al., 2014). Choice of approach may be dictated by programmatic requirements, type of data or equations available, as well as the scale and objective of the project or study. Care should be taken when comparing carbon stock estimates developed using different computation methods. Our findings can provide some insight as to the similarity of the estimates under comparison, and the general differences that might be expected between estimates produced by volume-based and biomass equation approaches. While a detailed examination of the effect of computational approaches on estimates of carbon stock change is beyond the scope of this study, it is important to note that the CRM and FFE approaches include tree height, while the Jenkins method does not. This introduces several additional sources of variability: if a user does not supply tree heights, FFE calculates those from equations based on diameter, and tree heights in some forest types can be difficult to measure accurately. Height errors can be compounded on remeasurement; inaccurate height measurements may result in an apparent decrease in carbon stock resulting from a "loss" of tree height.

A key finding of this study is that the Jenkins, FFE, and CRM methods are not universally equivalent, and that equivalence varies across regions, forest types, and levels of data aggregation. Other estimation methods should also be expected to be variable in the level of comparability. When a reporting area, offset project, or study area is covered by more than one FVS variant, our equivalence results should be taken into account. For example, if a study site consisting largely of hemlock/Sitka spruce is covered by two variants, and the CRM-FFE estimates are equivalent in one variant but not the other, then there is the possibility that the carbon stock estimates are affected by differences in the behavior of the underlying volume equations. In such cases, users may consider basing the entire site on a single, self-consistent, method such as the more common of the two variants or using the Jenkins approach, which is less susceptible to such boundaries. In addition, if one approach is shown to have greater equivalence for the variants or forest type groups of interest, then use of that approach over the other is recommended. As stated above, our results should be considered when comparing carbon stock estimates produced using different estimation methods. While this paper covers three approaches, it contributes to possible insight into the relative differences

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
Southeast Alaska (AK)	Spruce/fir	Jenkins	20.5	18.1	124
		CRM	11.6	10.6	
		FFE	19.0	16.7	
	Fir/spruce/mtn. hemlock	Jenkins	89.2	63.0	437
		CRM	60.4	49.5	
		FFE	64.2	50.1	
	Lodgepole pine	Jenkins	28.0	21.3	51
		CRM	15.9	12.7	
		FFE	17.5	14.1	
	Hemlock/Sitka spruce	Jenkins	140.6	82.7	728
		CRM	116.4	76.6	
		FFE	112.4	68.8	
	Elm/ash/cottonwood	Jenkins	74.8	68.2	37
		CRM	45.7	57.9	
		FFE	55.5	57.4	
	Aspen/birch	Jenkins	39.9	27.5	87
		CRM	25.8	20.3	
		FFE	28.4	20.9	
Inland CA/S. Cascades (CA)	Douglas-fir	Jenkins	170.4	103.6	157
		CRM	146.8	93.5	
		FFE	132.3	78.6	
	Ponderosa pine	Jenkins	71.5	48.7	61
		CRM	59.1	51.9	
		FFE	53.9	42.6	
	Fir/spruce/mtn. hemlock	Jenkins	151.3	87.8	67
		CRM	112.5	77.4	
		FFE	107.5	63.4	
	Calif. mixed conifer	Jenkins	132.8	72.3	301
		CRM	112.1	71.5	
		FFE	100.2	58.3	
	Western oak	Jenkins	69.6	54.1	288
		CRM	52.9	47.0	
		FFE	59.1	49.1	
	Other hardwoods	Jenkins	86.4	70.1	42
		CRM	76.6	62.1	
		FFE	78.0	60.5	
Klamath Mountains (NC)	Douglas-fir	Jenkins	202.1	125.8	196
		CRM	182.9	118.5	
		FFE	162.2	95.3	
	Redwood	Jenkins	242.3	171.4	64
		CRM	271.1	257.2	
		FFE	329.3	291.0	
	Calif. mixed conifer	Jenkins	184.5	107.9	86
		CRM	156.5	102.2	
		FFE	139.6	84.3	
	Western oak	Jenkins	98.0	80.1	67
		CRM	80.8	74.3	
		FFE	81.1	69.2	
	Tanoak/laurel	Jenkins	152.0	82.0	216
		CRM	139.2	83.2	
		FFE	157.0	85.0	
Pacific Northwest Coast (PN)	Douglas-fir	Jenkins	156.5	113.4	690
		CRM	153.8	119.9	
		FFE	128.4	94.1	
	Fir/spruce/mtn. hemlock	Jenkins	234.5	116.0	35
		CRM	207.3	122.5	
		FFE	204.2	106.5	
	Hemlock/Sitka spruce	Jenkins	190.1	100.3	221
		CRM	203.6	114.4	
		FFE	167.4	90.0	
	Alder/maple	Jenkins	109.8	68.1	139
		CRM	102.9	70.4	
		FFE	94.3	59.8	

Table 2 (*continued*)

Variant	Forest type group	Equation	Mean tC/ha[a]	SD	N
Westside Cascades (WC)	Douglas-fir	Jenkins	204.3	117.8	1112
		CRM	194.7	118.7	
		FFE	162.5	95.0	
	Fir/spruce/mtn. hemlock	Jenkins	157.1	93.4	466
		CRM	140.0	97.0	
		FFE	137.4	86.7	
	Lodgepole pine	Jenkins	65.1	27.9	32
		CRM	55.7	24.8	
		FFE	55.9	23.5	
	Hemlock/Sitka spruce	Jenkins	203.2	92.6	270
		CRM	196.8	94.2	
		FFE	168.8	75.4	
	Alder/maple	Jenkins	94.7	51.1	49
		CRM	88.6	52.3	
		FFE	80.6	45.5	
Blue Mountains (BM)	Douglas-fir	Jenkins	68.5	37.7	258
		CRM	52.9	35.2	
		FFE	51.8	32.1	
	Ponderosa pine	Jenkins	51.7	27.4	586
		CRM	42.5	26.5	
		FFE	41.6	23.2	
	Fir/spruce/mtn. hemlock	Jenkins	83.9	49.0	362
		CRM	67.5	43.1	
		FFE	65.9	38.8	
	Lodgepole pine	Jenkins	36.3	25.7	114
		CRM	30.6	23.3	
		FFE	30.3	22.1	
	Western larch	Jenkins	67.5	41.1	53
		CRM	74.7	53.6	
		FFE	66.7	44.4	
	Other western softwoods	Jenkins	17.3	12.9	134
		CRM	12.1	9.4	
		FFE	15.4	10.9	
Central Idaho (CI)	Douglas-fir	Jenkins	71.8	45.6	386
		CRM	45.4	32.0	
		FFE	45.3	29.6	
	Ponderosa pine	Jenkins	54.1	38.5	118
		CRM	44.0	36.7	
		FFE	44.1	33.5	
	Fir/spruce/mtn. hemlock	Jenkins	63.1	48.8	236
		CRM	45.1	36.5	
		FFE	44.1	33.2	
	Lodgepole pine	Jenkins	40.5	24.4	113
		CRM	36.2	23.8	
		FFE	34.5	21.2	
	Other western softwoods	Jenkins	26.9	23.5	80
		CRM	15.9	12.9	
		FFE	18.3	14.4	
East Cascades (EC)	Douglas-fir	Jenkins	89.5	60.5	595
		CRM	72.1	54.5	
		FFE	66.2	46.2	
	Ponderosa pine	Jenkins	48.2	34.0	211
		CRM	40.0	32.5	
		FFE	39.8	29.2	
	Fir/spruce/mtn. hemlock	Jenkins	106.8	71.0	288
		CRM	85.4	66.5	
		FFE	86.5	61.6	
	Lodgepole pine	Jenkins	49.9	31.8	100
		CRM	48.4	35.7	
		FFE	48.8	33.7	
	Hemlock/Sitka spruce	Jenkins	182.4	93.4	51
		CRM	170.6	91.3	
		FFE	159.1	82.0	
	Western larch	Jenkins	68.8	35.6	50
		CRM	81.5	44.4	

(*continued on next page*)

Table 2 (*continued*)

Variant	Forest type group	Equation	Mean tC/ha[a]	SD	N
		FFE	78.4	40.9	
	Other western softwoods	Jenkins	23.0	20.5	35
		CRM	13.7	12.2	
		FFE	17.5	14.4	
Inland Empire (IE)	Douglas-fir	Jenkins	71.4	46.3	899
		CRM	59.2	46.0	
		FFE	56.0	39.4	
	Ponderosa pine	Jenkins	49.6	33.0	208
		CRM	42.9	33.6	
		FFE	44.3	31.5	
	Fir/spruce/mtn. hemlock	Jenkins	75.9	47.6	996
		CRM	64.7	48.5	
		FFE	63.7	43.3	
	Lodgepole pine	Jenkins	50.8	26.5	307
		CRM	51.4	31.1	
		FFE	49.7	28.3	
	Hemlock/Sitka spruce	Jenkins	107.9	58.1	173
		CRM	102.5	59.4	
		FFE	96.4	52.7	
	Western larch	Jenkins	64.2	33.7	150
		CRM	73.1	44.9	
		FFE	67.3	37.9	
S. Central OR/Northeast CA (SO)	Ponderosa pine	Jenkins	55.1	30.3	612
		CRM	45.3	29.8	
		FFE	47.8	27.6	
	Fir/spruce/mtn. hemlock	Jenkins	117.8	71.2	282
		CRM	89.7	60.8	
		FFE	88.9	54.6	
	Lodgepole pine	Jenkins	36.3	22.5	318
		CRM	29.5	20.1	
		FFE	31.3	19.9	
	Other western softwoods	Jenkins	11.8	10.3	369
		CRM	8.3	7.5	
		FFE	11.6	9.4	
	California mixed conifer	Jenkins	74.9	35.9	74
		CRM	54.8	32.7	
		FFE	55.7	28.8	
Central Rockies (CR)	Other eastern softwoods	Jenkins	21.8	18.1	30
		CRM	14.2	12.7	
		FFE	12.1	10.0	
	Pinyon/juniper	Jenkins	16.3	12.4	5055
		CRM	11.2	9.9	
		FFE	16.2	12.9	
	Douglas-fir	Jenkins	74.5	40.2	371
		CRM	48.4	31.0	
		FFE	47.3	27.8	
	Ponderosa pine	Jenkins	48.1	25.4	1076
		CRM	36.9	24.2	
		FFE	37.1	21.6	
	Fir/spruce/mtn. hemlock	Jenkins	76.4	39.7	863
		CRM	54.8	33.7	
		FFE	56.8	31.0	
	Lodgepole pine	Jenkins	52.0	23.9	271
		CRM	45.2	24.5	
		FFE	43.2	21.6	
	Other western softwoods	Jenkins	54.6	33.6	63
		CRM	33.5	21.9	
		FFE	37.7	23.4	
	Oak/hickory	Jenkins	23.8	23.1	541
		CRM	13.1	12.6	
		FFE	12.3	10.7	
	Elm/ash/cottonwood	Jenkins	36.8	37.8	114
		CRM	24.7	27.4	

Table 2 (*continued*)

Variant	Forest type group	Equation	Mean tC/ha[a]	SD	N
		FFE	21.4	19.9	
	Aspen/birch	Jenkins	60.7	35.9	459
		CRM	43.7	31.1	
		FFE	49.9	31.2	
	Other hardwood groups	Jenkins	20.8	16.9	44
		CRM	10.3	8.2	
		FFE	13.0	11.2	
	Woodland hardwoods	Jenkins	7.3	10.1	2805
		CRM	5.9	9.2	
		FFE	8.8	11.7	
Eastern Montana (EM)	Pinyon/juniper	Jenkins	14.3	10.9	151
		CRM	7.6	6.2	
		FFE	17.8	15.4	
	Douglas-fir	Jenkins	72.3	43.1	464
		CRM	40.8	28.6	
		FFE	44.6	27.4	
	Ponderosa pine	Jenkins	30.4	20.6	242
		CRM	20.1	15.7	
		FFE	24.0	16.9	
	Fir/spruce/mtn. hemlock	Jenkins	62.9	37.3	266
		CRM	46.2	30.9	
		FFE	46.8	28.6	
	Lodgepole pine	Jenkins	50.2	26.9	326
		CRM	46.2	28.1	
		FFE	45.7	26.4	
	Other western softwoods	Jenkins	46.4	31.2	92
		CRM	30.0	23.8	
		FFE	29.7	20.9	
Tetons (TT)	Pinyon/juniper	Jenkins	14.6	9.9	55
		CRM	11.2	7.8	
		FFE	12.5	9.5	
	Douglas-fir	Jenkins	78.4	38.7	112
		CRM	54.4	30.2	
		FFE	52.2	26.7	
	Fir/spruce/mtn. hemlock	Jenkins	66.3	38.4	142
		CRM	48.1	31.2	
		FFE	47.0	27.4	
	Lodgepole pine	Jenkins	38.3	24.3	133
		CRM	35.5	25.6	
		FFE	33.3	22.1	
	Aspen/birch	Jenkins	29.9	20.0	67
		CRM	19.7	14.0	
		FFE	21.7	14.5	
Utah (UT)	Pinyon/juniper	Jenkins	21.9	14.2	2576
		CRM	13.3	9.4	
		FFE	18.5	12.8	
	Douglas-fir	Jenkins	68.7	40.2	71
		CRM	44.4	31.8	
		FFE	42.8	26.6	
	Ponderosa pine	Jenkins	43.1	23.7	47
		CRM	30.4	19.6	
		FFE	33.4	18.8	
	Fir/spruce/mtn. hemlock	Jenkins	64.3	38.6	210
		CRM	40.0	27.7	
		FFE	44.0	26.2	
	Lodgepole pine	Jenkins	48.2	26.8	61
		CRM	44.2	30.4	
		FFE	40.6	25.7	
	Aspen/birch	Jenkins	49.9	33.5	181
		CRM	32.1	24.9	
		FFE	36.9	25.5	
	Woodland hardwoods	Jenkins	18.9	14.2	294
		CRM	11.4	10.8	
		FFE	22.3	15.9	
Western Sierra Nevada (WS)	Pinyon/juniper	Jenkins	27.5	21.1	207
		CRM	11.9	9.6	

(*continued on next page*)

Table 2 (*continued*)

Variant	Forest type group	Equation	Mean tC/ha[a]	SD	N
		FFE	21.5	16.5	
	Ponderosa pine	Jenkins	65.4	43.4	108
		CRM	53.7	48.7	
		FFE	44.3	37.6	
	Fir/spruce/mtn. hemlock	Jenkins	195.7	100.2	126
		CRM	138.4	85.0	
		FFE	132.3	73.1	
	Lodgepole pine	Jenkins	104.7	54.9	111
		CRM	73.2	46.8	
		FFE	73.1	42.6	
	Other western softwoods	Jenkins	59.7	48.1	67
		CRM	32.2	26.5	
		FFE	36.8	31.0	
	California mixed conifer	Jenkins	142.6	74.1	388
		CRM	116.9	74.0	
		FFE	103.6	61.4	
	Western oak	Jenkins	83.6	63.4	134
		CRM	64.9	53.5	
		FFE	76.1	62.0	

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

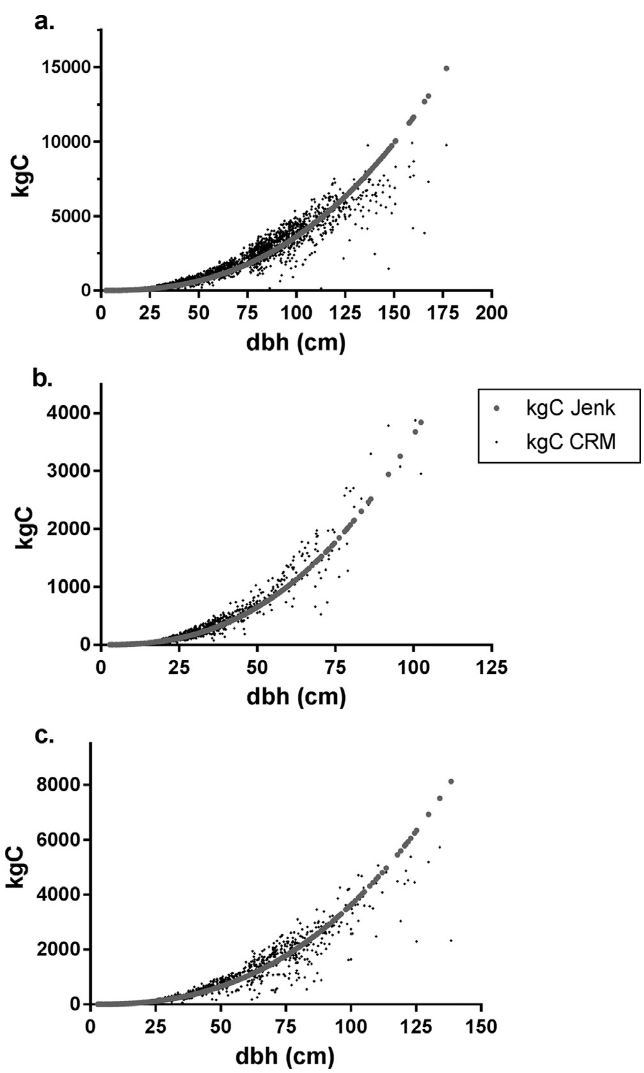

Fig. 5. Example scatterplots of live aboveground carbon biomass for individual hemlock trees calculated by the component ratio method (CRM) and Jenkins approaches, by diameter at breast height. Panel a, Pacific Coast Northwest, panel b, Inland Empire, panel c, Eastern Cascades. Note that scales of both axes differ.

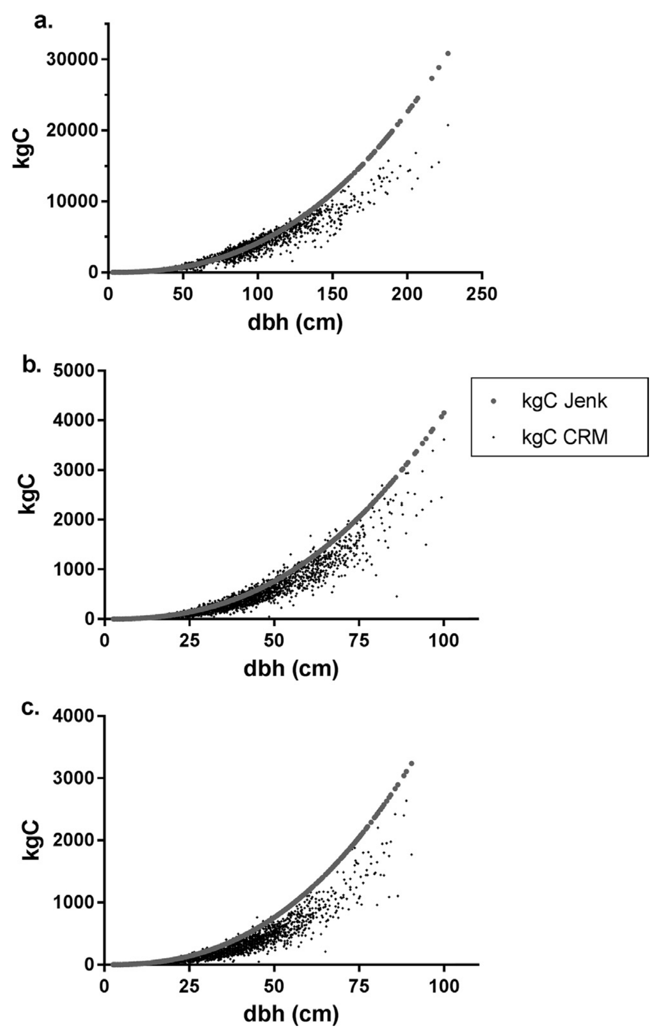

Fig. 6. Example scatterplots of live aboveground carbon biomass for individual Douglas-fir trees calculated by the component ratio method (CRM) and Jenkins approaches, by diameter at breast height. Panel a, Pacific Coast Northwest, panel b, Inland Empire, panel c, Central Rockies. Note that scales of both axes differ.

between volume-based and allometric approaches. Finally, if a change in computational approach occurs over time (Domke et al., 2012), all prior estimates must be recalculated using the new methodology.

Acknowledgements

We would like to thank Linda S. Heath, Susan L. Stout, and two anonymous reviewers for helpful feedback on this manuscript.

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.

Caldwell, M.E., Hawbaker, T.J., Briggs, J.S., Cigan, P.W., Stitt, S., 2013. Simulated impacts of mountain pine beetle and wildfire disturbances on forest vegetation composition and carbon stocks in the Southern Rocky Mountains. Biogeosciences 10, 8203–8222.

California Environmental Protection Agency Air Resources Board, 2015. <https://www.arb.ca.gov/cc/capandtrade/protocols/usforest/usforestprojects_2015.htm> (accessed 23 September 2016).

California Global Warming Solutions Act, 2016. <https://www.arb.ca.gov/cc/ab32/ab32.htm> (accessed 23 September 2016).

Carpenter, J., Bithell, J., 2000. Bootstrap confidence intervals: when, which, what? A practical guide for medical statisticians. Statis. Med. 19, 1141–1164.

Chojnacky, D.C., 2012. FIA's volume-to-biomass conversion method (CRM) generally underestimates biomass in comparison to published equations. In: Morin, R.S., Liknes, G.C., et al. (Eds.), Moving From Status to Trends: Forest Inventory and Analysis (FIA) Symposium 2012. Gen. Tech. Rep. NRS-P-105. U.S. Department of Agriculture, Forest Service, Northern Research Station, Newtown Square, PA, pp. 396–402.

Chojnacky, D.C., Heath, L.S., Jenkins, J.C., 2014. Updated generalized biomass equations for North American tree species. Forestry 87, 129–151.

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. Available at: <http://www.fs.fed.us/fmsc/ftp/fvs/docs/gtr/EssentialFVS.pdf> (last revised: November 2015).

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.

Efron, B., Tibshirani, R.J., 1993. An Introduction to the Bootstrap. Chapman and Hall, New York.

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.

Forest Trends, 2016. Raising Ambition: State of the Voluntary Carbon Markets 2016 http://www.forest-trends.org/documents/files/doc_5242.pdf (accessed 23 September 2016).

Fox, J., 2008. Bootstrapping regression models. In: Applied Regression Analysis and Generalized Linear Models. second ed. Sage, Inc., Thousand Oaks, CA, pp. 587–606.

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. 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.

Hurteau, M., North, M., 2009. Fuel treatment effects on tree-based forest carbon storage and emissions under modeled wildfire scenarios. Front. Ecol. Environ., 7 http://dx.doi.org/10.1890/080049.

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.

Kelsey, K.C., Barnes, K.L., Ryan, M.G., Neff, J.C., 2014. Short and long-term carbon balance of bioenergy electricity production fueled by forest treatments. Carbon Balance Manage. 49, 6. http://dx.doi.org/10.1186/s13021-014-0006-1.

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.

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

Rebain, Stephanie A., comp. 2010. 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> (revised March 23, 2015).

Regional Greenhouse Gas Initiative, 2016. <https://www.rggi.org/design/overview> (accessed 23 September 2016).

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.

USDA Forest Service, 2016a. Forest inventory and analysis national program: FIA library, database documentation. Washington, DC: U.S. Department of Agriculture, Forest Service. A website: <http://fia.fs.fed.us/library/database-documentation/> (23 Sep 2016).

USDA Forest Service, 2016b. FIA datamart. Washington, DC: U.S. Department of Agriculture, Forest Service. A website: <http://apps.fs.fed.us/fiadb-downloads/datamart.html> (23 Sep 2016).

USEPA, 2016. Inventory of U.S. greenhouse gas emissions and sinks: 1990–2014. EPA 430-R-16-002. U.S. Environmental Protection Agency, Office of Atmospheric Programs, Washington, D.C. Available at http: <https://www.epa.gov/ghgemissions/us-greenhouse-gas-inventory-report-1990-2014> (23 Sep 2016).

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.