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RESEARCH

Implications of alternative biomass and carbon estimation methods for standing dead trees in the United States

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Abstract New models quantifying tree volume, biomass, and carbon have recently been implemented across the USA, termed the National-Scale Volume and Biomass (NSVB) framework. Little research has been done to quantify the implications of these new models on the standing dead tree (SDT) carbon pool, which occupies a substantial portion of the nation's total forest ecosystem carbon stocks. This project compared predictions of carbon stocks in SDTs using the previous estimation approach (the Component Ratio Method) and NSVB using the most recent FIA data collected across the conterminous USA. Equivalence tests were conducted to compare predictions using the two modeling systems. Results show similar findings to what has been recently observed for live trees, namely that NSVB produces predictions of carbon in SDTs larger than those produced from CRM. However, predictions produced from NSVB and CRM for SDTs in advanced stages of decay (i.e., decay classes 4 and 5) are similar, likely due to the lack of tops and limbs in these SDTs, which has been suggested as a reason for the increased carbon stock predictions produced in live trees using the NSVB framework. Individual SDT predictions have important implications when scaled to the population (e.g., condition and state levels), where we similarly observed NSVB predictions to be larger compared to CRM predictions. These results highlight the role that biometrical methods play in determining carbon in SDTs, such as decay class and structural loss reduction factors and species-specific carbon fractions that are implemented in the NSVB framework.

Keywords Snags · Dead wood · Forest Inventory and Analysis · Component Ratio Method · National-Scale Volume and Biomass

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Introduction

The presence and abundance of dead wood in forests provides carbon (C) storage, wildlife habitat, biodiversity features, and structural diversity to support healthy forest ecosystems (Palik et al., 2020; Stokland et al., 2012; Wijas et al., 2024). The distribution, character, and structure of dead wood are

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key determinants of fire behavior and subsequent carbon dynamics (Jiang et al., 2025; Lutz et al., 2021). Natural disturbances can result in immediate or more gradual additions to dead wood carbon pools (Lorimer & Halpin, 2014), and forest management practices may seek to retain dead wood as a part of silvicultural prescriptions for the benefits they provide (Palik et al., 2020; Sandström et al., 2019). The amount of carbon stored in dead wood is a substantial portion of the total forest ecosystem. In the USA, dead wood represents 3184 MMT C, or approximately 18% of the aboveground biomass pool in forests (Domke et al., 2024). Biomass in SDTs in the USA has increased by 14.7%, a rate that has outpaced the accrual of biomass in live trees from approximately 2006 through 2010 and 2015 through 2019 (Woodall et al., 2021).

Quantifying the amount of carbon stored in dead wood is difficult, in particular for standing dead trees (SDTs). In nationwide forest inventories, fixed-area plots are the most popular design for sampling SDTs (Russell et al., 2015; Woodall et al., 2008) and are typically remeasured through time. Between inventory remeasurements, SDTs can transition through multiple pathways (e.g., live to SDT or SDT to downed; Klockow et al., 2023), which can lead to different decay patterns and SDTs of various structural characteristics. The decay class is a variable often collected to account for density and structural losses due to the stage of decay, yet decay class systems are not standardized and are subjectively assigned in field data collection efforts. While robust data exist on the volume, biomass, and carbon attributes for living trees (e.g., Radtke et al., 2015), fewer studies examine SDTs where carbon fractions are known to differ from their live tree counterparts (Martin et al., 2021). In the USA, the calculation of SDT carbon has historically begun with assuming the tree is alive and reducing its volume in a series of subsequent procedures (Westfall et al., 2024; Woodall et al., 2011). Additional analytical procedures must be taken into account for determining volume, biomass, and carbon content of SDTs, including the integration of wood density reductions (e.g., Harmon et al., 2011) and structural loss adjustments that represent the loss of carbon from components such as bark, tops, and limbs (e.g., Domke et al., 2011).

The Component Ratio Method (CRM) was developed by the USDA Forest Service to provide a nationally consistent approach to estimate volume, biomass, and carbon in live and SDTs for USA tree species (Heath et al., 2009). The CRM approach represented an important development over previous approaches that relied only on tree diameter and were limited for application at local or regional scales (i.e., Jenkins et al., 2003). The original CRM predictions did not have different estimation procedures for live and SDTs (Woodall et al., 2011) however, Domke et al. (2011) presented a set of wood density reductions and structural loss adjustment factors that were dependent on decay class and were applied to SDT components (e.g., top/branch and bark) to determine carbon. More recently, several issues with the CRM approach for determining tree volume, biomass, and carbon were realized, including (1) the numerous volume model forms employed from a range of studies, (2) the reliance on administrative units (e.g., states and regions) as opposed to ecological regions for implementing equations, and (3) the lack of use of species-specific carbon fractions to determine carbon content in trees. The National-Scale Volume and Biomass (NSVB) models were developed by compiling tree data and implementing a new prediction approach for volume, biomass, and carbon that is nationally consistent (Westfall et al., 2024). For SDTs, the findings of Harmon et al. (2011) were used to develop wood density reductions and structural loss adjustment factors to use in calculating carbon stored in SDT using the NSVB framework. To date, research on live trees has found that the NSVB predicts more aboveground biomass compared to CRM due to the underestimation of the top and limb components in CRM (Restrepo et al., 2025; Westfall et al., 2024). Little research has compared the quantification approaches for SDTs using both modeling systems and the implications of using the NSVB framework for the standing dead wood carbon pool.

The goal of this study is to determine the impact of utilizing the NSVB framework for determining SDT carbon by comparing it to the CRM framework. Specific objectives are to (1) determine aboveground SDT carbon using NSVB and CRM modeling frameworks and compare differences in the predictions resulting from methodological changes at the individual level across different species, decay classes, and ecological divisions and (2) analyze plot- and state-level differences in population predictions resulting from methodological changes.

Materials and methods

Forest inventory data

Field data were compiled from the nationwide forest inventory conducted by the USDA Forest Service, Forest Inventory and Analysis (FIA) program. All data were compiled from the conterminous 48 USA states at their most recent inventory (2011–2023). Forest types in this study area ranged from intensively managed timberlands to nonproductive forestlands that included a diversity of conifer, hardwood, and mixed-species forest types (Oswalt et al., 2019). The FIA program established inventory plots at a base intensity of approximately one plot per 2400 ha (Westfall et al., 2022). These plots consisted of four 7.32-m fixed radius subplots where live trees, SDTs, and site attributes were measured, for a total plot area of approximately 0.07 ha. All live and SDTs with a diameter at breast height (DBH) of at least 12.7 cm were measured on these subplots. Within each subplot, a 2.07-m microplot was established where live trees with a DBH between 2.5 and 12.7 cm were measured. In this analysis, all SDTs greater than 12.7 cm DBH were analyzed at the individual level, while all SDTs greater than 2.5 cm were included for analysis at the plot and population levels. The key SDT attributes were compiled from FIA's TREE table and included whether the observation was an SDT (STANDING_DEAD_CD), tree species (SPCD), DBH (DIA), total height (HT), actual height (ACTUALHT), height of the bole to a 10.2-cm top (BOLEHT), percent of the volume that is rotten or missing (CULL), and decay class (DECAYCD). In particular, the decay class is categorized using one of five classes based on decomposition characteristics of SDT components, like presence of bark and tops (USDA Forest Service, 2023). In total, 457,535 and 402,272 SDTs greater than 2.54 and 12.7 cm, respectively, were used in this analysis.

Carbon estimation for standing dead trees

This study evaluated aboveground carbon in SDTs using both the CRM and NSVB approaches.

Component Ratio Method

The CRM provides a consistent approach to estimating volume, biomass, and carbon in live and standing dead trees for USA tree species (Heath et al., 2009). Using tree measurements, models that are specific to regions or states are applied to determine gross and sound volume (Fig. S1), followed by a component proportion approach using the equations of Jenkins et al. (2003) to determine biomass and carbon (Woodall et al., 2011). In the CRM estimation approach, gross volume is typically determined using tree DBH and HT but, depending on the region and species, could also include site index or BOLEHT. Sound volume is then determined by adjusting gross volume using the percentage of volume that is missing or rotten (i.e., cull volume) or DBH. This project used equations from Woodall et al. (2011) and the reduction factors presented in Domke et al. (2011) to determine SDT carbon for the compiled data using the CRM estimation method (Table 1).

National-Scale Volume and Biomass

In the NSVB modeling system, a compatible system of equations predicting volume, biomass, and carbon in a nationally-consistent manner was developed using one of four model forms (Westfall et al., 2024). Models varied by species, ecological division (Fig. S1), and sometimes stand origin. The NSVB modeling framework employed species-specific carbon fractions as opposed to the default approximation of 0.5 as the ratio of carbon to dry wood weight used in the CRM approach. Wood density reductions and structural loss adjustment factors were developed that depended on SDT decay class, which differed from CRM values (Table 1).

Analysis of standing dead tree carbon predictions

Aboveground carbon stored in SDTs was evaluated and compared using both the CRM and NSVB

Table 1 Decay class, wood density, and structural loss adjustments applied to standing dead trees for Component Ratio Method (CRM; Domke et al., 2011) and National-Scale Volume and Biomass (NSVB; Westfall et al., 2024) estimation methods>[a]See USDA Forest Service (2023)

Decay class	Description[a]	Species type	Wood density reduction		Structural loss adjustments			
					Top/branch		*Bark*	
			CRM	NSVB	CRM	NSVB	CRM	NSVB
1	All limbs and branches present; top of the crown is still present; all bark remains; sapwood is intact, with minimal decay; heartwood is sound and hard	Hdwd	0.970	0.99	1.00	1.0	0.92	1.0
		Conifer	0.892	0.97				
2	Few limbs and no fine branches; top may be broken; a variable amount of bark remains; sapwood is sloughing with advanced decay; heartwood is sound at base but beginning to decay in the outer part of the upper bole	Hdwd	0.750	0.80	0.50	0.5	0.66	0.8
		Conifer	0.831	1.00				
3	Only limb stubs exist; top is broken; a variable amount of bark remains; sapwood is sloughing; heartwood has advanced decay in upper bole and is beginning at the base	Hdwd	0.540	0.54	0.20	0.1	0.39	0.5
		Conifer	0.591	0.92				
4	Few or no limb stubs remain; top is broken; a variable amount of bark remains; sapwood is sloughing; heartwood has advanced decay at the base and is sloughing in the upper bole	Hdwd	0.613	0.43	0.10	0	0.21	0.2
		Conifer	0.433	0.55				
5	No evidence of branches remains; top is broken; < 20 percent of the bark remains; sapwood is gone; heartwood is sloughing throughout	Hdwd	0.613	0.43	0	0	0	0
		Conifer	0.433	0.55				

modeling frameworks. For CRM predictions, carbon was predicted for each SDT using a series of functions developed using the R programming language (Fig. S2), while for NSVB, carbon values for each SDT were gathered from the TREE.CARBON_AG variable from the FIA database. Mean CRM- and NSVB-predicted aboveground carbon and their difference were calculated, in addition to the percentage of CRM predictions that were within ± 20% of NSVB predictions. Results were analyzed at the individual SDT level by region (i.e., eastern or western USA), ecological division, species type (i.e., conifer or hardwood), or decay class. We also compared predictions for the ten most common tree species in the eastern and western regions to assess species-level differences for the two estimation approaches.

At the plot and population levels, carbon stored in SDTs using the two methods was compared for five USA states: California, Colorado, Georgia, Maine, and Minnesota. These states were selected because they represented different ecological characteristics, had different disturbance histories which resulted in different SDT attributes, and had an adequate number of forested plots to provide a comparison between CRM and NSVB approaches. Plot-level SDT carbon was calculated by multiplying carbon stored in an SDT with its appropriate expansion factor. Population-level SDT carbon, i.e., carbon stored in SDTs across an entire US state, was calculated at the condition level by summarizing population predictions provided by the FIA program by weighting plot conditions by their population stratum and the corresponding timberland area that the stratum represented (i.e., the expansion factor; POP_STRATUM.EXPNS).

Equivalence tests were conducted comparing CRM- and NSVB-predicted aboveground carbon using two one-sided tests assuming a null hypothesis of dissimilarity (Robinson & Froese, 2004). In all equivalence tests, the magnitude of the region of similarity was specified as 20% of the standard deviation of the difference between CRM- and NSVB-predicted aboveground carbon. We also calculated the minimum percentage that would have resulted in a successful validation of the test, termed the minimum detectable negligible difference (MDND; Parkhurst, 2001). We used the TOSTER package in R to perform equivalence tests (Lakens, 2017).

Results

Standing dead tree level

The majority of SDTs occurred in the western USA region where 58.4% of SDTs were observed. Two ecological divisions in the western US, the Temperate Steppe Mountains (M330) and Marine Mountains (M240) divisions, contained the greatest number of SDTs (Table 2). Mean DBH and HT were greater in the western USA (32.0 ± 25.1 cm and 18.1 ± 11.4 m; mean ± standard deviation) compared to the eastern USA (22.3 ± 9.7 cm and 16.0 ± 5.3 m). In the eastern USA, SDTs in decay class 3 were most common (35.0% of all observations) and had a greater mean percentage of cull volume (33.1 ± 29.8%). In the western US, SDTs in decay class 2 were most common (36.1% of all observations) and the mean percentage of cull volume was lower (8.2 ± 15.6%). In the eastern US, balsam fir (*Abies balsamea* L.) and loblolly pine (*Pinus taeda* L.) were the most common SDTs, while in the western USA, Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) and lodgepole pine (*Pinus contorta* Dougl. ex. Loud.) were the most common SDTs (Table 3).

Table 2 Summary statistics for standing dead trees greater than 12.7 cm from the conterminous USA states by ecological division. Variables show number of observations (*n*) and mean attributes (standard deviations in parentheses) of tree diameter at breast height (DBH), height (HT), and percent cull

Division ID	Division name	*n*	Mean DBH (cm)	Mean HT (m)	Mean percent cull	Percent conifer	Percent hardwood
Eastern region							
210	Warm Continental Division	49,089	21.2 (8.4)	16.0 (4.3)	31.1 (26.3)	45.2	54.8
M210	Warm Continental Mountains	17,491	22.1 (9.0)	14.7 (4.1)	48.7 (32.4)	44.1	55.9
220	Hot Continental Division	34,325	23.1 (10.3)	16.8 (5.1)	26.5 (28.2)	16.2	83.8
M220	Hot Continental Mountains	17,589	23.5 (10.9)	17.4 (5.3)	37.6 (31.7)	26.3	73.7
230	Subtropical Division	34,660	22.6 (10.5)	17.5 (5.5)	33.7 (30.5)	47.1	52.9
M230	Subtropical Mountains	1,046	21.1 (8.2)	14.5 (4.6)	69.5 (32.1)	42.3	57.7
240	Marine Division	1,653	37.7 (35.2)	24.8 (13)	9.0 (19.6)	78.9	21.1
M240	Marine Mountains	56,652	42.9 (34.7)	25.6 (14.5)	7.9 (18.3)	95.5	4.5
250	Prairie Division	7,813	23.0 (10.7)	12.7 (4.6)	25.3 (25.8)	8.0	92.0
410	Savanna Division	430	20.6 (8.0)	13.6 (4.1)	13.8 (11.9)	41.2	58.8
Western region							
260	Mediterranean Division	2,177	56.2 (57.3)	27.2 (19.3)	15.5 (23.9)	52.9	47.1
M260	Mediterranean Mountains	27,714	42.8 (31.4)	20.8 (12.4)	6.2 (15.9)	75.8	24.2
310	Tropical/Subtropical Steppe Division	10,863	24.0 (10.9)	6.5 (4.5)	21.2 (22.8)	60.5	39.5
M310	Tropical/Subtropical Steppe Mountains	6,110	25.0 (12.5)	9.7 (6.4)	10.3 (17.5)	76.1	23.9
320	Tropical/Subtropical Desert Division	2,343	23.8 (11.4)	5.5 (4.3)	18.3 (23.8)	65.4	34.6
330	Temperate Steppe Division	3,235	22.6 (9.5)	10.3 (5.4)	12.0 (17.3)	68.8	31.2
M330	Temperate Steppe Mountains	114,945	25.4 (13.5)	16.2 (6.6)	7.5 (13.0)	92.7	7.3
340	Temperate Desert Division	6,916	25.8 (12.9)	7.3 (5.9)	11.8 (16.9)	82.3	17.7
M340	Temperate Desert Mountains	7,177	24.1 (11.0)	8.8 (5.8)	10.9 (16.1)	63.3	36.7

Table 3 Equivalence test results by decay class at the standing dead tree level for aboveground carbon in standing dead trees greater than 12.7 cm using the Component Ratio Method (CRM) and National-Scale Volume and Biomass (NSVB) estimation approaches across the conterminous USA

Decay class	Species type	*n*	Mean aboveground carbon (kg)		Mean difference (kg)	PA20[a]	Equivalence test result[b]	MDND[c]
			CRM	NSVB				
Eastern region								
1	Hdwd	15,289	101.3 (167)	121.2 (191.9)	19.9 (80.7)	47.5	NE	29
	Conifer	14,757	50.1 (82.7)	70.1 (107.3)	20.0 (43.7)	21.8	NE	51
2	Hdwd	22,203	59.7 (99.5)	76.8 (119.4)	17.0 (52.0)	34.5	NE	37
	Conifer	14,910	42.0 (77.8)	66.6 (112.8)	24.6 (53.8)	8.8	NE	50
3	Hdwd	40,396	29.5 (51.8)	44.2 (66.9)	14.7 (40.9)	20.7	NE	38
	Conifer	18,213	23.0 (43.9)	54.3 (88.4)	31.3 (59.4)	5.1	NE	55
4	Hdwd	23,202	23.2 (47.7)	27.0 (40.3)	3.8 (36.8)	19.6	E	12
	Conifer	9490	10.2 (21.3)	24.1 (40.2)	14.0 (30.7)	9.2	NE	49
5	Hdwd	6390	19.0 (38.8)	20.4 (30.8)	1.4 (33.4)	14.2	E	7
	Conifer	2395	8.6 (15.7)	19.1 (26.4)	10.5 (22.6)	13.9	NE	52
Western region								
1	Hdwd	5747	105.8 (255.2)	94.3 (205.3)	−11.5 (98.0)	44.4	E	18
	Conifer	54,452	206.5 (578.1)	244.1 (690.5)	37.6 (183.6)	29.3	NE	24
2	Hdwd	10,140	54.2 (161.7)	50.8 (107.2)	−3.5 (89.5)	20.3	E	7
	Conifer	74,735	168.4 (471.4)	205.2 (584)	36.9 (183.3)	18.2	NE	23
3	Hdwd	9,818	40.9 (119.2)	29.0 (58.6)	−11.9 (81.9)	19.3	E	17
	Conifer	57,621	225.4 (532.1)	251.3 (641.3)	25.9 (350.5)	14.8	E	9
4	Hdwd	1804	69.4 (183.7)	27.1 (54.6)	−42.3 (144.5)	10.9	NE	35
	Conifer	17,091	360.6 (576.3)	203.6 (355.7)	−157.0 (427.1)	15.7	NE	39
5	Hdwd	264	34.4 (76.9)	19.2 (52.4)	−15.1 (62.0)	9.1	NE	40
	Conifer	3355	273.5 (650.1)	136.8 (227.4)	−136.7 (553.3)	11.0	NE	29

[a]Percent of CRM predictions within ± 20% of NSVB predictions

[b]Equivalent (E) or not equivalent (NE)

[c]Minimum detectable negligible difference (MDND) required to reject dissimilarity, expressed in percent of standard deviation

The SDT predictions of carbon stocks calculated from the CRM and NSVB approaches were meaningfully different for several ecological divisions and species examined. Across all observations, NSVB predictions of aboveground carbon in SDTs were 14.0 ± 205.0 kg greater compared to CRM predictions. Differences in CRM and NSVB predictions were generally greater for SDTs that showed lower decay (i.e., decay classes 1–3), while SDTs in advanced decay stages (i.e., classes 4 and 5) showed similar predictions or ones where CRM predicted more carbon compared to NSVB predictions (Fig. 1). In the east, the largest difference was in decay class 3 SDTs for conifers, where NSVB predicted 31.3 kg more carbon on average compared to CRM. For eastern hardwoods, the largest difference was in decay class 1 SDTs, where NSVB predicted 19.9 kg more carbon on average compared to CRM. These differences were reduced to 10.5 and 1.4 kg in decay class 5 SDTs for eastern conifers and hardwoods, respectively. Two-sided equivalence tests resulted in no equivalence for all species types and decay class categories in eastern forests, with the exception of hardwoods in decay classes 4 and 5 where the mean difference was 3.8 and 1.4 kg, respectively (Table 3). For western conifers, CRM predictions were greater for NSVB only for decay classes 4 and 5 SDTs (up to 157.0 kg). For western hardwoods, CRM predictions were greater

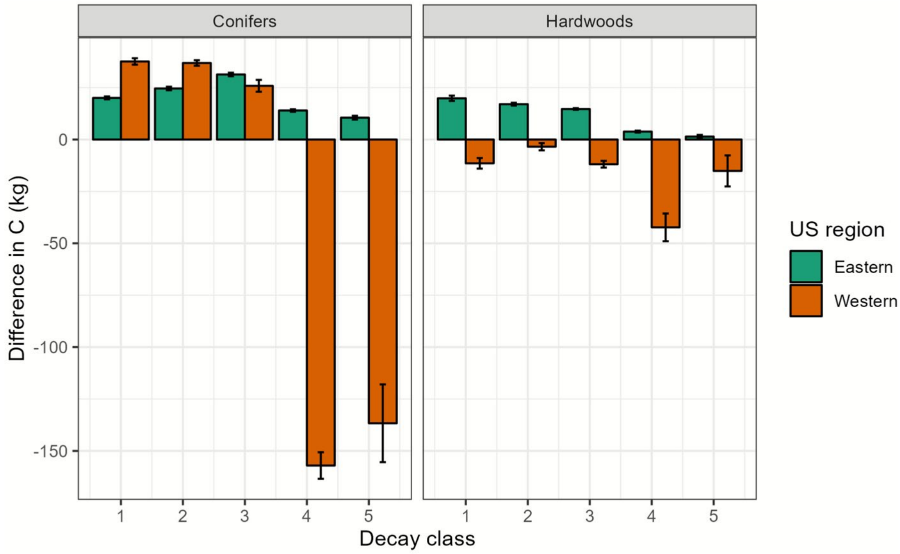


Fig. 1 Mean difference (with 95% confidence intervals) at the standing dead tree level for carbon in trees greater than 12.7 cm between National-Scale Volume and Biomass and Component Ratio Method estimation approaches by decay class and USA region in the 48 conterminous states of the U.S

than NSVB predictions across all decay classes. Equivalence between NSVB and CRM predictions was concluded for western hardwoods in decay classes 1, 2, and 3 and for conifers in decay class 3.

Conifers were the majority of SDTs across western ecological divisions while hardwoods were abundant in the eastern USA (Table 2). For 16 of the 19 ecological divisions, NSVB predictions

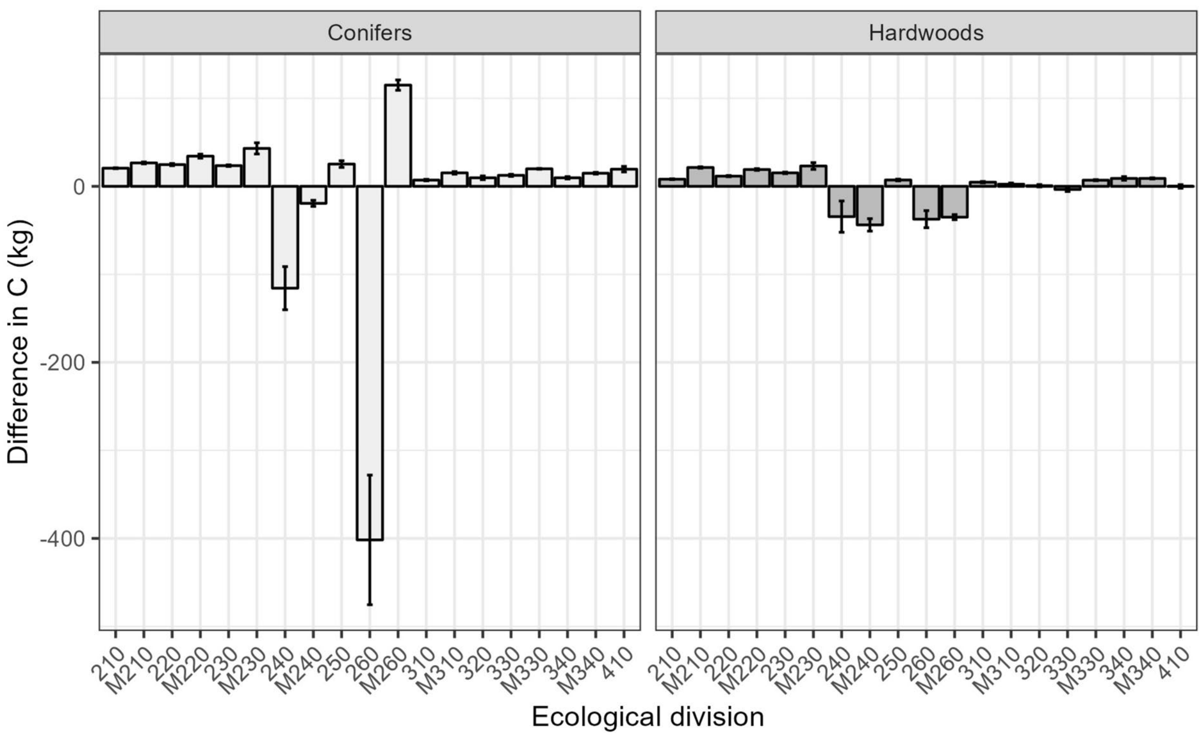


Fig. 2 Mean difference (with 95% confidence intervals) at the standing dead tree level for trees greater than 12.7 cm between National-Scale Volume and Biomass and Component Ratio Method estimation approaches by ecological division in the 48 conterminous states of the U.S

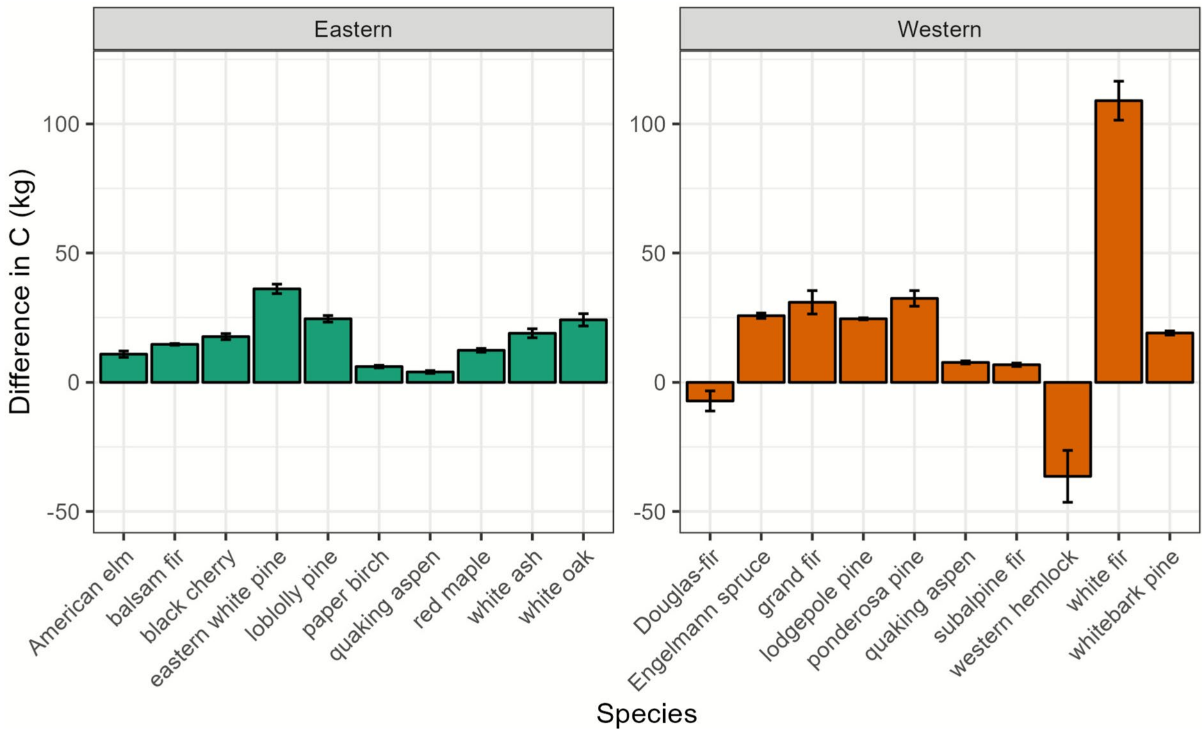


Fig. 3 Mean difference (with 95% confidence intervals) at the standing dead tree level for trees greater than 12.7 cm between National-Scale Volume and Biomass and Component Ratio Method estimation approaches for the ten most frequent tree species in the 48 conterminous states of the U.S

were greater than CRM predictions of SDT carbon. Predictions of SDT carbon from NSVB and CRM approaches were lower in magnitude for hardwoods, where mean differences ranged from −43.8 to 23.1 kg compared to −401.7 and 115.0 kg for hardwoods (Fig. 2). When analyzed by major species group, conifers in the Mediterranean Mountains (M260) showed the greatest positive difference between NSVB- and CRM-predicted SDT carbon. In contrast, conifers in the Mediterranean (260), Marine (240), and Marine Mountains (M240) ecological divisions showed CRM predictions greater than NSVB predictions of SDT carbon.

Predictions of SDT carbon from NSVB were greater than CRM predictions for the ten most frequent eastern species and eight of the ten most frequent western species. For eastern species, the mean difference ranged from 3.9 (*Populus tremuloides* Michx.) to 36.1 kg (*Pinus strobus* L.; Fig. 3; Table 4). In the western USA, Douglas-fir and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) were the only two species to show CRM predictions that exceeded NSVB predictions of SDT carbon (−7.2 and −36.4 kg, respectively). White fir (*Abies concolor* (Gord. & Glend.) Lindl. ex Hildebr.) showed the greatest positive difference between NSVB and CRM predictions of SDT carbon in the west (109.0 kg).

Population level

Population differences, which include all SDTs greater than 2.54 cm, were not equivalent in each of the five states examined. Although plot-level predictions were highly correlated (R^2 between CRM and NSVB predictions at the plot level ranged between 0.785 for Maine and 0.979 for Colorado), plot-level predictions from the NSVB approach were greater than CRM predictions in all states, with a mean difference ranging from 0.7 Mg/ha in Minnesota to 2.4 Mg/ha in Colorado. At a statewide level, Colorado's SDT carbon stock increased 23.9%, from 71.6 to 71.6 MMT comparing

Table 4 Mean aboveground carbon and difference (standard deviation in parentheses) at the standing dead tree level for predictions of carbon greater than 12.7 cm using the Component Ratio Method (CRM) and National-Scale Volume and Biomass (NSVB) estimation approaches for the 10 most frequent species Eastern and Western regions of the USA

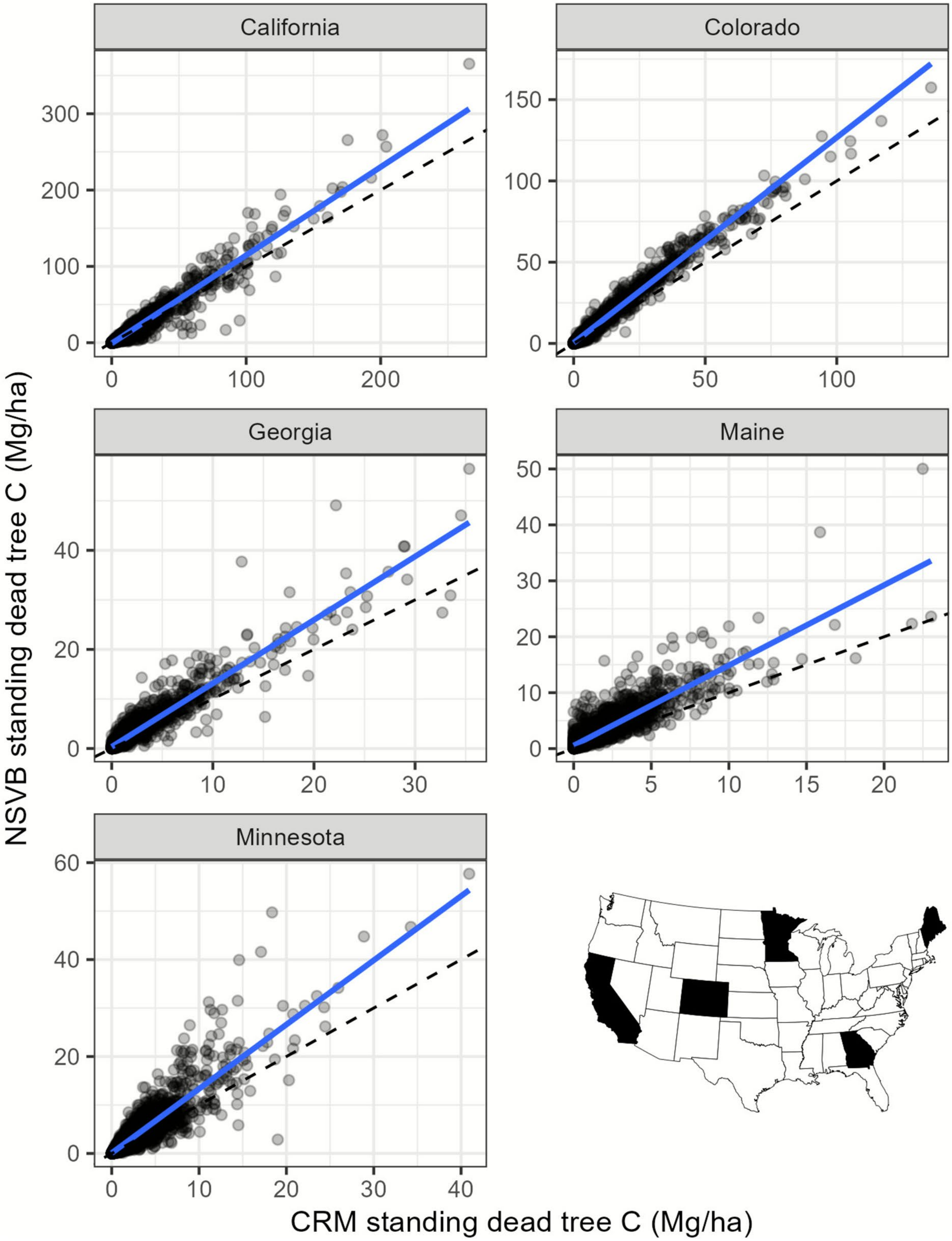
Common name	Scientific name	*n*	Mean aboveground carbon (kg)		Mean difference (kg)
			CRM	NSVB	
Eastern region					
Balsam fir	*Abies balsamea*	11,937	13.3 (18.7)	27.9 (28.1)	14.6 (17.8)
Loblolly pine	*Pinus taeda*	9318	52.3 (91.1)	76.7 (130)	24.5 (62.7)
Red maple	*Acer rubrum*	8347	26.9 (48.6)	39.2 (59)	12.3 (33.4)
Quaking aspen	*Populus tremuloides*	8211	27.4 (37.4)	31.3 (41.8)	3.9 (24.8)
Paper birch	*Betula papyrifera*	7065	24.0 (32.7)	30.0 (35.3)	6.0 (20.9)
White ash	*Fraxinus americana*	5941	96.1 (162.3)	115.0 (156.2)	18.9 (68.3)
Eastern white pine	*Pinus strobus*	5153	31.8 (84.1)	67.9 (127.4)	36.1 (67.2)
Black cherry	*Prunus serotina*	4616	25.2 (47.4)	42.9 (63.8)	17.6 (40.3)
American elm	*Ulmus americana*	4327	40.1 (69.2)	50.9 (96.6)	10.8 (40.8)
White oak	*Quercus alba*	3832	61.9 (124.1)	86.0 (171.5)	24.1 (75.3)
Western region					
Douglas-fir	*Pseudotsuga menziesii*	44,885	389.7 (773)	382.5 (892.3)	−7.2 (421.1)
Lodgepole pine	*Pinus contorta*	42,411	68.3 (105.3)	92.8 (135.9)	24.5 (38.3)
Subalpine fir	*Abies lasiocarpa*	20,828	63.7 (82.4)	70.4 (102.8)	6.7 (47.7)
Engelmann spruce	*Picea engelmannii*	13,651	132.7 (206.6)	158.4 (232.1)	25.7 (60.8)
Ponderosa pine	*Pinus ponderosa*	10,806	238.0 (497.5)	270.4 (576.6)	32.4 (160.3)
Quaking aspen	*Populus tremuloides*	9897	27.0 (46.3)	34.6 (48.1)	7.6 (29.4)
Whitebark pine	*Pinus albicaulis*	9196	70.2 (92.8)	89.1 (123.3)	19.0 (38.4)
White fir	*Abies concolor*	8751	323.5 (561.5)	432.5 (858.7)	109.0 (359.8)
Western hemlock	*Tsuga heterophylla*	6295	467.1 (750.2)	430.7 (847.9)	−36.4 (407.0)
Grand fir	*Abies grandis*	5796	212.2 (351.8)	243.2 (429.7)	30.9 (175.7)

CRM and NSVB estimation approaches, respectively. California displayed the greatest percent of CRM predictions within ± 20% of NSVB predictions (38.4%), while Maine displayed the lowest percent of predictions (13.1%; Figs. 4 and 5; Table 5).

Across the 48 states in the continental USA, aboveground carbon in SDTs was 832 and 1022 MMT for the CRM and NSVB predictions, respectively. Hence, NSVB predictions represented a 22.9% increase compared to CRM predictions for the aboveground SDT carbon pool.

Discussion

We observed greater aboveground carbon predicted using the NSVB approach for SDTs in less advanced decay stages (e.g., decay classes 1 through 3) and equivalent or greater CRM predictions in more advanced decay stages (e.g., decay classes 4 and 5). The finding of greater carbon predicted using the NSVB over the CRM estimation approach for SDTs in less advanced decay stages was similarly observed in live trees. Westfall et al. (2024) reported an increase of 14.6% in aboveground biomass using NSVB over CRM estimation approaches in live trees, which has been attributed to the underestimation of biomass in tops and limbs in the CRM approach, where top and limb biomass is not modeled directly but is assumed to be the difference between total aboveground biomass and the other tree components (Woodall et al., 2011). Within the top and limb biomass pool for live trees, biomass increased by 70.1% comparing NSVB and CRM


California
Colorado
Georgia
Maine
Minnesota
NSVB standing dead tree C (Mg/ha)
CRM standing dead tree C (Mg/ha)
0
100
200
300
0
50
100
150
0
10
20
30
40
50
60
5
15

◂**Fig. 4** Predictions of plot-level standing dead tree carbon between National-Scale Volume and Biomass (NSVB) and Component Ratio Method (CRM) estimation approaches for five selected USA states. Black dashed lines show 1:1 relationship and blue solid lines show linear regression. Note differences in scale in axes

approaches (Westfall et al., 2024). If top and limb biomass is the primary driver of NSVB and CRM differences for live trees, it makes intuitive sense that as trees die and their top and limb biomass is reduced through decay and breakage, the total amount of carbon stored in branches and tops would be lower. As structural loss adjustment factors for tops and branches are zero for SDTs in decay classes 4 and 5 in the NSVB estimation approach (Westfall et al., 2024), the amount of top and limb biomass is effectively zero. As merchantable wood volume only increased by 1.6% nationally when comparing NSVB over CRM estimation methods for live trees (Westfall et al., 2024), our finding of similar predictions of aboveground carbon for both approaches in SDTs in decay classes 4 and 5 aligns with results from live trees. Our finding of an increase of 22.9% in SDT carbon with NSVB compared to CRM predictions is higher than what Westfall et al. (2024) reported for live trees (14.6%). This is likely due to the influence of tops and limbs in the prediction approach and the differences in wood density and structural reduction factors used in determining SDT carbon.

We observed similar trends in SDT carbon compared to live tree carbon when analyzing NSVB and CRM differences by species, namely that NSVB predicted more biomass in SDTs than CRM for the most common species. Western hemlock was the only species reported by Westfall et al. (2024) to show CRM aboveground biomass to exceed NSVB predictions in live trees (by 6.47%), and we similarly noted CRM SDT aboveground carbon to average 36.4 kg more in SDT observations of the species compared to NSVB predictions. We also noted Douglas-fir SDT CRM predictions to be slightly greater than NSVB (average difference of 7.2 kg), whereas Westfall et al. (2024) observed NSVB predictions to be slightly larger than CRM predictions for live trees (increase of 0.74%). Western conifers are among the largest SDTs in this data set; hence, the largest differences are likely to exist for species in this region. In the western USA, SDTs were less decayed than those in the eastern US (i.e., the majority of SDT observations were found in decay classes 2 and 3 in the west and east, respectively). This is likely a result of recent large-scale forest disturbances that have impacted the western US, including agents that promote SDTs like insect outbreaks (e.g., Ye et al., 2021) and wildfires (e.g., Cyphers et al., 2019; Jiang et al., 2025). The abundance of SDTs in earlier stages of decay also confirms the finding of Woodall et al. (2021) who observed SDT carbon stocks to increase over the last decade. Analysis by ecological division showed similar trends, and CRM predictions were only greater than NSVB predictions for two geographic areas in the western USA with some of the fewest observations of SDTs (i.e., less than ~2200 SDTs in divisions 240 and 260). Analysis at the population level also showed the impact of the NSVB modeling framework on the SDT carbon pool. Increases in biomass and carbon from SDTs have been a result of SDT recruitment in recent years (Woodall et al., 2021) however, improved models of SDT longevity and height loss, used in combination with models of SDT carbon from the newer NSVB estimation framework, will be needed to better understand the duration that SDTs remain

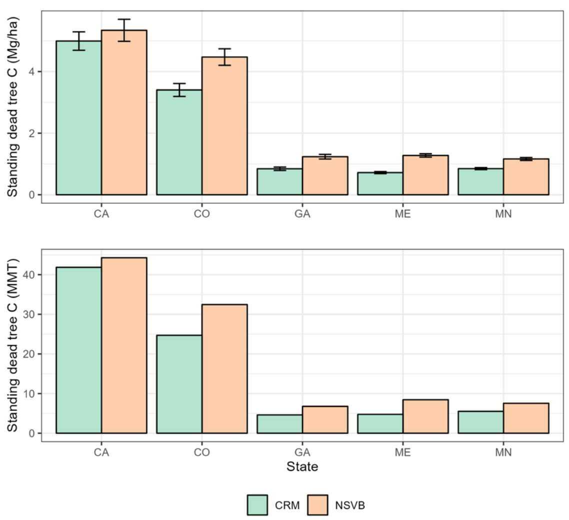


Fig. 5 Mean plot- and state-level standing dead tree carbon stocks (with 95% confidence intervals) using National-Scale Volume and Biomass (NSVB) and Component Ratio Method (CRM) estimation approaches for five selected USA states

Table 5 Equivalence test results by state for aboveground carbon in standing dead tree pool (trees > 2.54 cm) at the plot-level using the Component Ratio Method (CRM) and National-Scale Volume and Biomass (NSVB) estimation approaches

State	*n*	Mean aboveground carbon (Mg/ha)		Mean difference (Mg/ha)	PA20[a]	Equivalence test result[b]	MDND[c]
		CRM	NSVB				
California	3383	11.0 (19.6)	11.8 (23.4)	0.8 (6.7)	38.4	NE	25
Colorado	2958	7.5 (12.8)	9.9 (7.5)	2.4 (4.1)	23.5	NE	72
Georgia	2677	1.9 (3.2)	2.7 (4.4)	0.9 (1.7)	19.5	NE	62
Maine	2750	1.6 (2.0)	2.8 (3.3)	1.2 (1.7)	13.1	NE	78
Minnesota	4872	1.9 (2.6)	2.6 (3.7)	0.7 (1.8)	25.3	NE	45

[a]Percent of CRM predictions within ± 20% of NSVB predictions

[b]Equivalent (E) or not equivalent (NE)

[c]Minimum detectable negligible difference (MDND) required to reject dissimilarity, expressed in percent of standard deviation

standing prior to transitioning to other pools such as downed woody debris.

Structural differences in the approaches for modeling components between the CRM and NSVB approaches likely contribute to observed differences in SDT predictions of aboveground carbon. The CRM estimation approach relied on regionally developed volume equations (Heath et al., 2009; Woodall et al., 2011), whereas the NSVB approach predicted volume and biomass using one of four model forms and fitting parameters primarily by species and ecological division. In predicting carbon, a default value of 0.5 was used to convert biomass to carbon in the CRM approach, whereas the NSVB approach applied a species-specific value which averaged 0.477 across all species (Westfall et al., 2024). The implementation of species-specific carbon fractions aligns with emerging research that highlights the importance of these values in carbon in the world's trees and forests (Doraisami et al., 2022; Martin et al., 2018, 2021). Of particular importance to SDTs is the application of decay class and structural loss adjustment factors to account for reductions in carbon due to decay stage. These values differed slightly for both CRM and NSVB estimation methods (Table 1) and broadly characterize losses due to decay of components like bark and branches. Additional research that quantifies how carbon is reduced through time in these tree components would help in refining carbon stored in dead wood pools.

Conclusions

This study evaluated the implications of the newly implemented NSVB framework on standing dead tree carbon predictions within the USDA Forest Service's Forest Inventory and Analysis program. The findings show that NSVB consistently produces larger carbon predictions than the CRM for standing dead trees, similar to patterns recently observed in live trees. Differences in standing dead tree characteristics are important to consider, as carbon predictions converged for standing dead trees in advanced decay stages where structural components like tops and limbs are absent (e.g., decay classes 4 and 5). These findings demonstrate how biometrical improvements influence forest carbon stock assessments, particularly when evaluating population-level attributes of forest carbon at the USA state level.

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Data availability All data used in this work were acquired from the publicly-available USDA Forest Service's Forest Inventory and Analysis database: https:/apps.fs.usda.gov/fia/datamart/datamart.html

Declarations

Ethics approval All authors have read, understood, and have complied as applicable with the statement on "Ethical responsibilities of Authors" as found in the Instructions for Authors.

Competing interests The authors declare no competing interests.

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