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COMMENT

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Improving wood carbon fractions for multiscale forest carbon estimation

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Abstract

Background Wood carbon fractions (CFs)—the proportion of dry woody biomass comprised of elemental carbon (C)—are a key component of forest C estimation protocols and studies. Traditionally, a wood CF of 50% has been assumed in forest C estimation protocols, but recent studies have specifically quantified differences in wood CFs across several different forest biomes and taxonomic divisions, negating the need for generic wood CF assumptions. The Intergovernmental Panel on Climate Change (IPCC), in its 2006 "Guidelines for National Greenhouse Gas Inventories", published its own multitiered system of protocols for estimating forest C stocks, which included wood CFs that (1) were based on the best available literature (at the time) and (2) represented a significant improvement over the generic 50% wood CF assumption. However, a considerable number of new studies on wood CFs have been published since 2006, providing more accurate, robust, and spatially- and taxonomically- specific wood CFs for use in forest C estimation.

Main text We argue that the IPCC's recommended wood CFs and those in many other forest C estimation models and protocols (1) differ substantially from, and are less robust than, wood CFs derived from recently published data-rich studies; and (2) may lead to nontrivial errors in forest C estimates, particularly for countries that rely heavily on Tier 1 forest C methods and protocols (e.g., countries of the Global South with large expanses of tropical forests). Based on previous studies on this topic, we propose an alternative set of refined wood CFs for use in multiscale forest C estimation, and propose a novel decision-making framework for integrating species- and location-specific wood CFs into forest C estimation models.

Conclusion The refined wood CFs that we present in this commentary may be used by the IPCC to update its recommended wood CFs for use in forest C estimation. Additionally, we propose a novel decision-making framework for integrating data-driven wood CFs into a wider suite of multitiered forest C estimation protocols, models, and studies.

Keywords Carbon, Carbon accounting, Forest carbon, Functional trait, Tree, Wood, Wood carbon, Wood trait, Wood chemistry, IPCC

Background

Forests represent a critically important component of the global carbon (C) cycle, with estimates suggesting forests globally store ~45% of total terrestrial C [1]. More specifically, globally forests are estimated to store ~861 Pg of C, with the largest proportion being held in soils (~44%), followed by live biomass (~42%), deadwood (~8%), and litter (~5%) [2]. Across major forest biomes, tropical forests represent the largest C stock (~55% of total

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forest C stocks, or ~ 471 Pg of C), followed by boreal forests (~ 32% of total forest C stocks, or ~ 272 Pg of C) and temperate forests (~ 14% of total forest C stocks, or ~ 119 Pg of C) [2]. These C pools are dynamic over time, with their size and strength being sensitive to environmental change [3, 4]. Accurately accounting for or estimating forest C stocks and fluxes is therefore essential for quantifying the relative contributions of forests to the global C cycle, and for a better understanding of Earth's C budget under global environmental change.

However, both well-accepted methodologies and several landmark studies that quantify C stocks in forest biomass, continue to employ generic or nonspecific wood C fractions (CFs) to convert wood biomass into C stocks. For instance, a landmark study on forest biomass C stocks in tropical forests (the largest forest biomass C stock globally) employed the traditional assumption that 50% of total biomass is carbon [5]. Similarly, another key study on global forest C fluxes assumed a wood CF of 47% [6], which was derived from the multitiered (or 'multiscale') National Greenhouse Gas Inventory guidelines developed by the Intergovernmental Panel on Climate Change (IPCC) [7, 8]. These assumptions on wood CFs persist, despite recent reserch showing that generic wood CFs (e.g., a 50% assumption) lead to nontrivial errors in forest biomass C stocks of up to 8.9% [9].

This commentary is designed to illustrate this and help address this persistent error in forest C estimation models, by (1) critically reviewing the IPCC wood CFs presented in their 2006 and 2019 forest C estimation guidelines; (2) propose an updated set of wood CFs for use in large-scale forest C estimation; and (3) propose a novel decision-making framework that can be used to guide researchers and practitioners in selecting appropriate wood CFs for forest C estimation under different data availability scenarios. In doing so, this commentary aims to support improved accuracy in forest biomass C models and protocols, by facilitating the integration of accurate and species-specific wood CFs into forest C estimation methods at multiple scales. Our commentary here focuses specifically on the live woody biomass of forest C pools, which represent the largest component of forest biomass C [10]).

Forest carbon accounting and the IPCC's forest carbon estimation guidelines and tiers

In 2015, 196 parties to the United Nations Framework Convention on Climate Change (UNFCCC) signed on to the Paris Agreement [11]. In doing so, these nations agreed to develop national inventories of greenhouse gas (GHG) emissions (sources) and removals (sinks), in accordance with standardized IPCC-approved methods. The IPCC had already established standardized C estimation protocols in 1996, which were subsequently replaced by the 2006 IPCC Guidelines for National Greenhouse Gas Inventories [8]. This 2006 set of guidelines established a three-tiered system of sector-based approaches for executing national-scale GHG inventories. Generally, Tier 1 through 3 represent the least- to most- data intensive approaches to GHG inventories, respectively.

As they pertain to national forest C estimation, Tier 1 methods are the least data-intensive, whereby forest C stocks are estimated based on regionally resolved vegetation and climate data. Tier 1 forest C estimation methods therefore involve the use of coarse-scale or biome-specific "default" estimates of forest C and biomass, including predetermined estimates of forest aboveground biomass stocks and growth rates ("Table 4.7" and "Table 4.9" in IPCC, 2006). Because Tier 1 is the least data-intensive, these methods are predominantly employed by developing nations in the Global South [12], most of which possess large amounts of tropical forests. Due to the generic nature of Tier 1 C estimation parameters (particularly wood CFs; discussed below), errors and uncertainties in forest C estimates using Tier 1 methods are usually relatively high compared to Tier 2 and 3 approaches.

Tiers 2 and 3 forest C estimation protocols are more detailed and complex, incorporating country-specific or finer-scale data on land-use activities and associated C emission and sequestration data (the latter referred to as "removal" factors). While Tier 2 utilizes default forest biomass estimates, country-specific data including forest inventories or data on annual changes in forest biomass stocks, may also be incorporated (reviewed by [13]). For example, in Tier 2 protocols, where species-specific forest inventory data are available, species-specific wood density estimates (provided in IPCC, 2006) are used to estimate forest biomass (on a per unit area basis) and ultimately forest C densities (also on a per unit area basis).

Tier 3 requires the use of highly detailed and localized methods and data sources. For instance, data on total forest biomass and biomass change are incorporated into Tier 3 methods, as obtained from national forest inventories and permanent sampling plot data. In the United States (US) for example, the US Department of Agriculture Forest Service Forest Inventory and Analysis (FIA) program compiles population estimates of forest biomass C stocks and stock changes for its "Inventory of US Greenhouse Gas Emissions and Sinks" [14]. This is accomplished using annually surveyed permanent sample plots from the national forest inventory (NFI), which are distributed across all 50 states [15] alongside species-specific allometric equations to estimate forest biomass and

C densities. These data are then scaled up to national-level forest C estimates.

Key forest carbon estimation parameters and the role of wood carbon fractions

As part of forest C estimation models, certain wood CFs are explicitly recommended in "Table 4.3" of the IPCC Guidelines for National Greenhouse Gas Inventories [8]. These wood CFs are primarily recommended in Tier 1 and Tier 2 methods, with Tier 3 methods using "specific carbon fractions." (While the meaning of "specific carbon fractions" is not articulated in detail by the IPCC, we assume that these are species-specific wood CFs, or wood CFs that at least represent the most dominant tree species in a given country or region.) For example, in Tier 1 and 2 methodologies, the IPCC (2006) recommends a default wood CF of 0.47, suggesting that 47% of the dry mass of all aboveground parts of a tree is comprised of carbon. A biome-specific wood CF recommendation of 0.47 is also presented for tropical and subtropical forests (or "domains"), and a wood CF of 0.47 is presented for the temperate and boreal domains.

In 2019, the IPCC published a refinement to the 2006 IPCC Guidelines for National Greenhous Gas Inventories. However, this refinement failed to update wood CFs (i.e., the parameters proposed in "Table 4.3"). This is despite the fact that: (1) the most recent scientific studies used to establish the default CFs in "Table 4.3" were published nearly 20 years ago; (2) the total number of tree species included in the 10 studies used to obtain the 2006 default CFs is unclear; and (3) since 2006, more than 100 peer-reviewed studies, meta-analyses, and datasets explicitly focused on quantifying variation in wood CFs across and within > 800 tree species globally, have been published.

Based on this background, there is clearly room to improve the manner in which wood CF data is integrated into forest C modeling. In this commentary we posit that there is a clear scientific rationale (Theme 1) and data (Theme 2) for updating the wood CFs in the IPCC guidelines for forest C estimation [9, 16, 17]. At the same time, in this commentary we aruge that there is a methodical basis for integrating data-driven wood CFs into forest C estimation models (Theme 3).

Theme 1. The limitations of current wood carbon fraction assumptions in forest carbon estimation methods

In their 2006 National Guidelines for Greenhouse Gas Inventories, the IPCC provided data-driven CFs for use in forest C estimation, compared to a default 50% wood CF assumption (IPCC, 2006). Specifically, in the 2006 guidelines wood CFs ("Table 4.3") are provided for trees across three general biomes or "domains": "Tropical and Subtropical", "Temperate and Boreal", and a nonbiome- or domain-specific "Default value." Wood CFs in "Table 4.3" originated from a small number of studies (10 in total) that were available at the time, which cumulatively presented wood CFs from a limited and/or indiscernible number of species (Table 1). For instance, the exact number of species employed to compile wood CFs for the 2006 IPCC table is difficult to ascertain. This is because most of the cited studies (e.g., McGroddy et al., 2004, Andreae and Merlet, 2001; Chambers et al., 2001) either (A) did not explicitly state how many tree species were included in their analyses or (B) presented wood CF data that were pooled across multiple tree species. Indeed, only three studies of the cited studies included species-specific wood CFs.

Therefore, while the number of tree species used to populate the wood CF tables remains unclear, we estimate that fewer than 100 tree species globally were used to determine the IPCC's wood CFs, the large majority of which were from the temperate forest biome (Table 1). Moreover, many cited studies [18–20] did not provide meta-data such as geographic locations, therefore precluding the categorization of their data and CFs into specific forest biomes or environmental conditions. The studies that did provide geographic information covered a small number of sites and were exclusive to a particular habitat type. For example, Feldpausch et al. (2004) acquired data from 10 study sites situated within secondary forests in the central Amazon.

At the same time, within specific forest domains the IPCC (2006) provides tree tissue-specific wood CFs, classified under the header "Part of tree". However here, tree tissue designations differ widely across domains and are not necessarily biologically meaningful. For example, in the "Tropical/Subtropical" domain wood CFs are provided for "wood" and "foliage", with different estimates for trees in two size classes (i.e., < 10 cm in diameter vs. ≥ 10 cm in diameter). However, in these cases "wood" is not disaggregated according to functional tissue types such as bark, stems, branches, and roots, which differ in their wood CFs [9, 21]. Furthermore, the "Part of tree" listed in the "Temperate and Boreal" domain are "broadleaved" and "conifers", which are broad taxonomic classifications and not tree components.

Additional uncertainty exists when examining sources for other domain- and tissue-type specific wood CF recommendations. The IPCC's default (or nonbiome-specific) CF of 47% for "All" tree parts was obtained from a study that did not include wood CFs for live woody tissue, but rather foliage and litter including fallen leaves, reproductive tissue, bark, and fine twigs [22]. While this cited paper (McGroddy et al., 2004) was highly valuable in its

Table 1 Intergovernmental Panel on Climate Change (IPCC) default wood carbon fractions (CFs) and related study characteristics

Carbon fraction of aboveground forest biomass				Study characteristics						
Domain	**Part of tree**	**Carbon fraction (CF) [tonne C (tonne d.m.)− 1]**	**References**	**Number of species included**	**Number of studies included**	**Number of sample sites used for data collection**	**Biomass component**	**Carbon fraction confirmation**	**Aim of study**	**Comments**
Default value	All	0.47	[22]	Unknown. Species pools considered	56	100	Foliage and litter	Confirmed (0.47)	To establish C: N: P ratios for forest biomass globally, using foliage and litter nutrient data	Default value is derived from McGroddy et al. (2004), and is not a composite or mean of estimates from other papers mentioned below
Tropical and Subtropical	All	0.47 (0.44–0.49)	[18]	Unknown. Species pools considered	130	Unknown	Unknown	Unconfirmed	To establish emission factors of trace gases and aerosols from biomass burning	While # of sites is not stated, data is categorized into 3 general ecological zones: savannah and grassland, tropical forest, and extratropical forest
			[33]	Unknown. Species pools considered	70	21	Stem wood litter	Confirmed (0.49)	To quantify respiration rates and carbon loss from coarse wood litter in central Amazon forests	Samples were extracted from dead tree boles
			[22]	N/A	N/A	N/A	N/A	N/A	N/A	N/A
			[19]	Unclear. Study provides C content for species pools and individual species	12	Unknown (all data originates from within the Philippines)	Unknown	Confirmed (0.41–0.49)	To determine total carbon stocks and sequestration rates in the Philippines via an analysis of literature	
	wood	0.49	[34]	Unknown. Species pools considered	N/A (primary research article)	10 (all data originates from within Brazil)	Stem wood	Confirmed (0.49)	To quantify the effect of regenerating vegetation on C and N pools in secondary forests in the central Amazon	
	wood, tree d < 10 cm	0.46	[35]	Unknown. Species pools considered	N/A (primary research article)	4	Stem wood	Confirmed (0.46)	To quantify changes in biomass and nutrient pools resulting from deforestation	Species-specific C concentrations not provided. Rather, C concentrations for species pools are given
	wood, tree d ≥ 10 cm	0.49	[35]	Unknown. Species pool considered	N/A (primary research article)	4	Stem wood	Confirmed (0.49)	To quantify changes in biomass and nutrient pools resulting from deforestation	Species-specific C concentrations not provided. Rather, C concentrations for species pools are given
	foliage	0.47	[34]	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	foliage, tree d < 10 cm	0.43	[35]	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	foliage, tree ≥ 10 cm	0.46	[35]	N/A	N/A	N/A	N/A	N/A		N/A

Table 1 (continued)

Carbon fraction of aboveground forest biomass				Study characteristics						
Domain	**Part of tree**	**Carbon fraction (CF) [tonne C (tonne d.m.)− 1]**	**References**	**Number of species included**	**Number of studies included**	**Number of sample sites used for data collection**	**Biomass component**	**Carbon fraction confirmation**	**Aim of study**	**Comments**
Temperate and Boreal	All	0.47 (0.47–0.49)	[18]	Unknown	130	Unknown	Unknown	Unconfirmed	To establish emission factors of trace gases and aerosols from biomass burning	While number of sites is not stated, data is categorized into three general ecological zones: savannah and grassland, tropical forest, and extratropical forest
			[20]	~50	~55	Unknown	Wood	Confirmed (0.42–0.50)	To determine the C content of trees, based on published literature	Specific study sites are not explicitly mentioned. However, three general tree types are covered (broadleaf, conifer, tropical)
			(Gayoso et al., 2002)	N/A	N/A	N/A	N/A	N/A	N/A	Study not found
			(McGroddy et al., 2004)	Unknown. Species pools considered	56	100	Foliage and litter	Confirmed (0.47)	To establish C:N:P ratios for forest biomass globally, using foliage and litter nutrient data	
	broad-leaved	0.48 (0.46–0.50)	[36]	22	N/A (primary research article)	1	Heartwood and sapwood	Confirmed (0.46–0.50)	To establish a methodology for determining the C content of tree species in North America	
	conifers	0.51 (0.47–0.55)	[36]	21	N/A (primary research article)	1	Heartwood and sapwood	Confirmed (0.47–0.55)	To establish a methodology for determining the C content of tree species in North America	

Columns under the main heading "Carbon fraction of aboveground forest biomass" are replicated from the IPCC's 2006 National Guidelines for Greenhouse Gas Inventories, which were not updated during the 2019 refinement. Columns with the main heading "Study characteristics" represent our own observations of the studies used by the IPCC (2006) to create their "Table 4.3." The column entitled "Number of studies included" refers to how many individual peer-reviewed studies were utilized when an individual paper cited by the IPCC was meta-analytical in nature. "Number of sample sites used for data collection" refers to the number of field sites where wood samples were taken, either by the authors of meta-analyses or the individual papers where their data originated. The "Carbon fraction confirmation" column indicates whether or not we successfully identified the specific wood CF recommended by the IPCC (2006) within the cited paper

Table 2 Refined wood carbon fractions as proposed by this study for use in forest C estimation

Forest biome/domain	Taxonomic division	Mean ± S.E	Lower 95% CI	Upper 95% CI
Default value (all data)	N/A	47.6 ± 0.9%	45.7%	49.4%
Tropical	Angiosperm	45.6 ± 0.2%	45.3%	45.9%
	Conifer	44.7 ± 0.5%	43.7%	45.7%
Subtropical/Mediterranean	Angiosperm	45.7 ± 0.4%	44.9%	46.5%
	Conifer	49.8 ± 0.6%	48.6%	51.0%
Temperate	Angiosperm	46.5 ± 0.3%	46.0%	47.1%
	Conifer	50.1 ± 0.4%	49.3%	50.9%
Boreal	Angiosperm	49.2 ± 0.8%	47.6%	50.8%
	Conifer	46.8 ± 0.6%	45.5%	48.0%
All biomes	Angiosperm	46.8 ± 0.7%	45.3%	48.2%
	Conifer	48.5 ± 0.8%	47.0%	50.0%

Table estimates originate from the Martin et al. [18] meta-analysis of global wood carbon fractions ($n = 2{,}228$) and are applicable to levels 5, 6 and 7 of our decision framework for choosing appropriate wood CFs for forest carbon estimation. Mean wood carbon fractions are least-squares means, with corresponding standard errors and 95% confidence intervals, across all tissue types (tissue-specific wood CFs can be obtained from Martin et al. [18] and Doraisami et al., [17])

contribution to understanding plant tissue stoichiometry, it appears reasonable to contend that this study was not designed to inform global forest C estimation protocols like those of the IPCC (2006). Similarly, many of the studies cited in the 2006 guidelines (Table 1), particularly those assessing tropical wood CFs, were not explicitly designed to provide wood CFs for use in C stock estimation, as per the authors' stated objectives. For example, (1) Andreae and Merlot (2001) sought to quantify trace gases and aerosols emitted from burning biomass; (2) Chambers et al. (2001) aimed to quantify C respiration rates in coarse woody debris in the central Amazon; and (3) Feldpausch et al. (2004) quantified C and nutrient accumulation in secondary forests established on abandoned pastures in the central Amazon.

Theme 2. An updated set of wood carbon fractions for live tree carbon estimation

Since 2006, many peer-reviewed papers have been published that present and analyze species- and tissue-specific data on wood CFs [23–29]. Additionally, many of these include information on study site locations, allowing for more specific biome classifications compared to those that currently exist in the IPCC's (2006) "Table 4.3." For example, wood CF data from trees in boreal vs. temperate forests is now more readily differentiated and available. Based on this growing literature on wood CFs, in 2022, authors published a global database of wood CFs (referred to as the Global Woody Tissue Carbon Concentration Database ([GLOWCAD]). This database contains more than 3,500 observations of wood CFs from 864 tree species across all forested biomes, which were taken from 112 studies published between 2004–22 [17]. In addition to a wealth of species-specific wood CFs, georeferenced data points within GLOWCAD allow for biome- and climate zone-specific wood CF values [30] compared to the IPCC "Table 4.3" (2006). This includes wood CFs specific to tropical, subtropical/Mediterranean, temperate, and boreal forests (Table 2).

Based on the data in GLOWCAD, wood CFs can be recalculated in a manner that explicitly informs global forest C estimation guidelines such as those of the IPCC (specifically, "Table 4.3"). While this information was overlooked in the IPCC 2019 updates, we propose that these wood CFs—specifically outlined in Table 2 here—be used to update the IPCC's recommendations in "Table 4.3." Wood CFs in Table 2 are obtained from live stem wood specifically, since previous research [9] showed that (A) stem wood CF data is most widely available in the literature; and (B) within species, stem wood CFs are a strong predictor of CFs in other tissues.

Based on updated wood CFs provided here (Table 2), wood CFs would generally be reduced in most biomes compared to existing assumptions; though data support modest increases in wood CFs for subtropical/Mediterranean conifers and boreal angiosperms, compared to previous IPCC estimates. Notably, changes in wood CFs proposed for the tropical forest biome trees are the most pronounced and impactful for our understanding of global forest C dynamics. For example, employing the IPCC's recommended 49% wood CF for tropical forests results in a total C stock estimate of ~ 224.1 Pg of C (assuming a total AGB C stock of 457.4 Pg of C). Comparatively, when assuming a refined wood CF of 45.6% for tropical angiosperms (Table 2), the tropical forest AGB C stock would be ~ 208.6 Pg of C: a difference of ~ 15.5 Pg of C when compared to the IPCC-informed estimate. The magnitude of this difference/error is equivalent to ~ 3% of total tropical forest C stocks (471 Pg of C), ~ 50% of the global tropical regrowth forest C stock (33.9 Pg of C in 2007), and ~ all of Canada's boreal forest C stock (14.4 Pg of C) [2].

Theme 3. Decision framework for choosing appropriate wood CFs for forest carbon estimation

The availability of a large wood CF database allows for a range of possible wood CFs to be used in forest C stock estimation across Tier 1–3 forest C estimation. For example, data now exist that provide wood CFs with a high degree of specificity (i.e., wood CFs that are species- and tissue-specific), through to wood CFs with a low degree of specificity (i.e., wood CFs that are biome-specific; Table 2). However, there remains no explicit recommendation regarding how to integrate wood CF datasets into forest C estimation approaches, especially those of higher complexity such as Tier 2 and 3 methods.

We therefore propose the following hierarchical decision-making framework that outlines steps for applying wood CFs to forest inventory-based biomass estimates. Specifically, published research [9] supports the following steps and rationale when selecting an appropriate wood CF for C estimation in field studies, models, or meta-analyses. These steps are listed by decreasing specificity, and their relevance for the different IPCC forest C accounting Tiers are explicitly noted:

Level 1. Species-specific wood CFs for all tissue types (most relevant for Tier 3). Species- and tissue-specific mean wood CFs are the most accurate representations of wood CFs in trees. This level is most relevant for studies that employ Tier 3 methods, namely those where species- and tissue-specific biomass estimates exist. Species- and tissue-specific wood CFs therefore allow species-specific tree-level C estimates that are differentiated across tissue types.

Level 2. Species-specific wood CFs obtained from stem tissue (most relevant for Tier 3). In the absence of wood CFs data for specific tissue types, or in cases where tree biomass is not differentiated by tissue type (e.g., stem, bark and branches), stem wood CFs can be used to estimate whole-tree wood CFs, since these are strongly correlated with CFs in other tissue types [9].

Level 3. Species-specific mean wood CFs estimated from wood density (WD) (when available) using the equation:

$$\text{wood CF} = 49.3 + (-3.5 * \text{WD}) \tag{1}$$

where WD is the species-specific or genus-specific WD value, − 3.5 is the slope and 49.3 is the y-intercept [9] (most relevant for Tiers 2 and 3). Here, wood density may be used to approximate species- or genus-specific wood CFs according to Eq. 1 [9] in instances where species-specific wood CFs are not available.

Level 4. For species missing WD data, a genus-level mean WD can be used to estimate species-specific mean wood CFs (as in level 3 above) (relevant for Tiers 2 and 3). This recommendation follows the rationale that WD (A) is a widely recorded plant trait [31]; (B) is phylogenetically conserved [32]; and (C) can be used to predict wood CFs [9].

Level 5. Wood CFs that are specific to taxonomic divisions and forest biomes, as informed by Table 2 (relevant for Tiers 1 and 2). This recommendation is based on the fact that there exists robust wood CFs for different taxonomic divisions and forested biomes (e.g., tropical angiosperms; Table 2) [17].

Level 6. Wood CFs that are specific to taxonomic divisions across all forest biomes, as informed by Table 2 (relevant for Tiers 1 and 2). This level is suitable for forest C estimation studies and models that differentiate woody biomass at a general taxonomic level (i.e., hardwoods vs. conifers).

Level 7. Mean wood CFs for all trees in Table 2 (relevant for Tiers 1 and 2). Mean wood CFs for all trees are synonymous to the IPCC's "default" wood CF for all tree parts. We recommend employing this level only as a last resort, where tree- or forest-level biomass estimates are not disaggregated in any manner (e.g., across taxonomic divisions or biomes).

Level 8. Default wood CF of 50% (irrelevant for any Tier). We see no material basis for utilizing a default wood CF of 0.5 in forest C estimates, given the availability of data-driven wood CFs that exist in the literature and the above decision-making framework.

Conclusion

While the recommended wood CFs within the IPCC's 2006 and 2019 Guidelines for National Greenhouse Gas Inventories do represent an improvement over a 50% wood CF assumption, exisiting science suggests these do not reflect the most up-to-date wood CFs in trees. Given the large amount of wood CF data that has been published since the release of the IPCC Guidelines (2006), we recommend that the wood CFs and decision-making framework presented here, replace the IPCC's wood CFs recommendations. Furthermore, we suggest that our decision-making framework provides a guide to integrating wood CFs into multiple other forest C estimation models and studies. These decision-making steps are robust towards the highest and lowest data availability scenarios, and therefore inform forest C estimation across Tiers 1, 2, and 3. Additionally, our decision-making framework presented here indicates that a wood CF of 50% is no longer relevant for forest C estimation at any level or Tier.

Appendix

Forest carbon accounting in brief

Forest carbon (C) accounting is the practice of quantifying greenhouse gas (GHG) stocks and fluxes from forests through the measurement and reporting of GHG emissions, removals and emissions reductions within the forestry sector [13]. Conceptually, GHG accounting (of which forest C accounting is one component) began at the national scale after the creation of the United Nations Framework Convention on Climate Change (UNFCCC) in 1992 [37]. The UNFCCC required most industrialized countries to develop national inventories of GHG emissions. Subsequently, the Kyoto Protocol of 1998 introduced subnational or project-level GHG accounting [38], mainly through the establishment of the Clean Development Mechanism (CDM), which allowed industrialized countries to meet some of their GHG reduction targets by funding GHG mitigation/offset projects in nonindustrialized countries.

To support the creation of GHG inventories at different scales (national or individual project level), the Intergovernmental Panel on Climate Change (IPCC) created a series of guidelines, culminating in the IPCC Guidelines for National Greenhouse Gas Inventories [8]. These IPCC guidelines (2006) are the most prominent and widely adapted set of methodologies for forest C accounting and are adaptable to UNFCCC member states' technical capacity based on a multitiered approach to GHG accounting. Consequently, industrialized countries may choose to employ higher-order/complex methodologies and tools to suppor their national GHG inventories and to estimate forest C at smaller scales. Some examples of higher-order tools/models used in forest C accounting that may be applied at national and subnational/project scales include (1) the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3 [39]; (2) FORCARB2 [40], a modeling tool that is informed by the United States Department of Agriculture's (USDA) Forest Inventory Analysis (FIA); and (3) the European Forest Information Scenario Model (EFI-SCEN) [41].

It should also be noted that there are alternative forest C accounting guidance documents or protocols, including those developed by the World Resources Institutes [42] and Winrock International [43]. However, these guidelines are generally limited in scope such that they: (1) focus primarily on forest C accounting for corporate entities, communities, and projects; (2) do not include their own models and equations for estimating C stocks; and (3) refer to the IPCC guidelines for additional support. For example, the World Resource Institute's guidelines (Greenhalgh et al., 2006) refer users to the C accounting protocols in the IPCC's "Good Practice Guidance for Land Use, Land-Use Change and Forestry (LULUCF)" [44]. In sum, the IPCC Guidelines—the focus of our current commentary, which include the 2003 protocols (IPCC, 2003), their successor the 2006 IPCC Guidelines (IPCC, 2006), and the most recent 2019 refinements (IPCC, 2019)—remain among the world's most commonly employed suite of forest C accounting protocols worldwide.

Key forest carbon estimation parameters and the role of wood carbon fractions

Details on the model parameters recommended by the IPCC estimation guidelines across different estimation Tiers are described in Volume 4 (Agriculture, Forestry and Other Land Use), Chapter 4 (Forest Land), of the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006). Here, the IPCC presents specific recommendations on key parameters necessary for estimating aboveground biomass and C in trees and forests. These key parameters (among others) include ratios of belowground to aboveground biomass ("Table 4.4"), default biomass conversion and expansion factors ("Table 4.5"), and default estimates of aboveground biomass for different forest types across the globe ("Table 4.7"). Also included, and the focus of our present commentary, are wood C conversion factors (also referred to as "wood carbon fractions") that are employed to convert forest aboveground biomass into elemental C mass. Wood CFs are explicitly recommended in "Table 4.3" of the IPCC Guidelines for National Greenhouse Gas Inventories [8].

While the recommended wood CFs of "Table 4.3" are subject to scientific limitations (as we described in Theme 1), these estimates do represent improvements over the generic wood CF of 0.50 (i.e., 50% of dry mass is composed of elemental C) that has traditionally been employed in forest C estimation, including within earlier recommendations from the IPCC and other forest C accounting protocols [43]. However, despite the IPCC (2006) recommendations, many national inventories and individual studies that estimate global forest C stocks and fluxes still utilize the generic 50% wood CF when converting forest aboveground biomass to forest C stocks [2, 5, 45], even though this likely leads to nontrivial errors in forest C stock estimates. For example, Martin et al. [18 argued that a previous study [45] likely overestimated tropical forest C stocks by ~ 8.9% (~ 20 Pg of C) due to the use of the generic 50% wood CF. Additionally, a meta-analysis on deadwood CFs [46] showed that a generic 50% wood CF likely overestimates the total deadwood C stocks in tropical forests by as much as ~ 3 Pg of C, a quantity that is almost equivalent to the entire deadwood C pool in the temperate forest biome [2].

Updated forest carbon estimation guidelines and wood carbon fractions

In 2019, the IPCC published a refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, which sought to provide: (1) updated methodologies for estimating sources and sinks of GHGs where gaps previously existed; (2) updated emissions factors where significant differences existed from the default factors recommended in 2006; and (3) additional or alternative information that sought to clarify existing guidance in the 2006 document [7]. The refinement was not intended to be a fundamental revision of the 2006 Guidelines, since the IPCC's Bureau of the Task Force on National Greenhouse Gas Inventories (TFB) determined in 2014—based on expert opinion—that the methodologies of the 2006 Guidelines were "technically sound" [47]. At a scoping meeting of the TFI in 2016, an outline of the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories was prepared [47] and subsequently approved at the 44th session of the IPCC [48].

As it relates to forest C estimation specifically (i.e., Chapter 4 of IPCC 2019), refinements were made to sections and parameters involving: (1) methods for estimating GHG emissions and removals due to changes in soil C; and (2) GHG inventory reporting requirements, including completeness, time series, data quality assurance and control, reporting, and documentation. Additionally, several forest C estimation parameter tables were updated based on the latest science, including those focused on (1) the ratio of belowground to aboveground biomass (i.e., "Table 4.4"); (2) estimates of aboveground biomass and biomass growth in natural and plantation forests (i.e., "Tables 4.7–4.10", and "Table 4.12"); and (3) the reported growth rate of merchantable volume (i.e., "Table 4.11").

Abbreviations

C	Carbon
CF	Carbon fraction
GHG	Greenhouse gases
GLOWCAD	Global woody tissue carbon concentration database
IPCC	Intergovernmental panel on climate change
LULUCF	Land use, land-use change and forestry
NFI	National forest inventory
TFB	Bureau of the task force on national greenhouse gas inventories
TFI	Task force on national greenhouse gas inventories
UNFCCC	United nations framework convention on climate change

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A.R.M. conceived the study, while M.D. wrote the main manuscript text and compiled and reviewed the data. A.R.M. and G.M.D. also helped write and edit the paper.

Availability of data and materials
All data that support our commentary are available through the journal articles that we have cited and referenced.

Declarations

Competing interests
The authors declare no competing interests.

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