Informing IPCC accounting of forest carbon using the global forest carbon database (ForC v4.0)

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Abstract. Forests are critical for climate change mitigation and constitute a substantial portion of planned emissions reductions under the 2015 Paris Agreement. Yet, the efficacy of greenhouse gas mitigation planning and reporting is dependent upon the quality of available emission factors data, including forest carbon (C) stocks and changes therein. Tens of thousands of relevant forest C estimates have been published, yet are not readily accesible to the practitioners compiling national greenhouse gas inventories. Many of these data have, however, been compiled in the Global Forest C database (ForC; https://forc-db.github.io/) and stand to be of value to greenhouse gas accounting if made available through the Emission Factor Database (EFDB) of the International Panel on Climate Change (IPCC). Here, we develop and document a process for semi-automated transfer of data from ForC into the EFDB, assess the data available and transferred to date, and provide recommendations for improving forest data collection, analysis, and reporting to improve accounting of forest-sector greenhoouse gas emissions and removals. We begin by reconciling terminology and mapping ForC fields into EFDB. This process required some updates to the ForC database structure, leading to the release of a new version of ForC (v4.0; described here). As of May 06, 2023, ForC contained ~17204 independent records that would be relevant to EFDB, 1214 of which have been submitted to date. Among the data in ForC, there is disproportionate representation of biomass (particularly aboveground) stocks, with far fewer records for dead organic matter and soil C, and relatively few or no records for net annual increments or C fluxes into (gains) or out of (losses) the IPCC-defined C pools. Geographic representation is also quite uneven, with the highest densities of relevant records in temperate forests, and with relatively scant representation of tropical forests in Africa and Asia. ForC represents a diversity of

stand ages, although records for young stands are primarily limited to C stocks, as opposed to net increments of fluxes. This distribution of records is generally reflected in the subset of records that have been submitted to EFDB to date. In the future, forest C estimates in EFDB can be improved through targeted research to fill critical gaps, reporting of information required by IPCC, and continued submission of data from scientific publications to the EFDB. Given that climate change is rapidly impacting the world's forests, timely reporting of recent estimates will be especially critical to accurate forest C accounting.

1 Introduction

Forests are critical to management of atmospheric concentrations of the greenhouse gas carbon dioxide (CO_2), and thereby climate change. In recent decades, CO_2 uptake by forests, woodlands, and savannas has exceeded releases from deforestation and other severe disturbances, resulting in a net carbon CO_2 sink of ~0.88 Gt C yr^{-1} (all biomes with trees, Xu et al., 2021) to ~1.6 Gt C yr^{-1} (forests only, Harris et al., 2021). This has offset an estimated 10% to 18% of anthropogenic CO_2 emissions from fossil fuels and cement (Xu et al., 2021; Harris et al., 2021), dramatically slowing the pace of atmospheric CO_2 accumulation and climate change. Going into the future, the fate of this important CO_2 sink is highly uncertain, depending both upon forest responses to climate change, which are likely to reduce the sink strength (McDowell et al., 2020; Hammond et al., 2022), and on human conservation, restoration, and management of forests (IPCC, 2019b, 2022).

Reflecting their strong influence on Earth's climate, forests play a substantial role in international plans for climate change mitigation under the Paris Agreement (UNFCCC, 2015). Forest conservation, reforestation, and improved sustainable management all have significant – and relatively cost-effective – potential as climate change mitigation options, with conservation and reforestation having the fourth and fifth largest net emission reduction potentials or all mitigation options (**?**). As of 2016, forest-based mitigation accounted for 26% of total planned greenhouse gas mitigation within Nationally Determined Contributions under the Paris Agreement (Grassi et al., 2017). Yet, envisioned forest-based climate change mitigation initiatives do not always correspond to actual emission reductions through on-the-ground implementation (e.g., Badgley et al., 2022). One critical need for ensuring that forest-based climate change mitigation initiatives are effective is realistic planning and reporting, underlain by solid scientific data (Anderson-Teixeira and Belair, 2022; Deng et al., 2021).

The International Panel on Climate Change (IPCC) provides guidance for national greenhouse gas inventories for reporting to the United Nations Framework Convention on Climate Change (UNFCCC, IPCC, 2006, 2019a). Under this guidance, greenhouse gas inventories include all managed land, including most of the world's forest land (Ogle, 2018). The IPCC inventory guidelines include specific instructions for accounting for greenhouse gas (mainly CO_2) exchanges between forest land and the atmosphere (IPCC, 2006, 2019a). A tiered approach to accounting is employed, where the lowest tier (Tier 1) represents the simplest approach and relies on default parameter values – for example, forest carbon (C) stocks values by ecozone (FAO, 2012) and forest age class derived as the average of published estimates (IPCC, 2019a; Rozendaal et al., 2022). Tier 1 values have improved over the years as more of the relevant underlying data has become available (Requena Suarez et al., 2019; Rozendaal et al., 2022), but there remains room for continuous improvement as the science advances. For example, the year following the release of the latest IPCC guidelines, a more thorough analysis of C accumulation in regrowth forests found that

IPCC's Tier 1 default values underestimated C sequestration by 32% on average and failed to capture eight-fold variation within ecozones (Cook-Patton et al., 2020). In addition, it was revealed that C stocks in mature African tropical montane forests were two-thirds higher than the IPCC Tier 1 values for these forests (Cuni-Sanchez et al., 2021). This rapid evolution of scientific information on C cycling in forests is valuable for informing climate change mitigation efforts but requires improved mechanisms for communicating the latest information from scientific researchers to the practitioners who need reliable estimates for greenhouse gas mitigation planning. Moreover, high variability of forest C cycling within ecozones (e.g., Cook-Patton et al., 2020; Cuni-Sanchez et al., 2021) implies that it is useful for practitioners to have access to locally-specific information, when available.

To improve data accessibility for C accounting, the IPCC created the Emission Factor Database (EFDB; https://www.ipcc-nggip.iges.or.jp/EFDB/main.php), which is intended as a recognized library of emission factors and other parameters that can be used for estimating greenhouse gas emissions and removals. The EFDB can be used both for efforts to tally a nation's intended or accomplished greenhouse gas reductions, or as a basis of comparison for external parties to evaluate these inventories. The EFDB encourages researchers to submit estimates of emission factors or other related parameters from peer-reviewed journal papers or other accepted sources for inclusion in the database. In the case of forests, emission factors include C stocks, net increments ("stock changes"), and fluxes ("gains" and "losses") for various pools (IPCC, 2006, 2019a).

The Global Forest Carbon Database, ForC (https://forc-db.github.io/), is the largest collection of published estimates of forest C stocks, increments, and annual fluxes (Anderson-Teixeira et al., 2018, 2021). ForC includes data ingested from individual publications and relevant databases, including the Global Reforestation Opportunity Assessment (GROA) database (Cook-Patton et al., 2020, database doi: 10.5281/zenodo.3983644), the global soil respiration database (SRDB-V5, Bond-Lamberty and Thomson, 2010; Jian et al., 2021). As of May 06, 2023, ForC contained 39855 records from 10589 plots in 1535 distinct geographical areas, along with records of stand age and disturbance history. As such, ForC is positioned to improve forest C accounting through the transfer of data to EFDB. The purpose of this publication is to document that process and provide recommendations for future improvements.

Here, we (1) review IPCC methods and definitions for forest C accounting in the context of typical forest C estimation methodologies; (2) describe mapping of ForC to IPCC's EFDB; (3) describe updates to ForC (ForC v4.0), most of which were implemented to facilitate data transfer to EFDB; (4) summarize the data in ForC that's relevant to EFDB and records that have been transferred to date; and (5) provide recommendations for improving data collection, analysis, database, and accounting.

2 IPCC methods and definitions

The end goal of IPCC greenhouse gas inventories is to quantify greenhouse gas emissions to, or withdrawals from, the atmosphere on an annual basis, most commonly on a national level (IPCC, 2006, 2019a). For each stratum of subdivision within a land-use category, annual stock changes (ΔC; t C yr^{-1}) are calculated as the sum of changes in various pools (described in section 2.1), plus any harvested wood products. For each pool, ΔC may be calculated using the "Gain-Loss Method", which takes the difference between gains and losses, or using the "Stock-Difference Method", which computes ΔC based on C stocks at two points in time (IPCC, 2006). Thus, C cycle variables relevant to the IPCC methodology and to EFDB include C stocks, net annual increments, and fluxes in the IPCC-defined pools.

2.1 Carbon pools

Forest ecosystem C pools may be parsed in various ways, and while certain definitions and thresholds are more common than others, there is no single standard for measuring or reporting that is adhered to by all – or even most – scientific studies. IPCC parses forest C pools into biomass (aboveground and belowground), dead organic matter (dead wood and litter), and soil organic matter (Table 1). While there is some flexibility around the components included in each pool, each national inventory must apply these in a consistent manner.

2.1.1 Biomass

Biomass includes living vegetation, above- and below-ground, both woody and herbaceous, but with a focus on woody plants and trees given their much greater potential to sequester large amounts of C (IPCC, 2006).

Aboveground biomass, which is typically <200 t C ha^{-1} but can exceed 700 t C ha^{-1} (Anderson-Teixeira et al., 2021), is defined by the IPCC as "all biomass of living vegetation above the soil including stems, stumps, branches, bark, seeds, and foliage" (IPCC, 2003, 2006). IPCC's guidance is that the understory may be excluded the understory if it constitutes a "minor" component, *where quantitative definitions of "understory" and "minor" are not provided*, but where a commonly applied minimum size sampling threshold for mature forests would be 10 cm stem diameter at breast height (DBH). A recent study characterizing the contributions of trees in different DBH classes to ecosystem C stocks and fluxes found that trees 1 - 10 cm DBH contributed up to ~8% aboveground biomass, ~17% aboveground woody net primary productivity ($ANPP_{woody.stem}$), and ~20% woody mortality (M_{woody}) of mature closed-canopy forests worldwide (Piponiot et al., 2022). In regrowth forests, woodlands, or savannas, small trees and shrubs contribute a much larger proportion of C stocks and fluxes (Piponiot et al., 2022; **?**), and, correspondingly, biomass estimates for these ecosystems tend include smaller size classes (e.g., **?**). While IPCC guidance specifies that all living vegetation should be included in biomass estimates, forest censuses and biomass estimates do not consistently include life forms other than dicot trees (e.g., lianas, ferns, palms, bamboo), although thhese do tend to be censused when they consitute a large proportion of the biomass (**?**). Further, it is important to note that the IPCC definition of aboveground biomass excludes standing dead wood, which is included in remote sensing biomass estimates (Duncanson et al., 2021).

A universal challenge in estimating biomass (living or dead) from forest census data is applying appropriate allometric models to convert DBH measurements to biomass. Selection of allometric models has an enormous influence on estimates of biomass stocks, increments, of fluxes (Clark and Clark, 2000; Clark et al., 2001). While trusted and standardized allometric models are becoming increasingly available (Chave et al., 2014; Réjou-Méchain et al., 2017; Gonzalez-Akre et al., 2022), large uncertainties remain. IPCC Tier 1 values currently draw on studies applying a variety of allometric models (e.g., Requena Suarez et al., 2019; Rozendaal et al., 2022).

Table 1. IPCC-defined forest carbon pools with definitions and measurement methods. Definitions from IPCC Table 1.1. (See Table 1.1 in IPCC guidance).

pool	definition	important sources of estimate variation	IPCC guidance
aboveground biomass	all biomass of living vegetation	minimum size censused	may exclude understory if minor component
		include non-dicot trees?	yes
		include dead standing?	no
		biomass allometry	Tier 1 defaults draw on a variety of allometric models
belowground biomass	all biomass of live roots	all factors relevant to aboveground biomass	see above
		allometry or assumed ratio of below- to above-ground biomass (R)	can estimate based on R
		minimum root diameter	may exclude fine roots; suggested minimum diameter of 2 mm for fine roots
dead wood	all non-living woody biomass above a specified diameter, aboveground or belowground	minimum diameter	10 cm default, but may be chosen by country
		include belowground?	yes
litter	all non-living biomass smaller than dead wood but larger than soil organic matter, in various states of decomposition both above or within the mineral or organic soil	maximum diameter (= minimum diameter for deadwood)	10 cm default, but may be chosen by country
		minimum size (= size limit for soil organic matter)	suggested 2 mm
		layers included	entire O horizon: litter (OL), fumic (OF), and humic (OH) layers
		include belowground?	yes
soil organic matter	organic carbon in mineral soils to a specified depth	sampling depth	30 cm default, but may be chosen by country

Belowground biomass is defined as "all biomass of live roots" (IPCC, 2003, 2006), a definition including both coarse roots, whose biomass is typically estimated based on stem censuses and allometries or belowground to aboveground biomass ratios, and fine roots, whose biomass is typically estimated via extraction of roots from soil samples. The former, which is typically <40 t C ha^{-1} (Anderson-Teixeira et al., 2021), is methodologically linked to aboveground biomass estimates, sharing the same methodological sources of variation, but tending to be far more uncertain (**?**). Fine root biomass generally constitutes a much smaller C pool (typically <5 t C ha^{-1}, Anderson-Teixeira et al., 2021), and IPCC guidance is that it can be excluded when fine roots cannot be distinguished empirically from soil organic matter or litter (IPCC, 2006), which can be a painstaking process. Field methods for estimating root biomass are highly variable (**?**). IPCC's default method for Tier 1 estimates is to apply a ratio of belowground to aboveground biomass, with default factors defined based on ecological zone, continent, and forest age (IPCC, 2006, 2019a).

2.1.2 Dead Organic Matter

Dead organic matter includes all non-living biomass that is not within the mineral soil layer and smaller than the litter size threshold. It's inclusion in inventories is not required under Tier 1 methodology for Forest Land remaining Forest Land (see section 2.2), but is required for land that has transitioned to or from forest within the past 20 years (IPCC, 2006).

Dead wood, which is typically <50 t C ha^{-1} but can exceed 150 t C ha^{-1} (Anderson-Teixeira et al., 2021), is defined by IPCC as "all non-living woody biomass not contained in the litter, either standing, lying on the ground, or in the soil" (IPCC, 2003, 2006). This pool includes standing and fallen dead wood, stumps, and dead roots of diameter $\geq$10 cm (or a diameter specified by the country). Dead wood stocks and fluxes can be quite variable across forests (Anderson-Teixeira et al., 2021), and can at times be the dominant pool in a forest ecosystem (e.g., following a severe natural disturbance, Carmona et al., 2002). However, aboveground dead wood remains relatively poorly characterized at a global scale (Anderson-Teixeira et al., 2021), and belowground dead wood is rarely studied (Merganičová et al., 2012). In turn, dead wood pools are poorly characterized in large-scale forest C budgets (Pan et al., 2011; Harris et al., 2021), and IPCC's latest Tier 1 default values are based on just 1-31 references per climate zone (Table 2.2 in IPCC, 2019a).

Litter, which is typically <40 t C ha^{-1} but can exceed 100 t C ha^{-1} (Anderson-Teixeira et al., 2021), is defined by IPCCC as including "all non-living biomass with a diameter less than a minimum diameter chosen by the country (for example 10 cm), lying dead, in various states of decomposition above the mineral or organic soil" (IPCC, 2003, 2006). As noted above, live fine roots may be included in litter when difficult to separate empirically. The definition includes the entire O horizion, including litter (OL), fumic (OF), and humic (OH) layers, in addition to litter embedded within the soil. This definition contrasts with empirical studies that focus on aboveground litter, often including only the OL layer in the definition of litter, and do not always specify the components included. Similar to dead wood, litter is poorly characterized in large-scale forest C budgets (Pan et al., 2011; Harris et al., 2021), and IPCC's latest Tier 1 default values are based on just 1-7 references per climate zone (Table 2.2 in IPCC, 2019a).

2.1.3 Soil Organic Matter/ Carbon

Soil organic matter/ carbon (SOM/ SOC), which is typically >100 t C and can exceed 300 t C in the top two meters of soil (Sanderman et al., 2017), is defined by IPCC as “organic carbon in mineral and organic soils (including peat) to a specified depth chosen by the country and applied consistently through the time series” (IPCC, 2003, 2006). Live fine roots may be included with soil organic matter when it is not feasible to distinguish them empirically. The greatest source of methodological variation in measuring SOM/ SOC is sampling depth, which has a suggested default of 30 cm but may vary by country provided that consistent criteria are applied.

2.2 Land classification

IPCC defines land-use categories to include six categories – Forest Land, Grassland, Wetlands, Cropland, Settlements, and Other Land (IPCC, 2006). Sub-divisions include land that has remained in a particular category for >20 years (e.g., Forest Land remaining Forest Land) and land that has been converted from one category to another in the past 20 years (e.g., Cropland converted to Forest Land). Forest Land is defined as at least 10-30% crown cover of trees with potential to reach a minimum height of 2-5 m *in situ*, and shorter-stature natural vegetation would be classified as Grassland (IPCC, 2003). Definitions of forest are allowed to vary by country, but must be applied consistently. Forest Land includes land where vegetation temporarily falls below the threshold values for forest (e.g., due to disturbance), but is expected to exceed those thresholds in the future (IPCC, 2003).

The UNFCCC requires greenhouse gas reporting for all managed lands in a country, where management is defined as “human interventions and practices have been applied to perform production, ecological or social functions” (IPCC, 2006). This expansive definition of managed land implies that the majority of Forest Land in most countries is managed. However, the definition is applied differently across countries, and the majority of governments have yet to report their approach for defining managed land or provide maps of managed land (Ogle, 2018; Deng et al., 2021).

3 Updates to ForC (ForC v4.0)

Previous versions of ForC (Anderson-Teixeira et al., 2016, 2018, 2021) contained most of the information required by EFDB, and, more broadly, to inform C accounting under IPCC guidelines. However, modest changes to the structure and contents of ForC were needed in order to provide all information required by EFDB and to improve ForC’s capacity to serve as a repository of valuable information for forest C accounting under IPCC guidelines. To support export of data to EFDB, and to improve the overall quality of the ForC database, we added or modified 18 fields (Appendix A), defined 15 new variables, implemented enhanced quality control, manually reviewed >1705 records to obtain additional required information, and added 329 new records.

This section describes changes relative to ForC v3.0 (Anderson-Teixeira et al., 2021).

3.1 New or modified fields

We added or modified a total of 18 fields (Appendix A). Most notably, these included improvement of the representation of uncertainty, recording of original units and organic matter to C conversion factors, and expanding the information recorded in the citations table. For the latter, we *used an R script to automatically retrieve information based on the DOI (issue 41)*.

3.2 New variables

We added a total of 15 new EFDB-relevant variables to the set of named and defined variables (Fig. 1), counting each pair of variables with units in C (ending in `_C`) or organic matter (ending in `_OM`) as one. The majority of these were increment variables (n=11), adding to only one previously defined increment variable (aboveground biomass increment, *delta.agb*). These are directly related to C stocks as previously defined in ForC, with "*delta.*" added in front of the variable name. Further, we added variables capturing the belowground component of woody mortality (*woody.mortality_root*) and the combined aboveground and belowground components of woody mortality (*woody.mortality*). Although most of these variables lacked records in ForC as of May 06, 2023, their addition gave the structure such that records can be populated over time. Finally, to provide better definition of the previously existing variable *organic.layer*, which has a nebulous definition that reflects the varied definitions adopted by original studies, we added two clearly defined variables: *litter* (relatively undecomposed plant material/ OL horizon), and *O.horizon* (entire O-horizon, including OL).

3.3 Quality control measures

Prior to releasing ForC v4.0, we executed several quality control measures. First, we implemented a system of continuous integration using GitHub Actions (*sensu* Kim et al., 2022) to run some automatic checks any time the master data files are updated, including outlier tests and checks for completeness and naming consistency of records across data files. Second, to improve information on geographic coordinates, we created a field to record coordinate precision (Appendix A), and flagged and reviewed records with suspected low precision. Third, to identify erroneous climate data, we compared ForC climate values to those extracted from WorldClim version ## (**?**) based on site coordinates. Records deviating from WorldClim values by more variable-specific thresholds (>5°C for mean annual temperature, >7.5°C for mean temperatures of the warmest and coldest months, or >1 for log(mean annual precipitation in mm)) were flagged as requiring review prior to use in analysis or transfer to EFDB.

Because ForC v4.0 contained known duplicate records, we used R scripts to identify likely duplicates, as detailed in Anderson-Teixeira et al. (2021). Henceforth, we refer to the set of records with likely duplicates removed as "independent records". All records sent to EFDB were ensured to be independent and original through manual review, as detailed below.

3.4 Manual review of records to be sent to EFDB

EFDB data submissions required information that was not recorded in previous versions of ForC, but for which new fields were created for EFDB compatibility (Appendix A). It was therefore necessary to return to original publications to retrieve relevant

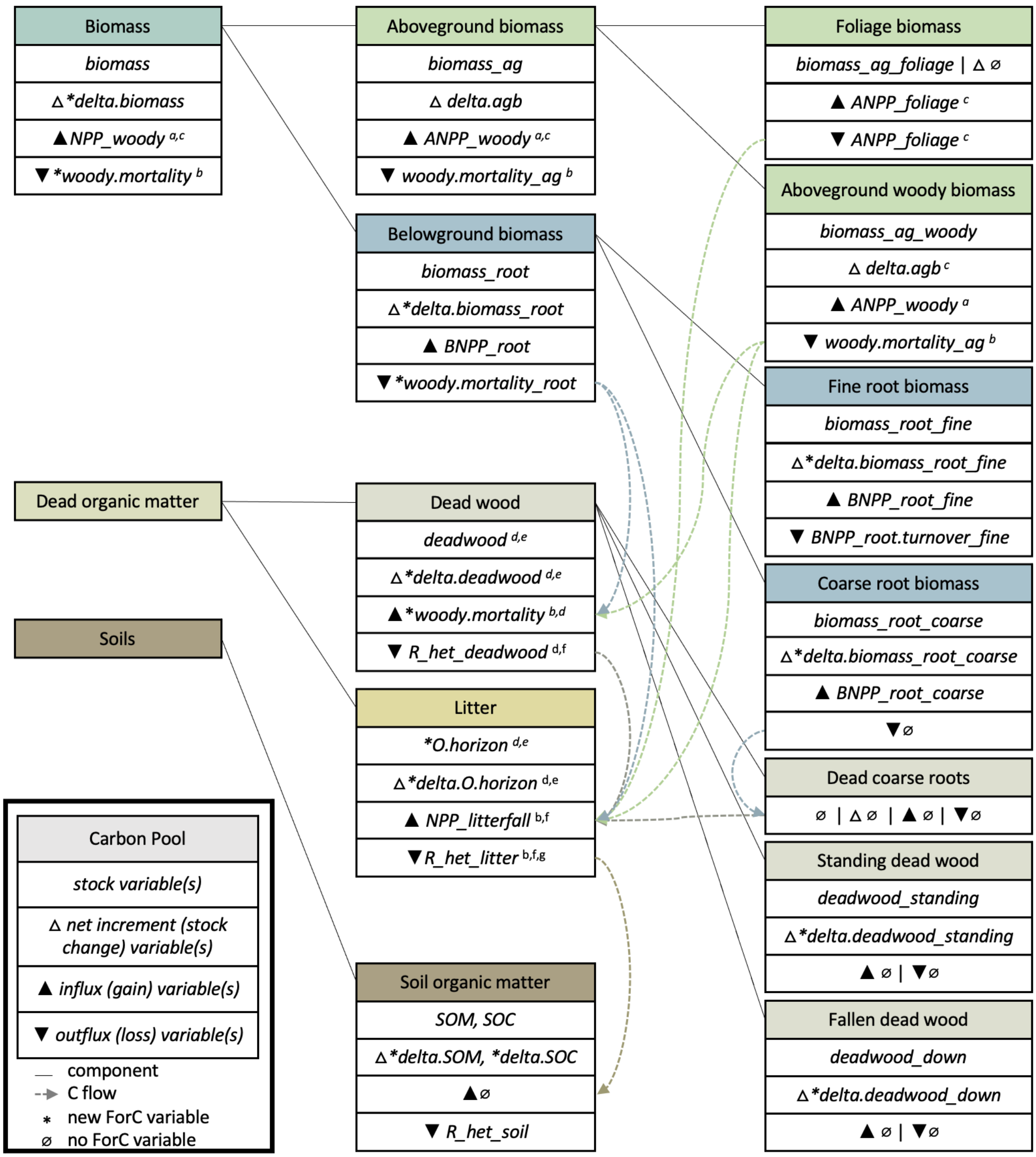

Figure 1. Schematic illustrating the carbon pools quantified under IPCC accounting; corresponding ForC variables, and relationships among them. For each C pool, we show ForC variables corresponding to the stock, stock change (net annual increment), gain (influx), and loss. Most, but not all, EFDB-relevant ForC variables are shown here. Correspondence of ForC variables to IPCC criteria often depends upon measurement protocols (e.g., min DBH). Additional caveats are as follows: (a,b) branch fall and mortality of stems below census min DBH, which are necessary for a full accounting of dead organic matter production but typically assumed negligible for calculations of biomass change, are excluded by common measurement practice (a) or ForC variable definition (b); (c) assumes that leaf production equals leaf fall, or that changes in foliage biomass are negligible; (d,e) belowground components excluded by common measurement practice (d) or ForC variable definition (e); (f) excludes movement of dead wood into litter through breakage or size reduction; (g) measurements often limited to litter horizon (OL) and may exclude larger branches and stems classified as litter and/or the more decomposed layers of the O horizon.

information, including (1) estimates in original units, (2) confidence intervals (when not already in ForC), (3) whether records of interest were presented in tables or text or digitized from figures (EFDB will not accept digitized data), (4) whether records of interest were presented directly, as opposed to having been calculated from related variables (for example, if a study presents aboveground biomass and root biomass but not total biomass, EFDB would not accept the sum of these as a valid record of total biomass) We also checked that existing ForC records were complete and correct.

Manual review of records was the limiting step for data transfer to EFDB. We prioritized review of (1) records from the Forest Global Earth Observatory (ForestGEO, Anderson-Teixeira et al., 2015; Davies et al., 2021), (2) studies with confidence intervals recorded in ForC (because uncertainty estimates are important to the IPCC), (3) original publications containing large numbers of EFDB-relevant records, and (4) records from tropical regions. The latter criteria was motivated by the fact that although tropical forest is the single most important biome for climate change mitigation (**?**), ground-based data on tropical forest C cycling tends to be more scarce due to a variety of challenges (**?**de Lima et al., 2022), and *tropical countries are more likely to apply Tier 1 methodology that bases forest C budgets on previously existing data (**?**).*

3.5 Addition of new records

In addition to reviewing existing records, we added a total of 329 new records to ForC. These included 104 records from two studies (Piponiot et al., 2022; Lutz et al., 2021) that were not previously included in ForC. In addition, we created new records for 225 EFDB-relevant estimates presented in the original publication that were not yet present in ForC.

4 Transfer of data from ForC to EFDB

To transfer complete, reviewed ForC records into EFDB, we created R scripts to restructure ForC records and populate EFDB's bulk import form ("EFDB bulk import.xlsx"). Criteria for data transfer were that (1) records had been checked against the original study and determined to be complete and correct (`EFDB.ready` field in `ForC_citations` table), (2) the original study presented values in tables or text, as opposed to the values having been digitized from graphs or calculated based on related variables (`data.location.within.source` field in `ForC_measurements` table), and (3) the records had not previously been sent to EFDB. Once converted into EFDB format, the records were reviewed and then sent to the IPCC's Technical Support Unit for inclusion in EFDB. Complete records needed to be reviewed by the EFDB editorial board prior to posting in the database – a process that lags behind records transfer and had not yet been completed for all records sent as of May 06, 2023.

4.1 Mapping ForC to EFDB

The mapping of ForC fields into EFDB fields is summarized in Appendix B, with details documented in the public GitHub repository associated with the project, IPCC-EFDB-integration repository within the ForC-db organization (file *ForC-EFDB_mapping.csv* available at https://github.com/forc-db/IPCC-EFDB-integration/blob/main/doc/ForC-EFDB_mapping/ForC-EFDB_mapping.csv).

For the majority of fields, contents of the field in ForC was transferred directly into an EFDB field, either as the only contents of that field or as part of a composite record. For example, ten ForC fields describing site location, climate, and edaphic properties all mapped into the EFDB field `Region/Regional conditions` (Appendix B). In cases where original studies did not present 95% confidence intervals (required by IPCC when available) but did present information required to calculate these (standard error or n and standard deviation), we calculated the 95% confidence intervals and populated the EFDB field with this information (noting the calculation in the EFDB field `Comments from Data Provider`). For some fields, simple conditional logic was used to populate EFDB fields based on ForC records. For example, for stock variables presented in the original publication in units of dry organic matter mass (as opposed to C), several greenhouse gasses (CO_2, CO, CH_4, NO, NO_2, N_2O) were entered in the EFDB field indicating the greenhouse gases to which the record could be pertinent (`Gases` field) because these values could be used in calculations of greenhouse gas emissions from biomass burning (IPCC, 2006); otherwise, the only pertinent greenhouse gas would be CO_2. There were two cases in which more complex mapping was required: (1) mapping of C cycle variables (section 4.1.1) and (2) land classification (section 4.1.2).

4.1.1 Carbon cycle variables

With input from the IPCC's Technical Support Unit, we reviewed the list of ForC variables to identify those that were relevant to EFDB and to appropriately map them into EFDB (Fig. 1). For each C pools (Table 1), we identified variables representing organic matter or C stocks, stock changes (a.k.a. "net annual increments" by IPCC, "increments" in ForC), gains (a.k.a. "gross annual increments" by IPCC, "fluxes" in ForC), and losses ("fluxes" in ForC). As described in section 3.2, we also defined 15 new EFDB-relevant variables that were not previously represented in ForC. It it important to note that the correspondence of ForC variables to IPCC criteria often depends upon measurement protocols ("important sources of estimate variation" in Table 1). For example, ForC records of biomass and dead wood vary in the minimum stem diameter censused, such that some records would match the IPCC criteria whereas others would not. Information on minimum diameters censused and other important sources of methodological variation are recorded as covariates in ForC and mapped into the EFDB field *Other Properties* (Appendix B). Details on the mapping of ForC variables to EFDB – including associated covariates, IPCC pools (Table 1) and relevant equations (IPCC, 2006) – are documented in the file ForC_variables_mapping.csv in the IPCC-EFDB-integration repository (https://github.com/forc-db/IPCC-EFDB-integration/blob/main/doc/ForC-EFDB_mapping/ForC-EFDB_mapping.csv).

4.1.2 Land classification

Determination of the IPCC land-use category (i.e., Forest Land, Grassland, Wetlands, Cropland, Settlements, or Other Land; section 2.2) was made based on the categorical ForC field *dominant.life.form*, sometimes drawing upon stand age. Records with "woody" *dominant.life.form* were classified as Forest Land. Those with *dominant.life.form* of "woody+grass", which in ForC is indicative of anything from a shrub-encroached grassland to a tree-dominated savanna, were given dual classification of Forest Land and Grassland. This dual classification indicates that records may be relevant to either category depending on the definition of forest applied (varies by country). For (rare) cases where *dominant.life.form* was grass and stand age was greater than zero, indicative of early successional vegetation, we assigned a classification of Forest Land, consistent with the IPCC definition that Forest Land includes land expected to succeed to forest. Cases where *dominant.life.form* was grass or crop and stand age was zero were indicative of a control for studies of forest regrowth following agricultural abandonment, and were classified as Grassland and Cropland, respectively.

Classification into sub-categories was dependent upon stand age and site history (section 2.2). For Forest Land $\geq$ 20 years old or of unknown (relatively mature) age, or Forest Land < 20 years old that was forest prior to a stand-clearing disturbance, the past land-use category was Forest Land, making the sub-category "Forest Land Remaining Forest land". For forests <20 years old with history including cultivation/ tillage or grazing, past land-use categories were Cropland and Grassland, respectively, making land-use subcategories were "Cropland converted to Forest Land" and "Cropland converted to Forest Land", respectively. For forests <20 years old with unspecified previous agricultural use, we assigned the sub-category "Land Converted to Forest land". Forests <20 years old with unknown land use prior to the study date were simply classified as "Forest Land". The same logic was applied for savannas, but including both Forest Land and Grassland as potentially relevant categories.

Given the lack of public information needed to determine whether lands are classified as mangaged (Ogle, 2018; Deng et al., 2021), and because the IPCC's definition of managed land is more expansive than is commonly applied in the scientific literature and hence in ForC, we did not transfer any classification of land management status from ForC to the EFDB. However, we do provide auxiliary information that should be useful in making this determination, including geographical location and notable disturbance events.

5 Results

5.1 ForC v4.0 contents

As of May 06, 2023, ForC (v4.0) contained 32693 independent records (39855 total), 17204 of which were for variables relevant to EFDB (Fig. 1). These records were distributed across all forested continents and ecozones, with particularly high concentrations in *[ecozone(s)]* and low concentrations in *[ecozone(s)]* (Fig. 2). The most widely represented forest type was *[type]*, followed by *[type]* and *[type]* (Fig. 3).

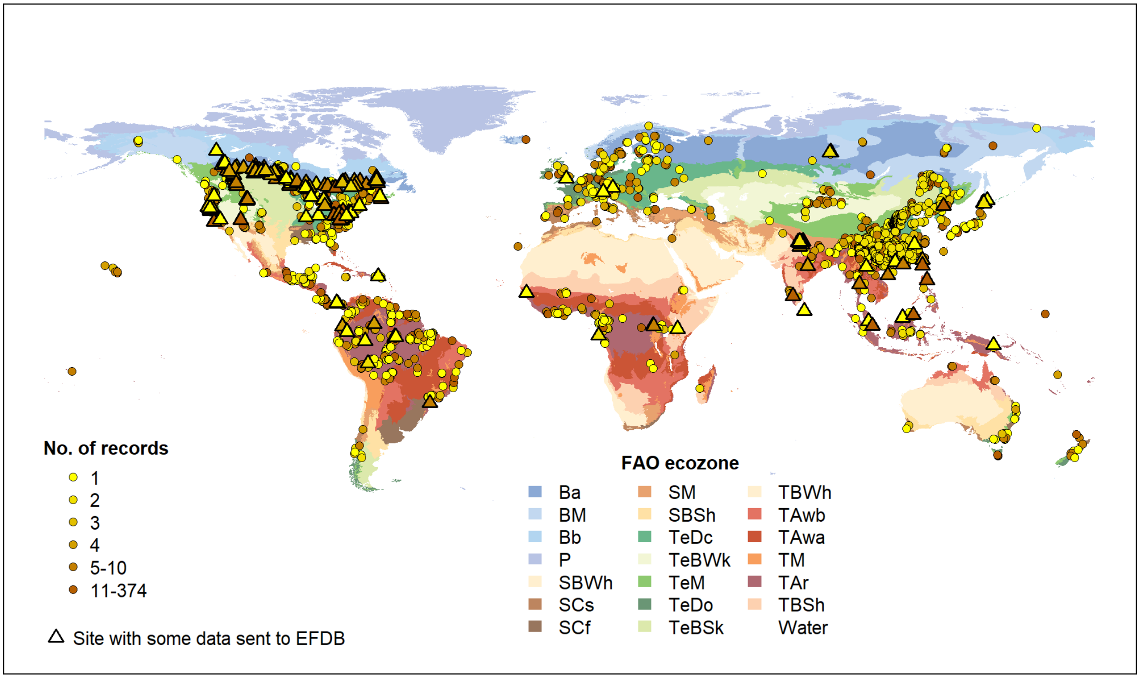

Figure 2. Map of sites in ForC shaded by number of records relevant to (circles) and transferred to (triangles) EFDB. Symbols are colored according to the number of records at each site. Underlying map shows FAO ecozones, which are coded as follows: Ba-Boreal coniferous forest, Bb-Boreal tundra woodland, BM-Boreal mountain systems, P-Polar, SBSh-Subtropical steppe, SBWh-Subtropical desert, SCf-Subtropical humid forest, SCs-Subtropical dry forest, SM-Subtropical mountain systems, TAr-Tropical rain forest, TAwa-Tropical moist deciduous forest, TAwb-Tropical dry forest, TBSh-Tropical shrubland, TBWh-Tropical desert, TeBSk-Temperate steppe, TeBWk-Temperate desert, TeDc-Temperate continental forest, TeDo-Temperate oceanic forest, TeM-Temperate mountain systems, TM-Tropical mountain systems.

ForC contained data for ## of the ## variables relevant to EFDB (Table 2, Fig. 1). The records were very unevenly distributed across variables. The most records colected were for the Aboveground biomass variable(biomass_ag).This variable

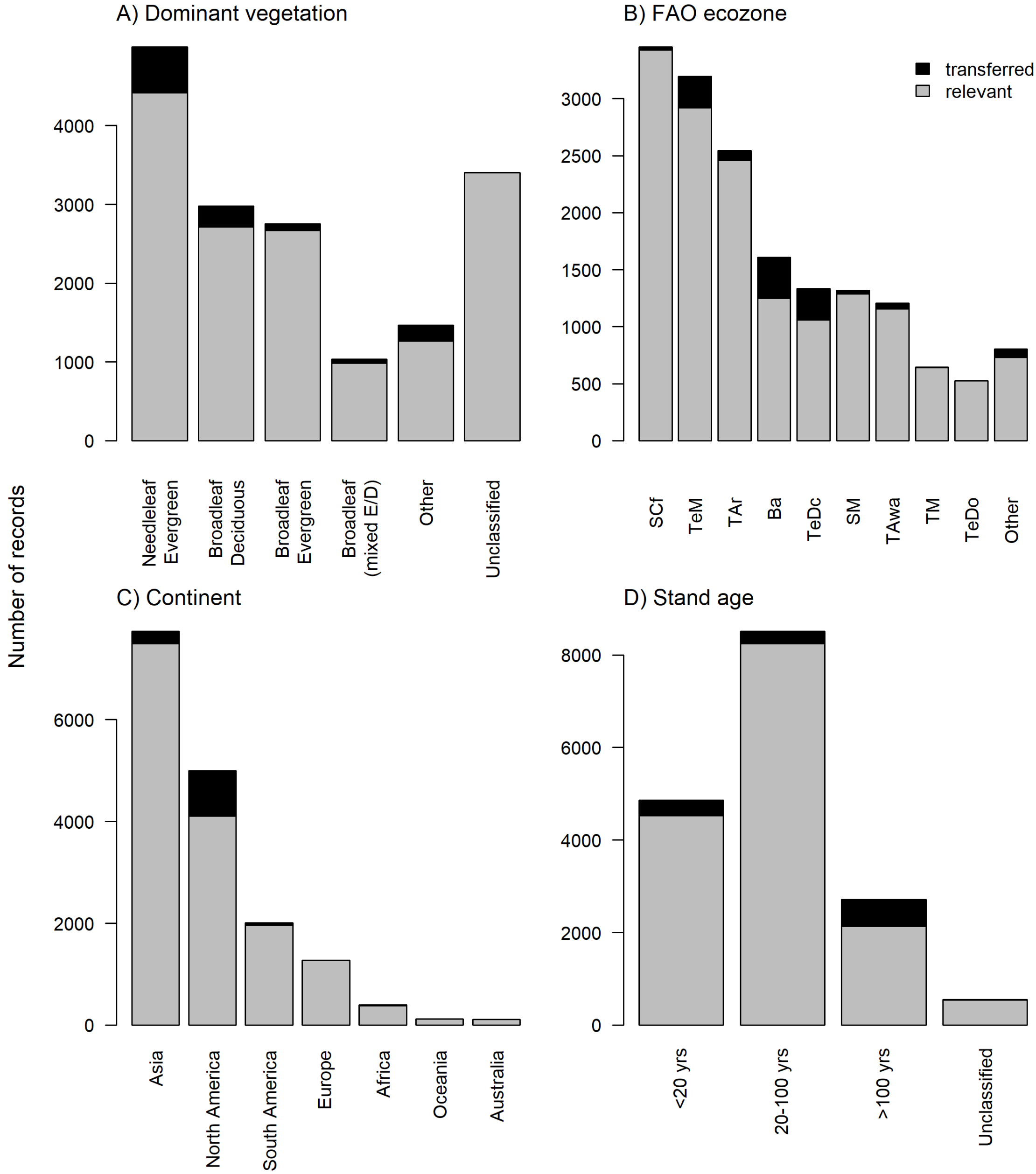

Figure 3. Histograms of number of records in ForC relevant to (grey) and transferred to (black) EFDB, organized by (a) dominant vegetation type, (b) FAO ecozone, (c) continent, and (d) stand age. For dominant vegetation (a), 'Other' includes deciduous needleleaf, mixed broadleaf- needleleaf, non-woody vegetation (e.g., early successional), and incompletely classified or mixed forest types. For FAO ecozones (b), codes are as listed in the caption of Figure 2.

Table 2: **Numbers of records of ForC variables relevant to, and sent to, EFDB.**

variable	n in ForC	n independent records in ForC	n reviewed	n sent to EFDB
Biomass				
biomass	1095	847	93	48
delta.biomass	0	0	0	0
NPP_woody	136	93	0	0
woody.mortality	0	0	0	0
Aboveground biomass				
biomass_ag	9050	7737	1251	693
biomass_ag_woody	460	366	10	10
biomass_ag_foliage	601	502	49	27
delta.agb	166	128	123	123
ANPP_woody	299	242	0	0
woody.mortality_ag	112	62	30	17
Belowground biomass				
biomass_root	4629	4180	123	55
biomass_root_fine	931	594	18	18
biomass_root_coarse	599	410	12	7
delta.biomass_root	0	0	0	0
delta.biomass_root_coarse	0	0	0	0
delta.biomass_root_fine	0	0	0	0
woody.mortality_root	0	0	0	0
BNPP_root_fine	489	333	0	0
BNPP_root.turnover_fine	91	56	0	0
BNPP_root_coarse	329	250	0	0
Dead wood				
deadwood	437	303	103	61
deadwood_standing	152	120	17	17
deadwood_down	424	368	51	27
delta.deadwood	0	0	0	0
delta.deadwood_standing	0	0	0	0
delta.deadwood_down	0	0	0	0
R_het_deadwood	0	0	0	0
Litter				
O.horizon	38	38	38	38
delta.O.horizon	4	4	4	4
litter	30	30	23	23
delta.litter	0	0	0	0
NPP_litter	0	0	0	0
R_het_litter	167	143	0	0

Table 2: **Numbers of records of ForC variables relevant to, and sent to, EFDB.** *(continued)*

variable	n in ForC	n independent records in ForC	n reviewed	n sent to EFDB
Soil organic matter				
SOM / SOC	693	398	89	46
delta.SOM / delta.SOC	0	0	0	0
R_het_soil	0	0	0	0
TOTAL	**20932**	**17204**	**2034**	**1214**

5.2 Data transfers to EFDB

As of May 06, 2023, we had reviewed or added 2034 EFDB-relevant records, 1214 records of which were sent to EFDB, and 73 of which have been reviewed, accepted, and posted (Figs. 2-3, Table 2). *[DETAILS]*

6 Recommendations

Based on our experience contributing forest C data to EFDB via ForC, we make several recommendations as to how scientists can improve forest C records in EFDB through database work (section 6.1), new data collection and analysis (section 6.2), and reporting (section 6.3). We also highlight notable mismatches between IPCC accounting methods and forest C mensuration (section 6.4).

6.1 Database needs

There is vast potential to expand forest C data in EFDB by completing the process of reviewing and sending data that are already in ForC (Figs. 2-3). So far, only ~7% of the EFDB-relevant data in ForC have been sent to EFDB.

Moreover, there are many published EFDB-relevant forest C data that are not included in ForC, with more being published on a nearly daily basis. Coverage of particular variables or regions could be vastly improved through systematic review of the literature. *(There are some efforts underway, including a few that Susan can specify.)* Such reviews are necessary to even develop a rigorous assessment of forest C data that are available, versus those that require additional data collection and analysis.

6.2 Data collection and analysis needs

New data collection and analysis is needed to fill notable knowledge gaps. While aboveground biomass stocks in particular have received – and continue to receive – significant research attention, other pools and variables remain poorly quantified (Table 2, Anderson-Teixeira et al., 2021). Furthermore, data distribution is uneven across forest types and geographical regions (Figs. 2-3). For instance, C cycling of tropical forests – particularly in Africa – remains relatively poorly characterized, in large part due to substantial barriers to data collection and distribution (de Lima et al., 2022) *(add some more here?)*

Several variables of value for IPCC C accounting have not been calculated and presented as would be possible given the same forest census data and minimal extra research effort. For example, aboveground woody mortality (*woody.mortality_ag*) and aboveground biomass increment (*delta.agb*) can be calculated from the same census data as aboveground woody productivity (*ANPP_woody*), yet the latter has received far more research attention, and correspondingly has far more records in ForC (Table 2, Anderson-Teixeira et al., 2021; but see Piponiot et al., 2022). Similarly, live coarse root biomass, total biomass, and changes in both of these pools could in theory be easily be estimated in parallel with aboveground biomass, with the greatest barrier being availability of reliable allometries, as have been developed for aboveground biomass (Chave et al., 2014; Réjou-Méchain et al., 2017; Gonzalez-Akre et al., 2022). However, while equations for estimating root (and thereby total) biomass require improvement, they do exist *for many forest types*(**?**), and IPCC provides default recommendations of below-ground to above-ground ratios for estimation of root biomass (IPCC, 2019a). In addition, standing dead trees are captured in most forest censuses and could be used to estimate standing dead wood, although additional data on breakage would be needed for accurate accounting. We recommend that, when possible, researchers calculate these, following the reporting guidelines specified in section 6.3.

Other EFDB-relevant variables require more effort but are warranted given their importance for forest C accounting. Given widespread trends of increasing tree mortality (**?**), including through severe natural disturbance (**?**), better characterization of dead wood will be critical. . . .

6.3 Data reporting needs

We recommend that, unless they have some specific reason to do otherwise, researchers calculate and report the values according to IPCC standards (Table 3). It is particularly noteworthy that simple decisions on the presentation of results will determine whether the data meet the criteria for inclusion in EFDB. Some examples are as follows: (1) presenting data only in a figure makes it ineligible for inclusion in EFDB, whereas presentation in a table or supplementary data file allows inclusion; (2) direct presentation of all relevant variables allows inclusion, whereas presenting only components of variables of interest (e.g., parsing litter into fine woody debris, OL, OF, and OH layers) or requiring simple mathematical operations to obtain a variable of interest (e.g., *delta.agb* = *ANPP_woody* - *woody.mortality.agb*) disqualifies data from inclusion; (3) matching IPCC-defined thresholds for defining C pools (Table 1), which may vary by country, can make the data far more relevant for IPCC accounting (e.g., using a 10 cm cutoff between dead wood and litter, presenting soil C to a depth of 30 cm). It should also be emphasized that reporting of 95% confidence intervals (or other metrics of error), when applicable, is highly desirable and makes the data more relevant to IPCC. Reports which had the most successful data transfers used EFDB variables and had clear tables showing their results.

For those compiling published data (e.g., for meta-analyses), the data set can have added value if all information required by IPCC is extracted from original publications. This includes – but is not limited to – retaining original values as presented without modification or rounding, noting whether data were digitized, recording confidence intervals, and recording all required fields (as indicated in the EFDB's bulk import template). The significant effort required to map a database into EFDB has been accomplished here (Appendix B), and we welcome other researchers to use the ForC template.

Table 3. Recommended best practices for reporting forest C estimates of value to national greenhouse gas inventories under IPCC guidance. ....

criteria	recommendation	rationale
variables to include	When possible, calculate and present all relevant variables that can be readily caluclated based on available data.	Estimates of relevant variables are not always calcualted.
forest census methods	Adopt IPCC guidelines (country-specific) for minimum stem size in censues in census and reporting. Ideally, census stem down to the smallest diameter feasible.	IPCC biomass pool definition includes all living vegetation, but understory may be excluded when contribution is minor.
	taxa to include	
dead organic matter sampling	*include damage estimates on standing dead trees*	
	Adopt IPCC recommendations for minimum diameter of deadwood (country-specific, default 10 cm).	
belowground sampling	Select and report soil sampling increments to include a cutoff at 30 cm depth (or country-specific depth).	IPCC biomass pool definition includes all living vegetation
reporting variiables	Present each variable individually, as opposed to requiring that variables of interest be calculated from related variables.	EFDB requires that values in the database be presented in the original article, and cannot accept subsequent calculations.
reporting estimates	Report all relevant values in tables, text, or supplementary tables/ data files, as opposed to in figures only.	EFDB does not acceptvalues digitized from figures.
reporting confidence intervals	Report 95% confidence intervals, standard error, or standard deviation and sample size.	EFDB requires confidence invervals, when possible.

Once EFDB-relevant data are available in peer-reviewed publications, they may be submitted directly to EFDB or may use the ForC - EFDB data pipline developed here. For individual publications, the former option will generally be more efficient. However, by getting the data into ForC as well as EFDB, the latter option will allow the data to be more broadly useful–for example, being used for basic science (e.g., Banbury Morgan et al., 2021; Anderson-Teixeira et al., 2021) or model benchmarking (Fer et al., 2021).

6.4 Mismatches between IPCC accounting methods and forest C mensuration

Remote sensing biomass estimates include standing dead wood (Duncanson et al., 2021).

IPCC accounting methods cannot leverage eddy-covariance measurements, which are widely seen as the best available method for quantifying ecosystem-atmosphere gas exchange.

An important challenge is that forests are changing rapidly, and data collected a decade ago may no longer be relevant, particularly in the cases of C increments and fluxes.

7 Conclusions

Appendix A. Updates to ForC

Table A1: **Table of changes to ForC fields.**

Table	Column	Description	Changes	Motivation
Sites	coordinates.precision	Precision of geographic coordinates, as reported by source or estimated from maps.	field added	allow identification of records with poor coordinate precision
Measurements	data.location.within.source	Location of data within the source listed in citation.ID.	field added	facilitate review, ensure traceability
	sd, se, lower95%CI, upper 95%CI	Standard deviation, standard error, and lower and upper 95 percent confidence intvervals, respectively.	replaces ‘stat‘ and ‘stat.name‘	cleaner format; ability to handle assymetrical 95 percent confidence intervals
	mean.in.original.units, original.units	mean value and units presented in original publication	fields added	provide IPCC with original units, reduce errors/improve reproducibility
	C.conversion.factor	Assumed/ measured C content of organic matter used to convert organic matter to C.	field added	track units conversion, allow back-calculation of OM if conversion factor deemed inappropriate
PFT	description	Definition of the pftcode at the community level. Differs from individual level in that properly describes mixed plant functional types.	field added	
	description.individual	Definition of the pftcode at the individual plant level.	field name change (previously ‘description‘)	
Citations	citation.citation	Full citation. Most of these records are automatically generated in R based upon DOI lookup.	field added	field required by IPCC
	citation.language	Language of original publication, automatically generated based on the title and abstract, with some manual entries and corrections.	field added	field required by IPCC

(continued)

Table	Column	Description	Changes	Motivation
	citation.url	URL of original publication, generally retrieved automatically via URL lookup.	field added	field required by IPCC
	citation.abstract	Abstract, generally retrieved automatically via DOI lookup.	field added	field required by IPCC
	source.type	citation source type	field added	field required by IPCC
	pdf.in.repository	Indicates whether pdf of original study has been retrieved and saved in ForC's reference repository	field added	housekeeping
	EFDB.ready	Indicates whether data have been checked for export to EFDB.	field added	housekeeping

Appendix B. Mapping ForC to EFDB

Table B1: **Mapping of ForC fields to EFDB.** See footnotes at end of table (STILL NEED TO BE PROPERLY INSERTED).

ForC table	ForC field	EFDB field	Usage	Required
Measurements	measurement.ID	Other Properties	direct mapping	(no)
	dominant.life.form	1996 Source/Sink Categories, 2006 Source/Sink Categories	used to determine land subcategories (see defining_land_subcategory.md)	yes
	stand.age	1996 Source/Sink Categories, 2006 Source/Sink Categories, Parameters/ Conditions	used to determine land subcategories (see defining_land_subcategory.md), directly listed in Parameters/ Conditions	(yes)
	dominant.veg, veg.notes, min.dbh	Parameters/ Conditions	direct mapping/ linking to dominant.veg description	no
	variable.name	-	link to variable info in ForC_variables table	yes
	date / start.date, end.date	Other Properties	direct mapping	no
	mean	Value	direct mapping	yes
	mean.in.original.units	Value in Common Units	direct mapping	yes
	original.units	Common Unit	direct mapping	yes
	lower95%CI, upper 95%CI, se, sd and n	Lower Confidence Limit, Upper Confidence Limit	direct or calculated	(yes)
	depth, covariate_1, cov_1.value, covariate_2, cov_2.value	Other Properties	direct mapping	no
	allometry_1, allometry_2	Comments from Data Provider	link to biomass allometry source, when provided	no
	data.location.within.source	-	confirm that data weren't digitized, facilitate finding data in original publication	yes
	ForC.investigator	Data Provider, Data Provider Contact	link to Data Provider, Data Provider Contact info	yes
Sites	site.ID, sites.sitename	Other Properties	direct mapping	(no)
	lat, lon	Region/Regional conditions	direct mapping; used to extract continent, Koeppen, and FAO.ecozone	(no)
	country, state, city, masl, mat, map	Region/Regional conditions	direct mapping	no
	continent, Koeppen	Region/Regional conditions	direct mapping	auto
	soil.texture, sand, silt, clay, soil.classification	Parameters/ Conditions	direct mapping	no
	FAO.ecozone	Parameters/ Conditions	direct mapping	auto

(continued)

ForC table	ForC field	EFDB field	Usage	Required
History	date, hist.cat, hist.type	1996 Source/Sink Categories, 2006 Source/Sink Categories, Abatement/Control technologies	used to determine distmrs.type for Source/Sink Categories, generate list of events for Abatement/Control technologies	(yes)/no**
	plot.area	Other Properties	direct mapping	no
Plots	plot.ID, plot.name	Other Properties	direct mapping	(no)
	distmrs.type	1996 Source/Sink Categories, 2006 Source/Sink Categories	used to determine land subcategories (see defin-ing_land_subcategory.md)	auto
	distmrs.type, distmrs.year, regrowth.type, regrowth.year	Other Properties	direct mapping	auto
PFT	description	Parameters/ Conditions	direct mapping	auto
variables	variable.type	Gases	For stocks in unit of organic matter, gases include CO2, CO, CH4, NO, NO2, N2O. For increments, fluxes, and stocks in units of C, gases includes only CO2.	auto
	variable.name	C pool, Equation	link to C pool, Equation	auto
	description	Description	direct mapping	auto
	extended.description	Other Properties	direct mapping	auto
	units	Unit (ID)	link to IPCC units	auto
Citations	citation.citation	Full Technical Reference	direct mapping	yes/auto
	citation.language	Reference Language	direct mapping	yes/auto
	citation.url	URL	direct mapping	no/auto
	citation.abstract	Abstract in English	direct mapping	no/auto
	source.type	Source of Data	direct mapping	yes

'Required' field indicates whether the field is required by EFDB: yes = value required; (yes) = input required, missing value acceptable if not reported; auto = present within ForC infrasructure, and therefore will always be exported to EFDB ; (no) = not required for EFDB, but required for ForC and therefore will always be exported to EFDB; no = not required, but exported to EFDB when a value is present.

** '(yes)' for most recent severe disturbance; 'no' for other history events

Code and data availability. use this to add a statement when having data sets and software code available

Author contributions. (fill this in)

Competing interests. The authors declare no competing interests.

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