**Title:** Informing forest carbon inventories under the Paris Agreement using ground-based forest monitoring data

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# Summary

* Humans have been influencing Earth’s climate via transformative impacts on forests for >12,000 years, and forests are now recognized as critical to climate change mitigation under the Paris Agreement. However, the efficacy of climate change mitigation planning and reporting depends on having quality data on forest carbon (C) stocks and changes. The Emission Factor Database (EFDB) of the International Panel on Climate Change (IPCC) is intended to be a definitive source for such data, but needs comprehensive and well-documented data to be so.
* To facilitate submission of forest C estimates from scientific studies to EFDB, we develop and document a process for semi-automated data submission from the Global Forest C database (ForC v4.0), which is the largest compilation of ground-based forest C estimates. We then assess the data currently available through ForC and provide recommendations for improving forest data collection, analysis, and reporting.
* As of January 2024, ForC contained ~19316 independent records relevant to EFDB, 1068 of which had been submitted and posted to EFDB. Records were unevenly distributed across variables (skewed towards aboveground biomass stocks) and geographic regions (skewed towards temperate forests). 59% of ForC records reviewed could not be submitted because the original publication lacked required information.
* In the future, ground-based forest C estimates should target gaps in the record, and studies should ensure that they report all information necessary for inclusion in 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 inventories.

**Keywords:**

# Societal Impact Statement

* helps bridge scientific research accounting under Paris agreement

# Introduction

Humans have been influencing Earth’s climate via ecologically transformative land use practices for >12,000 years (Bonan, 2016; Sanderman *et al.*, 2017; Ellis *et al.*, 2021). In recent decades, as both anthropogenic land transformation and climate change have accelerated, this relationship has come into increasing focus (IPCC, 2019a). Deforestation and forest degradation are substantial sources of the greenhouse gas carbon dioxide (CO2), currently accounting for >10% of anthropogenic emissions (Friedlingstein *et al.*, 2022). Yet at the same time, CO2 uptake by remaining forests, woodlands, and savannas has exceeded releases from deforestation and other severe disturbances, resulting in a net carbon CO2 sink of ~0.88 - 1.6 Gt C yr-1 (Xu *et al.*, 2021; Harris *et al.*, 2021), ofsetting an estimated 10 - 18% of anthropogenic CO2 emissions from fossil fuels and cement (Xu *et al.*, 2021; Harris *et al.*, 2021). The future of this important CO2 sink depends primarily upon future trajectories of direct human impacts on forests (i.e., deforestation/ degradation vs. conservation/ restoration, IPCC, 2019a, 2022a), and also upon forest responses to climate change, which are likely to reduce the sink strength (McDowell *et al.*, 2020).

In recognition of their important role in climate regulation, forests play a substantial role in international plans for climate change mitigation under the Paris Agreement (UNFCCC, 2015; Grassi *et al.*, 2017). Forest conservation, reforestation, and improved sustainable management all have significant – and relatively cost-effective – potential as climate change mitigation options (Roe *et al.*, 2021), with conservation and reforestation having the fourth and fifth largest net emission reduction potentials or all mitigation options (IPCC, 2022b). 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 (Deng *et al.*, 2021; Anderson-Teixeira & Belair, 2022).

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, 2006a; IPCC, 2019b). Under this guidance, greenhouse gas inventories include all managed land, which includes most of the world’s forest land (Ellis *et al.*, 2010; Ogle *et al.*, 2018). The IPCC inventory guidelines include specific instructions for inventories for greenhouse gas (mainly CO2) exchanges between forest land and the atmosphere (summarized in Notes S1, IPCC, 2006b, 2019b). A tiered approach 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, 2019b; 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 improvement as datasets grow and become more widely accessible. For example, following the 2019 release of the latest IPCC guidelines, it was revealed that IPCC’s Tier 1 default failed to capture eight-fold variation of C accumulation in regrowth forests within ecozones (Cook-Patton *et al.*, 2020) and 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 preparing greenhouse gas estimates, 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 (e.g., C stocks, net annual increments, and annual fluxes for various pools, IPCC, 2006a; IPCC, 2019b) from peer-reviewed journal articles or other accepted sources for inclusion in the database. Tens of thousands of relevant forest carbon estimates have been published – and continue to be published at an accelerating rate – but are not readily accessible to the practitioners assembling national greenhouse gas inventories. To contribute to the goal of making forest C parameters available for accounting under IPCC guidelines, forest scientists need an accessible summary of EFDB’s requirements and an efficient system for submission of data to the EFDB.

The goal of this publication is to facilitate submission of forest C estimates from scientific studies to EFDB. We document the process of submitting data to EFDB from the Global Forest Carbon Database, ForC (<https://forc-db.github.io/>), which is the largest collection of published estimates of forest C stocks, increments, and annual fluxes (Anderson-Teixeira *et al.*, 2018, 2021; Anderson-Teixeira *et al.*, 2023), including 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), and the Global Soil Respiration Database (SRDB-V5, Bond-Lamberty & Thomson, 2010; Jian *et al.*, 2021). We (1) map common scientific forest C estimation methods and definitions to those used by the IPCC; (2) develop a semi-automated process for preparing ForC data for submission to EFDB; and (3) assess the data in ForC relevant to EFDB and records that have been submitted to date. We conclude with recommendations as to how the scientific community can better provide useful data for forest C inventories under the Paris Agreement.

# Materials and Methods

Major steps for submission of data from ForC to EFDB included (1) mapping ForC into EFDB, including aligning ForC terms and concepts with those defined by IPCC guidelines (summarized in Notes S1), (2) revising ForC v3.0 to support semi-automated submissions to EFDB, yielding ForC v4.0 (detailed in Methods S1), and (3) submitting data to EFDB. These steps are detailed below.

## 1. Mapping ForC to EFDB

With input from the IPCC’s Technical Support Unit and referencing IPCC guidance (IPCC, 2003, 2019b; IPCC, 2006a), we mapped ForC fields into EFDB fields, as summarized in Table S2. For the majority of fields, contents of the field in ForC mapped directly into an EFDB field, either as the only contents of that field or as part of a composite record. For some fields, simple conditional logic was used to populate EFDB fields based on ForC records. For example, in cases where original studies did not present 95% confidence intervals (required by IPCC when available) but did present standard error or n and standard deviation, we calculated the 95% confidence intervals. There were two cases in which more complex mapping was required: (1) mapping of C cycle variables (detailed below in **Carbon cycle variables**) and (2) land classification (detailed below in **Land classification**).

### Carbon cycle variables

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 pool (Table 1), we identified variables representing organic matter or C stocks, net annual increments, influxes (a.k.a. “gross annual increments” by IPCC), and outfluxes. As described in section 3.2, we also defined 15 new EFDB-relevant variables that were not previously represented in ForC. It is 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* (Table S2). Details on the mapping of ForC variables to EFDB – including associated covariates, IPCC pools (Table 1) and relevant equations (IPCC, 2006a) – are documented in the file ForC\_variables\_mapping.csv in the GitHub repository associated with this publication IPCC-EFDB-integration repository in ForC-db organization (<https://github.com/forc-db/IPCC-EFDB-integration>).

**Table 1. IPCC-defined forest carbon pools with definitions and measurement methods.**

| **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 diameter cutoff 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 |



**Figure 1. Schematic illustrating the carbon pools defined under IPCC Guidelines for national greenhouse gas inventories; corresponding ForC variables, and relationships among them.** For each C pool, we show ForC variables corresponding to the stock, net annual increment, influx, and outflux. 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., minimum stem diameter censused). Additional caveats are as follows: (a,b) branch fall and mortality of stems below the minimum stem diameter censused, 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 negligble; (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. \*\*This variable is techically EFDB-relevant but not selected for submission because their is no corresponding influx variable.

### 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 ≥ 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 “Grassland 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 managed (Ogle *et al.*, 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 include any classification of land management status from ForC in the records submitted to EFDB. However, we did provide auxiliary information that should be useful in making this determination, including geographical location and notable disturbance events.

## 2. Updating ForC

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 stock change calculations under the Paris Agreement. 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 inventories 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 (Table S1), defined 15 new variables, implemented enhanced quality control, manually reviewed >1963 records to obtain additional required information, and added 329 new records. Having implemented these changes to ForC v3.0 (Anderson-Teixeira *et al.*, 2021), which are described in detail in Methods S1, we released a new major version: ForC v4.0.

## 3. Submission of ForC data to EFDB

To submit 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 submission were that (1) records had been checked against the original study and determined to be complete and correct, and as originally presented, (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, and (3) the records had not previously been submitted to EFDB. Once converted into EFDB format, the records were reviewed and then sent to the IPCC’s Technical Support Unit for submission to EFDB.

# Results

## ForC v4.0 contents

As of January 29, 2024, ForC (v4.0) contained 32686 independent records (39848 total), 19316 of which were for the 42 variables relevant to EFDB (Fig. 1). These records were distributed across all forested continents and ecozones, albeit unevenly (Fig. 2). The largest number of records came from Asia, followed by North America, South America, and Europe, with relatively few records from Africa, Australia, and Oceania (Fig. 3c). Categorized by FAO ecozone, the greatest numbers of records came from subtropical humid forests, temperate mountain systems, and tropical rain forests, each with >2,000 independent records (Fig. 3b). Boreal coniferous forests, temperate continental forests, subtropical mountain systems, and tropical moist deciduous forests had >1,000 independent records each, while other ecozones all had <1,000 records. The most widely represented forest type was needleleaf evergreen, followed by broadleaf deciduous and broadleaf evergreen (Fig. 3a). In terms of stand age, the most represented age class was 20-100 years, followed by <20 years and then >100 years (Fig. 3d).



**Figure 2. Map of sites in ForC shaded by number of independent records relevant to (circles) and submitted 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.



**Figure 3. Histograms of number of independent records in ForC relevant to (grey) and submitted 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.

ForC contained records for 29 of the 42 variables (or closely-related variable groups) relevant to EFDB (Table 2, Fig. 1). The records were very unevenly distributed across variables. The variable with most records was aboveground biomass, representing 42% of all independent records relevant to EFDB, and aboveground biomass components (woody biomass or foliage) representing an additional 5%. A total of 27% of relevant records were for root biomass (including fine and coarse root components), while 4% described total biomass. The non-living pools were less represented, with 4% of relevant were for dead wood (including standing and fallen components), 0.4% for litter, 0.3% for total ecosystem C excluding soils, and 2.1% for soil carbon.

Increment and flux variables were poorly represented (Table 2). The increment variable with most records was the aboveground biomass increment, representing 0.8% of all independent records relevant to EFDB. The only other relevant increment variable with any records was the O horizon (litter) increment, with just 4 records. Relevant flux variable records (n=2751) together constituted 14% of ForC’s independent records relevant to EFDB.

**Table 2. Numbers of records of ForC variables (or closely related variable groups) relevant to, and sent to, EFDB.**

| **variable** | **n in ForC** | **n independent records in ForC** | **n reviewed** | **n submitted to EFDB** |
| --- | --- | --- | --- | --- |
| **Biomass** |  |  |  |  |
| biomass | 1094 | 850 | 95 | 50 |
| delta.biomass | 0 | 0 | 0 | 0 |
| NPP\_woody | 136 | 93 | 0 | 0 |
| woody.mortality | 0 | 0 | 0 | 0 |
| **Aboveground biomass** |  |  |  |  |
| biomass\_ag | 9449 | 8148 | 1357 | 764 |
| biomass\_ag\_woody | 460 | 366 | 10 | 10 |
| biomass\_ag\_foliage | 601 | 520 | 73 | 45 |
| delta.agb | 166 | 150 | 145 | 123 |
| ANPP\_woody | 299 | 242 | 0 | 0 |
| ANPP\_woody\_stem | 949 | 622 | 60 | 61 |
| ANPP\_woody\_branch | 243 | 200 | 4 | 4 |
| woody.mortality\_ag | 112 | 75 | 47 | 50 |
| stem\_pC | 9 | 0 | 0 | 0 |
| **Belowground biomass** |  |  |  |  |
| biomass\_root | 4629 | 4185 | 125 | 57 |
| biomass\_root\_fine | 930 | 595 | 18 | 18 |
| biomass\_root\_coarse | 599 | 413 | 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 | 577 | 416 | 0 | 0 |
| BNPP\_root\_fine | 488 | 331 | 0 | 0 |
| BNPP\_root.turnover\_fine | 91 | 56 | 0 | 0 |
| BNPP\_root\_coarse | 329 | 250 | 0 | 0 |
| **Dead wood** |  |  |  |  |
| deadwood | 438 | 304 | 104 | 70 |
| deadwood\_standing | 153 | 121 | 18 | 17 |
| deadwood\_down | 425 | 369 | 52 | 28 |
| 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 | 45 | 45 | 45 | 40 |
| delta.O.horizon | 4 | 4 | 4 | 4 |
| litter | 30 | 30 | 23 | 23 |
| delta.litter | 0 | 0 | 0 | 0 |
| ANPP\_litterfall | 294 | 253 | 11 | 11 |
| NPP\_litter | 94 | 70 | 0 | 0 |
| R\_het\_litter | 167 | 143 | 0 | 0 |
| **Total Ecosystem C (excl. soils)** |  |  |  |  |
| total.ecosystem\_2 | 64 | 64 | 0 | 0 |
| delta.total.ecosystem\_2 | 0 | 0 | 0 | 0 |
| **Soil organic matter** |  |  |  |  |
| SOM / SOC | 693 | 401 | 89 | 56 |
| delta.SOM / delta.SOC | 0 | 0 | 0 | 0 |
| **TOTAL** | **23568** | **19316** | **2292** | **1438** |

## Data submissions to EFDB

As of January 29, 2024, we had reviewed or added 2292 EFDB-relevant records, 1438 records of which were submitted to EFDB, and 1068 of which have been reviewed, accepted, and posted (Figs. 2-3, Table 2). The 37% attenuation between records reviewed and those sent to EFDB was attributable to the presence of digitized records and records where a variable’s value had been calculated as the sum or difference of related variables rather than presented directly in the text. The discrepancy between the number of records sent and that posted to EFDB is because some records (26%) were deemed not applicable to EFDB by the review panel. As of January 29, 2024, the 1438 ForC records posted in EFDB represented 19% of the total EFDB records for forest land.

The ForC records submitted to EFDB were broadly distributed across Earth’s forests (Fig. 2). However, the density of these records was very unevenly distributed across continents, biomes, and forest types and was not proportional to the numbers of relevant records in ForC (Fig. 3). Rather, the largest number of records came from North America, followed by Asia, South America, and Africa (Fig. 3c), with the most represented FAO ecozones being boreal coniferous forest, temperate continental forest, and temperate mountain systems, followed by tropical rain forests and moist deciduous forests (Fig. 3b). In terms of dominant vegetation, by far the most records came from needleleaf evergreen forests, followed by broadleaf deciduous and broadleaf evergreen (Fig. 3b). The largest records came from mature forests (>100 years), followed by young and intermediate-aged stands (Fig. 3d).

In terms of variables, records were submitted for 19 variables (or closely-related variable groups), including variables from each C pool (Table 2). The majority (82%) of records sent were for C stocks, including 3% for total biomass, 53% for aboveground biomass, 4% for components of aboveground biomass (wood or foliage), 4% for root biomass, 2% for components of root biomass (coarse or fine roots), 5% for dead wood, 3% for components of dead wood (standing or fallen), 4% for litter (entire O horizon or OL layer component), and 4% for SOM/ SOC. Increment records totaled 9% of records sent, virtually all for aboveground biomass (excepting 4 records for delta.O.horizon). The remaining 9% of records sent described fluxes, all of which were either inputs or outputs to the aboveground biomass pool, a subset of which also described inputs to the dead wood or litter pool (Table 2, Fig. 1).

# Discussion

\*\* RECOMENDATIONS \*\*

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).

## Database needs

There is vast potential to expand forest C data in EFDB by completing the process of reviewing and submitting data that are already in ForC (Figs. 2-3). So far, only ~7% of the EFDB-relevant data in ForC have been submitted to EFDB. Although this process requires manual review of records, the submission of new records to EFDB is hugely facilitated by the fact that most pertinent information for each record is already entered in ForC and can be easily prepared for submission to EFDB using the system developed here. Future efforts to review studies for submission should optimize for representation across geographic regions, forest types, and variables, giving priority to those from currently under-represented regions and forest types (Figs. 2-3, Table 2), to records from countries relying on existing data for their greenhouse gas inventories (Tier 1 or 2 methodology), to the variables most needed by EFDB users, and to the more contemporary records.

In addition to the large potential to expand EFDB using records already in ForC, there are innumerous published EFDB-relevant forest C data that are not currently 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. Indeed, recent efforts have compiled large databases of relevant data from monoculture plantation forests (Bukoski *et al.*, 2022) and mixed species plantation forests (Warner *et al.*, 2022; Feng *et al.*, 2022), and such a compilation is in works for agroforestry (Susan Cook-Patton, unpublished data). Beyond expanding collections of relevant forest C records, such reviews are valuable for assessing the availability of published records and identifying variables and regions that require additional data collection and analysis.

## 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 – by far the most research attention (NISAR, 2018; Quegan *et al.*, 2019; Dubayah *et al.*, 2020; Table 2, Anderson-Teixeira *et al.*, 2021), production of an accurate global map of forest C stocks remains an ongoing challenge (Araza *et al.*, 2023). Other pools and variables remain very poorly quantified (Table 2, Anderson-Teixeira *et al.*, 2021), introducing substantive uncertainties into global forest C budgets (Pan *et al.*, 2011; Harris *et al.*, 2021). Furthermore, data distribution is uneven across forest types and geographical regions (Figs. 2-3). For instance, data on C cycling of tropical forests – particularly in Africa – remains relatively sparse, in large part due to substantial barriers to data collection and distribution (de Lima *et al.*, 2022). Significant investment in research and researchers focused on ground-based measurement of forest C in such regions will be important to filling knowledge gaps in forest C cycling (de Lima *et al.*, 2022; Labrière *et al.*, 2023; Araza *et al.*, 2023).

Several EFDB-relevant variables have not been calculated and presented as frequently as would be possible given existing 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 estimated in parallel with aboveground biomass, with the greatest barrier being that allometric models for estimating root biomass are not as reliable or easily available as are those 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 (Mokany *et al.*, 2006; e.g., Brassard *et al.*, 2011; Chojnacky *et al.*, 2014; Waring & Powers, 2017). 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 estimates. We recommend that, when possible, researchers calculate and report these variables, following the reporting guidelines specified in section 6.3.

Filling knowledge gaps in other EFDB-relevant variables will require more effort, but this effort is warranted given their importance for estimating forest C stock chnages. Although aboveground biomass is the most studied variable considered here (Table 2) and is the target of satellite missions (NISAR, 2018; Quegan *et al.*, 2019; Dubayah *et al.*, 2020), significant ground-based research effort is required to create accurate global maps of forest biomass and changes therein (Duncanson *et al.*, 2019; Calders *et al.*, 2022; Labrière *et al.*, 2023). Given observations of increasing tree mortality in some forested regions (McDowell *et al.*, 2020), better characterization of forest dead wood will be critical. Additionally, C stocks in forest organic horizons and soils can be quite substantial and highly uncertain in many parts of the world (Tifafi *et al.*, 2018). Significant investment in ground-based forest research will be critical to filling these gaps.

## Data reporting needs

We recommend that, in order to make research valuable to estimate C stock changes according to methods provided in the IPCC guidelines, researchers calculate and report results according to IPCC good practice (Table 3). It is particularly noteworthy that simple decisions on the presentation of results will determine whether the records meet the criteria for inclusion in EFDB. Some examples are as follows: (1) presenting data only in a figure makes them ineligible for inclusion in EFDB, whereas presentation in a table or supplementary data file allows inclusion while supporting FAIR goals (Stall *et al.*, 2019); (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 records 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 estimating forest C stock changes according to IPCC guidelines (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.

**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 estimated 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. |
|  | Census all taxa crontributing signficantly to biomass | IPCC biomass pool definition includes all living vegetation. |
| dead organic matter sampling | Adopt IPCC recommendations for minimum diameter of deadwood (country-specific, default 10 cm). | Diameter cutoff must be applied consistently by each country. |
| belowground sampling | Select and report soil sampling increments to include a cutoff at 30 cm depth (or country-specific depth). | Diameter cutoff must be applied consistently by each country. |
| reporting variables | Present each EFDB- relevant variable individually, as opposed to requiring summation of 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 accept values digitized from figures. |
| reporting confidence intervals | Report 95% confidence intervals, standard error, or standard deviation and sample size. | EFDB requires confidence invervals whenever possible. |

For those compiling published records (e.g., for meta-analyses), the data set can have added value if all information required by EFDB 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 (Table S2), and we welcome other researchers to use the ForC template.

Once EFDB-relevant data are available in peer-reviewed publications, they may be submitted directly to EFDB or may use the ForC - EFDB data pipeline developed here. For individual publications, the former option will generally be more efficient. However, data incorporated into ForC as well as EFDB will be more broadly useful; for example, these data may be used for basic science (e.g., Banbury Morgan *et al.*, 2021; Anderson-Teixeira *et al.*, 2021), analyses of forest-based climate change mitigation potential (Goldstein *et al.*, 2020; e.g., Cook-Patton *et al.*, 2020), and model benchmarking (Fer *et al.*, 2021).

# Conclusions

The ForC database contains large numbers of records that could potentially be useful for estimating C stock changes applying methodological guidance provided by the IPCC. Here we have developed a framework for submitting these records to the EFDB, thus making those data more accessible for reporting CO2 emissions and removals from forest land consistent with good practice in the IPCC guidelines (IPCC, 2006a; IPCC, 2019b). As of January 29, 2024, we have submitted 1438 records to EFDB. Although this represents just 7% of relevant records in ForC, it substantially increases the number of forest land records in EFDB. The records submitted to EFDB and present in ForC are very unevenly distributed across variables, regions, and forest types (Figs. 2-3, Table 2), reflecting broader patterns in allocation of research effort.

Going forward, forest researchers can make their research more useful for forest C inventories under IPCC guidelines by calculating and reporting results in ways that are consistent with methodologies provided in the IPCC guidelines (Tables 1, 3). In addition, substantial investments in research and researchers focused on ground-based measurement of forest C will be required to fill knowledge gaps and thereby increase the accuracy of forest CO2 inventories for forest lands under teh Paris Agreement. This challenge is heightened by the fact that forests are changing rapidly (e.g., McDowell *et al.*, 2020), and data collected a decade or more in the past may no longer be relevant. This heightens the need for an efficient system of making forest C data accessible for national greenhouse gas inventories. We view the system developed here for submitting ForC data to the IPCC EFDB as one important step towards that goal.

# Acknowledgements

We gratefully acknowledge the substantial contributions of Valentyna Slivinska and Sandro Federici for collaboration on the conception, design, and technical review of this project. Thank you to all researchers who collected and published the data contained in ForC, and to all research assistants and collaborators who have contributed to building the database. Thank you to Avni Malhotra for helpful comments on an earlier draft of this manuscript. Funding for this study was provided by the Smithsonian (Forest Global Earth Observatory, Smithsonian Working Land and Seascapes); a Bezos Earth Fund grant to the Nature Conservancy, with a sub-grant to NZCBI; and the Institute for Global Environmental Strategies.

# Author Contribution

KAT and VH conceived and designed the project; VH wrote the scripts for database management, data submission to EFDB, and the analyses presented here; MW, TR, and RBM added and reviewed ForC data, BBL and SCP contributed large databases to ForC (EFDB and GROA, respectively); CP provided methodological expertise; KAT, VH, and MW prepared the first draft of the manuscript; all authors reviewed the results and approved the final version of the manuscript.

# Data Availability Statement

All code and data are openly available. The ForC database and associated code are available via the ForC repository within the ForC-db organization on GitHub (<https://github.com/forc-db/ForC>), and the version used here (ForC v4.0) is archived in Zenodo (Anderson-Teixeira *et al.*, 2023, DOI: 10.5281/zenodo.8020861). The data and code associated with data submission to EFDB and preparation of this manuscript are available via the the IPCC-EFDB-integration repository within the ForC-db organization on GitHub (<https://github.com/forc-db/IPCC-EFDB-integration>) and archived in Zenodo (DOI: 10.5281/zenodo.8021474).

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