## *Plants, People, Planet* Supporting Information

Article title: Informing forest carbon inventories under the Paris Agreement using ground-based forest monitoring data

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**Table S1. Updates to ForC fields implemented between releases of v3.0 and v4.0.**

| Table | Field | 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's EFDB 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 | clarify PFT at community and individual levels |
|  | description.individual | Definition of the pftcode at the individual plant level. | field name change (previously `description`) | clarify PFT at community and individual levels |
| Citations | citation.citation | Full citation. Most of these records are automatically generated in R based upon DOI lookup. | field added | field required by IPCC's EFDB |
|  | 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's EFDB |
|  | citation.url | URL of original publication, generally retrieved automatically via URL lookup. | field added | field required by IPCC's EFDB |
|  | citation.abstract | Abstract, generally retrieved automatically via DOI lookup. | field added | field required by IPCC's EFDB |
|  | source.type | citation source type | field added | field required by IPCC's EFDB |

**Table S2. Mapping of ForC fields to EFDB.** 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>).

| 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 |
| 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 | most recent severe disturbance: (yes) / other history events: 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 defining\_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.

**Table S3.** **Numbers of ForC records and EFDB submissions by variable.**

| **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** |

**Methods S1.** **Updates to ForC (ForC v4.0)**

Here, we describe changes relative to ForC v3.0 (Anderson-Teixeira *et al.*, 2021), which were implemented prior to the release of ForC v4.0.

***New or modified fields***

We added or modified a total of 18 fields (Table S1). 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 harvest (scrape) the URL, citation, abstract and language of the publications, based on their DOI, using R package rvest (Wickham & RStudio, 2022). That information was manually retrieved when the web scraping failed.

***New variables***

To create structure for EFDB-relevant records, we added a total of 15 new variables to the set of named and defined variables, 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 February 02, 2024, 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).

***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 (Table S1), 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 2.1 (van de Pol *et al.*, 2016; Bailey & Pol, 2016) 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 submission 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.

***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 (Table S1). It was therefore necessary to return to original publications to retrieve relevant 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), and (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 submission 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 (Griscom *et al.*, 2017; Griscom *et al.*, 2020), ground-based data on tropical forest C cycling tends to be more scarce due to a variety of challenges (Anderson-Teixeira *et al.*, 2021; de Lima *et al.*, 2022), and tropical countries are more likely to apply Tier 1 methodology that bases forest C budgets on internationally defined IPCC default values (Romijn *et al.*, 2015).

***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 (Lutz *et al.*, 2021; Piponiot *et al.*, 2022) 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.

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**Notes S1.** **Primer on forest land classification and carbon pools under IPCC guidelines**

***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 *et al.*, 2018; Deng *et al.*, 2021).

***Carbon pools***

For each stratum of subdivision within a land-use category, annual stock changes (; t C yr-1) are calculated as the sum of changes in various pools, plus any harvested wood products. 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.

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.

*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; IPCC, 2006). IPCC’s guidance is that the understory may be excluded if it constitutes a “minor” component (defined as < 25 - 30 % of emissions/removals for the overall category, IPCC, 2006), and 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 (), and ~20% woody mortality () of mature closed-canopy forests worldwide (Piponiot *et al.*, 2022), and therefore stems < 10 cm DBH can usually be considered a minor component of aboveground biomass for these forests. In regrowth forests, woodlands, or savannas, small trees and shrubs contribute a much larger proportion of C stocks and fluxes (Hughes *et al.*, 1999; Lutz *et al.*, 2018; Piponiot *et al.*, 2022), and, correspondingly, biomass estimates for these ecosystems tend include smaller size classes. 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 these do tend to be censused when they constitute a large proportion of the biomass (e.g., Fukushima *et al.*, 2007). 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, and such selection has an enormous influence on estimates of biomass stocks, increments, and fluxes (Clark & Clark, 2000; Clark *et al.*, 2001; Calders *et al.*, 2022). 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).

Belowground biomass is defined as “all biomass of live roots” (IPCC, 2003; IPCC, 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, and tending to be very uncertain (e.g., Keller *et al.*, 2001). 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 (Freschet *et al.*, 2021). 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; IPCC, 2019).

*Dead Organic Matter*

Dead organic matter includes all non-living biomass larger than the litter size threshold. Its inclusion in inventories is not required under Tier 1 methodology for Forest Land remaining Forest Land 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; IPCC, 2006). This pool includes standing and fallen dead wood, stumps, and dead roots of diameter ≥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, 2019).

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 IPCC 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; IPCC, 2006). As noted above, live fine roots may be included in litter when difficult to separate empirically. The definition includes the entire O horizon, 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, 2019).

*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; IPCC, 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.

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