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

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Abstract. The abstract goes here. It can also be on *multiple lines*.

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1 Introduction

As we seek to mitigate climate change (UNFCCC, 2015), forests are critical. *(See intros to other papers for relevant refs)* Under Paris Agreement, ##% of Nationally Determined Contributions relate to forests (Grassi et al., 2017).

The International Panel on Climate Change (IPCC) provides guidance for national greenhouse gas (GHG) inventories for reporting to the United Nations Framework Convention on Climate Change (UNFCCC, (REFS for older guidelines), IPCC, 2019a). Under this guidance, GHG 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 forest land ... (IPCC, 2006, 2019b). This guidance has improved as more of the relevant underlying data has become available (Requena Suarez et al., 2019), but there remains room for continuous improvement as the science advances. For example, Cook-Patton et al. (2020) *(summarize IPCC comparison results). Moreover, it is useful for those compiling national greenhouse gas inventories to have access to locally-specific information, when available.* To improve the data accessible 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 Global Forest Carbon Database, ForC, is the largest collection of published estimates of forest carbon stocks, increments, and annual fluxes (Anderson-Teixeira et al., 2018, 2021). *(add stats/ details, maybe record of how ForC has grown over time)* 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 definitions of relevant carbon stocks and increments (2) describe mapping of ForC to IPCC's EFDB, (3) describe updates to ForC (ForC v4.0), (4) summarize the data in ForC that's relevant to EFDB, identifying gaps, and (5) provide recommendations for improving data collection, analysis, database, and accounting.

2 IPCC definitions of carbon stocks and incremenets

For quantifying forest role in global C cycle, we ultimately care about: (1) C stocks – stores of C that would be vulnerable to release to the atmosphere upon land use change (2) C increments – changes in those C stocks.

2.1 Carbon stocks

Forest ecosystem C stocks may be parsed into pools in various ways. IPCC parses into biomass (aboveground and belowground), dead organic matter (dead wood and litter), and soil organic matter (Table @ref(table_variables)). Quantifying these requires a one-time measurement.

2.1.1 Biomass

Biomass includes living vegetation, above- and below-ground.

The IPCC defines aboveground biomass as "all biomass of living vegetation, both woody and herbaceous, above the soil including stems, stumps, branches, bark, seeds, and foliage" [].

Belowground biomass is defined as "all biomass of live roots" [].

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.

Dead wood is defined as...

Litter is defined 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. This includes litter (OL), fumic (OF), and humic (OH) layers. Live fine roots (of less than the suggested diameter limit for belowground biomass) are included in litter where they cannot be distinguished from it empirically." (2003 IPCc GPG for LULUCF (https://www.ipcc-nggip.iges.or.jp/public/gpglulucf/gpglulucf_files/Glossary_Acronyms_BasicInfo/Glossary.pdf)

Table 1. Variables with definitions and measurement methods. Definitions from IPCC Table 1.1. (See Table 1.1 in IPCC guidance).

pool	**definition**	**major sources of estimate variation**	**IPCC guidance**
aboveground biomass	all biomass of living vegetation, both woody and herbaceous, above the soil	allometry, min dbh	acceptable to exclude understory
belowground biomass	all biomass of live roots	allometry, min dbh, assumed ratio of belowground to aboveground biomass (IPCC table 4.4)	fine roots may be excluded when they cannot be distinguished empirically from soil organic matter or litter
dead wood	all non-living woody biomass not contained in the litter, either standing, lying on the ground, or in the soil	min dbh, ...	default min dbh = 10cm, but may be chosen by country
litter	all non-living biomass with a size greater than the limit for soil organic matter and less than the minimum diameter chosen for dead wood, lying dead, in various states of decomposition above or within the mineral or organic soil	min dbh for dead wood , ..	includes entire O horizon
soil organic matter	organic carbon in mineral soils to a specified depth	sampling depth	default sampling depth = 30cm, but may be chosen by country

2.1.3 Soil Organic Matter

Soil organic matter is defined as…

2.2 Carbon increments

C increments are defined as the change over time, in annual increments, in each C pool. These may be estimated as the difference between C stocks at two time points, or as the difference between inputs and outputs to the pool (i.e., fluxes). Quantifying these requires at least two measurements. (*But, Can carbon increments be inferred from a single measure and a known age (i.e., the approach we used in GROA)?*) Fluxes are the inputs and outputs to each pool.

3 Mapping ForC to EFDB

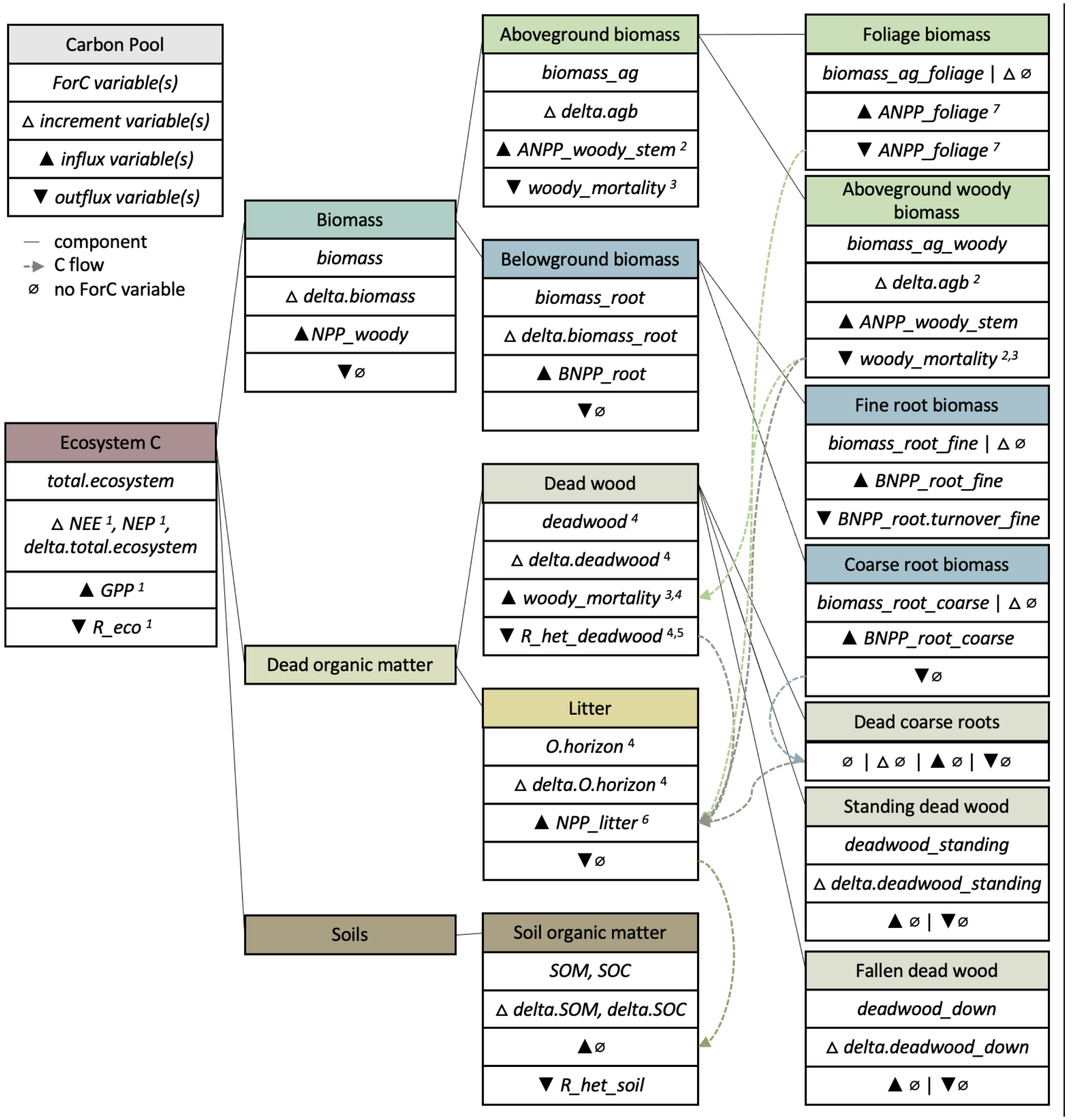

Figure 1. Schematic illustrating the carbon pools quantified under IPCC accounting; ForC variables corresponding to the stock, increment, influx and outflux; and relationships among them. In many cases, the match of ForC variables to IPCC criteria depends upon measurement protocols (e.g., minimum DBH). Additional caveats are as follows: 1- assumes minimal non-respiratory C fluxes,... (Chapin et al. 2006); 2- assumes that change in foliage biomass is negligible (see note 7); 3- incomplete: excludes large branch fall; also, under IPCC definitions, outflux from aboveground biomass should include all sizes, influx to deadwood should include only above the minimum diameter chosen for dead wood; 4- incomplete: excludes belowground components; 5-incomplete: excludes breakage into pieces less than dead wood threshold size; 6-incomplete: excludes woody mortality of stems <10 cm DBH, decomposition of dead wood (aboveground and coarse roots) into sizes classified as litter; 7-foliage production is generally measured by collecting leaf-fall, a method that assumes that the influx = outflux (foliage biomass is roughly constant year-to-year).

Table 2: **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 defin-ing_land_subcategory.md)	yes
	stand.age	1996 Source/Sink Categories, 2006 Source/Sink Categories, Parameters/ Conditions	used to determine land subcategories (see defin-ing_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

Table 2: **Mapping of ForC fields to EFDB.** See footnotes at end of table (still need to be properly inserted). *(continued)*

ForC table	ForC field	EFDB field	Usage	Required
	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	(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

Table 2: **Mapping of ForC fields to EFDB.** See footnotes at end of table (still need to be properly inserted). *(continued)*

ForC table	ForC field	EFDB field	Usage	Required
	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

3.1 Carbon cycle variables

Mapping of variables is shown in Fig. 1

Define relationship among NEE, NEP, and delta.C., especially noting role of harvest (Chapin et al., 2006).

3.2 Land use categories

Documented at https://github.com/forc-db/IPCC-EFDB-integration/blob/main/doc/ForC-EFDB_mapping/defining_land_subcategory.md, https://github.com/forc-db/IPCC-EFDB-integration/blob/main/doc/ForC-EFDB_mapping/IPCC_LandUse_mapping.csv, and in issue #8.

The UNFCCC requires GHG 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 full report REF*]. This definition is applied differently across countries, and is not clearly defined by the majority of governments (Ogle, 2018). Given this, and because the IPCC definition of management does not necessarily match that which would be reported in scientific publications and hence in ForC, we do not transfer any classification of land management status from ForC to the EFDB, but do provide auxiliary info that may be useful in making this determination (e.g., geographical location).

4 Updates to ForC (ForC v4.0)

To support export of data to EFDB, and to improve the overall quality of the ForC database, we defined ## new variables, implemented some modest restructuring, resolved duplicate records, and conducted quality control. This section describes changes relative to ForC v2.0 (Anderson-Teixeira et al., 2018).

4.1 Defining new variables

We added eleven increment variables to the set of named and defined variables (or 22, counting _OM and _C versions), which previously included only one (aboveground biomass increment, *delta.agb*). *(https://github.com/forc-db/IPCC-EFDB-integration/issues/6)* These are directly related to C stocks as previously defined in ForC, with "*delta.*" added in front of the variable name.

Although these variables currently lack records, the structure exists such that records can be populated over time.

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 *litter* (OL)).

4.2 ForC restructuring

Table 3: **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	

Table 3: **Table of changes to ForC fields.** *(continued)*

Table	Column	Description	Changes	Motivation
	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
	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

Table 3: **Table of changes to ForC fields.** *(continued)*

Table	Column	Description	Changes	Motivation
	EFDB.ready	Indicates whether data have been checked for export to EFDB.	field added	housekeeping

4.3 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. in prep) to run some automatic checks any time the master data files are updated. Second, to improve information on geographic coordinates, we flagged and reviewed records with suspected low precision *(Issue #29)[https://github.com/forc-db/ForC/issues/229]*. Third, to identify erroneous climate data… *(Issue #212)[https://github.com/forc-db/ForC/issues/212]*.

4.4 Resolving duplicates

5 Results

figure: map of relevant ForC data with underlying FAO ecozones

(summarize the data in ForC that's relevant to EFDB, identifying gaps)

dead wood and litter comparisons will be particularly interesting, as IPCC values are based on just a handful of references for each climate zone (table 2.2 in 2019 guidelines)

6 Recommendations

(*strongly flag both useful variables that the EFDB does not track and useful variables that papers fail to include that EFDB needs*)

6.1 Data collection and analysis needs

(Paragraph highlighting important gaps in variables / regions)

Several variables of value to IPCC, including standing dead wood, woody mortality, delta.agb, are not calculated and presented as frequently as are AGB and ANPP_woody, even though they can readily be derived from the same census data. We recommend that researchers calculate and report these, as specified below. Furthermore, there is an opportunity to fill data gaps by calculating these from existing census data. For example, the core census protocol of the Forest Global Earth Observatory [ForestGEO; REFS] collects the data required to calculate standing dead wood, woody mortality, and delta.agb, but these have not been calculated and reported for all sites for which the appropriate number of censuses are available (n=1 for standing dead wood, n=2 for woody mortality and delta.agb) [but see REFS].

A universal challenge in estimating biomass (living or dead) from forest census data is applying appropriate allometries to convert DBH measurements to biomass. *(Camille/Helene can write this paragraph easily.)*

6.2 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:

- adopt common standards for variables like min diameter of deadwood, select soil sampling increments to include a cutoff at 30.
- report 95% CIs, SE, or STD and n
- report C variables in article text, table, or SI table. EFDB cannot accept data digitized from figures

For data synthesis projects, compilation can only be useful to the EFDB if they include all the required, along with transparent description on the methodology applied to derive emission factors (or have a brief description and a reference to the original source) and the original emission factor values are present (not modified/rounded).

Contributing data to ForC and/or EFDB directly will ensure its broader impact. The latter is more efficient for getting data to EFDB, but does not get the data into ForC, where it can 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).

6.3 Database needs

There are plenty of relevant, published data that are not included in ForC. Systematic review of the literature could vastly improve data coverage. *(There are some efforts underway, including a few that Susan can specify.)*

6.4 IPCC

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

Remote sensing biomass estimates include standing dead wood (Duncanson and MANY_MORE, 2021).

7 Conclusions

The conclusion goes here. You can modify the section name with `\conclusions[modified heading if necessary]`.

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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