~~New~~ FAO estimates of net forest emissions and removals, 1990-2025

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Abstract. ~~The~~ FAO officially collects, analyzes and disseminates forest data by country via the Forest Resources Assessment (FRA) program since the late 1950s. Since 2015, FAO uses a subset of the FRA data, namely forest area and carbon stocks, to compute and disseminate in FAOSTAT net forest emissions/removals ~~estimates were further developed and updated using as input new data on forest land area and carbon stock collected from countries through the 2025 Forest Resources Assessment~~estimates, as part of its efforts to assess emissions from agrifood systems. This paper presents the most recent update of the FAO net emission/removal estimates, based on estimates of carbon stock change from all pools, i.e., above- and below-ground living biomass, litter, dead wood and soils, covering over 200 countries and territories for the period 1990‑2025. R~~Unlike previous versions, the FAO estimates were expanded to reflect carbon stock changes not only in living biomass, but also in litter, dead wood and soils. Averaged~~esults show that forests acted globally as net carbon sinks since the 2000s, on average ranging ~~over the most recent decade 2015-2025, the FAO results indicated strong removals on forest land, ranging~~ from -~~3.6~~1~~0~~.08 to -~~6.0~~2~~.~~.32 Gt CO_2 yr^{-1} ~~—with lower and upper boundaries reflecting inclusion of stock change for living biomass only or for all pools~~ over the most recent decade 2015-2025.~~.~~ This net flux was a result of substantial carbon removals on forest land over the same period, ranging from -3.8~~6~~ to -6.1~~0~~ Gt CO_2 yr^{-1}, only ~~The forest removals were~~ partially counterbalanced by emissions from net forest loss ~~net forest conversion of 2.8 to 3.8 Gt CO_2 yr^{-1} — used herein as a proxy for deforestation~~of 2.8 to 3.8 Gt CO_2 yr^{-1} —used herein as a proxy of deforestation.~~.~~ ~~Furthermore,~~ Annex I (AI) and non-Annex I (NAI) countries contributed equally to the estimated forest removals ~~on forest land~~, whereas 90% of emissions from net forest ~~conversion~~ loss were generated in NAI countries. Comparisons of~~i~~ the FAO estimates~~sons~~ with~~to~~ ~~country~~ data submitted independently by countries to the United Nations Framework Convention (UNFCCC), as well as with output from the Global Carbon Budget, showed good agreement ~~indicated close alignment with FAO estimates~~ at global, AI and NAI level, including for~~including for the world's~~ major forest ~~contributing~~ countries. ~~Additional comparisons with the Global Carbon Budget confirmed good alignment of the FAO data with major international assessments, showing good agreement at global level while highlighting s~~At the same time, important discrepancies between FAO, UNFCCC and global carbon model data were identified in about a dozen countries~~pecific country discrepancies linked to heterogeneous reporting issues to FAO and UNFCCC. At the same time, grouping such discrepancies by typology helped to identify areas of possible data quality improvements aimed at better aligning the country forest statistics submitted to both FAO and UNFCCC —~~. Improved convergence of evidence is achievable through dedicated statistical development programs in specific countries, to support~~needed for the coherent~~ international implementation and monitoring of effective climate mitigation actions. ~~.~~The FAO estimates and country data

collected from UNFCCC were ~~produced~~ disseminated in FAOSTAT for 194 countries and 42 territories, with regional and global aggregates, in annual time-series covering the period 1990–~~-~~2025. They were made available as open access at 10.5281/zenodo.20085666~~10.5281/zenodo.20085666~~.

Keywords: Forest emissions and removals, FAO, FRA, FAOSTAT, carbon stock change, national GHG inventory

1 Introduction

The United Nations Food and Agriculture Organization (FAO) officially collects, analyzes and disseminates forest data by country via its signature Forest Resources Assessment (FRA) program (FAO, 2025a). The FRA is the longest standing official international forest data collection process in existence today. It provides information on a wide range of forest variables since the 1950s, making it one of the most authoritative sources of official national forest data, useful for tracking long-term trends in forest resources. As such, FRA data are regularly used as key inputs in assessments of the state of the planet, for instance in relation to the world's climate and forests (IPCC, 2019; FAO, 2024), relevant sustainable development goals (FAO, 2017) and the global carbon cycle (Friedlingstein et al., 2026).

Since 2015, FAO uses a subset of the FRA data, namely forest area and carbon stocks, to estimate and disseminate in FAOSTAT net forest emissions/removals data (Federici et al., 2015; Tubiello et al., 2021), as part of its effort to assess and document agrifood systems emissions worldwide (FAO, 2025b,c). The FAOSTAT forest net emissions/removals dataset ~~of the United Nations Food and Agriculture Organization (FAO) was developed over a decade ago as~~is a global knowledge product, providing relevant information ~~on forests contribution to climate change~~ to users worldwide for over 200 countries and territories and a long time-series ~~(Federici et al., 2015; Tubiello et al., 2021). The data are regularly updated in FAOSTAT as part of FAO agrifood systems emissions (FAO, 2022)~~.

In parallel with the FRA process, with the establishment of the UN Framework Convention on Climate Change (UNFCCC) in 1992, countries began reporting forest data (mainly area and carbon stocks) independently of FAO to the UNFCCC, as part of their national greenhouse gas (GHG) inventory (NGHGI) submissions. ~~The~~ Within this separate reporting, the FAO ~~estimates are produced directly at national level, using forest area and carbon stock change information officially submitted by countries to FAO via the Forest Resources Assessment (FRA), the longest standing official international forest data collection process in existence today, providing information on a wide range of forest variables (FAO, 2025a). As such, the FAO forest emissions/removals and its underlying input FRA~~ data ~~represent a valuable resource and~~provide a useful ~~practical~~ benchmark~~ing~~ ~~tool for~~in support of country reporting to UNFCCC~~-~~, for example in technical expert review~~er~~s and as a reference for ~~and national greenhouse gas inventory (~~NGHGI~~)~~ ~~compilers~~ compilation (IPCC, FAO, IFAD, 2015)~~, working under) the enhanced transparency framework of the Paris Agreement~~. ~~As a global knowledge product, t~~Within this context and more generally, the FAO data have been used widely to identify, contextualize, and better characterize differences ~~observed~~ across published global datasets of land use, land~~-~~-use change and forestry (LULUCF), including within IPCC Assessment Reports (e.g., Lamb et al., 2026; Grassi et al., 2023; Nabuurs et al., 2022; ~~Grassi et al., 2023; Lamb et al., 2026~~Mbow et al., 2019).

~~While a recognized contributor to LULUCF analyses provided in previous IPCC reports (Mbow et al., 2019; Nabuurs et al., 2022), r~~Recent work had however suggested limitations to the applicability of FAO estimates to both country and global assessments, citing ~~for instance~~ boundary and definitional issues related to the IPCC managed land use proxy (Grassi et al., 2023), FRA data quality (Grassi et al., 2022) and completeness of carbon pools, previously limited to above- and below-ground living biomass (Tubiello et al., 2021). We address~~ed~~ all three issues in this paper ~~in this manuscript,~~ by presenting more detailed analyses based on the new FRA 2025 input data, by including more detailed comparisons with UNFCCC data,~~, and importantly~~ and by extending the ~~previous~~ FAO carbon stock approach ~~-~~to ~~allow for inclusion of~~ all carbon pools covered by the FRA, ~~namely not only carbon stock in~~i.e., above- and below-ground living biomass, ~~-as in previous version, but adding~~ litter, dead wood and soil ~~carbon pools~~.

The main goal of this ~~manuscript~~ paper was therefore to ~~document the revised~~present the new FAO net forest emissions/removals statistics 1990-2025 and to ~~compare results~~demonstrate their usefulness as an international data source to usefully complement ~~-to~~ UNFCCC country data and the scientific results published by ~~other independent sources disseminated via~~ the Global Carbon Budget (Friedlingstein et al., 2026~~5~~). In doing so, we identified important ~~current and future data quality~~areas of improvement~~s~~ needed to ~~better~~ further align the existing~~relevant~~ international efforts on forest emissions and removals data, ~~-reporting processes aimed at strengthening country data comparability and thus~~highlighting the need for coordinated statistical capacity development programs in countries, aimed at ~~-~~supporting ~~the~~ evidence-base decision making for effective ~~for effective~~ climate action.

2. Materials and Methods

~~The FAOSTAT database on forest emissions/removals (FAO, 2025b) disseminates FAO estimates and publicly available UNFCCC country data. The FAO net forest emissions/removals estimates were originally developed by Federici et al. (2015) and Tubiello et al., (2021). They are based on a carbon stock change approach (IPCC, 2019), using as input country data on forest area and carbon stock collected by FAO via the FRA. The FRA data serve as an authoritative, official source for tracking long-term trends in forest resources and as such are used as key inputs for assessing the state of the planet, for instance in relation to the world's climate and forests (IPCC, 2019; FAO, 2024), relevant sustainable development goals (FAO, 2017) and the global carbon cycle (Friedlingstein et al., 2025). Conversely, the UNFCCC country data on forest emissions and removals also disseminated in the FAO dataset were collected from publicly available Biennial Transparency Reports, Common Reporting Tables and National Communications, including National Inventory Reports (UNFCCC, 2026).~~

~~The~~ We discuss below the input data on forest area and carbon stocks sourced from the FRA, as well as the methods for collection and re-dissemination by FAO of UNFCCC emission/removal data (sect. 1.1). We then describe the equations used to estimate the FAO net forest emissions and removals (sect. 2.2), closing with a detailed list of limitations and associated uncertainty (sect. 2.3).~~FRA input data considered herein were submitted to FAO by its member countries, following a standardized methodology aimed at transparency and comparability (FAO, 2025a). FRA data sources may include national forest inventories, remote sensing, administrative data, academic and specialized studies and, in the lack of other data, expert opinion. Data quality improvements across~~

~~successive data collection cycles are often the result of relevant capacity development efforts, and may lead to revisions of entire time series, based on the most recent national forest monitoring data. The FRA 2025 data coverage was substantially higher compared to previous data collection cycles. It saw the highest country participation (197 national correspondents, up from 187 in 2020), with increased numbers of direct reports. In addition, a greater number of countries – representing over half of the world's forest area – monitored their forests using more sophisticated data collection approaches, including more frequent national forest inventories and remote sensing analysis.~~

2.1 Input data

The FRA input data considered herein are those submitted to FAO by its member countries, following a standardized methodology aimed at data transparency, consistency and comparability (FAO, 2025a). FRA data sources may include national forest inventories, remote sensing, administrative data, academic and specialized studies and, in the lack of other data, expert opinion. Data quality improvements across successive data collection cycles are often the result of relevant capacity development efforts, and may lead to revisions of entire time series, based on the most recent national forest monitoring data. The FRA 2025 data coverage was substantially higher compared to previous data collection cycles. It saw the highest country participation (197 national correspondents, up from 187 in 2020), with increased numbers of official data submitted, thus reducing the need for FAO imputations. Furthermore, since the FRA 2015 cycle, more countries have monitored their forests using increasingly sophisticated data collection approaches, including more frequent national forest inventories and remote sensing analyses. The FRA 2025 data used in this work to estimate the FAO net forest emission~~s~~/removal fluxes~~s~~ included: i. *Forest* area and its two components: *Naturally Regenerating Forest* area and *Planted Forest* area; and ii. *Forest Carbon Stock* and *Forest Carbon Density* for the following carbon pools: *above-ground biomass; below-ground living biomass*; *litter*; *dead wood*; and *soil* ~~*carbon*~~ (FAO, 2025a).

In terms of UNFCCC data, independent country information was collected from publicly available official submissions to the UNFCCC, such as Biennial Transparency Reports, Common Reporting Tables and National Communications, including National Inventory Reports/ National Inventory Documents (UNFCCC, 2026). The UNFCCC data, disseminated together with the FAO estimates in FAOSTAT (FAO, 2025b), were collected from available submissions to the UNFCCC, with a cut-off time of March 15 2026~~, including~~. They included: i. *Forest Land* area and, where available, *Managed Forest* ~~*Land*~~ area; ii. ~~*Deforestation*~~ *A*~~*a*~~*rea of forest conversion to non-forest land use*; iii. *Emissions/removals on Forest Land*; and iv. *Emissions from* ~~*deforestation*~~*forest conversion*. We mapped UNFCCC data to the relevant FAO forest categories for dissemination in FAOSTAT (https://files-faostat.fao.org/production/GF/GF_map.pdf), ~~used the same approach of~~similarly to the mapping used by the European Commission Joint Research Center (JRC) for the JRC NGHGI dataset (Melo et al., 202 6~~5~~) ~~for mapping UNFCCC data to the above forest categories (FAO, 2025b)~~. We note to this end that ~~At the same time, we~~FAOSTAT only disseminates official UNFCCC country data, whereas the JRC NGHGI also disseminates ~~made no attempt to~~ gap-filled ~~missing~~ information produced either ~~statistically~~ via linear interpolation and carry-forward and backward, or through additional ~~additional assumptions~~imputations (e.g.~~i.e.~~, using LULUCF data ~~to infer~~ as a proxy for forest ~~information~~data). Hence ~~, resulting in~~the FAOSTAT UNFCCC dataset has generally less data points and country coverage than ~~disseminated by~~ the JRC NGHGI.

~~The FRA 2025 dataset covered a broader thematic, geographical and temporal coverage compared to the UNFCCC dataset, the former covering all forest area and carbon stock variables for 194 countries and 42 territories for the 1990-2025 period. Conversely the UNFCCC data covered a similar period (1990-2023) but with much sparser thematic coverage (Tab. 1).~~

~~**Table 1.** Country coverage of UNFCCC data disseminated in FAOSTAT, 1990-2023.~~

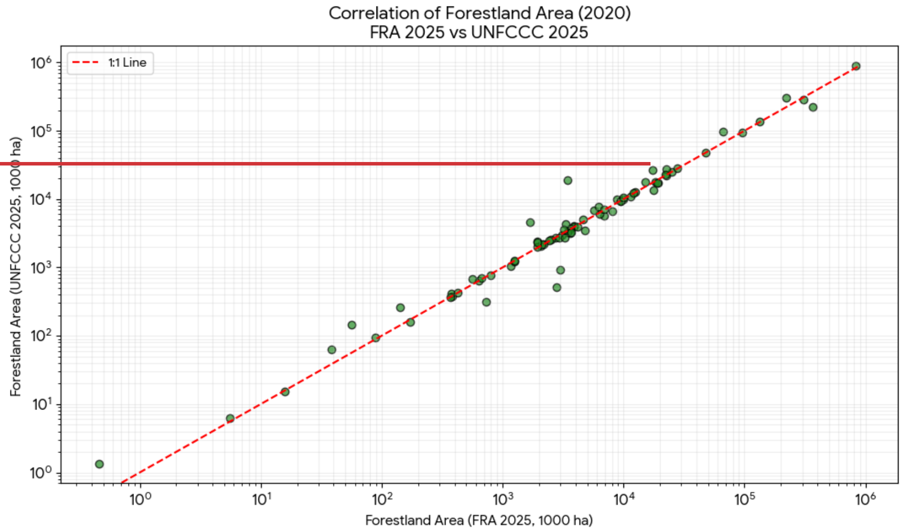
	~~**n**~~	~~**Min (Year)**~~	~~**Max (Year)**~~
~~Total countries~~	~~136~~	~~61 (1991)~~	~~103 (2015)~~
~~AI countries~~	~~41~~	~~40 (2023)~~	~~41 (2022)~~
~~NAI countries~~	~~95~~	~~20 (1991)~~	~~62 (2015)~~
~~FL area~~	~~94~~	~~55 (1991)~~	~~81 (2020)~~
~~NFC area~~	~~73~~	~~49 (1990)~~	~~66 (2020)~~
~~FL emissions~~	~~133~~	~~55 (1991)~~	~~100 (2015)~~
~~NFC emissions~~	~~80~~	~~47 (1990)~~	~~67 (2020)~~
~~All 4 variables~~	~~68~~	~~42 (1990)~~	~~64 (2021)~~

~~*Note: The USA had not yet reported for 2023, reducing the AI count to 40 for that year. Monaco reports only null values hence the effective number of countries is 41 instead of 42.*~~

~~2.1.2 Forest land area~~

~~The FAO world total forest land area (FAO, 2025c) corresponding to the 236 countries and territories covered in this work was 4.2 Gha for the year 2025, with a net forest area loss of nearly 200 Mha over the period 1990-2025 (FAO, 2025d). This net loss was the result of opposite trends, with the area of naturally regenerating forest decreasing by around 300 Mha (-5%) and the area of planted forest increasing by about 100 Mha (over +60%) over the same period.~~

~~Country data were highly correlated between FRA 2025 and FRA 2020 (FAO, 2020) (R^2 > 0.9 across the timeseries) and in close numerical agreement with each other. In particular, major updates in reported forest land area in FRA 2025, compared to FRA 2020, resulted in better alignment of FAO and UNFCCC country data (R^2 = 0.9473, Fig. 1). The most important of these improvements was Argentina, updated to 47 Mha in FRA 2025 from 29 Mha in FRA 2020 and very close to the 48 Mha reported by the country to UNFCCC. Similar improvements were found for South Africa (revised upwards in FRA 2025, from 17 to 22 Mha; 26 Mha reported to UNFCCC); and Nigeria (revised downwards in FRA 2025, from 22 to 18 Mha; 14 Mha reported to UNFCCC).~~



~~**Figure 1**. Correlation of the log-transformed forest land area (year 2020) reported by countries to both FAO via the FRA 2025 and the UNFCCC.~~

~~In line with Grassi et al. (2022) and Melo et al. (2025), we interpreted the UNFCCC area data to refer to managed forest in the following comparisons, unless specified otherwise in the relevant reports. Limited to the 81 countries reporting forest area to UNFCCC for the year 2020, the FAO total forest land area was 3.2 Gha, virtually the same as the corresponding UNFCCC total managed forest area. This global agreement masked an important regional feature in the data, showing the Americas to be the only world region where UNFCCC total managed forest area was smaller than FAO total forest area. Conversely, for all other regions the UNFCCC total managed forest areas were larger than FAO (Tab. 2).~~

~~**Table 2**. Global and regional aggregates of forest area reported to FAO and UNFCCC for the year 2020.~~

	~~**Global**~~		~~**Reporting to both FAO and UNFCCC**~~			
~~**Region**~~	~~FAO~~		~~FAO~~	~~UNFCCC~~	~~Difference~~	
	~~*Gha*~~	~~*n countries*~~	~~*Mha*~~			~~*n countries*~~
~~Africa~~	~~0.7~~	~~54~~	~~0.2~~	~~0.3~~	~~30%~~	~~11~~

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Northern America	0.7	2	0.7	0.5	-25%	2
Latin America and the Caribbeans	1.0	33	0.7	0.6	-18%	9
Asia	0.6	47	0.4	0.5	24%	20
Europe	1.0	43	1.0	1.1	7%	36
Oceania	0.2	15	0.1	0.2	3%	3
World	**4.2**	**194**	**3.2**	**3.1**	**-1%**	**81**

~~At country level, the FRA 2025 and UNFCCC forest area data were strongly correlated (R^2 = 0.9827, log-normalized) (Fig. 1), with six countries largely driving the observed regional differences (Tab. 3). Specifically, Brazil (-150 Mha), Canada (-140 Mha) and the USA (-25 Mha) alone explained the UNFCCC world total managed forest area being smaller than FAO, in agreement with previous findings (Grassi et al. 2022; Melo et al., 2025). Conversely, China (+85 Mha), Russian Federation (+70 Mha) and Namibia (+60 Mha) were responsible for UNFCCC world total managed forest area being larger than the corresponding FAO forest land area. The latter finding suggested inclusion in NGHGIs of tree covered areas, such as wooded savannah or tundra, that are typically not considered part of forest under FAO definitions (and rather classified as 'other wooded land.'), but that can be reported as such under UNFCCC definitions. Indeed, the relevant FRA country profiles for the top three countries mentioned above fully confirmed this dynamic. In particular, adding other wooded land to the total FAO forest land area increased Namibia's (managed) forest area by roughly 9 times (Tab. 3). These findings showed that, based on the actual data reported by countries, boundary issues related to smaller reported managed forest area compared total forest land area were limited to a few countries, rather than representing a global feature of UNFCCC vs. FAO statistics.~~

~~**Table 3**. Largest absolute differences between FRA and UNFCCC forest area data for the year 2020 (Gha)~~

Country	FAO	UNFCCC	Difference
Brazil	0.5	0.3	-0.2
Canada	0.4	0.2	-0.1
United States of America	0.3	0.3	-0.0
China	0.2	0.3	+0.1
Russian Federation	0.8	0.9	+0.1
Namibia	0.0	0.1	+0.1

~~*Note*: Brazil's UNFCCC managed forest area was estimated based on the FRA country profile. Results were in line with Melo et al. (2025).~~

~~2.1.3 Forest biomass and carbon stock change~~

~~The FRA 2025 carbon stock data showed overall increases in world total above and below-ground living biomass from 2000 to 2025, on average by 260 Mt C yr^{-1}, whereas the FRA 2020 data for the same period had shown decreases of -50 Mt C yr^{-1}. For the other pools considered in this work, carbon in litter and dead wood increased by 130 Mt C yr^{-1} on average over the same 2000-2025 period, while the soil pool decreased by -76 Mt C yr^{-1} (all changes included losses from net forest conversion to other land use classes).~~

~~Of specific interest to this update, the changes in biomass dynamics between the FRA 2025 and FRA 2020 were driven by substantial updates of country biomass stock density values – driven by Russia, USA and China – which substantially improved the alignment of the corresponding FAO net removals with UNFCCC data (see results section), resulting in a stronger forest sink compared to earlier estimates, by about 1 Gt~~ ~~CO_2 yr^{-1}~~. ~~At the same time, the number of countries reporting constant carbon density values over the entire dataset timeseries, a data quality issue highlighted previously in relation to the FRA 2020 (Grassi et al., 2021), did not decrease in the FRA 2025, applying to nearly 90 countries and territories for a total forest land area of about 900 Mha (although driven by 20 countries covering nearly 90% of that area). As discussed in more detail in the next sections, most countries having constant biomass density values in FRA reported significant carbon sinks in forest land under UNFCCC, implying growing carbon stocks and creating a gap between FAO and UNFCCC estimates of removals on forest land of up to 1.3 Gt~~ ~~CO_2 yr^{-1}~~.

2.2 Computing carbon stock change and n~~N~~et forest emissions/removals ~~estimation~~

The FAO n~~As discussed, n~~et forest emission~~s~~/removal fluxes~~s~~ were estimated~~-~~ using carbon stock data from the FRA 2025. Whereas previous FAO estimates were limited to carbon stock change in the above- and below-ground living biomass pool~~s~~, this update also included ~~-stock~~ change~~s~~ in ~~the~~ the litter, dead wood and soil ~~carbon~~ pools. This important extension allowed for a better alignment in scope with ~~country inventories~~NGHGI submissions by countries, which~~-~~ are expected to include ~~include additional~~ as many carbon pools as possible, depending on their national capacity, in an effort~~pools~~ to increase ~~accuracy~~completeness of their emission inventories. Importantly, the application herein of concepts, methods and, where relevant, coefficients from IPCC (2006; 2019b) contributed to ~~increase~~increasing consistency between FAO estimates and NGHGI data. ~~, depending on national capacity.~~

In terms of FRA inputs, let A, A^{nr}, A^{pl} be the total area of *forest land* and of its two strata, i.e., *naturally regenerating forest* and *planted forest*; B_{p} and $b_p = B_p/A$ be the total carbon stock and carbon density of reservoir p, i.e., ~~=~~ *above and below-ground living biomass*, *litter* and~~, and~~ *dead woo*~~d~~*d, soil*. Let furthermore Δt be the time interval between two subsequent FRA periods, equal to 5 or 10 years depending on the FRA time-series. Let then ΔA^{nr}, ΔA^{pl} ~~and CSC_p~~ be the net area change of each forest strata occurred during Δt. L~~and~~et CSC_p be the ~~net~~ overall forest carbon stock change in~~of carbon~~ pool p~~,~~, ~~computed over the~~ occurred during the time interval Δt~~Δt between two successive FRA data points~~. ~~With reference to previous work (Tubiello et al., 2021), t~~For each pool, ~~he total~~ CSC ~~of each pool~~ was split into ~~can be split into~~ two distinct components, following Tubiello et al., (2021). Specifically, let NFC, ~~, specifically carbon stock change~~or carbon stock change net forest conversion, be the negative portion of CSC associated to ~~-due to~~ net forest area loss in either of the two forest strata.~~net forest conversion (to other land uses)~~ Additionally, let FL, or carbon stock change on forest land, ~~, NFC – used herein as a proxy for deforestation losses; and carbon stock changes within the r~~be the portion of CSC on the forest area present at the end of ~~emaining forest land~~the time interval Δt~~, FL~~. ~~(Fig. 2).~~ With the above definitions, t~~T~~he equations to compute ~~the FAO net forest emission/removal estimates~~carbon stock change ~~(E/R)~~ and its two components for each carbon pool p, country c, ~~and time~~ FRA year t and time interval~~,~~ Δt, were as follows:

$$CSC_{p,c,t} = \cancel{\Delta} B_{p,c,t} - B_{p,c,t-\Delta t}; \qquad (1)$$

~~with p = living biomass, litter, dead wood, soil (1)~~

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$$NFC_{p,c,t} = b_{p,c,t} * \cancel{\Delta} A_{NFC\,c,t}\ ; \quad \text{with } \cancel{\Delta} A_{NFC\,c,t} = \cancel{\Sigma_A [}\min(\Delta A^{nr}_{c,t}, 0) + \min(\Delta A^{pl}_{c,t}, 0)\cancel{]} \qquad (2)$$

$$FL_{p,c,t} = CSC_{p,c,t} - NFC_{p,c,t} \qquad (3)$$

~~$E/R^{NFC}_{c,t} = - \Sigma_p ((1-\alpha_p) * NFC_{p,c,t} * 1000 * 44/12) / \Delta t$ (4)~~

~~$E/R^{FL}_{c,t} = - \Sigma_p (FL_{p,c,t} * 1000 * 44/12) / \Delta t$ (5)~~

~~$E/R^{CSC}_{c,t} = E/R^{NFC}_{c,t} + E/R^{FL}_{c,t}$ (6)~~

Where~~:~~ A, A^{nr}, A^{pl} were expressed in hectares (ha); *CSC*, *NFC* and *FL* ~~were expressed~~ in kilotonne of carbon (kt C)~~ and E/R were in units of Mt CO_2 yr^{-1}. Annualized emissions were expressed as 10 year (or 5 year) means between FRA periods.~~

Equation (1) computes the overall forest carbon stock change occurred during the time interval Δt. Of this total, equation (2) represents the portion of carbon losses associated with net forest area decreases. Equation (3) captures the remainder carbon stock change on forest land, ~~due~~due to all relevant processes such as afforestation/reforestation, natural and managed forest growth, forest disturbances and harvest losses. ~~(2) was used to compute net area conversion of forest land to non-forest classes~~ E~~using national statistics~~quation (2) follows~~, a simple proxy for deforestation in line with~~ approach 1 of the IPCC (2006; 2019b) guidelines for estimating net deforestation fluxes.~~. Our equations, however, track change~~Unlike simpler equations based only on total net forest area change, however, by tracking two separate strata~~ for two separate strata, *naturally regenerating forest* and *planted forest* area, thus accounting for more nuanced dynamics in the overall carbon fluxes.~~ *NFC* captures emissions even when the overall net forest area may be increasing—for instance, ~~For instance,~~ losses in naturally regenerating forest area masked by larger area increases in plantation forests during the same time interval.~~the FAO equations could track area decreases and associated carbon losses in natural regenerating forest regardless of overall increases in total forest land area. Conversely, equation (3) could account for increased area of forest plantation and associated carbon sequestration even in presence of overall losses of total forest area.~~

~~Equations (4)-(6) were needed to transform~~Net forest carbon stock change~~s over given FRA periods~~ computed via equations (1)-(3) were the basis for estimating~~into~~ net forest CO_2 emissions and removals, occurred during the same interval Δt, expressed here conventionally as~~mean annual CO_2 emissions/removals, with the sign used conventionally to~~ positive for CO_2 ~~consider~~ fluxes from the forest~~land~~ to the atmosphere~~ as positive~~ (net emissions) ~~(corresponding to negative stock change)~~ and vice-versa (net removals) for fluxes from the atmosphere into the forest.

~~Equation (2) was used to compute net area conversion of forest land to non-forest classes using national statistics, a simple proxy for deforestation in line with approach 1 of the IPCC (2019) guidelines. Our equations, however,~~

~~track change for two separate strata, *naturally regenerating forest* and *planted forest* area, thus accounting for more nuanced dynamics in the overall carbon fluxes. For instance, the FAO equations could track area decreases and associated carbon losses in natural regenerating forest regardless of overall increases in total forest land area. Conversely, equation (3) could account for increased area of forest plantation and associated carbon sequestration even in presence of overall losses of total forest area.~~ ~~Equation (4)~~Specifically, let E/R^{CSC} be the net overall forest emissions/removals associated with *CSC* in equation (1); ~~*was written to compute*~~ E/R^{NFC} the emissions ~~to the atmosphere following *NFC* carbon losses~~from net area losses, associated with *NFC* in equation (2)~~,~~; and E/R^{FL} the emissions/removals on forest land associated to *FL* in equation (3). E/R^{CSC} fluxes will also be referred to, in the results section, as the overall net forest carbon sources and sinks. For E/R^{NFC}, in line with the IPCC (2006; 2019b) guidelines, we assumed~~ing~~ 'complete~~instant~~ oxidation' ~~to the atmosphere of~~ of carbon in~~carbon~~ the~~in~~ forest biomass, litter and dead wood pools in the transition to non-forest land classes. Conversely, ~~while retaining a portion~~ a portion of the forest soil carbon was assumed to be retained in the transition to non-forest classes~~after transition to the new land use~~. To this end, let ~~the coefficient~~ α_p be the coefficient ~~in equation (4) represented retention in the destination pool between FRA periods~~describing the portion of forest carbon in pool *p* remaining in the new non-forest class ~~class~~ after a land use change.~~consistently with the relevant F_{LU} and F_{MG}~~ W~~default coefficients~~e assigned α_p =0 for *p* = above- and below-ground living biomass, litter, dead wood, representing complete carbon oxidation, whereas we set α_{soil} =2/3 for *p* = soil, to describe soil carbon retention in the new non-forest classes, with reference to default IPCC coefficients provided in ~~specified in~~ Tab. 5.5 and Tab. 6.2 of the IPCC (2006) guidelines. Note that the forest to non-forest transitions considered herein occur over a time interval *Δt* of 5 to 10 years, i.e., intermediate between instant oxidation and the 20-year period recommended by IPCC for soil carbon stock change calculations.

With the above definitions, the FAO net annual forest emission/removal fluxes (*E/R*) for country *c*, FRA period *t* and time interval *Δt*, were computed as follows:~~, specifically: α_p =0 for *p* = above and below carbon, litter, dead wood; and α_{soil} =2/3; consistently with the relevant F_{LU} and F_{MG} default coefficients specified in Tab. 5.5 and Tab. 6.2 of the IPCC (2006) guidelines The fluxes estimated between FRA years represented in practice 10-year transitions (5 years for 2020-2025), mid-way between instant oxidation and the 20 years IPCC default transition recommended for computing soil losses.~~

$$E^{NFC}_{c,t} = -\Sigma_p\,((1-\alpha_p) * NFC_{p,c,t} * 1000 * 44/12)/\Delta t \qquad (4)$$

$$E/R^{FL}_{c,t} = -\Sigma_p\,(FL_{p,c,t} * 1000 * 44/12)/\Delta t \qquad (5)$$

$$E/R^{CSC}_{c,t} = E^{NFC}_{c,t} + E/R^{FL}_{c,t} \qquad (6)$$

where: E/R^{CSC}, E/R^{NFC} and E/R^{FL} were expressed in million tonnes of CO_2 (Mt CO_2 yr^{-1}). A factor of 1000*44/12 was used to convert from kt C in (1)-(3) to Mt CO_2. Quantities in (4)-(6) represented mean annual fluxes over the time interval *Δt* occurring between two successive FRA periods (5 or 10 years).

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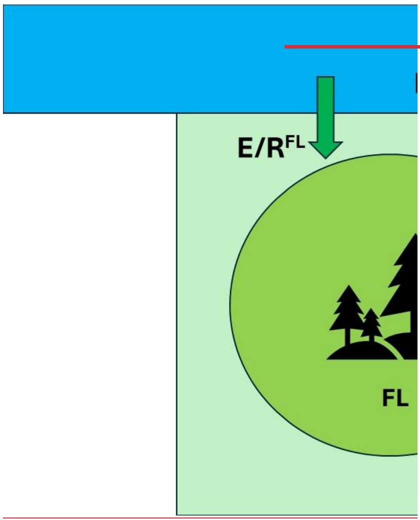
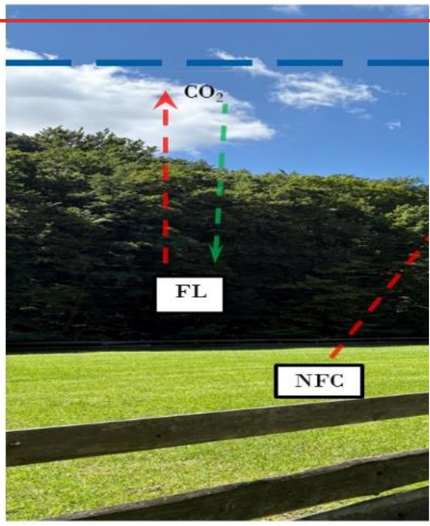
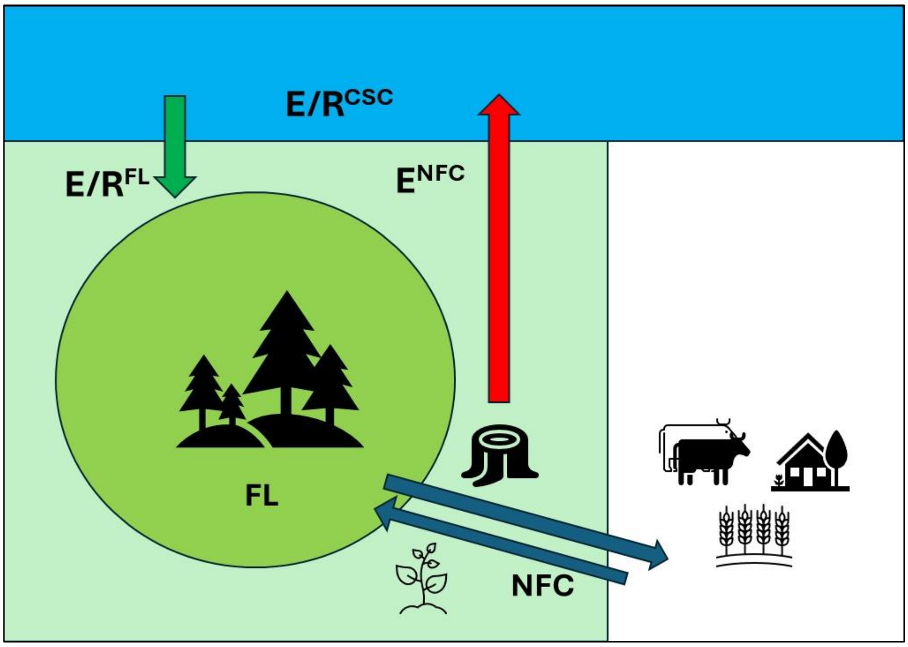
~~The fluxes estimated between FRA years represented in practice 10-year transitions (5 years for 2020-2025), mid-way between instant oxidation and the 20 years IPCC default transition recommended for computing soil losses. The sums over carbon pools in equations (1)-(6) were used to distinguish among three increasingly complete FAO carbon stock change models: *FAO 1*, for which carbon stock changes were limited to above and below-ground living biomass; *FAO 2*, which included in addition carbon stock change for litter and dead wood; and *FAO 3*, which also included soil carbon stock change, thus taking full advantage of the input FRA data. When presenting results, the corresponding FAO model range was considered appropriate for comparisons to UNFCCC data, Conversely FAO 3 was considered biophysically more complete and conceptually better aligned with more complex carbon cycle models, which tended to include all pools. given that the underlying NGHGIs were typically compiled by countries using a variety of approaches, dependent on many factors including carbon stock data availability and national capacity (Melo et al., 2025). Conversely FAO 3 was considered biophysically more complete and conceptually better aligned with more complex carbon cycle models, which tended to include all pools. Data for all the three FAO models, as well as relevant UNFCCC country data, were provided as open source at 10.5281/zenodo.20085666.~~

Figure 1. Forest carbon fluxes included in the FAO approach and relevant components.





~~**Figure 2.** Forest fluxes included in the FAO dataset, including carbon stock change (CSC) and its component fluxes, net forest conversion (NFC) and forest land (FL).~~



Based on the above equations, three FAO estimation models were defined based on the number of carbon pools used for the carbon stock change calculations: *FAO 1*, limited to above and below-ground living biomass; *FAO 2*, including in addition litter and dead wood; and *FAO 3*, including all carbon pools, i.e., above- and below-ground living biomass, litter and dead wood, and soil carbon. Data for all the three FAO models, as well as relevant UNFCCC country data, were provided as open source at 10.5281/zenodo.20085666.

2.3 Comparisons with UNFCCC and Global Carbon Budget

As discussed in the results section below, we used the range of estimates from the three FAO models for comparisons to UNFCCC data, considering that countries may include one or more carbon pool in NGHGI, depending on their national capacity and methodological choices for reporting (Melo et al., 2026). Conversely, FAO 3 output was used for comparisons to the Global Carbon Budget models, which tend to include all carbon pools. A subset of the most recent Global Carbon Budget (GCB2025; Friedlingstein et al., 2026) data was selected for comparison to the FAO estimates. Specifically, FAO NFC estimates were compared to GCB2025 deforestation data, which, based on bookkeeping models, quantify the contribution of deforestation emissions to the net GCB emissions from land use change (ELUC). Further, FAO FL emissions/removals were compared to the sum of all GCB net forest fluxes, also based on bookkeeping models, due to afforestation/reforestation, shifting cultivation and wood harvest, complemented by the anthropogenic portion of the GCB2025 natural land sink (SLAND), computed with Dynamic Global Vegetation Models (DGVMs), but adjusted to the boundaries of managed forest land to ensure alignment with NGHGI data (Grassi et al., 2023). The components of the GCB2025 fluxes used herein were kindly provided by the GCB land use change subgroup (C. Schwingshackl, personal communications).

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2.3 Limitations and uncertainty

Several limitations to the FAO methodology ~~were~~ exist and were in part highlighted in previous work (Tubiello et al., 2021; Grassi et al., 2022). A first set refers~~red~~ to forest area boundaries, which determine whether the estimated net forest emission~~s~~/removal fluxes~~s~~ can be considered anthropogenic or not, in the sense of the IPCC (2006; 2019b) managed land proxy. ~~Following the IPCC land use proxy approach, w~~Accordingly, we considered all emission~~s~~/removal fluxes~~s~~ estimated on managed land as anthropogenic, irrespective of direct and indirect climatic and CO_2 effects ~~(IPCC, 2019)~~. The critical issue was that the FRA area statistics employed in this work referred to total ~~total~~ forest ~~land~~ area, of which managed forest area is generally understood as a subset, leading to the criticism that~~implying that some of~~ the FAO estimate~~d fluxe~~s may contain natural components, i.e., beyond those occurring on managed forest area (Grassi et al., 2022). ~~At the same time however, as discussed previously in methods, we found that~~ We show in the results section below, however, that for m~~m~~ost countries analyzed in this work, the opposite in fact held, i.e., the ~~reported managed forest area to~~ UNFCCC reported managed area ~~that~~ was equal to or even greater than ~~the~~ the FAO ~~total~~ forest ~~land~~ area~~, thereby annulling in most cases or substantially reducing the perceived mismatch between FAO and UNFCCC area boundaries~~. In all such cases therefore, the FAO estimates were considered anthropogenic.~~.~~

~~Furthermore,~~ More generally, we had previously noted that ~~we had argued (Federici et al., 2015; Tubiello et al., 2021) that~~ only a subset of estimated forest fluxes will depend~~ed~~ on the managed land use proxy for attribution as anthropogenic (Federici et al., 2015; Tubiello et al., 2021)~~ managed vs. total forest area boundaries~~. ~~Specifically, e~~For example, FAO *NFC* estimates of emissions from net forest ~~conversion~~area losses ~~, including their indirect climate and CO_2 components, could be considered~~can be considered anthropogenic regardless of their occurring on managed or ~~unmanged~~unmanaged forest land, including their indirect climate and CO_2 components, whenever the corresponding land use change was caused by human action—which is very often the case~~as long as human agency determined the underlying land use change~~. ~~The same~~A similar consideration ~~would~~ applies~~y~~ to forest land removals ~~on forest land due to~~from the establishment of plantations—which are, by definition, anthropogenic. ~~-~~It follows that, limited to those countries reporting managed forest areas smaller than the total forest area, only a portion of the~~Of the~~ FAO emission~~s~~/removal estimates on forest land~~s estimated in this work~~, *FL*, will ~~only a portion on remaining forest land may~~ have ~~a~~ non-anthropogenic components, directly linked to natural forest processes occurring on non-managed land.

~~We suggest that, based on actual country data comparisons, that the boundaries of FAO estimates and UNFCCC data were in fact greatly aligned~~Even when the underlying forest area boundaries may coincide between FAO and UNFCCC, the coverage of forest fluxes included in the NGHGI may nonetheless complicate comparisons of FAO and UNFCCC data. An important example is represented by carbon fluxes from peatlands drainage and peat fires, which are included in our estimates but reported separately in FAOSTAT (Conchedda and Tubiello, 2020; Prosperi et al., 2020), may conversely be reported by some countries within their forest emissions, without distinction. ~~.~~In conclusion, although differences in forest area boundaries remain important drivers of possible misalignment between FAO and UNFCCC data, we suggest that this was a much smaller concern than previously suggested in the literature, and as we show in the next result section, limited in practice to a small number of countries.

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A second set of limitations in the FAO estimates presented here is their ‘Tier 1’ national -level approach~~ with which they were computed, as opposed to higher Tiers methods~~. We recognize that higher tiers approaches, driven by the recent tremendous progress in remote sensing and machine learning, make already possible today the production of increasingly accurate forest estimates at increasingly fine scales, including recent efforts by FAO (e.g., Mozafari et al., 2023; Araza et al., 2023; FAO, 2024). At the same time, we emphasize that the value of the FAO net forest/emissions dataset precisely lies in providing a robust and transparent Tier 1 reference for assessing higher-Tier estimates. Its straightforward, reproducible equations, grounded in official national statistics, make it a practical tool for both national compilers, expert reviewers of NGHGIs and modelers (FAO, IFAD, IPCC, 2015). ~~Nonetheless~~At the same ~~time~~time, we recognize that~~,~~ using national statistics as input and constant national coefficients has ~~recognized~~ limitations and carries uncertainty. *First*, estimates of net forest~~ land~~ area change may systematically underestimate gross forest area changes and associated emissions or ~~/~~removals. We have noted however ~~(see methods)~~in the previous section that the FAO equations ~~may~~ limit such bias, by ~~considering approximating~~the important ~~independent~~ gross ~~loss~~components, i.e., by tracking independently area changes in ~~es of~~ naturally regenerating forest and planted forest area~~s as approximations for national-level gross forest area loss~~. *Second*, the use of national-level biomass stock density data may~~would~~ lead~~tend~~ to underestimate~~s~~ of net forest conversion emissions, for example in cases when the forest being lost is primary or old-growth ~~forest, or~~forest or anyway characterized by biomass densities higher than the national average. *Third*, net emission/removal estimates on~~ remaining~~ forest land depend strongly on the quality of the underlying ~~biomass~~ carbon density data. As noted by Grassi et al. (2022), missing information on changes over time may generate underestimates of removals in countries with increasing carbon stock densities, while leading to overestimat~~eing emission~~s in countries with decreasing forest biomass densities. Furthermore, in relation to newly established forest areas, the use of national biomass stock density values may overestimate removals in countries with new forests of lower carbon density than the national average, and vice -versa. A final limitation of the FAO estimates was related to the inclusion of additional carbon pools~~, because~~; while ~~while adding~~adding– biophysical detail improves ~~biophysical~~ completeness, the dependence on more input data tends to ~~to the underlying FAO carbon stock change model, they would tend to~~ increase uncertainty. In particular, the FRA 2025 soil carbon data submitted by countries had limited coverage and consistency compared to the other pools and were gap-filled with published soil organic carbon maps (FAO, 2025a). In relation to the soil carbon pool, we furthermore note, as discussed in the previous section, that the FAO equations for *NFC* used a constant coefficient α_{soil} = 2/3 ~~for retention of~~to approximate soil carbon retention for non-forest transitions~~across all possible net forest conversions (see methods)~~. This value was considered a good balance with respect to the available ~~The value chosen was the recommended~~ IPCC default coefficients, including ~~for transitions~~ forest conversion to annual cropland in temperate zones~~ure~~ ~~zones~~(α_{soil} = 2/3; 20% uncertainty); forest conversion to annual cropland in tropical zones ~~, while lower default coefficients~~ (α_{soil} = 0.5–0.6; 60% ~~but with~~ uncertaint~~yies of 60%~~); and forest conversion to either grassland (α_{soil} = 1; 15% uncertainty) or permanent crops (α_{soil} = 1; 50% uncertainty). If anything, we suggest that our coefficient may lead to overestimates of related emissions, considering that the ~~were recommended for tropical countries. This implied in principle that the FAO *NFC* emissions estimates may be underestimated in tropical countries. However,~~ FAO land use change data available in FAOSTAT (FAO, 2025c) show ~~uggests that~~ a substantial portion of ~~net~~ forest conversion in the tropics going ~~occurs through~~ to either grassland (Latin America) or permanent crops (West Africa and Southeast Asia), for which the IPCC defaults generally imply no soil carbon loss. ~~conversion to either grassland (Latin America) or permanent crops (West Africa and Southeast Asia), for which the default IPCC coefficients are $\alpha_{soil} = 1$, hence reducing the possible overestimation.~~

Finally, we note that the use of the FRA dataset as direct input into the FAO emission/removal estimates may affect the timeliness of the resulting FAO data, specifically because new information depends on the FRA update cycle, performed only every 5 years currently—while also recognizing that in some countries forest data collection cycles may still be in the order of a decade. Recent provisions implemented by FAO will nonetheless increasingly allow countries to perform FRA updates annually, in fact as often as new national data became available, thus greatly improving the timeliness of future FAO emission/removal estimates. For this version depending on the FRA 2025 data, the most important issue related to the above was that the FRA carbon stocks submitted for the year 2025 were estimated by countries, rather than based on direct measurements—due to the temporal mismatch between national data production and the FAO data collection cycle. This introduced additional uncertainty specific to the FAO emission/removal estimates for 2020-2025. For instance, the USA carbon stock data submitted to FRA for the year 2025 were produced by the country via carry forward of the 2022 value. This implies for specific countries a FAO underestimate of 2020-2025 mean removals, had national carbon stock kept increasing past 2022—and an overestimate in the opposite case. A second, more obvious issue may arise from potential errors in the FRA input data. We found only one country for which corrections were necessary, and these were documented in the relevant FAOSTAT country notes. ~~Finally, we note that FRA data corresponding to the year 2025 were country projections, typically performed via linear trend extrapolation or carry forwards of the last available observation. Therefore, our estimates of emissions/removals over the period 2020-2025, which we report nonetheless below when discussing the most recent global and regional results, should be considered provisional, until the next FRA update.~~ The 2025~~se~~ reporting issues were minimized by~~less important when~~ reporting trends ~~over the last decade 2015-2025 or when averaging~~ over the longer period 2001-2023, the standard used in this work for comparisons of FAO/UNFCCC data~~comparisons~~.

The long list of limitations discussed above implied that the FAO estimates were characterized by substantial uncertainty. ~~We followed~~ Tubiello et al. (2021) ~~in assigning~~ indicated a generic uncertainty of 50% (95% CI) ~~uncertainty~~ for~~to~~ all FAO emission~~s~~/removal~~s~~ components~~ derived in this work~~, consistently with established literature on LULUCF (e.g., IPCC, 2022; Friedlingstein et al., 2026~~5~~). In this work, we used instead the output of the three FAO models as a practical and heuristic, if imperfect approach to quantify uncertainty, indicating a range of about ±30% around FAO 2 values.

To this end, we made an effort in this paper to follow recommendations of ~~We conclude by noting that according to~~ the relevant guidelines ~~on communicating uncertainty published by~~of the International Bureau of Weights and Measures (BIPM et al., 2008), with respect to the need to align ~~, the level of uncertainty underlying measured or estimated quantities determines the precision – i.e., the number of significant figures – with which results should be communicated~~the number of significant figures (or digits) of results to their underlying uncertainty. ~~Generally, uncertainties~~In particular, in concomitance with high uncertainty, such as the case for ~~of 50%~~LULUCF fluxes, the BIPM guidelines suggest that results be communicated with ~~imply use~~ one, ~~of~~ at most two significant figures ~~in. reporting estimated means and their confidence intervals. We applied this guidance through this paper.~~ We have applied this rule in presenting results throughout this manuscript.~~Finally, we used the upper and lower FAO~~

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~~stock change models estimates to qualitatively provide uncertainty ranges for comparing FAO to UNFCCC data. This range roughly coincided with roughly 30% uncertainty bounds around FAO 2 estimates.~~

2.4 Data Availability: Structure of FAOSTAT dataset

The FAOSTAT dataset covers the period 1990~~-~~-2025 for 194 countries and 42 territories. Aggregates were computed for ~~22 sub-regions,~~ 5 region ~~continent~~s, 22 sub-regions and 8 special aggregates, including UNFCCC Annex and non-Annex I, OECD, least-developed countries, small island developing states. The FAO dataset further included available ~~country data submitted to the~~ UNFCCC data, ~~. They were~~ disseminated without interpolation of missing values, resulting in nearly 9000 data points for a combined total of 137 countries over the period 1990-2023. The FAO 2025 net forest emission~~s~~/removal estimates~~s~~ and corresponding UNFCCC data are available as open data via Zenodo (Tubiello and Obli-Laryea, 2026), ~~with DOI~~at 10.5281/zenodo.2008566~~10.5281/zenodo.20085666~~. ~~Limited to results for living biomass, t~~They a~~we~~re also available via FAOSTAT (FAO, 2025b~~6~~).

3. Results

We provide~~d~~ below a wide synthesis of results from the new FAO ~~dataset~~net forest emission/removal estimates dataset, comprised of FAO estimates and relevant UNFCCC country data. Results were organized in three main sections. In section 3.1, we analyze differences in input forest data statistics, by comparing country data independently submitted to FAO via the FRA and to UNFCCC. In this section we also highlight data quality improvements arising from the use of the most recent FRA data compared to the previous data cycle. In section 3.2, we focus on presenting global, regional and country trends of the new FAO estimates, with comparisons to UNFCCC country-reported emissions and removals data. ~~by presenting results~~Global and regional trends were discussed in terms of~~aggregated a t~~ World, ~~Annex I (~~AI~~)~~ and ~~non-Annex I (~~NAI~~) levels~~ aggregates, as well as by main FAO~~STAT~~ region. ~~and by major contributing countries. In doing so, we first presented an overview of net forest emissions/removals for the full geographical country coverage characterizing the FAO estimates, followed by comparisons to UNFCCC over the more limited geographical scope noted earlier. For World, AI, NAI and country data we discussed the full range of results across the FAO carbon stock change models *FAO 1*, *FAO 2* and *FAO 3* presented in the previous section, while for simplicity we only reported FAO 3 results for regional storylines.~~ We used the range of estimates from three FAO models for comparisons to UNFCCC data, and from FAO 3 for comparisons to Global Carbon Budget data. ~~We did not report estimates together with their uncertainty values. While each estimate carried in principle 50% uncertainty, we used the range of the three FAO models to provide a heuristic, practical if imperfect way to communicate uncertainty.~~

3.1 Comparison of FAO and UNFCCC input data

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The FRA 2025~~-~~ data (FAO, 2025a) used as input into the emission/removal calculations ~~set provided~~ had complete coverage of forest area and carbon stock variables for 194 countries and 42 territories, for the 1990~~-~~-2025 period considered herein. Conversely, the UNFCCC data~~-~~ collected for this work and re-disseminated alongside the FAO estimates in FAOSTAT (FAO, 2025b), were characterized by ~~covered a similar period (1990-2023) but with much~~ sparser country and thematic coverage, albeit over a similarly long timeseries, i.e., 1990-2023 (Tab. 1). ~~(Tab. 1).~~

~~Note that compared to a total of 42 Annex I (AI) parties regularly reporting to UNFCCC each year, the FAOSTAT dataset covered 41 countries for the period 1990-2022, and 40 for 2023. Monaco reports null values to UNFCCC throughout the timeseries and was thus excluded. The USA has not yet reported data for 2023.~~

Table 1. Country coverage of collected UNFCCC data ~~disseminated in FAOSTAT,(~~ 1990-2023), with a cut-off date of Mar 2026.~~.~~

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	n	Min (Year)	Max (Year)
Total countries	136	61 (1991)	103 (2015)
AI countries	41	40 (2023)	41 (2022)
NAI countries	95	20 (1991)	62 (2015)
FL area	94	55 (1991)	81 (2020)
NFC area	73	49 (1990)	66 (2020)
FL emissions	133	55 (1991)	100 (2015)
NFC emissions	80	47 (1990)	67 (2020)
All 4 variables	68	42 (1990)	64 (2021)

3~~2~~.1.1~~2~~ Forest ~~land~~ area

Trends in w~~The FAO w~~orld total~~tal~~ forest ~~land~~ area of the 194 countries and 42 territories covered by the FRA (2025a) and disseminated in FAOSTAT (FAO, 2025b~~e~~) ~~corresponding to the 236 countries and territories covered in this work~~ was 4.2 Gha ~~for the year~~in 2025~~, with a net~~. The same data showed net world forest area loss of nearly 200 Mha over the period 1990-2025 (FAO, 2025c~~d~~), due to~~. This net loss was the result of opposite trends~~predominance of forest area loss over forest area increase. Specifically, ~~, with~~ the FAO data showed that the area of naturally regenerating forest decreased~~ing~~ by ~~around~~ 300 Mha (-5%) from 1990 to 2025, while ~~and the area of~~ planted forest area increased ~~ing~~ by about 100 Mha (~~over~~ +60%) ~~over the same period~~. In terms of FRA data cycles, we found that ~~Country data were highly correlated between~~ FRA 2025 and FRA 2020 ~~(FAO, 2020) (R^2 > 0.9 across the timeseries) and~~data were in close numerical agreement~~ with each other~~. Limiting the analysis to the subset of countries also reporting forest area data to UNFCCC for the year 2020, we found that the~~In particular, major updates in reported forest land area in~~ FRA 2025~~, compared to~~ data were very well aligned to UNFCCC data (R^2 = 0.9473, Fig. 2), improving from the ~~-~~FRA 2020 data cycle~~, resulted in better alignment of FAO and UNFCCC country data (R^2 = 0.9473, Fig. 1)~~. Note that in line with Grassi et al. (2022) and Melo et al. (2026), we interpreted the UNFCCC forest area data to refer to managed forest area, unless specified otherwise in the relevant country submissions. To this end, the most important of these improvements in forest area data was Argentina, updated to 47 Mha in FRA 2025 from 29 Mha in FRA 2020—and very close to the 48 Mha reported by the country to UNFCCC. Similar improvements were found for South Africa (which revised its forest area upwards in FRA 2025, from 17 to 22 Mha; 26 Mha reported to UNFCCC); and Nigeria (revised downwards in FRA 2025, from 22 to 18 Mha; 14 Mha reported to UNFCCC). Even in cases of convergence of information such as those reported above, residual differences in country values may remain, reflecting reporting to FAO or UNFCCC by different national agencies.

Figure 2. Correlation of log-transformed forest land area reported by countries to FAO and the UNFCCC.

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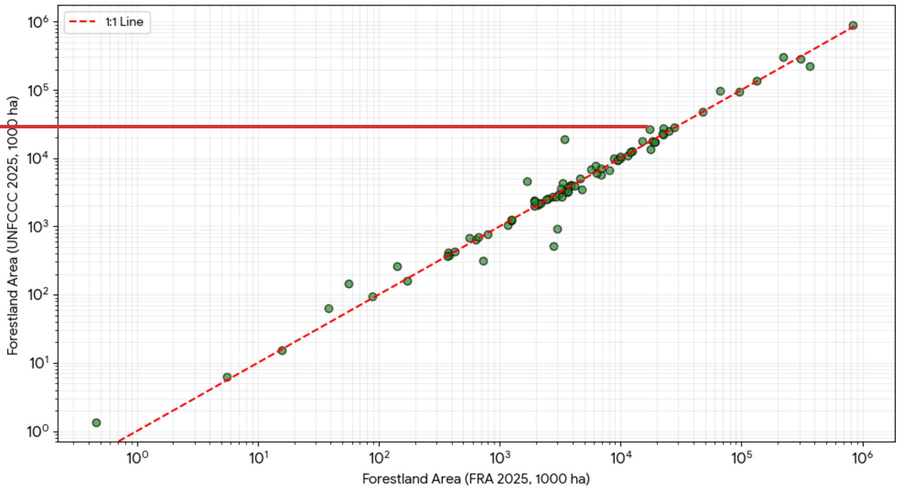

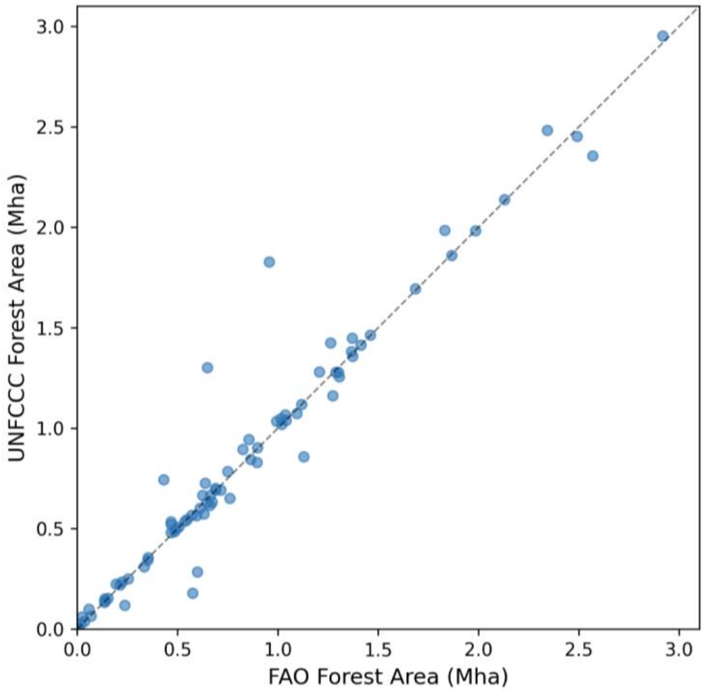

~~**Figure 1**. Correlation of the log-transformed forest land area (year 2020) reported by countries to both FAO via the FRA 2025 and the UNFCCC.~~

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~~In line with Grassi et al. (2022) and Melo et al. (2025), we interpreted the UNFCCC area data to refer to managed forest in the following comparisons, unless specified otherwise in the relevant reports.~~ L~~L~~imited to the 81 countries reporting forest area to UNFCCC for the year 2020, the FAO world total forest ~~land~~ area was 3.2 Gha, virtually the same as the corresponding UNFCCC world total ~~managed forest area (Tab. 2)~~. At the same time, t~~T~~he~~ir~~ agreement at global level between the FAO and UNFCCC data masked important regional ~~features in the data~~trends. For instance, ~~the Americas region was the only world region where~~ UNFCCC ~~total managed~~ forest land area was smaller than the corresponding FAO statistics for the Americas, while ~~total forest area. fConversely, for~~or ~~all~~ the other regions, ~~UNFCCC total managed forest areas~~it w~~ere~~ase larger than the FAO forest area data (Tab. 2).

Table 2. Comparison of forest area statistics based on country data reported to FAO and UNFCCC (year 2020), globally and by world region. '~~All countries~~FAO Reporters' = world and regional aggregates of FAO statistics of forest area corresponding to complete country reporting to FAO (194 countries ~~countries globally~~). 'UNFCCC country reporters' = world and regional aggregates of forest area (FAO) and managed forest area (UNFCCC), limited to the 81 countries reporting to UNFCCC ~~(81 countries globally)~~.

	~~All countries~~FAO Reporters		**UNFCCC ~~country r~~Reporters**			
Region	FAO		FAO	UNFCCC	~~Difference~~UNFCCC-FAO	
	Gha	*n countries*	*Gha*		*%*	*n countries*
Africa	0.7	54	0.2	0.3	30%	11
Northern America	0.7	2	0.7	0.5	-25%	2
Latin America and the Caribbeans	1.0	33	0.7	0.6	-18%	9
Asia	0.6	47	0.4	0.5	24%	20
Europe	1.0	43	1.0	0.9~~1.1~~	7~~7~~%	36
Oceania	0.2	15	0.1	0.2	3%	3
World	**4.2**	**194**	**3.2**	**3.1~~1~~**	**-1~~1~~%**	**81**

At country level, the FRA 2025 and UNFCCC forest area data were strongly correlated (R^2 = 0.9827, log-normalized) (Fig. 1), with six countries largely driving the observed regional differences (Tab. 3). Specifically, Brazil (-150 Mha), Canada (-140 Mha) ~~,~~ and the USA (-25 Mha) alone explained the UNFCCC world total ~~managed~~ forest area being smaller than FAO, in agreement with previous ~~findings~~findings (Grassi et al. 2022; Melo et al., 202~~6~~5). Conversely, China (+85 Mha), Russian Federation (+70 Mha) ~~Russian Federation (+70 Mha)~~ and Namibia (+60 Mha) ~~were responsible~~largely drove ~~for~~ the discussed regional trends, showing UNFCCC-reported world total ~~managed~~ forest areas ~~being~~ larger than the corresponding FAO ~~forest land area~~values. The latter ~~finding~~ suggested inclusion, within the UNFCCC country-reported forest area, ~~in NGHGIs of~~of additional land area, for instance tree covered areas~~,~~ such as wooded savannah or tundra, that under FAO land use

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classification are ~~typically~~ not ~~considered part of~~included in ~~-~~forest land, but rather are~~under FAO definitions (and rather classified as~~ reported under ‘other wooded land~~.~~’~~), but that can be reported as such under UNFCCC definitions~~. Indeed, additional analyses of the relevant FRA country profiles for the top three countries mentioned above~~ fully~~ confirmed this situation~~dynamic~~. In particular~~,~~ adding the FAO-reported area of other wooded land, to the ~~the total~~ FAO forest ~~land~~ area by Namibia, increased ~~Namibia’s~~ this country’s ~~(managed)~~ forest area by roughly 9 times, coinciding with the ‘forest land area’ it reported to UNFCCC (Tab. 3). These findings ~~showed that, based on the actual data reported by countries,~~suggest that forest area boundary ~~issues related to smaller reported managed forest area compared total forest land~~issues ~~area~~, albeit remaining a critical factor when comparing national data, ~~were critical but limited to, a countries, where they nonethelessare generated important differences between FAO and UNFCCC emissions/removals data~~ limited in practice to a small number of countries, rather than representing a structural feature in the differences between FAO and UNFCCC data.

Table 3. Largest absolute differences between FRA and UNFCCC forest area data for the year 2020 ~~(Gha)~~.

Country	**FAO**	**UNFCCC**	**~~Difference~~UNFCCC-FAO**
	Gha	Gha	Gha (%)
Brazil	0.5	0.3	-0.2 (-40%)
Canada	0.4	0.2	-0.1 (-50%)
United States of America	0.3	0.3	-0.0 (-8%)
China	0.2	0.3	+0.1 (+50%)
Russian Federation	0.8	0.9	+0.1 (+13%)
~~**Russian Federation**~~	~~0.8~~	~~0.9~~	~~+0.1~~
Namibia	0.0	0.1	+0.1 (+800%)

Note: Brazil’s UNFCCC managed forest area was estimated based on the FRA country profile. Results were in line with Melo et al. (2026~~5~~).

3~~2~~.1.2~~3~~ Forest biomass and carbon stock change

The FRA 2025 carbon stock data showed overall increases in world total above and below-ground living biomass from 2000 to 2025, on average by 260 Mt C yr^{-1}, whereas the FRA 2020 data ~~for the same period~~ had shown decreases up to 2020 of -50 Mt C yr^{-1}. For the other carbon pools considered in this work, the FRA 2025 data showed that ~~carbon in~~ litter and dead wood increased by 130 Mt C yr^{-1} on average over the same 2000–~~-~~2025 period, while the soil pool decreased by -76 Mt C yr^{-1} ~~(all changes included losses from net forest conversion to~~

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~~other land use classes)~~. We did not evaluate FRA 2020 results for the additional pools, because those data were more uncertain.

Of specific interest to this update, the changes in carbon biomass ~~dynamics~~ between the FRA 2025 and FRA 2020 were driven by substantial updates of country biomass stock density values—driven by Russia, USA and China—which substantially improved the alignment of the corresponding FAO net removals with UNFCCC data ~~(see results section)~~, as detailed in the next section, resulting in a stronger forest sink compared to earlier estimates, by about 2 Gt CO_2 yr^{-1}~~1 Gt CO_2 yr^{-1}~~. At the same time, the number of countries reporting constant carbon density values over the entire dataset timeseries, a data quality issue highlighted previously in relation to the FRA 2020 (Grassi et al., 2022~~1~~), did not decrease in the FRA 2025, applying to nearly 90 countries and territories for a total forest land area of ~~about~~ 900 Mha (although driven by 20 countries covering nearly 90% of that area). As discussed in more detail in the ~~next section~~next sections, most countries ~~having~~ reporting constant biomass density values in~~in~~ FRA also reported significant forest ~~carbon sinks in~~ removals ~~forest land under~~ to UNFCCC, ~~implying growing carbon stocks and creating~~resulting in a ~~gap~~ discrepancy between FAO and UNFCCC estimates ~~of removals on forest land~~ of up to 1.3 Gt CO_2 yr^{-1}.

Finally, we note that the use of three FAO models allows, within the discussed underlying uncertainty of each estimate, to evaluate the contribution of different pools to the overall estimates. Specifically, we found that compared to computations limited to carbon biomass pools, the inclusion of litter and dead wood carbon generally increased net forest removals by 20% in both AI and NAI countries across FRA periods. Including additionally the carbon soil pool further increased removals on forest land by another 30-40% in both AI and NAI countries across FRA periods. These results underscored the critical importance of soil carbon in our estimates and thus the importance of ensuring their good data quality.

3.2~~1~~ N~~Global and regional results~~et forest emissions and removals

3.2~~1~~.1 FAO estimates

The FAO data showed increasing carbon stocks in forests ~~, hence negative carbon stock change fluxes,~~ for all FRA periods except for 1990–2000~~, indicating~~. Hence ~~that~~ since the year 2000, the data suggested that forests acted globally as overall net sinks of atmospheric CO_2, sequestering up to -2~~1~~.0~~8~~ Gt CO_2 yr^{-1} on average in 2020-2025—the most recent period in the FAO estimates (see complete range of FAO estimates in Tab. 4). ~~The two separate components of *CSC* defined earlier further showed strong carbon sequestration on remaining forest land, with *FL* removals of~~This sink was the result of substantial removals on forest land, up to -5.8~~7~~ Gt CO_2 yr^{-1}, ~~compared to losses from net forest conversion, NFC~~only partially counterbalanced by emissions from net forest conversion ~~,~~ of up to 3.8 Gt CO_2 yr^{-1}. ~~At the same time, the *CSC* fluxes were consistently negative for the entire time series for~~Forests acted overall as carbon sinks in AI countries over the entire period 1990-2025, ~~and positive for~~but were carbon sources in NAI countries. Regional values showed opposite trends (not shown, available in Tubiello and Obli-Laryea, 2026), with *CSC* in the Americas and Africa, indicating a net ~~emissions~~ source over the entire period, about +1.5 Gt CO_2 yr^{-1} on average for 2020-2025. Conversely, Europe and Asia were net overall sinks, about -2.0 Gt CO_2 yr^{-1} in the most recent period. Forests in Oceania switched from small net sources in 2010–2020 to net sinks in 2020–2025.

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Over the time-series 1990-2025, the FAO data showed that *NFC* ~~With respect to~~ emissions ~~from net forest conversion, the FAO estimates showed~~ substantially decreased over time, globally from 5-7 Gt CO_2 yr^{-1} on average during 1990-2000 to 3-4 Gt CO_2 yr^{-1} in 2020-2025 (~~Tab. 4;~~ Fig 3~~a~~). This trend was almost entirely driven by NAI countries, which were responsible for about 90% of the world total ~~net forest conversion~~ emissions. Regionally, the Americas (2.4 Gt CO_2 yr^{-1} during 2020-2025) and Asia (0.4 Gt CO_2 yr^{-1}) were the main drivers of the global trends in *NFC*, each showing reductions in deforestation emissions greater than 1 Gt CO_2 yr^{-1}. The FAO data furthermore showed that in Africa, *NFC* increased over time, reaching a peak of about 1.8 Gt CO_2 yr^{-1} during 2010-2015, then decreasing to less than 1.0 Gt CO_2 yr^{-1} in 2020-2025. Europe and Oceania were minor global contributors.

~~With respect to net emissions/removals on forest land,~~ Over the time-series 1990-2025, ~~the~~ FAO results showed ~~substantial carbon sinks on remaining forest land, with~~ large net removals on forest land, with *FL* as strong as -7.1 Gt CO_2 yr^{-1} on average during 2000-2010 and decreasing ~~in subsequent FRA periods,~~ to -5.7 Gt CO_2 yr^{-1} on average during 2020-2025 (Tab. 4, Fig. 3~~a~~). These removals ~~The global *FL* net removals~~ were equally divided between AI and NAI aggregates in the most recent period, about -2 to -3 Gt CO_2 yr^{-1} on average over 2020-2025 (Tab. 4), whereas in earlier periods ~~removals on forest land~~they were stronger in AI countries. Results showed consistent net forest removals for all regions ~~al sinks over the study period~~ except for Africa. Specifically, Europe, Asia and the Americas had large ~~sinks~~ net removals on forest land, with Europe being the most substantial at about -2 Gt CO_2 yr^{-1} in 2020-2025. Additionally, the FAO data suggested opposite regional trends~~, with decrease in removal strength,d~~ with decreases of ~~by about~~ 15% in Europe and by nearly 40% in the Americas from 2000 to 2025 but increases of 30% in Asia. Africa and Oceania had comparatively small net fluxes on forest land, with less notable trends.

Table 4. FAO 2025 net forest emission/removal estimates (Gt CO_2 yr^{-1}) corresponding to FRA periods, by FAO model. Fluxes categories include carbon stock change (CSC) and its two components, emission/removal fluxes on forest land (FL) and emissions from net forest conversion (NFC). FAO models include different carbon pools. FAO 1: above- and below-ground living biomass; FAO 2: above- and below-ground living biomass, litter and dead wood; FAO 3: above- and below-ground living biomass, litter, dead wood and soils.

		1990-2000			2000-2010			2010-2020			2020-2025		
		FAO 1	FAO 2	FAO 3	FAO 1	FAO 2	FAO 3	FAO 1	FAO 2	FAO 3	FAO 1	FAO 2	FAO
CSC	**World**	1.1	0.9	0.7	-0.8	-1.5	-3.0	-1.4	-1.9	-2.9	-0.9~~8~~	-1.2~~1~~	-2~~1~~.
	AI	-2.4	-2.7	-3.4	-2.5	-3.1	-4.2	-2.1	-2.4	-3.3	-1.8~~7~~	-2~~1~~.0~~9~~	-2.6
	NAI	3.5	3.5	4.1	1.7	1.6	1.2	0.9	0.8	0.6	0.9	0.8	0.6
NFC	**World**	5.2	5.7	7.1	3.2	3.5	4.3	2.9	3.2	4.0	2.8	3.2	3.8
	AI	0.3	0.5	0.6	0.1	0.2	0.2	0.2	0.2	0.3	0.2	0.3	0.4
	NAI	4.9	5.2	6.5	3.1	3.4	4.1	2.8	3.0	3.3	2.7	2.9	3.5
FL	**World**	-4.0	-4.8	-6.3	-3.9	-4.9	-7.1	-4.1	-4.7	-6.6	-3.7~~6~~	-4.4~~2~~	-5.8
	AI	-2.7	-3.1	-4.0	-2.6	-3.3	-4.5	-2.3	-2.6	-3.6	-1.9~~8~~	-2.3~~2~~	-3~~2~~.
	NAI	-1.4	-1.7	-2.4	-1.4	-1.8	-2.9	-1.9	-2.4	-3.1	-1.8	-2.1	-2.

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3.2~~1~~.2 Comparisons of FAO and~~to~~ UNFCCC emission/removal fluxes ~~data~~

We compared FAO *NFC* and *FL* results to the UNFCCC data collected and re-disseminated within ~~the same dataset presented in this work~~FAOSTAT. ~~In order to provide a consistent basis for comparison,~~To this end, we ~~re-~~computed new World, AI and NAI aggregates, limited to the countries present in the UNFCCC dataset. We performed such comparisons over the entire time series 1990–2025 (Fig. 3a-c), as well as in terms of long-term 2001–2023 averages (Tab. 5), consistently with ~~recent~~ published analyses (Grassi et al., 2022; Melo et al., 2026~~5~~). Results of both timeseries comparison and long-term averages indicated good agreement of FAO estimates ~~and~~ with UNFCCC data—with the range of FAO models consistently including the corresponding UNFCCC values—across ~~all items~~flux category (NFC, FL) and ~~group~~regional aggregate (World, AI, NAI) combinations, except for *FL* fluxes for the NAI aggregate. Within the underlying ~~50%~~ uncertainties ~~making~~implied that ~~all~~ results presented herein were not statistically different, our ~~results~~ findings highlighted, at least qualitatively, a 'sink gap' in NAI countries, i.e., stronger forest removals in UNFCCC data vs FAO estimates, ranging between 1.2–2.4 Gt CO_2 yr^{-1} ~~across FAO estimates~~—with the smaller gap corresponding to FAO 3 model estimates (Tab. 5). As discussed in more detail in the next section, this gap ~~coincided almost entirely with the FAO/UNFCCC difference arising from the set of~~was largely generated in countries reporting zero carbon stock ~~change~~ density change~~ies~~ to FAO via the FRA, but conversely strong removals on forest land to UNFCCC. Furthermore, it is worth noting that the decline of the global FL sink seen in the FAO data, while also supported by recent independent work (Rossi et al., 2026), could at least in part in part be attributed to incomplete reporting of C stocks for the year 2025 period, as discussed previously.

Figure 3~~a~~**.** ~~World total net~~Net forest emission~~s~~/removal~~s~~ estimates, 1990–2025 for FL, NFC, for t~~t~~hree FAO ~~stock change~~ models and UNFCCC data. (a) World total; (b) AI; and (c) NAI. ~~and global coverage. UNFCCC and FAO LMTD aggregates limited to UNFCCC reporting countries. Shaded areas represent 50% uncertainty (95% CI) around the intermediate FAO 2 model.~~

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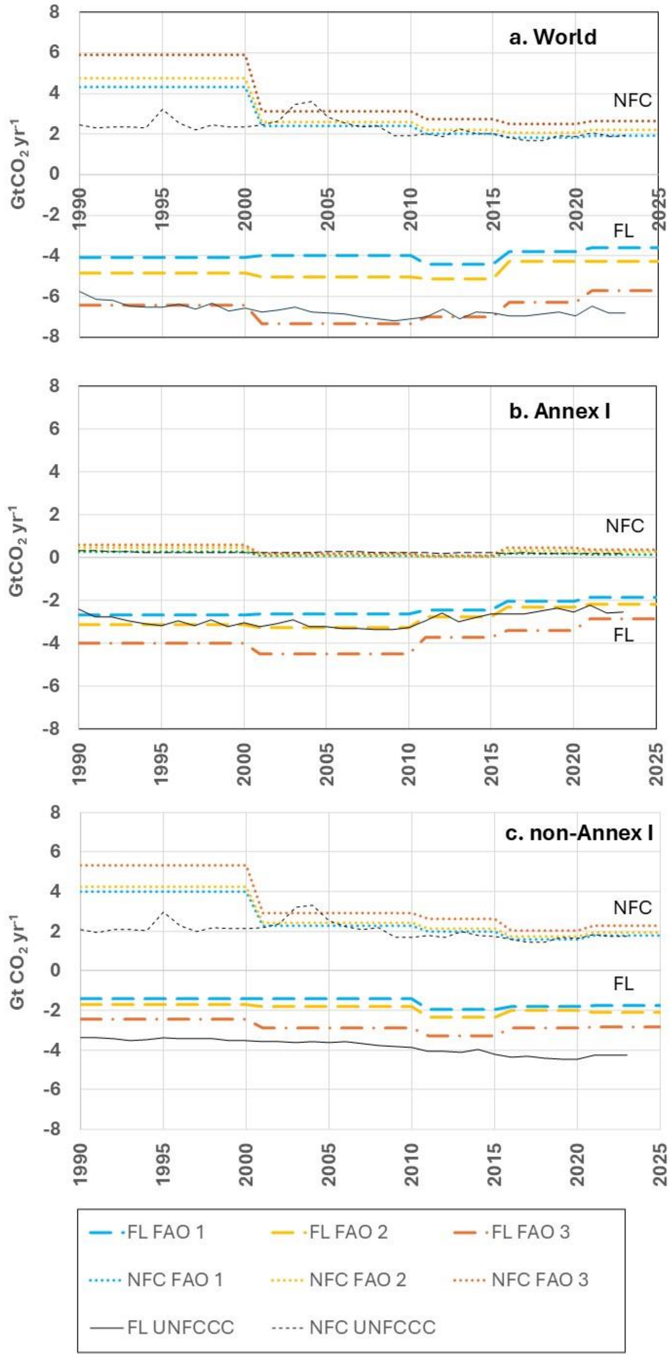
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b. Annex I
c. non-Annex I
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GtCO2 yr-1
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NFC FAO 1
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FL UNFCCC
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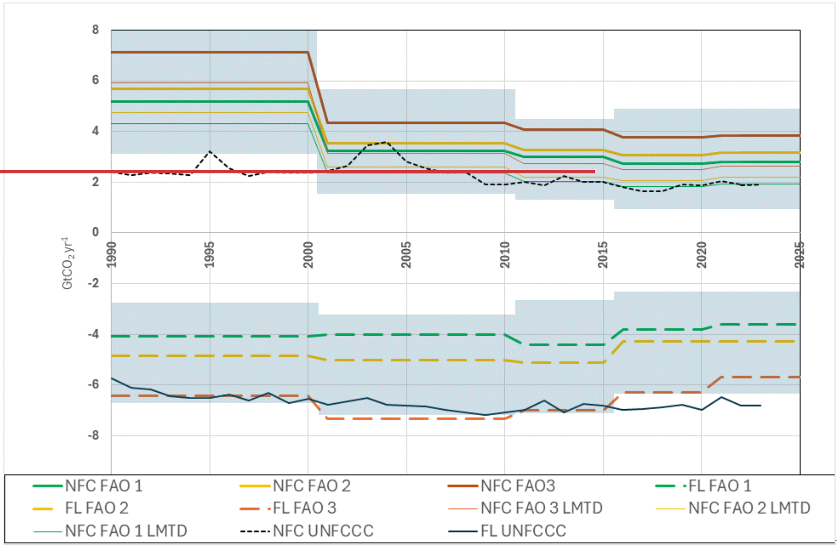

~~**Figure 3b.** AI aggregates of net forest emissions/removals estimates, 1990-2025 for three FAO stock change models and global coverage. UNFCCC and FAO LMTD aggregates limited to UNFCCC reporting countries. Shaded areas represent 50% uncertainty (95% CI) around the intermediate FAO 2 model.~~

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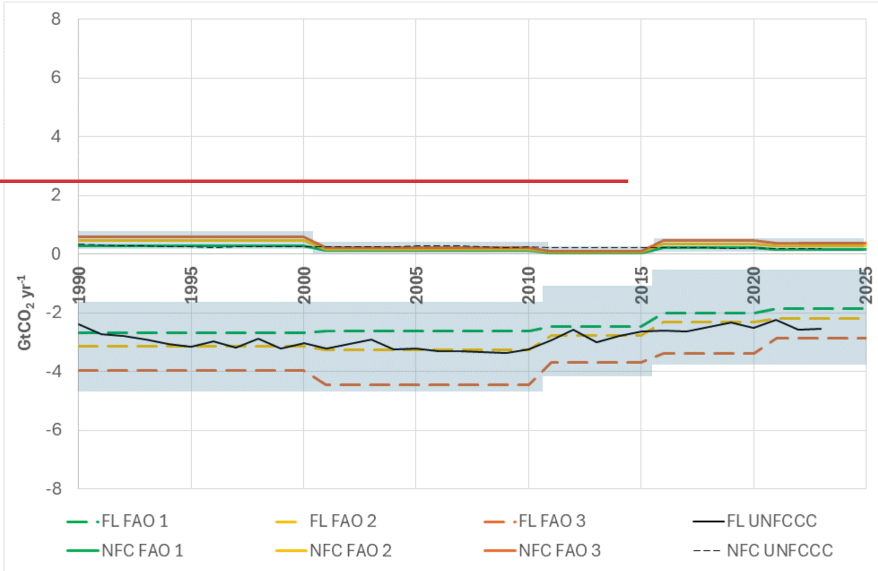

~~**Figure 3c.** NAI aggregates of net forest emissions/removals estimates, 1990-2025 for three FAO stock change models and global coverage. UNFCCC and FAO LMTD aggregates limited to UNFCCC reporting countries. Shaded areas represent 50% uncertainty (95% CI) around the intermediate FAO 2 model.~~

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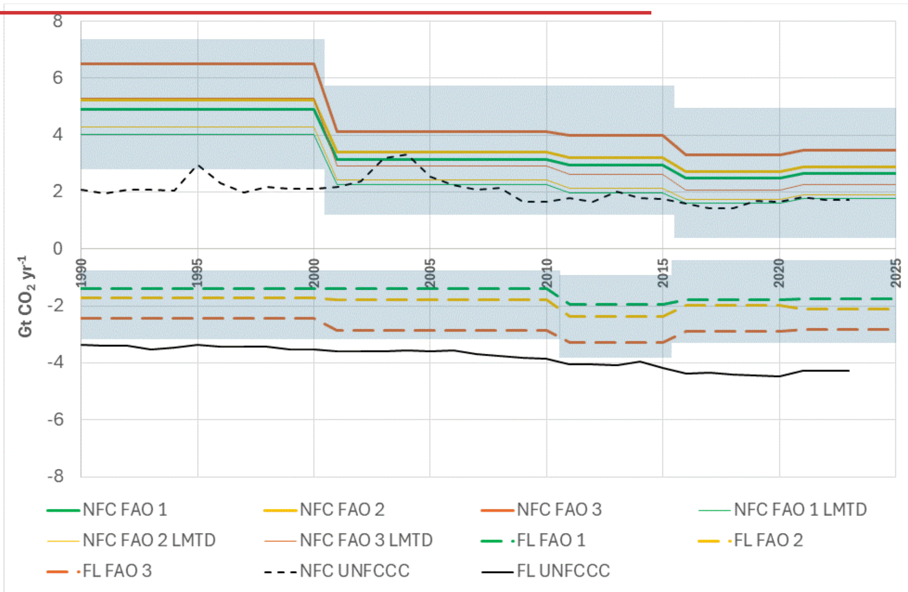

Table 5. Average 2001-2023 ~~Comparison of FAO net forest emission/removal estimates and UNFCCC country data, by world, Annex I (AI) and non-Annex I (NAI) aggregate groups~~FAO and UNFCCC fluxes (Gt CO_2 yr^{-1}). World, Annex I (AI) and non-Annex I (NAI) regional aggregates, l~~, 2001-2023 averages (Gt CO_2 yr^{-1}~~imited to~~)~~ ~~.~~ ~~The column n (%) indicates the number of countries included in the analysis~~countries reporting to ~~based on~~ UNFCCC ~~reporting, and their percentage coverage with respect to full geographic coverage. FAO~~ . FAO 2 estimates provided ~~show~~with the range defined by FAO 1, FAO 3 ~~three~~ ~~carbon stock change~~ models.

Item	Group	Country coverage~~n (%)~~	FAO ~~2~~ ~~FAO 3~~		UNFCCC
NFC	World	81 ~~(42%)~~	2.3	(2.1-2.8)	2.2
	AI	42 ~~(100%)~~	0.2	(0.1-0.3)	0.2
	NAI	39 ~~(25%)~~	2.2	(2.0-2.6)	2.0
FL	World	134 ~~(69%)~~	-4.7	(-3.9-6.7)	-6.9
	AI	42 ~~(100%)~~	-2.8	(-2.3--3.9)	-2.9
	NAI	92 ~~(60%)~~	-1.9	(-1.6--2.8)	-4.0

3.2.3 Country results

Country-level analyses were ~~carried out~~performed over the same long-term 2001~~1~~-2023 average used above. Results underscored that the observed global and regional ~~trends~~ differences between FAO and UNFCCC were driven by a relatively small number of countries, typically no more than 10-15, most of them countries with large forest area~~s~~. Specifically, ~~both FAO and UNFCCC data suggested that~~ world total *NFC* emissions were mainly driven by just two countries, Brazil and the Democratic Republic of Congo (DRC), which were responsible for roughly 70% of the world total according to both FAO and UNFCCC data, with the top ten countries covering about 90% (Tab. 6).

Table 6. Top~~Top~~ ten ~~net forest conversion fluxes~~NFC fluxes, 2001-2023 averages (Gt CO_2 yr^{-1}), o~~. O~~rdered by UNFCCC values.
FAO 2 estimates provided with the range defined by FAO 1, FAO 3 models.

Country	FAO ~~2~~ ~~FAO 3~~		UNFCCC
Brazil	1.2~~3~~	(1.2-1.5~~5~~)	1.0~~0.97~~
DRC	0.4~~36~~	(0.3-0.5~~0~~)	0.6~~57~~
Indonesia	0.03	(0.03-0.05)	0.2~~16~~
USA	0.03	(0.02-0.05)	0.1~~0~~
Côte d'Ivoire	0.05	(0.05-0.05)	0.06
Australia	0.04	(0.02-0.05)	0.05
Argentina	0.1~~0~~	(0.09-0.12)	0.05
Paraguay	0.06	(0.06-0.09)	0.03
Ecuador	0.03	(0.03-0.04)	0.02
Malaysia	0.03	(0.03-0.05)	0.02

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~~Furthermore,~~ FAO NFC estimates were consistent with UNFCCC data for Brazil, Cote d'Ivoire, Australia and Ecuador. Conversely, ~~they~~ They were smaller than UNFCCC for DRC, Indonesia and United States of America (USA), while they were larger for Argentina, Paraguay and Malaysia. Additionally, the FAO dataset included several countries that either had UNFCCC data but did not appear within the UNFCCC top ten (Fig. 4), such as Canada (0.06-~~–~~0.15 Gt CO_2 yr^{-1}), or did not appear in the UNFCCC dataset collected for this work, such as Peru (0.1-~~–~~0.2 Gt CO_2 yr^{-1}), Myanmar (0.07 – 0.09 Gt CO_2 yr^{-1}), Colombia (0.08-~~–~~0.09 Gt CO_2 yr^{-1}), Tanzania (0.05-~~–~~0.08 Gt CO_2 yr^{-1}), Bolivia (0.06~~–~~-0.08 Gt CO_2 yr^{-1}) and Cameroon (0.05-~~–~~0.06 Gt CO_2 yr^{-1}).

With regards to *FL* fluxes, both FAO and UNFCCC data showed that just three countries, Russian Federation, USA and China, were responsible for 40-60% of world total ~~net forest~~ removals, with the top ten countries ~~summing up~~representing ~~to~~ 70-80% of the total (Tab. 7). Within the top ten countries, FAO estimates were consistent with UNFCCC data for the Russian Federation, USA, and China. They were substantially smaller than UNFCCC for DRC, Mali, Venezuela, Malaysia and Mexico, and substantially larger for Brazil. The drivers of these country-level discrepancies we~~a~~re further investigated and presented in the d~~D~~iscussion section below. Finally, ~~the~~ FAO ~~estimates~~ identified possible ~~important~~ forest sinks ~~countries~~ that did not appear within the UNFCCC top ten (Fig. 4), albeit with a large noise across FAO models. These included~~such as~~ Canada (+0.06 ~~–~~-0.2 Gt CO_2 yr^{-1}), India (- 0.1-~~–~~0.2 Gt CO_2 yr^{-1}), Belarus (- 0.06-~~–~~0.1 Gt CO_2 yr^{-1}), France (- 0.05-~~–~~0.09 Gt CO_2 yr^{-1}) and Vietnam (- 0.05-~~–~~0.07 Gt CO_2 yr^{-1}).

Table 7. Top ten FL fluxes~~removals on forest land~~, 2001-2023 averages (Gt CO_2 yr^{-1}), o~~. O~~rdered by UNFCCC values.

FAO 2 estimates provided with the range defined by FAO 1, FAO 3 models.

Country	**FAO ~~2~~** ~~**FAO 3**~~		**UNFCCC**
Russia	-1.2~~2~~	(-1.0 -1.5~~5~~)	-1.3
USA	-0.9	(-0.8 -1.1)	-0.9~~9~~
China	-0.8	(-0.6- -1.3~~3~~)	-0.8~~7~~
DRC	-0.02	(-0.0-0.02)	-0.3~~3~~
Mali	0.02	(0.0-0.06)	-0.3
Brazil	-0.5~~5~~	(-0.5 -0.6~~6~~)	-0.3
Venezuela	-0.08	(-0.0- 0.1)	-0.3
Indonesia	-0.1	(-0.1 -0.3~~3~~)	-0.3~~3~~
Malaysia	-0.03	(-0.03- -0.05~~1~~)	-0.2
Mexico	- 0.05~~1~~	(-0.04 -0.05~~1~~)	-0.2~~2~~

Figure 4. Comparison of FAO and UNFCCC country data for top 10 *NFC* emissions and *FL* removals, 2001-~~-~~2023 averages. FAO estimates include all three carbon stock change models, with FAO 2 representing the central value and FAO 1 and FAO 3 providing the range of FAO estimates.

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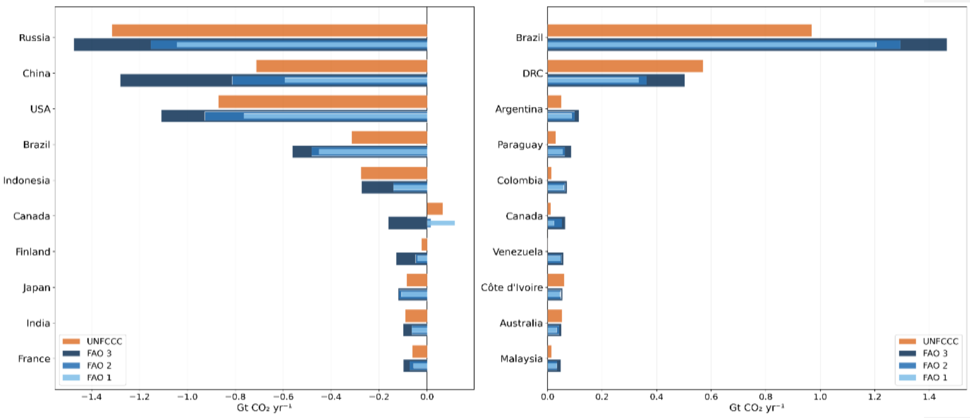

~~4. Discussion~~

3.3 Discrepancies in forest land removals

Notwithstanding the uncertainty ~~considerations highlighted~~discussed earlier, which makes most of the differences highlighted above not statistically significant, we performed additional country-level analyses to better characterize, at least qualitatively, ~~-~~the 'sink gap' ~~identified earlier~~ between the FAO and UNFCCC data on forest removals in NAI countries, amounting to ~~roughly~~ roughly 2~~1~~ ~~Gt CO_2 yr^{-1}~~(-3.0–-.0.2) Gt CO_2 yr^{-1} ~~when using FAO 3 estimates~~ (~~see~~ Tab. 5). Extending the country-level discrepancies identified in Tab. 7, our analysis showed that in~~this aggregate~~ NAI ~~ga~~countries the discrepancy~~p~~ was driven by a dozen~~13~~ countries (Tab. 8), concentrated in tropical Africa (Mali, DRC, Madagascar, Cameroon, Gabon and Namibia), Latin America and the Caribbean (Venezuela, Guyana and Mexico) and Southeast Asia (Indonesia and Malaysia~~), collectively generating a cumulative sink gap of about 2 Gt CO_2 yr^{-1} (Tab. 8). This was diminished by a cumulative source gap of about 1 Gt CO_2 yr^{-1} generated in~~). ~~three additional countries,~~Additionally, ~~-~~Brazil, USA and Nigeria represented opposite trends, i.e., cases in which ~~and China, for which~~ the FAO removals on forest land were larger than UNFCCC~~, with the balance fully explaining the noted NAI FAO/UNFCCC discrepancy~~. Remarkably, the 'outlier' countries in Tab. 8 were virtually the same identified in recent similar comparisons developed in the context of the LULUCF data hub (Melo et al., 2026~~5~~). This suggested that this list of countries was likely not random, making it sensible to investigate reasons for the observed discrepancy. While this is a topic deserving its own independent effort, we note that certain data typologies could be readily identified, building on previous work (Grassi et al., 2022; Melo et al., 2026~~5~~). For instance, our analysis showed that all of the six outlier countries in tropical Africa~~,~~ had reported to FAO zero carbon stock density change to FAO via the FRA, while reporting strong net forest removals to UNFCCC, corresponding to a cumulative ~~UNFCC/FAO~~FAO/UNFCCC ~~sink gap~~discrepancy of 1.3 Gt CO_2 yr^{-1}~~, had conversely zero carbon stock density change in the FRA~~. To this end, Melo et al. (2026) have suggested that UNFCCC-reported forest removals for Mali, Malaysia and Namibia might be 'not plausible.' We currently lack complete observations, however, to conclude whether FAO or the UNFCCC data are closer to a true value. ~~Thus a first typology identified here was a p~~Thus, a first typology characterizing the differences observed between FAO and UNFCCC identified herein relates to~~otential~~ data quality issues ~~gap~~. This could ~~that could~~ be ~~further~~ usefully addressed by FAO in coordination with UNFCCC and interested partners, through dedicated statistical capacity development programs~~,~~ in identified countries, aimed at improving the accuracy and the alignment of ~~alignment between FAO and UNFCCC~~forest activity data used in multiple reporting. ~~At the same time, Melo et al. (2025) suggested that the forest sinks in these same countries were 'not credible,' considering that current evidence rather suggested forest degradation due to human intervention.~~

Table 8. Comparison of FAO 2 and UNFCCC ~~net emissions/removals on forest land~~FL fluxes (2001--2023 average), ~~showing top~~ordered by FAO-UNFCCC difference~~s~~ for countries with removals greater than 0.1 Gt CO_2 yr^{-1}. ~~FAO 3 results used for simplicity.~~

Country	FAO 2	UNFCCC	DIFF
Mali [a]	0.0	-0.3	+0.3
Venezuela [a]	0.0	-0.3	+0.3
DRC [a]	0.0	-0.3	+0.3
Malaysia	0.0	-0.2	+0.2
Madagascar	0.0	-0.2	+0.2
Russia	-1.2	-1.3	+0.2
Guyana [a]	0.0	-0.2	+0.2
Mexico	0.0	-0.2	+0.1
Indonesia	-0.1	-0.3	+0.1
Cameroon [a]	0.0	-0.1	+0.1
Gabon [a]	0.0	-0.1	+0.1
Namibia [a]	0.0	-0.1	+0.1
Ethiopia	0.0	-0.1	+0.1
USA	-0.9	-0.9	-0.1
Brazil	-0.5	-0.3	-0.2
Nigeria	-0.0	0.3	-0.3

~~Country~~	~~FAO~~	~~UNFCCC~~	~~DIFF~~
~~Mali[a]~~	~~-0.0~~	~~-0.3~~	~~+0.3~~
~~DRC[a]~~	~~-0.0~~	~~-0.3~~	~~+0.3~~
~~Venezuela~~	~~-0.0~~	~~-0.3~~	~~+0.3~~
~~Malaysia~~	~~-0.1~~	~~-0.2~~	~~+0.2~~
~~Madagascar[a]~~	~~+0.0~~	~~-0.1~~	~~+0.2~~
~~Guyana[a]~~	~~+0.0~~	~~-0.2~~	~~+0.2~~
~~Mexico~~	~~-0.1~~	~~-0.2~~	~~+0.1~~
~~Cameroon[a]~~	~~-0.0~~	~~-0.1~~	~~+0.1~~
~~Gabon[a]~~	~~-0.0~~	~~-0.1~~	~~+0.1~~
~~Namibia[a]~~	~~+0.0~~	~~-0.1~~	~~+0.1~~
~~Brazil~~	~~-0.6~~	~~-0.3~~	~~-0.3~~
~~Nigeria[a]~~	~~-0.0~~	~~+0.3~~	~~-0.3~~
~~China~~	~~-1.3~~	~~-0.7~~	~~-0.6~~

[a] Constant carbon stock density data in FRA

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A second typology in the observed FAO/UNFCCC~~of~~ discrepanciés~~y~~ was related to land use ~~boundary issues~~coverage~~, specifically concerning~~, specifically when UNFCCC country-reported managed forest area~~s that~~ was~~ere~~ either ~~larger~~ smaller or larger than the corresponding FAO ~~total~~ forest ~~land~~ area ~~(see also methods)~~. Namibia exemplified ~~such~~ the latter case, ~~-~~perhaps in the extreme. In this country, as discussed previously, the UNFCCC managed forest area was nearly 10 times larger than the FAO value, allowing for carbon accounting in ~~accounting for forest carbon sinks on~~ woody savannah encroachments areas (Stevens et al., 2017; IPCC, 2022). This led~~, leading~~ to ~~a UNFCCC forest area nearly 10 times larger than the FAO forest land area (see methods), was likely the underlying reason for the~~ much larger UNFCCC removals on forest land than could be estimated by FAO on much smaller forest areas~~observed UNFCCC/FAO gap at country level~~. ~~A third discrepancy also related to land use boundary issues, but in the opposite direction, i.e., concerning UNFCCC country-reported managed forest areas smaller than the corresponding FAO total forest land – a case much~~ Conversely, the former case, i.e., UNFCCC-reported managed forest area smaller than FAO forest area, has been discussed in detail in the literature (Grassi et al., 2022). ~~We showed earlier (see methods) that available UNFCCC and FRA statistics indicate~~We found ~~-~~that only a few, albeit very large forest area countries, fit this typology. Among them,~~se,~~ Brazil was ~~perhaps~~ the most extreme case, reporting to UNFCCC managed land areas that were only about 60% ~~smaller than~~ the FAO-reported~~O~~ forest ~~land~~ area. ~~We found that p~~A~~roportionally a~~djusting the much larger FAO removal estimates by this proportion was in fact sufficient to align FAO and UNFCCC forest removal data for this country~~s~~. ~~These typologies could be used to guide dedicated statistical programs in countries as discussed. At the same time, the fact~~We conclude from the above analysis that the discrepancies between FAO and UNFCCC data, albeit important, ~~-~~were concentrated in a handful of countries, suggesting~~ed~~ that the underlying FAO and UNFCCC forest activity data were already well aligned overall ~~for most other countries~~.

3.4 FAO estimates and the Global Carbon Budget

~~With the above increased understanding, which pointed to specific country differences within an overall credible global assessment,~~In addition to comparisons to UNFCCC, w ~~we~~ ~~further tested~~ compared the FAO ~~global forest~~ net forest emissions~~s~~/removal~~s~~ estimates ~~against~~ to the most recent Global Carbon Budget 2025 data (GCB20205; Friedlingstein et al., 2026)~~(GCB,) data, including forest-related bookkeeping and dynamic global vegetation model output, JRC NGHGI data, and atmospheric inversions (Friedlingstein et al., 2026). To this end we used FAO 3 estimates as the most relevant in the context of global land carbon cycle assessments.~~ Results showed that ~~the~~ FAO estimates of~~fer~~ ~~both~~ world total *NFC* and *FL* fluxes were in very close agreement with ~~the independent estimates published within~~ the GCB2025 (Fig. 5). The ~~, the~~ latter dataset indicat~~ed~~ing world total deforestation emissions of roughly 4 Gt CO_2 yr^{-1}, counterbalanced by forest removals of -6 to ~~-~~-7 Gt CO_2 yr^{-1}. ~~The resulting FAO estimates of net carbon stock change in forest, about -2 Gt CO_2 yr^{-1} were additionally consistent with the average results of fourteen atmospheric inversion models.~~

Figure 5. Comparison of FAO ~~3 full~~ net forest emission/removal ~~carbon stock change~~ estimates (all carbon pools), 2001-2023, to ~~to datasets published~~ the GB2025~~in GCB (Friedlingstein et al., 2025)~~. FAO NFC: Net forest

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conversion (this work); FAO FL: Forest land (this work); ~~;~~ JRC NGHGI Def: country deforestation emissions compiled by the J~~gap-filled~~oint Research Center; JRC NGHGI FL: country forest land removals compiled by the Joint Research Center~~ NGHGI data~~; GCB2025 def: deforestation component of the GCB2025 ELUC flux~~Bookkeeping models;~~ ~~for NFC and~~ GCB2025 SLAND: forest component of the GCB2025 SLAND (net fluxes from afforestation/reforestation, shifting cultivation, wood harvest, plus net land sink adjusted to align to NGHGI)~~adjusted DGVMs for FL; Inversions: net land carbon stock change from atmospheric inversions~~.

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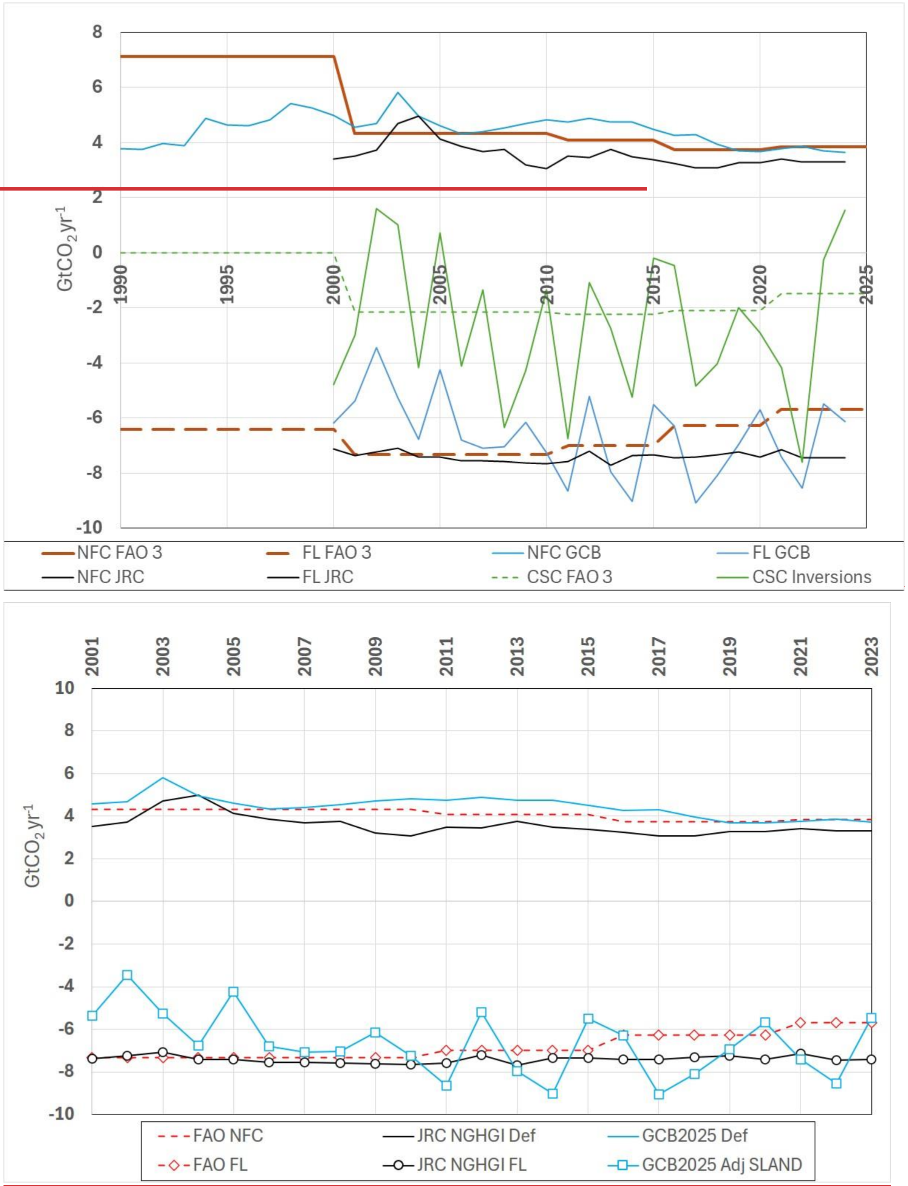

~~The country analysis and the global agreement shown above helped to confirm the positive role that FAO data can play alongside other established approaches, to help build confidence in the robustness of national, regional and global net forest emissions/removals assessments, while demonstrating the consistency of the underlying national data sources. We nonetheless feel compelled to close this discussion by highlighting that the large ±50%~~

~~uncertainty (95% CI) underlying the emissions/removal estimates discussed herein made most country estimates produced across FAO, UNFCCC and GCB models, statistically indistinguishable. The valuable qualitative insights discussed were nonetheless useful to highlight areas of improvement in FAO and UNFCCC data collection efforts aimed at ensuring better alignment and comparability.~~

4~~5~~. Conclusions

~~We provided a~~Our detailed analysis based on the most recent FRA 2025 data ~~to~~ showed that the FAO net forest emissions and removals dataset 1990–~~-~~2025 ~~continue to~~ represents a useful ~~benchmarking tool~~reference in support of country reporting processes and a solid contributor to global assessments. First, we found~~showed~~ that land use boundary issues~~, while conceptually~~, though important in ~~distinguishing~~ interpreting differences in FAO and UNFCCC at country level, ~~data, were less important than suggested in current literature.~~ were not a major driver of discrepancy globally. Specifically, ~~We found that~~ apart from a small set of countries for which either smaller or larger managed forest areas made a difference in the UNFCCC FAO comparisons (e.g., Brazil, Canada, Namibia), ~~in practice,~~ most countries reported managed forest areas to UNFCCC that were ~~larger or~~ equal to the~~,~~ ~~not smaller than,~~ total forest land area they reported to FAO. Hence flux estimates made on the entire forest land area could be considered anthropogenic in the sense of the IPCC managed land use proxy, ~~increasing~~ ensuing consistency and thus comparability of FAO and UNFCCC ~~reporting~~data. Secondly, we found a substantial agreement of the new FAO estimates with recent NGHGI-adjusted Global Carbon Budget data, following inclusion of all relevant carbon pools in the FAO calculations. Finally, we argued that while the knowledge gained through the comparison of multiple independent approaches was extremely useful in highlighting areas of agreement and disagreement –and therefore in providing insight into ~~needed~~ necessary future work to improve national, regional and global assessments—~~,~~ the large and specific uncertainties underlying FAO, NGHGI and GCB data need to be acknowledged in country data comparisons. We nonetheless strongly support the recommendations that are emerging in the current literature, recently outlined in the context of the JRC LULUCF data hub (Melo et al., 2026), towards the development ~~towards the development~~ of internationally coordinated capacity development programs~~, contributed by relevant actors in collaboration with countries, as recently outlined by the LULUCF data hub consortium~~. To this end, we underline that FAO is uniquely positioned to contribute to such efforts, as the UN agency with the official mandate to collect, analyze and disseminate forest and land use statistics from its member countries and to support national experts via dedicated capacity development activities. Our ultimate goal was and remains to improve the quality, ~~and~~ comparability and consistency of country data submitted to relevant international processes, in support of improved evidence-based decision making for effective action on~~on~~ climate change and forests.

Authors' contributions. FNT led the development and analysis of the FAOSTAT data. AP OJ and AB provided the FRA 2025 data and contributed to data analysis. GO, NR, MP, NW, RB, RDC and GC contributed data analysis and helped develop the FAOSTAT database. FNT and GO led the comparisons of FAO, UNFCCC and GCB data.

Competing interests. Author Francesco N. Tubiello is a member of the editorial board of the journal.

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Data Availability. Full dataset is available on Zenodo (Tubiello and Obli-Laryea, 2026) at: 10.5281/zenodo.20085666~~10.5281/zenodo.20085666~~.

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