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

Francesco N. Tubiello[1], Anne Branthomme[2], Griffiths Obli-Laryea[1], Michelle Piccoli[1], Nidal Ramadan[1], Rocio Danica Condor[2], Nathan Wanner[1], Rachele Brivio[1], Orjan Jonsson[2], Giulia Conchedda[3] and Anssi Pekkarinen[2]

[1]Statistics Division, Food and Agriculture Organization of the United Nations, Rome, 00153, Italy
[2]Forestry Division, Food and Agriculture Organization of the United Nations, Rome, 00153, Italy
[3]Land and Water Division, Food and Agriculture Organization of the United Nations, Rome, 00153, Italy

Correspondence to: Francesco N. Tubiello (francesco.tubiello@fao.org)

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

Francesco N. Tubiello[1], Anne Branthomme[2], Griffiths Obli-Laryea[1], Michelle Piccoli[1], Nidal Ramadan[1], Rocio Danica Condor[2], Nathan Wanner[1], Rachele Brivio[1], Orjan Jonsson[2], Giulia Conchedda[3] and Anssi Pekkarinen[2]

[1]Statistics Division, Food and Agriculture Organization of the United Nations, Rome, 00153, Italy
[2]Forestry Division, Food and Agriculture Organization of the United Nations, Rome, 00153, Italy
[3]Land and Water Division, Food and Agriculture Organization of the United Nations, Rome, 00153, Italy

Correspondence to: Francesco N. Tubiello (francesco.tubiello@fao.org)

Abstract. The FAO 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. 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 over the most recent decade 2015-2025, the FAO results indicated strong removals on forest land, ranging from -3.6 to -6.0 Gt CO_2 yr^{-1}—with lower and upper boundaries reflecting inclusion of stock change for living biomass only or for all pools. The forest removals were partially counterbalanced by emissions from net forest conversion of 2.8 to 3.8 Gt CO_2 yr^{-1} —used herein as a proxy for deforestation. Furthermore, Annex I (AI) and non-Annex I (NAI) countries contributed equally to removals on forest land, whereas 90% of emissions from net forest conversion were generated in NAI countries. Comparisons to country data submitted to the United Nations Framework Convention (UNFCCC) indicated close alignment with FAO estimates at global, AI and NAI level, including for the world's major 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 specific 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—needed for the coherent implementation and monitoring of effective mitigation actions. The FAO estimates and country data collected from UNFCCC were produced 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.

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

1 Introduction

The forest net emissions/removals dataset of the United Nations Food and Agriculture Organization (FAO) was developed over a decade ago as 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). 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 a practical benchmarking tool for technical expert reviewers and national greenhouse gas inventory (NGHGI) compilers (IPCC, FAO, IFAD, 2015), working under the enhanced transparency framework of the Paris Agreement. As a global knowledge product, the FAO data have been used to identify, contextualize, and better characterize differences observed across published global datasets of land use land use change and forestry (LULUCF) (Nabuurs et al., 2022; Grassi et al., 2023; Lamb et al., 2026). While a recognized contributor to LULUCF analyses provided in previous IPCC reports (Mbow et al., 2019; Nabuurs et al., 2022), recent work had 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 land proxy (Grassi et al., 2023), FRA data quality (Grassi et al., 2022) and completeness of carbon pools (Tubiello et al., 2021). We addressed all three issues in this manuscript, by presenting more detailed analyses based on the new FRA 2025 input data, and importantly by extending the previous FAO approach to allow for inclusion of all carbon pools covered by the FRA, namely not only carbon stock in 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 was therefore to document the revised FAO net forest emissions/removals statistics and to compare results to UNFCCC country data and other independent sources disseminated via the Global Carbon Budget (Friedlingstein et al., 2025). In doing so we identified current and future data quality improvements needed to better align relevant international forest data reporting processes aimed at strengthening country data comparability and thus the evidence-base 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 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 2025 data used in this work to estimate the FAO net forest emissions/removals 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).

The UNFCCC data were collected from available submissions to the UNFCCC, including i. *Forest Land* area and, where available, *Managed Forest Land* area; ii. *Deforestation* area; iii. *Emissions/removals on Forest Land*; and iv. *Emissions from deforestation*. We used the same approach of the European Commission Joint Research Center (JRC) (Melo et al., 2025) for mapping UNFCCC data to the above forest categories (FAO, 2025b). At the same time, we made no attempt to gap-fill missing information either statistically or through additional assumptions (i.e., using LULUCF data to infer forest information), resulting in less data points and country coverage than disseminated by the JRC. 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).

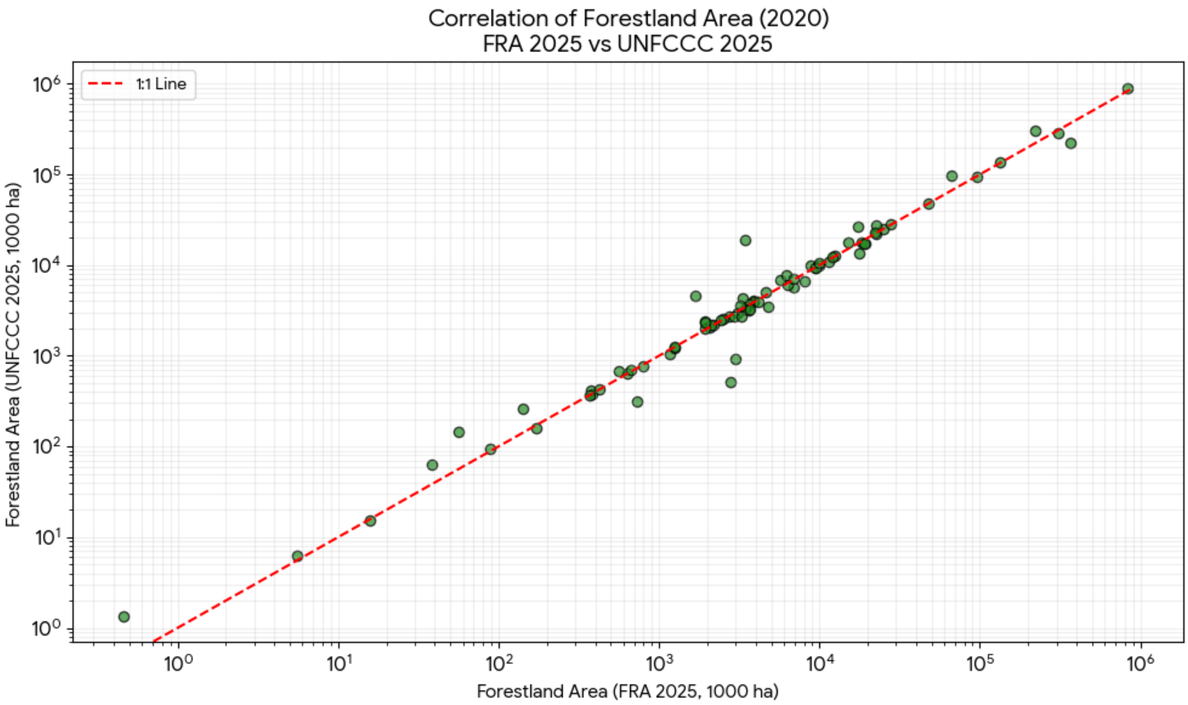


Figure 1. Correlation of the log-transformed forest land area (year 2020) reported by countries to both FAO via the FRA 2025 and the UNFCCC.

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.

Region	**Global**		**Reporting to both FAO and UNFCCC**			
	FAO		FAO	UNFCCC	Difference	
	Gha	*n countries*		*Mha*		*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	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 Net forest emissions/removals estimation

As discussed, net forest emissions/removals were estimated using carbon stock data from the FRA 2025. Whereas previous FAO estimates were limited to stock change in above- and below-ground living biomass pools, this update also included stock change in the litter, dead wood and soil carbon pools. This important extension allowed for a better alignment in scope with country inventories, which are expected to include additional pools to increase accuracy, depending on national capacity. In terms of FRA inputs, let A, A^{nr}, A^{pl} be the total area of *forest* and of its two strata, *naturally regenerating forest* and *planted forest*; B_r and $b_p = B_p / A$ be the total carbon stock and carbon density of reservoir *p* = *above and below-ground living biomass*, *litter*, and *dead wood*. Let furthermore ΔA^{nr}, ΔA^{pl} and CSC_p be the net area change of each forest strata and the net carbon stock change of carbon pool *p*, computed over the time Δt between two successive FRA data points. With reference to previous work (Tubiello et al., 2021), the total *CSC* of each pool can be split into two distinct components, specifically carbon stock change due to net forest conversion (to other land uses), *NFC*—used herein as a proxy for deforestation losses; and carbon stock changes within the remaining forest land, *FL* (Fig. 2). The equations to compute the FAO net forest emission/removal estimates (*E/R*) for country *c* and time *t*, were as follows:

$$CSC_{p,c,t} = \Delta B_{p,c,t}\,; \qquad \text{with } p = \textit{living biomass, litter, dead wood, soil} \tag{1}$$

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

$$FL_{p,c,t} = CSC_{p,c,t} - NFC_{p,c,t} \tag{3}$$

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

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

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

Where: *CSC*, *NFC* and *FL* were expressed in 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.

Equations (4)-(6) were needed to transform carbon stock change over given FRA periods into mean annual CO_2 emissions/removals, with the sign used conventionally to consider fluxes from land to atmosphere as positive (corresponding to negative stock change) and vice-versa.
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) was written to compute emissions to the atmosphere following *NFC* carbon losses, assuming 'instant oxidation' to the atmosphere of carbon in biomass, litter and dead wood, while retaining a portion of soil carbon after transition to the new land use. To this end the coefficient α_p in equation (4) represented retention in the destination pool between FRA periods, 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. 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, 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.

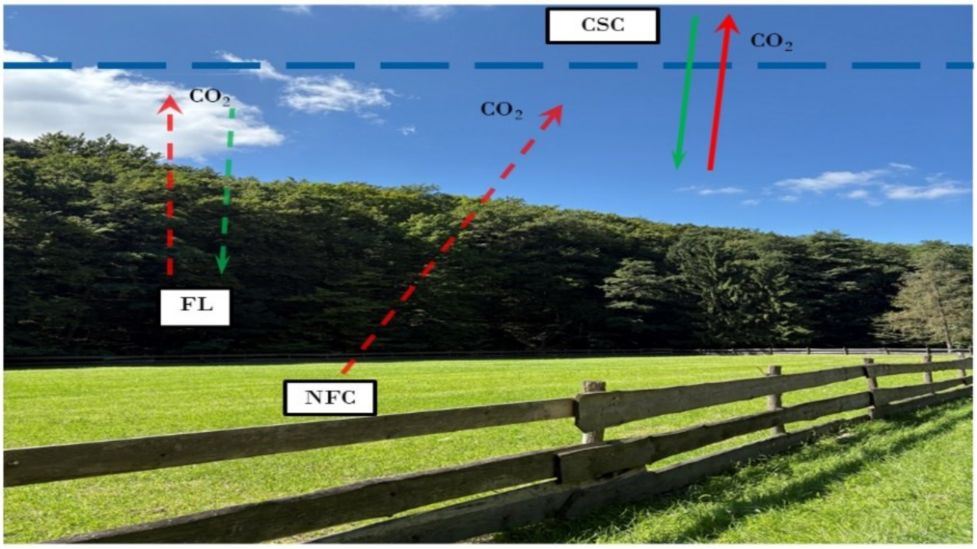


Figure 2. Forest fluxes included in the FAO dataset, including carbon stock change (CSC) and its component fluxes, net forest conversion (NFC) and forest land (FL).

2.3 Limitations and uncertainty

Several limitations to the FAO methodology were highlighted in previous work (Tubiello et al., 2021; Grassi et al., 2022). A first set referred to area boundaries, which determine whether the estimated net forest emissions/removals can be considered anthropogenic or not. Following the IPCC land use proxy approach, we considered all emissions/removals 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 forest land area, implying that some of the FAO estimated fluxes may contain natural components. At the same time however, as discussed previously in methods, we found that most countries reported managed forest area to UNFCCC that was equal to or greater than the FAO total forest land area, thereby annulling in most cases or substantially reducing the perceived mismatch between FAO and UNFCCC area boundaries.

Furthermore, we had argued (Federici et al., 2015; Tubiello et al., 2021) that only a subset of estimated fluxes depended on managed vs. total forest area boundaries. Specifically, emissions from net forest conversion, including their indirect climate and CO_2 components, could be considered anthropogenic as long as human agency determined the underlying land use change. The same would apply to removals on forest land due to the establishment of plantations. Of the emissions/removals estimated in this work, only a portion on remaining forest land may have a non-anthropogenic component. We suggest that, based on actual country data comparisons, that the boundaries of FAO estimates and UNFCCC data were in fact greatly aligned.

A second set of limitations in the FAO estimates presented here is the 'Tier 1' national -level approach with which they were computed, as opposed to higher Tiers methods. We recognize that remote sensing and machine learning make already possible today the production of accurate forest estimates at increasingly fine scales including 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 lies in providing a robust and transparent 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, using national statistics as input and constant national coefficients has recognized limitations. *First*, estimates of net forest land area change may systematically underestimate gross forest area changes and associated emissions/removals. We have noted however (see methods) that the FAO equations may limit such bias, by considering the independent losses of naturally regenerating forest and planted forest areas as approximations for national-level gross forest area loss. *Second*, the use of national-level biomass stock density would tend to underestimate net forest conversion emissions in cases when the forest being lost is primary 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 overestimating emissions 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 adding biophysical completeness to the underlying FAO carbon stock change model, they would tend to increase uncertainty. In particular, the FRA 2025 soil carbon data 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 note that the FAO equations for *NFC* used a constant coefficient $\alpha_{soil} = 2/3$ for retention of soil carbon across all possible net forest conversions (see methods). The value chosen was the recommended IPCC default for transitions to annual cropland in temperature zones, while lower default coefficients ($\alpha_{soil} = 0.5$-0.6; but with uncertainties of 60%) 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 (FAO, 2025c) suggests that a substantial portion of net forest conversion in the tropics occurs through 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 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. These issues were less important when reporting trends over the last decade 2015-2025 or when averaging over 2001-2023 for FAO/UNFCCC 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 50% (95% CI) uncertainty to all FAO emissions/removals components derived in this work, consistently with established literature on LULUCF (e.g., IPCC, 2022; Friedlingstein et al., 2025).

We conclude by noting that according to the relevant guidelines on communicating uncertainty published by the International Bureau of Weights and Measures (BIPM et al., 2008), 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. Generally, uncertainties of 50% imply use of at most two significant figures in reporting estimated means and their confidence intervals. We applied this guidance through this paper. Finally, we used the upper and lower FAO 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 continents 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. 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 emissions/removals and corresponding UNFCCC data are available as open data via Zenodo (Tubiello and Obli-Laryea, 2026), with DOI [10.5281/zenodo.20085666](https://doi.org/10.5281/zenodo.20085666). Limited to results for living biomass, they were also available via FAOSTAT (FAO, 2026).

3. Results

We provided below a synthesis of the new FAO dataset, by presenting results aggregated at World, Annex I (AI) and non-Annex I (NAI) levels, as well as by FAOSTAT 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 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 Global and regional results

3.1.1 FAO estimates

The FAO data showed increasing carbon stocks, hence negative carbon stock change fluxes, for all FRA periods except for 1990-2000, indicating that since the year 2000 forests acted globally as net sinks of atmospheric CO_2, sequestering up to -1.8 Gt CO_2 yr^{-1} on average in 2020-2025—the most recent period in the FAO estimates (Tab. 4). The two separate components of *CSC* defined earlier further showed strong carbon sequestration on remaining forest land, with *FL* removals of up to -5.7 Gt CO_2 yr^{-1}, compared to losses from net forest conversion, *NFC*, 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 AI and positive for NAI countries. Regional values showed opposite trends, with *CSC* in the Americas and Africa, indicating net emissions 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.

With respect to emissions from net forest conversion, the FAO estimates showed substantial decreases 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 3a). This trend was almost entirely driven by NAI countries, 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, the FAO results showed substantial carbon sinks on remaining 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. 3a). 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 were stronger in AI countries. Results showed consistent regional sinks over the study period except for Africa. Specifically, Europe, Asia and the Americas had large sinks on forest land, with Europe the most substantial at about -2 Gt CO_2 yr^{-1} in 2020-2025. Additionally, the FAO data suggested opposite regional trends, with decreased 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.

		1990-2000			2000-2010			2010-2020			2020-2025		
		FAO1	FAO2	FAO3	FAO1	FAO2	FAO3	FAO1	FAO2	FAO3	FAO1	FAO2	FAO3
CSC	**World**	1.1	0.9	0.7	-0.8	-1.5	-3.0	-1.4	-1.9	-2.9	-0.8	-1.1	-1.8
	AI	-2.4	-2.7	-3.4	-2.5	-3.1	-4.2	-2.1	-2.4	-3.3	-1.7	-1.9	-2.5
	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	-3.6	-4.2	-5.7
	AI	-2.7	-3.1	-4.0	-2.6	-3.3	-4.5	-2.3	-2.6	-3.6	-1.8	-2.2	-2.9
	NAI	-1.4	-1.7	-2.4	-1.4	-1.8	-2.9	-1.9	-2.4	-3.1	-1.8	-2.1	-2.8

3.1.2 Comparisons to UNFCCC data

We compared FAO *NFC* and *FL* results to the UNFCCC data collected and re-disseminated within the same dataset presented in this work. In order to provide a consistent basis for comparison, we re-computed World, AI and NAI aggregates limited to 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 analyses (Grassi et al., 2022; Melo et al., 2025). Results of both timeseries comparison and long-term averages indicated good agreement of FAO estimates and UNFCCC data—with the range of FAO models consistently including the corresponding UNFCCC values—across all items (NFC, FL) and group (World, AI, NAI) combinations, except for *FL* fluxes for the NAI aggregate. Within the underlying 50% uncertainties making all results presented herein not statistically different, our results 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 countries reporting zero carbon stock change densities to FAO via the FRA.

Figure 3a. World total 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.

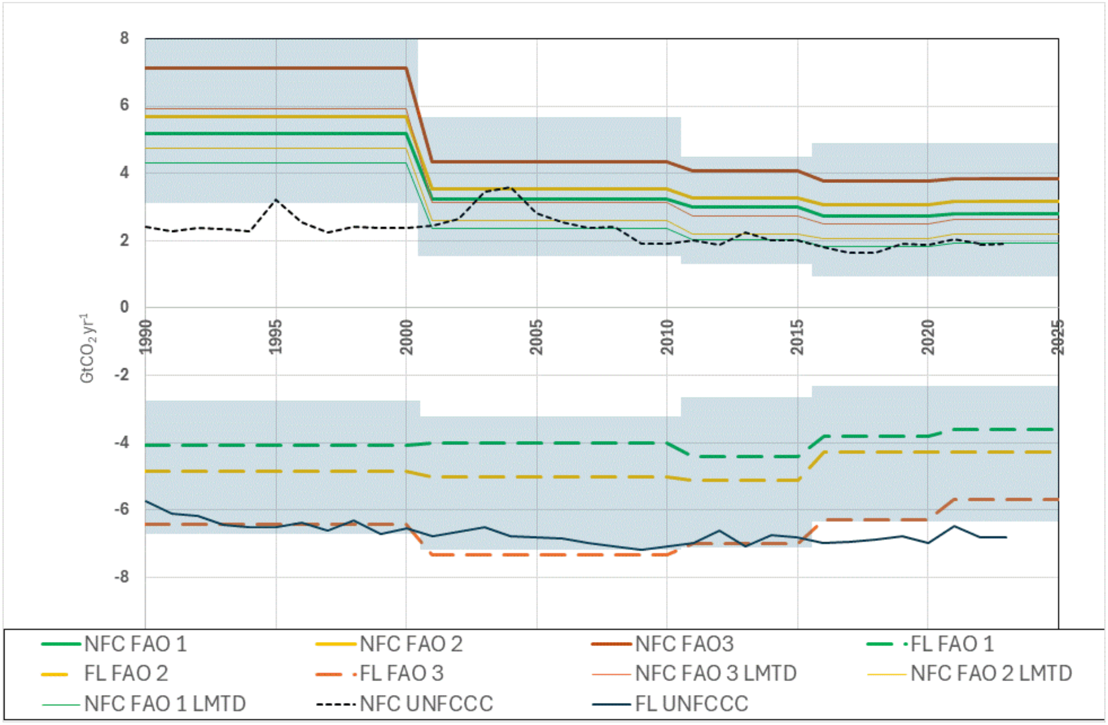


Figure 3b. AI aggregates of net forest emissions/removals estimates, 1990-2025 for three FAO stock change models and global coverage. UNFCCC and FAO LMTD aggregates limited to UNFCCC reporting countries. Shaded areas represent 50% uncertainty (95% CI) around the intermediate FAO 2 model.

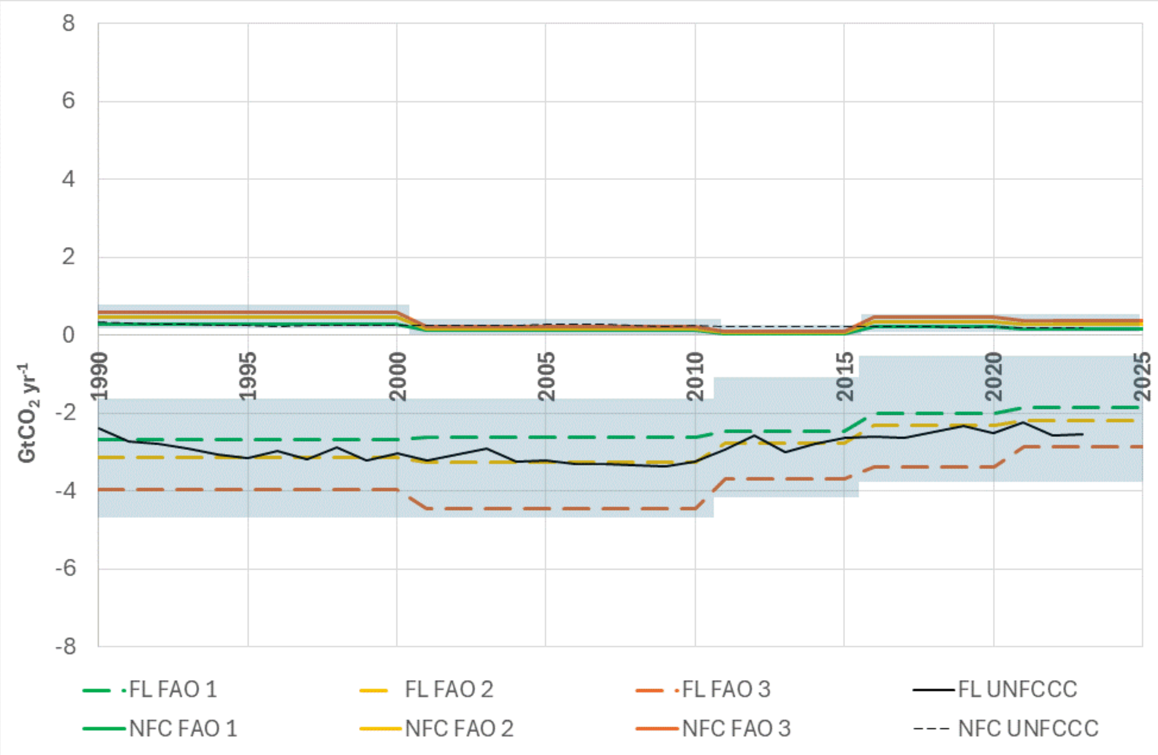


Figure 3c. NAI aggregates of net forest emissions/removals estimates, 1990-2025 for three FAO stock change models and global coverage. UNFCCC and FAO LMTD aggregates limited to UNFCCC reporting countries. Shaded areas represent 50% uncertainty (95% CI) around the intermediate FAO 2 model.

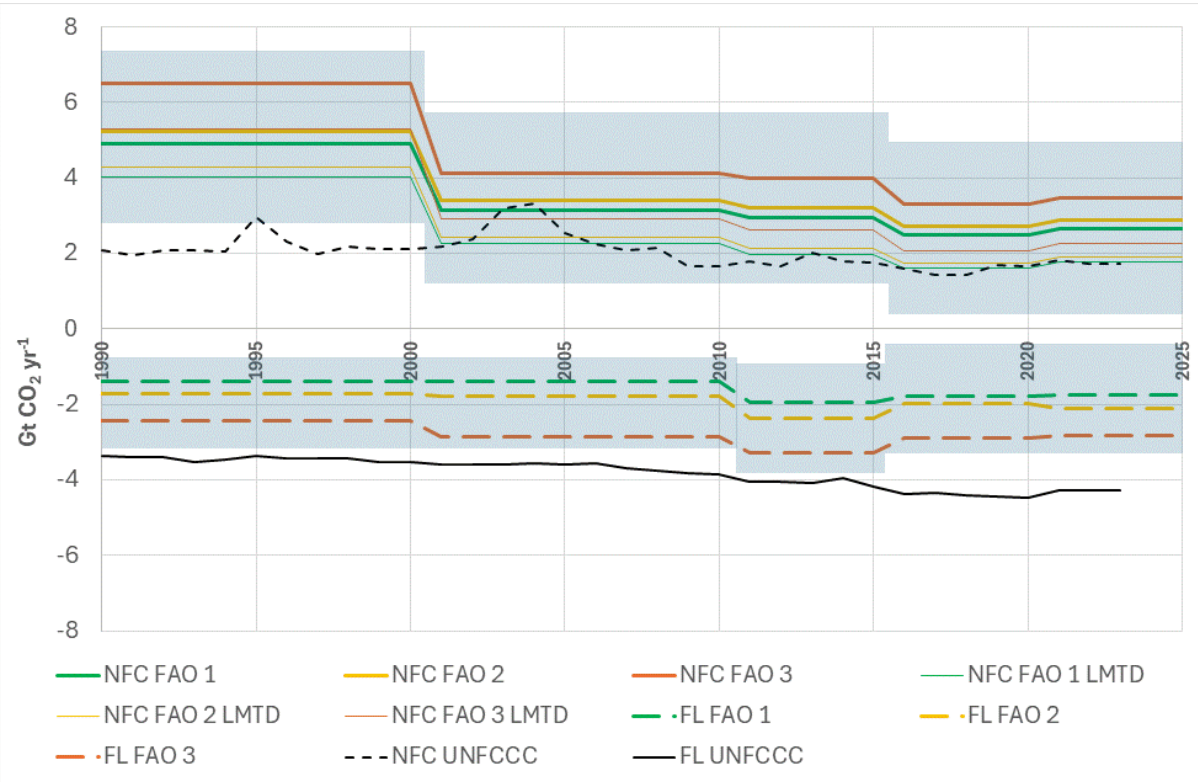


Table 5. Comparison of FAO net forest emission/removal estimates and UNFCCC country data, by world, Annex I (AI) and non-Annex I (NAI) aggregate groups, 2001-2023 averages (Gt CO_2 yr^{-1}). The column n (%) indicates the number of countries included in the analysis based on UNFCCC reporting, and their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

Item	Group	n (%)	FAO 1	FAO 2	FAO 3	UNFCCC
NFC	World	81 (42%)	2.1	2.3	2.8	2.2
	AI	42 (100%)	0.1	0.2	0.3	0.2
	NAI	39 (25%)	2.0	2.2	2.6	2.0
FL	World	134 (69%)	-3.9	-4.7	-6.7	-6.9
	AI	42 (100%)	-2.3	-2.8	-3.9	-2.9
	NAI	92 (60%)	-1.6	-1.9	-2.8	-4.0

3.2 Country results

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

Table 6. Top ten net forest conversion fluxes, 2001-2023 averages (Gt CO_2 yr^{-1}). Ordered by UNFCCC values.

Country	FAO 1	FAO 2	FAO 3	UNFCCC
Brazil	1.2	1.3	1.5	0.97
DRC	0.34	0.36	0.50	0.57
Indonesia	0.03	0.03	0.05	0.16
USA	0.02	0.03	0.05	0.10
Côte d'Ivoire	0.05	0.05	0.05	0.06
Australia	0.03	0.04	0.05	0.05
Argentina	0.09	0.10	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

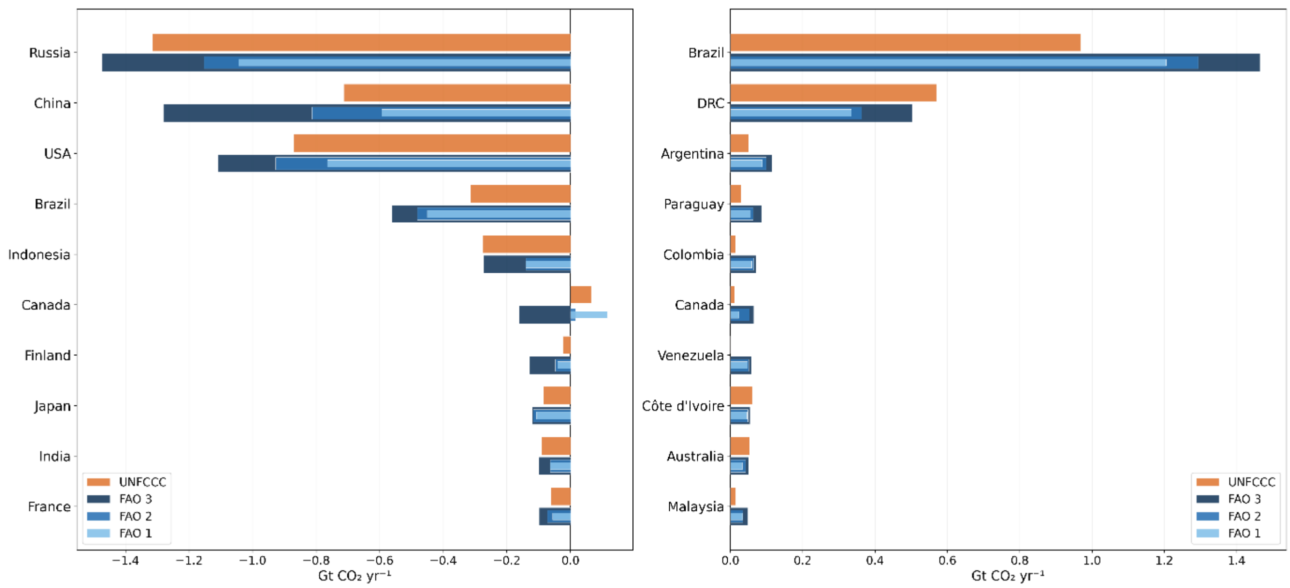
Furthermore, FAO estimates were consistent with UNFCCC data for Brazil, Cote d'Ivoire, Australia and Ecuador. Conversely they were smaller than UNFCCC for DRC, Indonesia and United States of America (USA), while they were larger for Argentina, Paraguay and Malaysia. Additionally, the FAO dataset included 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 to 70-80% (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 are further investigated in the Discussion. Finally, the FAO estimates identified important forest sink countries that did not appear within the UNFCCC top ten (Fig. 4), 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 removals on forest land, 2001-2023 averages (Gt CO_2 yr^{-1}). Ordered by UNFCCC values.

Country	FAO 1	FAO 2	FAO 3	UNFCCC
Russia	-1.1	-1.2	-1.5	-1.3
USA	-0.8	-0.9	-1.1	-0.9
China	-0.6	-0.8	-1.3	-0.7
DRC	0.0	-0.0	-0.0	-0.3
Mali	0.0	0.0	0.0	-0.3
Brazil	-0.5	-0.5	-0.6	-0.3
Venezuela	0.0	-0.0	-0.0	-0.3
Indonesia	-0.1	-0.1	-0.3	-0.3
Malaysia	-0.0	-0.0	-0.1	-0.2
Mexico	-0.0	-0.1	-0.1	-0.2

Figure 4. Comparison of FAO and UNFCCC country data for top 10 *NFC* emissions and *FL* removals, 2001-2023 averages.



4. Discussion

Notwithstanding the uncertainty considerations highlighted earlier, we performed additional country-level analyses to better characterize the 'sink gap' identified earlier between the FAO and UNFCCC data on forest removals in NAI countries, amounting to roughly 1 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 this aggregate NAI gap was driven by 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 (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, Brazil, Nigeria and China, for which FAO removals 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., 2025). 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 typologies could be readily identified, building on previous work (Grassi et al., 2022; Melo et al., 2025). For instance, our analysis showed that all of the six outlier countries in tropical Africa, corresponding to a UNFCC/FAO sink gap of 1 Gt CO_2 yr^{-1}, had conversely zero carbon stock density change in the FRA. Thus a first typology identified here was a potential data quality gap that could be further addressed by FAO through dedicated statistical capacity development programs, aimed at improving alignment between FAO and UNFCCC activity data. 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 and UNFCCC net emissions/removals on forest land (2001-2023 average), showing top differences for countries with removals greater than 0.1 Gt CO_2 yr^{-1}. FAO 3 results used for simplicity.

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

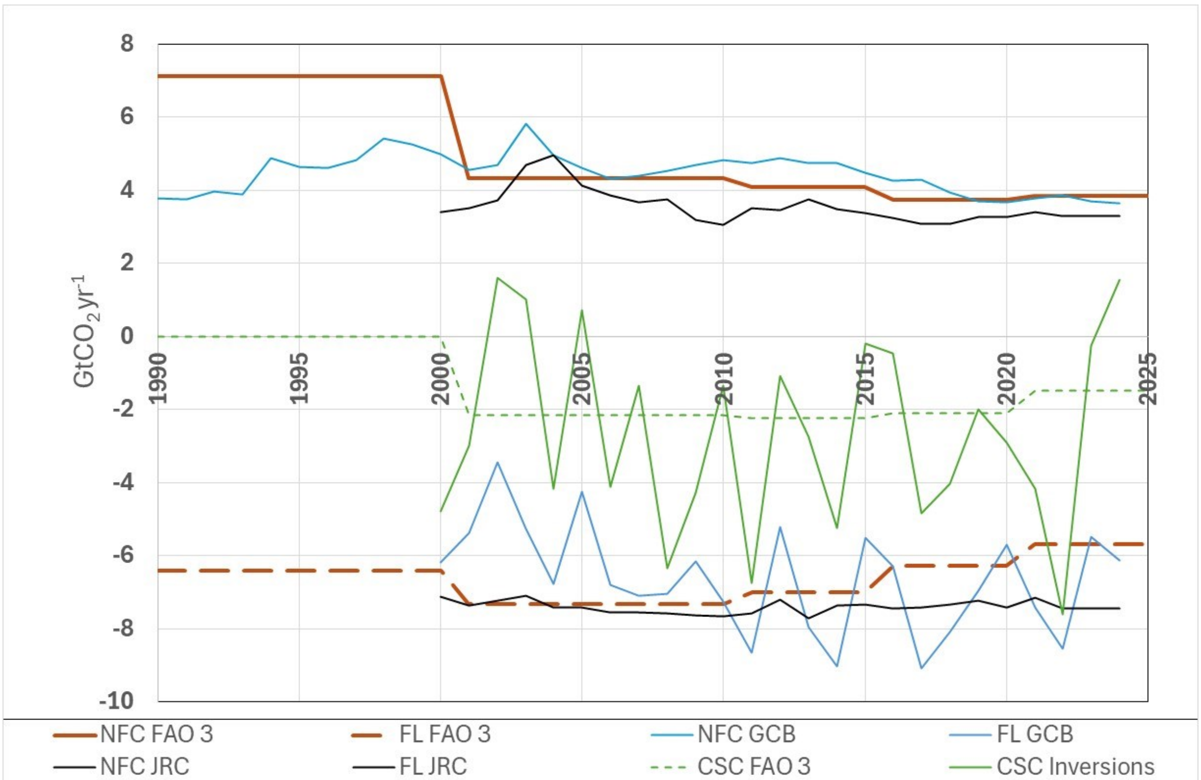
[a] Constant carbon stock density data in FRA

A second typology of discrepancy was related to land use boundary issues, specifically concerning UNFCCC country-reported managed forest areas that were larger than the corresponding FAO total forest land area (see also methods). Namibia exemplified such case perhaps in the extreme. In this country, accounting for forest carbon sinks on woody savannah encroachments areas (Stevens et al., 2017; IPCC, 2022), 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 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 discussed in the literature (Grassi et al., 2022). We showed earlier (see methods) that available UNFCCC and FRA statistics indicate that only a few large countries fit this typology. Among these, Brazil was perhaps the most extreme, reporting to UNFCCC managed land areas that were about 60% smaller than the FAO forest land area. We found that proportionally adjusting the FAO removal estimates by this proportion was sufficient to align FAO and UNFCCC removals.

These typologies could be used to guide dedicated statistical programs in countries as discussed. At the same time, the fact that the discrepancies between FAO and UNFCCC data were concentrated in a handful of countries suggested that the underlying forest activity data were already aligned for most other countries.

With the above increased understanding, which pointed to specific country differences within an overall credible global assessment, we further tested the FAO global forest net emissions/removals estimates against the most recent Global Carbon Budget (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 for both *NFC* and *FL* fluxes were in very close agreement with the independent estimates published within the GCB (Fig. 5), the latter indicating world total deforestation emissions of roughly 4 Gt CO_2 yr^{-1}, counterbalanced by forest removals of 6-7 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 carbon stock change estimates to datasets published in GCB (Friedlingstein et al., 2025): JRC: gap-filled NGHGI data; GCB: Bookkeeping models for NFC and adjusted DGVMs for FL; Inversions: net land carbon stock change from atmospheric inversions.



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.

5. Conclusions

We provided a detailed analysis based on the most recent FRA 2025 data to show that the FAO net forest emissions and removals dataset 1990-2025 continue to represent a useful benchmarking tool in support of country reporting processes and a solid contributor to global assessments. First, we showed that land use boundary issues, while conceptually important in distinguishing FAO and UNFCCC data, were less important than suggested in current literature. We found that in practice, most countries reported managed forest areas to UNFCCC that were larger or equal to, not smaller than, total forest land area reported to FAO. Hence flux estimates made on the entire forest land area could be considered anthropogenic in the sense of the IPCC land use proxy, increasing comparability of FAO and UNFCCC reporting. Secondly, we found a substantial agreement of the new FAO estimates with recent 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 future work to improve national, regional and global assessments, the large 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 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 and disseminate forest and land use statistics from its member countries. Our ultimate goal was and remains to improve the quality and comparability of country data submitted to relevant international processes in support of improved evidence-based decision making on climate change and forests.

Authors' contributions. FT 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.

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

Acknowledgments. This work was made possible by the FAO regular budget. The views expressed in this publication are those of the authors and do not necessarily reflect the views or policies of FAO.

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

References

Araza, A., Herold, M., de Bruin, S., Ciais, P., Gibbs, D. A., Harris, N., Santoro, M., Wigneron, J.-P., Yang, H., Málaga, N., et al.: Past decade above-ground biomass change comparisons from four multi-temporal global maps, Int. J. Appl. Earth Obs. Geoinf., 118, 103274, https://doi.org/10.1016/j.jag.2023.103274, 2023.

BIPM, IEC, IFCC, ILAC, ISO, IUPAC, IUPAP, and OIML: Guide to the expression of uncertainty in measurement. Joint Committee for Guides in Metrology, JCGM 100, https://www.bipm.org/documents/20126/2071204/JCGM_100_2008_E.pdf, 2008.

FAO: Global Forest Resources Assessment 2025. Rome. Available at: https://doi.org/10.4060/cd6709en, 2025a

FAO: FAOSTAT Emissions from Forests. Available at http://www.fao.org/faostat/en/#data/GF. FAO, Rome, Italy, 2025b

FAO: Land statistics 2001–2023: Global, regional and country trends. FAOSTAT Analytical Brief Series No. 107. Rome. https://doi.org/10.4060/cd5765en., 2025c.

FAO: The State of the World's Forests 2024 – Forest-sector innovations towards a more sustainable future. Rome, FAO. https://doi.org/10.4060/cd1211en, 2024.

FAO: Greenhouse gas emissions from agrifood systems. Global, regional and country trends, 1990–2020. FAOSTAT Analytical Brief Series No. 50. Rome. Available at https://doi.org/10.4060/cc5768en, 2022.

FAO. *Global Forest Resources Assessment 2020: Main report.* Rome. https://doi.org/10.4060/ca9825en, 2020.

Federici, S., Tubiello, F. N., Salvatore, M., Jacobs, H., & Schmidhuber, J.: New estimates of CO_2 forest emissions and removals: 1990–2015, *Forest Ecology and Management*, 352, 89-98, 2015.

Friedlingstein, P., et al.: Global Carbon Budget 2025, Earth Syst. Sci. Data Discuss. [preprint], https://doi.org/10.5194/essd-2025-659, in review, 2025.

Grassi, G., Conchedda, G., Federici, S., Abad Viñas, R., Korosuo, A., Melo, J., Rossi, S., Sandker, M., Somogyi, Z., Vizzarri, M., and Tubiello, F. N.: Carbon fluxes from land 2000–2020: bringing clarity to countries' reporting, Earth Syst. Sci. Data, 14, 4643–4666, https://doi.org/10.5194/essd-14-4643-2022 , 2022.

Grassi, G., Schwingshackl, C., Gasser, T., Houghton, R. A., Sitch, S., Canadell, J. G., Cescatti, A., Ciais, P., Federici, S., Friedlingstein, P., Kurz, W. A., Sanz Sanchez, M. J., Abad Viñas, R., Alkama, R., Bultan, S., Ceccherini, G., Falk, S., Kato, E., Kennedy, D., Knauer, J., Korosuo, A., Melo, J., McGrath, M. J., Nabel, J. E. M. S., Poulter, B., Romanovskaya, A. A., Rossi, S., Tian, H., Walker, A. P., Yuan, W., Yue, X., and Pongratz, J.: Harmonising the land-use flux estimates of global models and national inventories for 2000–2020, Earth Syst. Sci. Data, 15, 1093–1114, https://doi.org/10.5194/essd-15-1093-2023, 2023.

IPCC: 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, edited by: Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize, S., Osako, A., Pyrozhenko, Y., Shermanau, P., and Federici, S., IPCC, Switzerland, 2019.

IPCC, FAO, IFAD: Emerging activities to combat climate change – use of FAO data and IPCC GHG Inventory Guidelines for Agriculture and Land Use. Eds: Tubiello, F.N., Neeff, T., Tanabe, K., Baasansuren, J. and Fukuda, M. Report of the joint FAO-IPCC-IFAD Expert Meeting, Pub. IGES, Japan, 2015.

Lamb, W. F., Andrew, R. M., Jones, M., Nicholls, Z., Peters, G. P., Smith, C., Saunois, M., Grassi, G., Pongratz, J., Smith, S. J., Tubiello, F. N., Crippa, M., Gidden, M., Friedlingstein, P., Minx, J., and Forster, P. M.: Differences in anthropogenic greenhouse gas emissions estimates explained, Earth Syst. Sci. Data, 18, 2549–2572, https://doi.org/10.5194/essd-18-2549-2026, 2026.Mozafari, M., Alemohammad, S. H., and Gentine, P.: Regional carbon flux estimation using remote sensing and machine learning, *Biogeosciences*, 20, 1205–1220, https://doi.org/10.5194/bg-20-1205-2023, 2023.

Nabuurs, G-J., R. Mrabet, A. Abu Hatab, M. Bustamante, H. Clark, P. Havlík, J. House, C. Mbow, K.N. Ninan, A. Popp, S. Roe, B. Sohngen, S. Towprayoon: Agriculture, Forestry and Other Land Uses (AFOLU). In IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change[P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926.009, 2022.

Stevens, N., Lehmann, C. E. R., Murphy, B. P., and Bond, W. J.: Savanna woody encroachment is widespread across three continents, *Glob. Change Biol.*, 23, 235–244, https://doi.org/10.1111/gcb.13409, 2017.

Tubiello, F.N., Obli-Laryea, G.: New FAO net forest emissions/removals 1990-2025, available at Zenodo, DOI . 10.5281/zenodo.20085666, 2026.

Tubiello, F.N., Conchedda, G., Casse, L. *et al.*: Measuring the world's cropland area, *Nat Food* 4, 30–32, https://doi.org/10.1038/s43016-022-00667-9, 2023.

Tubiello, F. N., Conchedda, G., Wanner, N., Federici, S., Rossi, S., and Grassi, G.: Carbon emissions and removals from forests: new estimates, 1990–2020, Earth Syst. Sci. Data, 13, 1681–1691, https://doi.org/10.5194/essd-13-1681-2021, 2021.

UNFCCC, 2026. GHG data from UNFCCC, available at: https://unfccc.int/topics/mitigation/resources/registry-and-data/ghg-data-from-unfccc. Last visited on March 15 2026.