

Carbon Emissions and Removals from Forests: New Estimates, 1990 2020

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Abstract. National, regional and global CO₂ emissions and removals from forests were estimated for the period 1990–2020, using as input the country reports of the Global Forest Resources Assessment 2020. The new FAO estimates, based on a simple carbon stock change approach, update published information on net emissions and removals from forests in relation to: a) net forest conversion; and b) forest land. Results show a significant reduction in global emissions from net forest conversion over the study period, from a mean of 4.3 in the 1991–2000 to 2.9 Gt CO₂ yr⁻¹ in 2016–2020. At the same time, forest land was a significant carbon sink globally, but decreasing in strength over the study period, from -3.5 to -2.6 Gt CO₂ yr⁻¹. Combining net forest conversion with forest land, our estimates indicated that globally forests were a small net source of CO₂ to the atmosphere on average during 1990–2020, with mean net emissions of 0.4 Gt CO₂ yr⁻¹. The exception was the brief period 2011–2015, when forest land removals counterbalanced emissions from net forest conversion, resulting in a global net sink of -0.7 Gt CO₂ yr⁻¹. Importantly, the new estimates allow for the first time in the literature to characterize forest emissions and removals for the decade just concluded, 2011–2020, showing that in this period the net contribution of forests to the atmosphere was very small, i.e., a sink of less than -0.2 Gt CO₂ yr⁻¹— an estimate not yet reported in the literature. This near-zero balance was nonetheless the result of large global fluxes of opposite sign, namely net forest conversion emissions of 3.1 Gt CO₂ yr⁻¹ counterbalanced by net removals on forest land of -3.3 Gt CO₂ yr⁻¹. Finally, we compared our estimates with data independently reported by countries to the United Nations Framework on Climate Change, indicating close agreement between FAO and country emissions and removals estimates. Data from this study are openly available via the Zenodo portal (Tubiello, 2020), with DOI <https://10.5281/zenodo.3941973>, as well as on the FAOSTAT Emissions database (FAO, 2021).

1 Introduction

Emissions from agriculture, forestry and other land uses represent nearly a quarter of world total anthropogenic emissions (Smith et al., 2014; IPCC 2019). Importantly, the CO₂ component of these emissions is generated on land at the margin between farm and natural ecosystems, largely in relation to processes that convert land for agricultural use, such as deforestation and

1 drainage of peatlands, generating roughly 4-5 Gt CO₂ yr⁻¹ in recent decades (e.g., Tubiello, 2019). Additional important
2 anthropogenic emissions and removals of CO₂ are located directly on forest land, in relation to processes linked to forest
3 management or degradation.

4 There is nonetheless significant disagreement between carbon cycle models on the one side, and national greenhouse gas
5 inventories (NGHGI) on the other, on the quantification of the combined emissions and removals of CO₂ from all these land
6 processes, though it is being increasingly shown that most differences are due to boundaries and definitional issues (e.g., Grassi
7 et al., 2018; 2021). Greatly simplifying and limiting our scope to forests, terrestrial carbon cycle models have tended to focus
8 on the CO₂ emissions from deforestation and forestry activities (land use change processes defined under the term ELUC), while
9 NGHGI have typically added removals on forest land beyond those linked to forestry practices, which the models tend not to
10 consider anthropogenic. These forest removals in NGHGI counterbalance the positive emissions, resulting in near-zero
11 estimated total net contributions of forests to the atmosphere (Grassi et al., 2018). Beyond the critical issues of the differences
12 in boundaries and definitions between the two approaches, which are addressed elsewhere (e.g., Grassi et al., 2021), there is a
13 significant need to improve the underlying activity input data used by both approaches. To this end, the Food and Agriculture
14 Organization of the United Nations (FAO) collects, analyses and disseminates at regular intervals a wealth of country-based
15 forest statistics through its Global Forest Resources Assessment (FRA), describing the status of forests with data at country,
16 regional and global level (FAO, 2020a). FRA activity data of forest land area and carbon stock serve as critical inputs for
17 estimates of forest carbon fluxes by FAO (Federici et al., 2015; FAO, 2020b) and other major international efforts (e.g.,
18 Friedlingstein et al., 2019; IPCC, 2019; Houghton and Nassikas, 2017). This paper describes the forest statistics available at
19 FAO to estimate emissions and removals of CO₂ from forests that, being based on a simple though powerful (and replicable)
20 carbon stock change method, generate data that can serve as boundary conditions to help evaluate more complex terrestrial
21 carbon model results and NGHGI data. Our analysis highlights new trends based on the use of FRA 2020 input data,
22 documenting the differences with respect to the previous use of FRA 2015. Finally, it compares results to national data
23 independently reported by countries to the United Nations Framework Convention on Climate Change (UNFCCC).

24 **2 Material and Methods**

25 The estimates of CO₂ emissions and removals from forests made by FAO and published in FAOSTAT (FAO 2020b) are
26 computed by applying a simplified carbon stock change method based on the 2006 IPCC Guidelines for National Greenhouse
27 Gas Inventories (IPCC, 2006). Previous estimates covered the period 1990-2015, using as inputs activity data from the FRA
28 2015 (Federici et al., 2015). This work extends the FAO estimates of emissions and removals to 2020, by adding new input
29 data for the period 2015-2020, while incorporating any revision in time series that may have occurred in the FRA 2020 with
30 respect to FRA 2015. In describing the methods used in this work, we also discuss their limitations and uncertainties and the
31 scope for comparing FAO estimates to UNFCCC country data.

32

2.1 Gap-filling

The FRA 2020 data used herein are: *forest land* area, as a total and for its two sub-categories, i.e., *Naturally regenerating forest* area (including both primary and secondary forest) and *Planted forest area*; and carbon stock in above and below-ground living biomass. Data cover the period 1990-2020. We gap-filled missing carbon stock data when needed, by using relevant regional averages of carbon stock density (carbon stock per unit forest land area), multiplied by country forest land area. Additionally, we checked the consistency of forest land area values against its two sub-components. In the few cases when such consistency was violated, we re-computed *naturally regenerating forest* area as the difference between *forest land* and *planted forest* area. The slightly revised dataset was used as input into the emissions calculations. It is openly available via the Zenodo portal (Tubiello, 2020), with DOI <https://10.5281/zenodo.3941973>, as well as via the FAOSTAT database (FAO, 2020a).

2.2 Forest Definition

The term *forest land* used herein follows the international FAO land use definitions (FAO, 2020b), also adopted by the UN system for environmental economic accounting (SEEA AFF, 2020), based on the FRA. As a land use category, the FAO definition of *forest land* comprises areas under forestry production, forest conservation including natural parks, and in general any area regulated administratively in terms of destination and use, including unmanaged forests, as long as three basic biophysical conditions are met, namely: i) minimum tree height of 5 m at maturity; ii) overall crown cover greater than 10%; and iii) minimum 0.5 ha in extension. (for complete definitions see, e.g., the FAO Land Use questionnaire, <http://www.fao.org/economic/ess/ess-home/questionnaires/en/>).

Countries reporting forest land data to FAO are expected to adhere to the above definitions and explicitly present how the conversion from national land use categories to the FAO categories was done. However, the uncertainty of the related area and stock estimates remains largely unreported. The magnitude of these uncertainties can vary significantly depending on the underlying estimation and/or mapping methodology. It has been recently shown that estimates based on land use and land cover information derived from remote sensing can result in differences of up to 20% at regional level, largely due to the difficulty of mapping land cover characteristics to land use status (FAO, 2020c). For well-defined forest land areas, typical uncertainties in national forest inventories may be nonetheless an order of magnitude smaller. For lack of additional knowledge of how uncertainty in local measurements carried out at national to regional levels, we applied the generic uncertainty suggested by IPCC for FAO activity data (20%) to the forest land area and biomass stock data used in this work.

In terms of comparison with UNFCCC data, we note that the FAO forest land use definitions used herein may differ from those used by countries for reporting their national GHG inventories (NGHGI), for instance in relation to minimum forest area thresholds or in criteria to assign land use status. Furthermore, country reporting to UNFCCC of emissions and removals data is limited to areas of managed forest, as per IPCC guidelines, while the FAO land use definitions comprise both managed and unmanaged forests, as discussed above. In practice, such differences may often be small, considering that a large portion of

1 the world's forest land area in many countries is administratively regulated. Finally, we note that the FAO forest land area
 2 considered herein does not track separately, as done instead in UNFCCC reporting, the two- sub-components *forest land*
 3 *remaining forest land* (FL-FL) and newly converted forest land. This is often overlooked in the literature, where FAO estimates
 4 of forest land emissions and removals may be incorrectly compared to UNFCCC data for FL-FL (e.g., Petrescu et al., 2020).

6 **2.3 Emissions and Removals**

7 The estimates presented herein provide information on total net emissions and removals from forests, in total as well as by
 8 component processes. Specifically, for each country a and total carbon stock B_a , the total forest emissions/removals, ER_a , were
 9 computed as a simple carbon stock change, as follows:

$$11 \quad ER_a(t_i) = - \Delta C_a(t_i) = - [B_a(t_i) - B_a(t_{i-1})] = NFC_a(t_i) + FL_a(t_i) \quad (1)$$

12
 13 Where biomass stock information was derived from the FRA 2020 as indicated in the previous section, and $t_i = 1990, 2000,$
 14 $2010, 2015, 2020$ represent FRA years. The minus sign was used to adhere to the convention of considering emissions as
 15 positive fluxes to the atmosphere, corresponding to decreases in forest carbon stock— and vice-versa to consider removals as
 16 negative fluxes, i.e., from the atmosphere into forest land, corresponding to increases in forest carbon stock. We note that the
 17 estimates in equation (1) are robust as well as easily replicable by anyone having access to FRA data. At the same time, it is
 18 noted that the FAO carbon stock change estimates include only two of the five carbon pools typically reported by countries
 19 according to IPCC. This difference may affect the magnitude of the estimated C stock changes, although likely not the sign,
 20 because of biophysical linkages across carbon pools. The net forest signal to the atmosphere, ER , was split into two mutually
 21 exclusive components, specifically emissions from *net forest conversion*, NFC , and emissions/removals from *forest land*, FL
 22 (Fig. 1).

24 **2.3.1 Emissions from Net Forest Conversion**

25 For each country a , total carbon stock B_a , and time period t_i , the emissions from *net forest conversion*, $NFC_a(t_i)$ in equation (1)
 26 were computed as the positive carbon flux to the atmosphere associated with net forest land area loss, tracked separately for
 27 sub-categories *naturally regenerating forest*, NR_a , and planted forest, PL_a as follows:

$$29 \quad NFC_a(t_i) = - [B_a(t_i)/A_a(t_i)] * \{ \text{Min} [NR_a(t_i) - NR_a(t_{i-1}), 0] + \text{Min} [PL_a(t_i) - PL_a(t_{i-1})], 0 \} \quad (2)$$

31 Thus net forest conversion tracks losses of both naturally regenerating (including primary and secondary forests) and planted
 32 forest areas. It should be noted that in cases when net forest land area change is positive, indicating net area gains, NFC is zero
 33 by definition and the relevant emissions/removals are instead accounted for on forest land (see next section). A number of

1 limitations apply to the computation of emissions in (2), First, results are limited by the lack of carbon stock data by forest
2 sub-component, resulting in the need to apply a single value for both naturally regenerating forest and planted forest.
3 Considering that the majority of forest area losses in the FRA 2020 pertain to the natural forest component, however, the use
4 of a single carbon density value in (2) is not a significant issue to this end. At the same time, carbon stock density can be
5 expected to be higher in natural forests than the average biomass stock (which also includes carbon stock in plantations),
6 implying that the NFC emissions computed in (2) are likely underestimates. Furthermore, we note that equation (1) above does
7 not depend on the availability of carbon stock values by forest sub-component. A second important limitation to equation (2)
8 is that forest losses are computed net of forest area gains taking place over the same period. The underlying activity data used
9 as input do not in fact allow separate tracking of gross gains and losses. Thus in terms of comparison to UNFCCC, FAO *net*
10 *forest conversion* data would roughly correspond to the sum of UNFCCC-reported land use changes from forest land to non-
11 forest land, for those countries using the so-called ‘IPCC approach 1’ to land use representation, which like our estimates relies
12 on net area changes. By contrast, use of more accurate national forest inventories, with more detailed identification of gross
13 area fluxes, would generate larger differences between FAO estimates and the corresponding UNFCCC country data for this
14 category. Finally and importantly, estimates in equation (2) are limited by the underlying uncertainty in the activity data.
15 Simple error propagation of the component uncertainties in area and carbon stock discussed in the previous section give an
16 uncertainty in NRC emissions of roughly 50%. This is consistent with values used for land use change emissions estimates
17 published in recent IPCC reports (IPCC, 2019) and in relevant carbon cycle literature (Friedlingstein et al., 2019). For
18 coherence, we applied this uncertainty value to ER and FL estimates.

19

20 **2.3.2 Emissions and Removals on Forest Land**

21 For any country a , total carbon stock B_a , and time period t_i in equations (1) and (2) above, the emissions/removals on *forest*
22 *land*, $FL_a(t_i)$, were computed as the residual between total forest carbon stock change and net forest conversion, as follows:

23

$$24 \quad FL_a(t_i) = ER_a(t_i) - NFC_a(t_i) \quad (3)$$

25

26 The emissions/removals computed in (3) represent the net carbon flux to or from the atmosphere located within the boundaries
27 of forest land area, arising from a combination of carbon stock and forest area changes between successive FRA periods. These
28 changes in principle may arise from both anthropogenic and natural causes, including legacy effects of deforestation prior to
29 the study period, afforestation, forest management, climate signals, as well as the impacts on plant growth of nitrogen
30 deposition and increased atmospheric CO₂ concentrations. As discussed above, we associated an uncertainty level of 50% to
31 estimates in equation (3), consistently with those computed for the emissions from net forest conversion and in line with the
32 uncertainty used in the literature.

1 Within the differences highlighted above, with regards to land accounting approaches and differences in national forest
2 definitions, the FAO emissions/removals on *forest land* largely correspond to those used by countries in their reporting to
3 UNFCCC with respect to forest land.
4

5 **2.4 Comparisons to UNFCCC data**

6 A final consideration on the limitations of the approach presented herein concerns the underlying drivers of the
7 emissions/removals estimates, i.e., whether they could be labelled as anthropogenic or natural fluxes. On the one hand, the
8 definitions underlying equation (1)-(3) make the association impossible within our approach. On the other, a bit more can be
9 said in practice. This is because human intervention is typically required to determine land use changes—for instance the
10 establishment of specific activities, for instance agriculture, preventing natural forest regrowth and recovery following forest
11 loss. To this end, and within the limitations discussed above, *net forest conversion*, representing permanent forest loss in the
12 FAO statistics, can be considered virtually all anthropogenic in nature, hence a good proxy for human-driven deforestation.
13 Conversely, only a portion of the emissions/removals estimated on forest land can be considered anthropogenic. At the same
14 time, recent work shows that the anthropogenic portion of this component can be substantial, once the concept of ‘managed
15 land’ is expanded beyond forestry practices to include all forest areas except in very remote places (Grassi et al., 2021).
16 Nonetheless, because of the above complexities, we chose not to determine *a priori* the anthropogenic portion of our
17 emissions/removals estimates. Instead, we complemented our analysis of results with a comparison between our estimates of
18 emissions and removals and the anthropogenic fluxes submitted by countries to UNFCCC. In this context, although it is
19 recognized that countries report data to both FAO and UNFCCC, we reserve herein the term ‘country data’ to the
20 emissions/removals reported by countries to the UNFCCC.

21 To this end, we used country data accessed at the UNFCCC data portal (UNFCCC, 2020) and complemented with information
22 from national Biennial Update Reports (BURs). While data from Annex I countries (AI) are fairly complete over the period
23 1990– 2018, data from non-Annex I (NAI) countries are sparse, although becoming increasingly available through BURs.
24 Given these data limitations, a full comparison was possible only for Annex I countries for the FRA periods 1990–2000; 2001–
25 2010; and 2011– 2015. First, we compared results of equation (3) with aggregate Annex I reporting of emission/removal for
26 the category ‘4.A Forest land’ (UNFCCC, 2020). To gain further insights, we also separately analyzed emissions/removals on
27 forest land reported by individual countries in their national GHG inventories (NGHGs), focusing on those reporting large
28 sinks, i.e., Canada, Russian Federation and the United States of America among Annex I parties, and China among non-Annex
29 I parties. We also compared our results for net forest conversion to available non-Annex I country data from Brazil and
30 Indonesia, representing large emission sources, according to FAOSTAT estimates respectively the first and third emitters in
31 this category (FAO, 2020b). Unfortunately, no BUR submissions have been made so far by the Democratic Republic of
32 Congo—the second largest emitter from deforestation according to FAOSTAT data—which therefore could not be included

1 in this comparison exercise. Data for NAI countries were sourced from China’s second Biennial Update Report (2018), Brazil’s
2 third Biennial Update Report (2019) and from Indonesia’s second Biennial Update Report (2018).

3 4 **2.5 Structure of the datasets on emissions-forest land and online access**

5 The FAO emissions and removals estimates and associated area information statistics are disseminated in the FAOSTAT
6 Emissions Land Use/ Forest Land domain as yearly statistics, over the period 1990–2020 (FAO, 2021), for 220 countries and
7 territories. Annual mean fluxes are obtained by dividing the outcomes of (1)-(3) by the relevant time-period underlying FRA
8 intervals, i.e., by 5 or 10 years. They therefore refer to the following periods: 1991–2000; 2001–2010; 2011–2015; and 2016–
9 2020. For completeness, values for the year 1990 were set equal to the averages computed for 1991–2000, and the full period
10 of analysis was referred to as 1990-2020. Data include, by country and year, forest land area and area of net forest conversion
11 (in 1000 ha), emissions from net forest conversion; emissions/removals on forest land; and total emissions/removals from
12 forests (in kt CO₂). The carbon stock in living biomass (in Mt C) is available under the FAOSTAT database, Inputs/Land Use
13 (FAO, 2020c). Data are disseminated by country, by standard FAO regional aggregations and special groups, including the
14 Annex I and non-Annex I country grouping relevant to UNFCCC reporting.

15 **3 Results**

16 We present below the main findings of annual CO₂ emissions/removals estimates from net forest conversion, forest land, and
17 their aggregate, total emissions and removals from forest, for the period 1990–2020, computed for more than 200 countries
18 and territories, based on equations (1)-(3) above. Emissions and removals are expressed in annual means (Gt CO₂ yr⁻¹) relative
19 to the relevant FRA period. Results are presented at global level, by Annex I and non-Annex I countries and by region, where
20 relevant. Differences with estimates based on earlier FRA 2015 input data are also discussed, where of interest.

21 22 **3.1 Emissions from Net Forest Conversion**

23 Results show that carbon fluxes to the atmosphere from *net forest conversion* were significant, with world-total means of 3.7
24 Gt CO₂ yr⁻¹ for the period 1990—2020, and almost entirely located in non-Annex I countries, which contributed more than 90
25 % of the world total (Table 1). In terms of temporal trends, the global mean decreased by 20% from 1990 to 2015, from 4.3 to
26 3.3 Gt CO₂ yr⁻¹, less than previously estimated over the same period using the FRA 2015 (-40 %). It decreased by another 10%
27 to 2.9 Gt CO₂ yr⁻¹ during 2016–2020. For the period 2016–2020, the Americas and Africa were nearly equal contributors, but
28 with markedly opposite trends compared to the period 1991–2000. Specifically with respect to the two time periods, emission
29 in the Americas nearly halved, from 2.2 to 1.3 Gt CO₂ yr⁻¹, while they increased in Africa, from 0.9 Gt to 1.1 CO₂ yr⁻¹. Asia

1 was the third region in terms of emissions from net forest conversion, showing a slight decrease, from 0.6 Gt to 0.4 CO₂ yr⁻¹
2 over the same time periods (Fig. 2).

4 **3.2 Emissions and removals on forest land**

5 Emissions/removals on forest land showed a net sink over the entire period 1990–2020, with a mean removal of -3.3 Gt CO₂
6 yr⁻¹ globally. This forest carbon flux was nearly equally divided between Annex I (-1.8 Gt CO₂ yr⁻¹) and non-Annex I countries
7 (-1.5 Gt CO₂ yr⁻¹) (Table 1). Additionally, we computed that the new FAO estimates indicated a stronger forest sink than
8 previously estimated using FRA 2015 data, i.e., on average 1.0 Gt CO₂ yr⁻¹ (35 %) stronger, due to larger estimated sinks in
9 Europe (dominated by trends in Russian Federation) and Asia (China).

10 At the same time, the estimated global forest land sink weakened in strength over the study period, with the world total mean
11 decreasing from -3.5 to -2.6 Gt CO₂ yr⁻¹, i.e., about 20 % decrease from 1990 to 2020. The period 2011–2015 represented an
12 exception to this decreasing trend, showing the strongest forest sink over the study period, with mean world total rates of -4.0
13 Gt CO₂ yr⁻¹. In terms of regional distribution and averaged over the period 1990–2020, Europe, the Americas and Asia nearly
14 equally contributed to the estimated forest land removals, within a narrow range of -1.0 to -1.2 Gt CO₂ yr⁻¹, with Europe
15 (including the Russian Federation) being the largest contributor. Conversely, forest land in Africa was a source to the
16 atmosphere, with mean emissions increasing significantly from 2000 to 2015, i.e., from 1.4 to 43 Mt CO₂ yr⁻¹ (Fig. 3). By
17 associating net forest land emission to forest degradation, as done in Federici et al. (2015), our results suggest a significant
18 relative increase in forest degradation (defined as carbon stock reduction in forest land) in Africa over the last twenty years.

19 **3.3 Total emissions and removals from forests**

20 Our estimates show that the net effects of emissions from net forest conversion and removals on forest land were a small net
21 source of CO₂ emissions to the atmosphere, with a world total mean of 0.4 Gt CO₂ yr⁻¹ over the 1990–2020 period. This new
22 estimated value was significantly less than reported earlier based on FRA 2015 data (Table 1). It is further of interest to note
23 that the estimated small global source was the result of a balance of larger fluxes: a net sink on forest land, largely located in
24 in UNFCCC Annex I countries (-1.5 Gt CO₂ yr⁻¹), counterbalanced by a net emission source from net forest conversion, mainly
25 in non-Annex I countries (1.9 Gt CO₂ yr⁻¹).

26 A more detailed analysis focusing on trends over time (Fig. 4) revealed two notable new findings of our analysis with respect
27 to previous results. First, the period 2015-2020 saw a reversal of the decreasing trend in non-Annex I sources and the increasing
28 trend in Annex I sinks seen for the period 1990 to 2015. Specifically, non-Annex I sources from net forest conversion began
29 to increase again in 2016-2020, from 1.3 to 1.6 Gt CO₂ yr⁻¹, while Annex I sinks on forest land began decreasing in strength,
30 from -2.0 to -1.3 Gt CO₂ yr⁻¹. Second, and remarkably, forests acted as a net overall sink of atmospheric CO₂ during 2011–
31 2015, averaging nearly -0.7 Gt CO₂ yr⁻¹, largely a result of decreased emissions from net forest conversion in this period,

1 counterbalanced by a strong sink on forest land. Conversely, FAO had previously estimated for the same period, based on FRA
2 2015 input data, a net emission source of 1.1 Gt CO₂ yr⁻¹ (Table 1).

4 **3.4 Comparisons with UNFCCC**

5 *Forest Land*

6 As discussed in the methodology section, we first compared our estimates of emissions/removals on forest land to data reported
7 by Annex I countries, i.e., for category “4.A Forest land” in their national GHG inventory (UNFCCC, 2020). In the aggregate,
8 e.g., summing up all country data and averaging over the period 1990–2015, our estimates agreed in both sign and magnitude
9 with the UNFCCC country data (14 % relative absolute error). Specifically, our estimates indicated a mean sink of -1.8Gt CO₂
10 yr⁻¹ vs -2.2 Gt CO₂ yr⁻¹ reported. Using the FRA 2015 in earlier work (Federici et al., 2015) had given a 33 % smaller sink
11 (Table 2). Our estimates were particularly well aligned with country reporting for the period 2010–2015, i.e., within 5 %,
12 predicting a sink on forest land of -2.1 Gt CO₂ yr⁻¹ vs -2.2 Gt CO₂ yr⁻¹ reported. As in the previous case, earlier sink estimates
13 based on the FRA 2015 were 40 % smaller (Fig. 5).

14 Comparisons of estimated emissions/removals on forest land for specific countries with large reported sinks confirmed the
15 good overall agreement found for Annex I parties in aggregate. For instance, on average over the period 1990–2015, our
16 estimates of forest land sinks for the Russian Federation were within 5 % of those reported by the country NGHGI. Agreement
17 with NGHGI data was even closer after the year 2000, i.e., for the period 2001–2010 our estimates indicated a mean sink on
18 forest land of -800 Mt CO₂ yr⁻¹ versus country data of -750 Mt CO₂ yr⁻¹, and a mean sink of -730 Mt CO₂ yr⁻¹ versus -680 Mt
19 CO₂ yr⁻¹ for the period 2011–2015 (Fig. 6). Comparisons for the USA were also encouraging, albeit with larger differences
20 than found for the Russian Federation. On average over the period 1991–2010, the FAO estimates were of a 25 % smaller sink
21 on forest land compared to the NGHGI country data. Averaged over the period 2011–2015 our estimates were 29 % smaller
22 than the country data, or -460 Mt CO₂ yr⁻¹ and -650 Mt CO₂ yr⁻¹, respectively.

23 We performed comparisons for China, using data from the country’s Second Biennial Update Report (2018), to extend our
24 analysis to non-Annex I countries reporting large sinks on forest land. Specifically, we used national data on total removals
25 from LULUCF for the period 2011–2015. We concluded that China LULUCF data were a good proxy for forest land data,
26 considering that: 1) zero emissions from net forest conversion were indicated in the same BUR; and 2) emissions from cropland
27 and grassland—the other main component of LULUCF within a national inventory—were likely small, as indicated by
28 independent emissions estimates published in FAOSTAT (FAO, 2020b). Within these assumptions, our estimates of a sink on
29 forest land in China for the period 2011–2015 agreed well with country data (within 20 % of country data), i.e., -710 Mt CO₂
30 yr⁻¹ compared to -840 Mt CO₂ yr⁻¹ reported to UNFCCC (Fig. 6).

31 Conversely, our estimates of emissions/removals on forest land did not agree well to those reported by Canada. Our results
32 indicated a net source on forest land, declining from 2000 to 2015, whereas the NGHGI country data reported a progressively
33 smaller sink over the same period (Fig. 6). Specifically for the period 2011–2015, our estimates indicated a weak net source,

1 about 23 Mt CO₂ yr⁻¹, compared to a net sink of -150 Mt CO₂ yr⁻¹ in the country data. Finally, our estimates for the most recent
2 period, 2016–2020, for which however there is no available NGHGI data yet from the country, began to show a sink on
3 forest land, of -80 Mt CO₂ yr⁻¹, thus indicating a possible alignment with NGHGI data in recent years. A possible reason for
4 the discrepancies found in this case may relate to differences in land use definitions, particularly those related to managed
5 forest land. For the purpose of the NGHGI, in fact, the area of managed forests defined by Canada is 65 % of the total forest
6 land area reported to FAO (Canada’s 7th National Communication and 3rd Biennial Report, 2017; Ogle et al., 2018).

7 8 *Net forest conversion*

9 We also compared estimates of emissions from net forest conversion with data reported to UNFCCC. As discussed in the
10 methodology section, FAO estimates of emissions from net forest conversion are proxies for deforestation emissions data. The
11 two countries for which relevant data were available were Brazil and Indonesia. For Brazil, we compared our estimates of net
12 forest conversion directly to deforestation emissions from the country’s BUR. For Indonesia, we compared our estimates to
13 sum of LULUCF emissions arising from land use change to cropland and grassland—assuming, in line with current
14 understanding of deforestation trends in this country, that land converted to cropland and grassland in Indonesia originated
15 largely from loss of forest land area. For Indonesia, for the period 1991–2000, our estimates of emissions from net forest
16 conversion greatly overestimated country data for deforestation, by over a factor of 10 (Fig. 7). Conversely, for the more recent
17 period 2011–2015, they were on average within 25 % of country data, specifically 180 Mt CO₂ yr⁻¹ vs country data of 165 Mt
18 CO₂ yr⁻¹. Our estimates further suggested a 50% decrease in emissions from net forest conversion in the period 2016-2020, for
19 which however BUR data are not yet available (Fig. 7).

20 For Brazil, our estimates were in good agreement (within 10 %) of country data over the period 1990 to 2015, i.e., on average
21 1.4 vs. 1.5 Mt CO₂ yr⁻¹ reported data (Fig. 7). More in detail by decade, our estimates were 1.4 vs 1.9 Gt CO₂ yr⁻¹ during 1991–
22 2000 and 1.6 vs 1.6 Gt CO₂ yr⁻¹ over 2001–2010. Conversely, for the period 2010–2015, our estimates of emissions from net
23 forest conversion were significantly higher than reported in the BUR.

24 **4. Discussion**

25 The availability of new forest area and carbon stock data from the FRA 2020 enabled a new analysis of the role of forests in
26 generating CO₂ emissions and removals at country, regional and global level, during the period 1990–2020. In particular, the
27 new information allowed us, for the first time in the literature, to estimate emissions and removals relative to the most recent
28 decade, covering the period 2011–2020. Our findings indicate that in the decade just concluded the net contribution of forests
29 to the atmosphere, representing the combination of emissions from net forest conversion and removals on forest land, was very
30 small, i.e., an overall emission sink of less than -0.2 Gt CO₂ yr⁻¹, estimated for the first time in the literature for this period. It
31 nonetheless resulted from the balance of large global fluxes of opposite sign, namely mean net forest conversion emissions of
32 3.1 Gt CO₂ yr⁻¹, counterbalanced by mean net removals on forest land of -3.3 Gt CO₂ yr⁻¹ (Table 1). Both fluxes, and hence

1 the overall net near zero balance for forests, were shown to be in very good agreement with the data reported by countries in
2 national GHG inventories, and in line with independent findings by Grassi et al. (2021). At the same time, the consistency of
3 our estimates with those of terrestrial carbon cycle models were limited to the anthropogenic carbon flux from forests to the
4 atmosphere (i.e., IPCC, 2019). Results further showed that, with respect to the previous decade 2001–2010, emissions from
5 net forest conversions had decreased by 15 %, while removals on forest land had decreased by 5 %. Further analysis of the
6 underlying FRA 2020 data (not shown) indicated that such decreases were due to a reduced pace of natural expansion and
7 afforestation in Annex I countries, which have functioned historically (1990-2020) as forest sinks, as well as a decrease in
8 forest loss in non-Annex I countries, which have represented the bulk of deforestation. The new estimates also show that over
9 the earlier period 1991–2010 forests were a smaller net source of emissions than previously calculated (Federici et al. 2015).
10 largely due to much stronger sinks on forest land estimated using the new FRA 2020 as opposed to FRA 2015 data, respectively
11 for Europe (+ 0.7 Gt CO₂ yr⁻¹) and Asia (+ 0.6 Gt CO₂ yr⁻¹).
12

13 The main new finding of this work is the large estimated sink on forest land over the period 2011–2015, averaging -4.0 Gt CO₂
14 yr⁻¹, causing the overall net negative carbon flux from forests highlighted in the results section. Notable contributors to this
15 forest land sink were the Russian Federation, USA, China, Indonesia and India, which all had stronger carbon uptake compared
16 to the previous 2001–2010 period. Comparisons with country data reported to the UNFCCC support our estimates, indicating
17 that they represent an improvement compared to previous results. In particular, the good agreement between our new estimates
18 and country NGHGI data on emissions/removals on forest land and emissions from net forest conversion suggests that the
19 definition of forest land area underlying both FAO and UNFCCC reporting was consistent across the countries considered,
20 i.e., they considered most of the forest land area reported to FAO as managed for UNFCCC purposes—confirming the analysis
21 provided in the methodological section of this paper. This implies that, limited to the countries tested and within the range of
22 limitations discussed earlier in this paper, the estimates of emissions and removals from forests provided in this paper can be
23 considered largely anthropogenic. Finally, the good agreements found between our estimates and country reports support the
24 finding of a large anthropogenic sink on forest land for the period 2011–2015, leaving open the possibility, in need of
25 verification in coming years, that even when considering deforestation, the world forests were a small sink, rather than a source
26 of atmospheric carbon during this period. In fact, the discussed progressive reduction of the overall forest source observed
27 across the two most recent decades is consistent with these findings.

28 **5. Data availability**

29 The emissions and removals data, alongside with input activity data of forest land area and carbon stock, are disseminated in
30 FAOSTAT (FAO, 2021). An exact replica of the data used for this paper is available as open access at
31 <http://doi.org/10.5281/zenodo.3941973> (Tubiello, 2020).

1 **6. Conclusions**

2 Estimates of CO₂ emissions and removals from forests were updated based on the most recent FRA 2020 data and by applying
3 a simple yet robust, transparent and easily replicable carbon stock change approach. Over the period 1990–2020, result
4 confirmed known country, regional and global trends, providing additional detail to specific dynamics while extending
5 available information to the period 2016–2020. Importantly, the new estimates allowed to characterize for the first time forest
6 emissions and removals for the decade just concluded, 2011-2020, showing that in this period the net contribution of forests
7 to the atmosphere was very small, sink i.e., less than -0.2 Gt CO₂ yr⁻¹. This near-zero balance was nonetheless the result of
8 large global fluxes of opposite sign, namely net forest conversion emissions of 3.1 Gt CO₂ yr⁻¹ counterbalanced by net removals
9 on forest land of -3.3 Gt CO₂ yr⁻¹.

1 **Author contributions.**

2
3 **Competing interests.** The authors declare that they do have no conflict of interest.

4
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7
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1 **Tables**

2
3 **Table 1.** Estimates of total emissions and removals from forests (ER), net forest conversion (NFC) and emissions/removals on forest
4 land (FL) for World, Annex I and non-Annex I totals, based on FRA 2020 and FRA 2015 (Gt CO₂ yr⁻¹).
5

	FRA 2020			FRA 2015		
	ER	NFC	FL	ER	NFC	FL
1991—2000	0.8	4.3	-3.5	1.8	4.7	-2.9
Annex I countries	-1.4	0.3	-1.7	-1.0	0.2	-1.2
Non-Annex I countries	2.2	3.9	-1.7	2.8	4.5	-1.7
2001—2010	0.5	3.7	-3.1	1.2	3.7	-2.6
Annex I countries	-1.6	0.3	-1.9	-1.4	0.4	-1.8
Non-Annex I countries	2.1	3.4	-1.3	2.6	3.3	-0.8
2011—2015	-0.7	3.3	-4.0	1.1	2.9	-1.9
Annex I countries	-2.0	0.2	-2.1	-1.1	0.1	-1.3
Non-Annex I countries	1.3	3.1	-1.8	2.2	2.8	-0.6
2016—2020	0.3	2.9	-2.6			
Annex I countries	-1.3	0.2	-1.6			
Non-Annex I countries	1.6	2.7	-1.1			
2011—2020	-0.2	3.1	-3.3			
Annex I countries	-1.7	0.2	-1.9			
Non-Annex I countries	1.5	2.9	-1.5			
AVERAGE 1990—2020	0.4	3.7	-3.3			
Annex I countries	-1.5	0.3	-1.8			
Non-Annex I countries	1.9	3.4	-1.5			
AVERAGE 1990—2015	0.4	3.8	-3.4	1.4	4.0	-2.5
Annex I countries	-1.6	0.3	-1.8	-1.2	0.3	-1.4
Non-Annex I countries	2.0	3.6	-1.6	2.6	3.7	-1.1

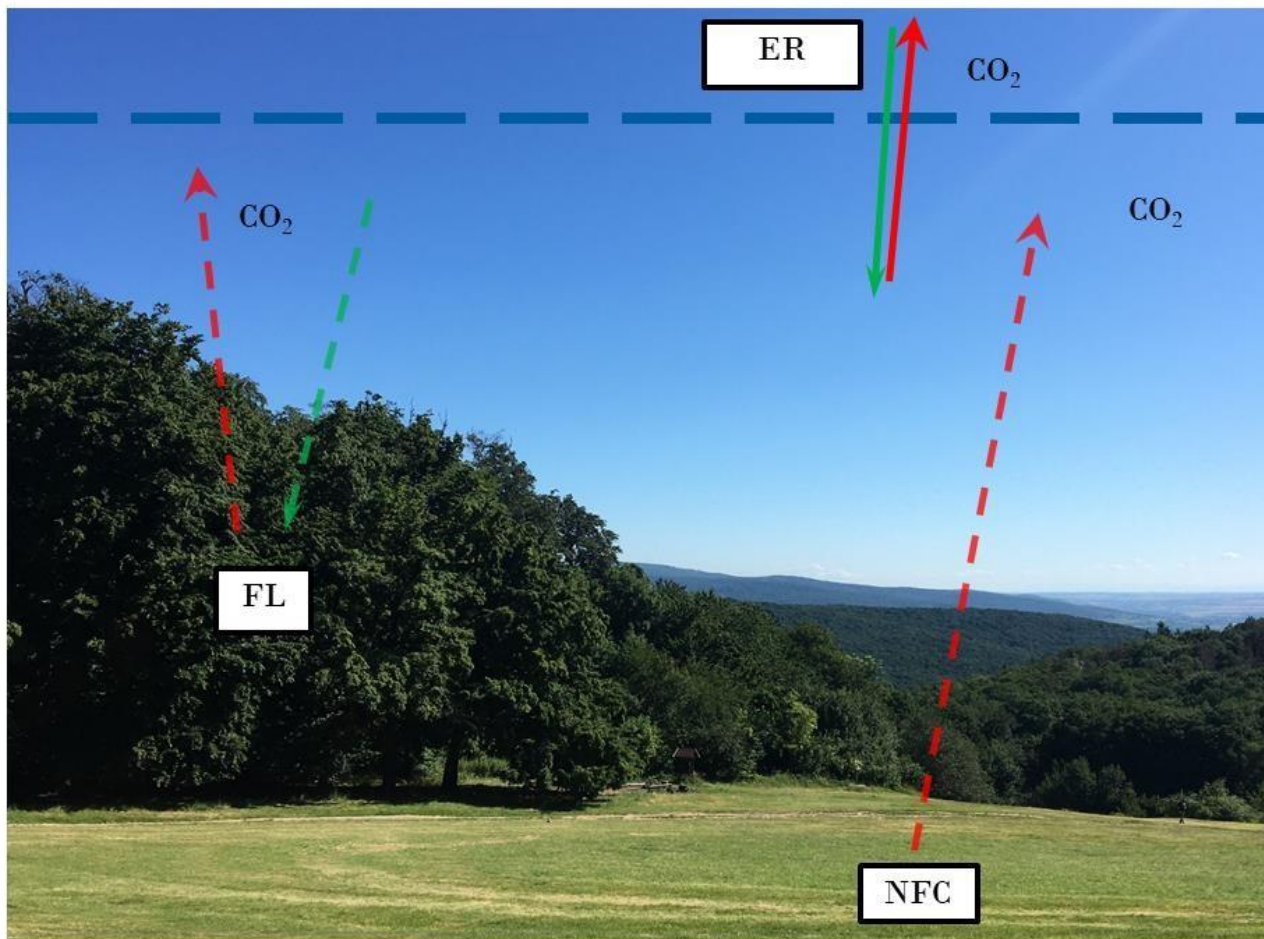
Table 2. Estimates of emissions/removals on forest land for Annex I countries, based on FRA 2020 and FRA 2015, compared to country data reported to UNFCCC (Gt CO₂ yr⁻¹).

Annex I total emissions/removals			
	FRA 2020	FRA 2015	UNFCCC
1991-2000	-1.7	-1.2	-2.1
2001-2010	-1.9	-1.8	-2.1
2011-2015	-2.1	-1.3	-2.2
2016-2020	-1.6		
AVERAGE 1991—2015	-1.8	-1.4	-2.2

1 **Figures**

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Figure 1. The three main carbon fluxes considered in this paper, consisting of emissions from net forest conversion (NFC), emissions and removals on forest land (FL) and their aggregate, representing total net emissions/removals from forests (ER).

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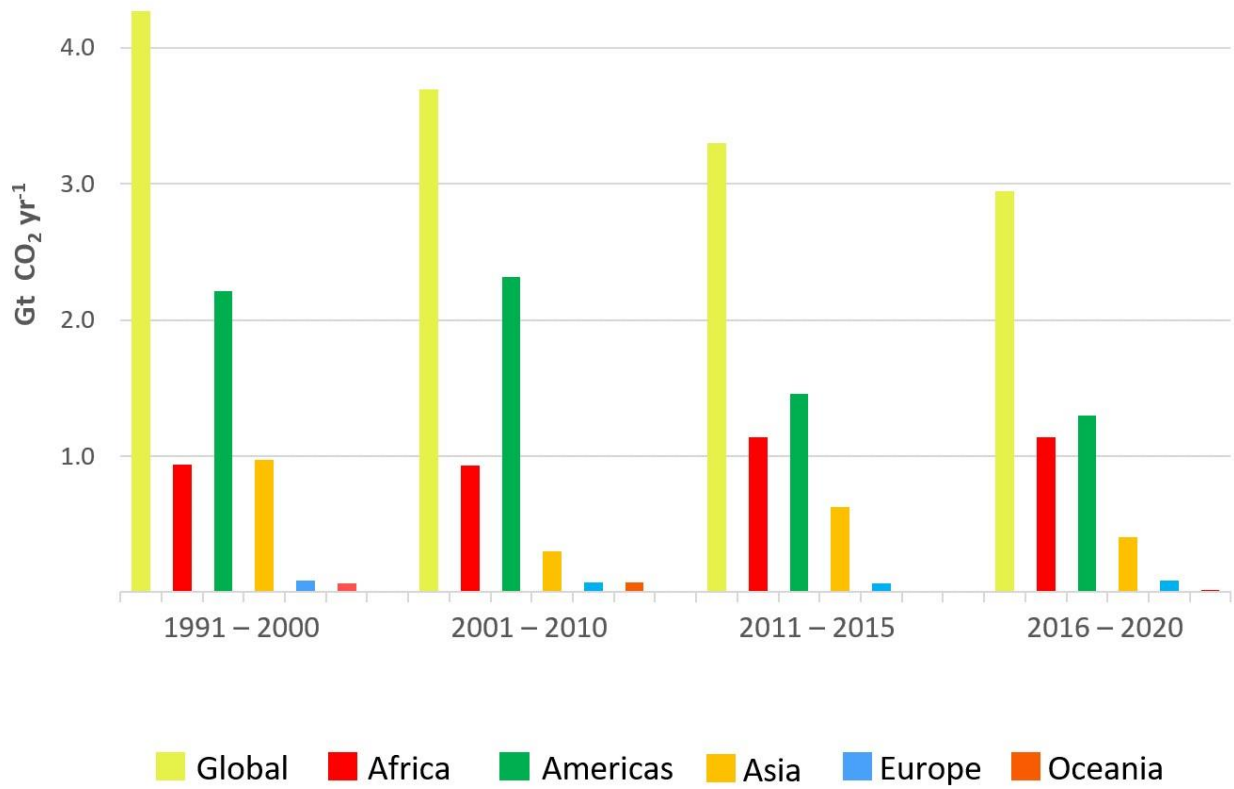
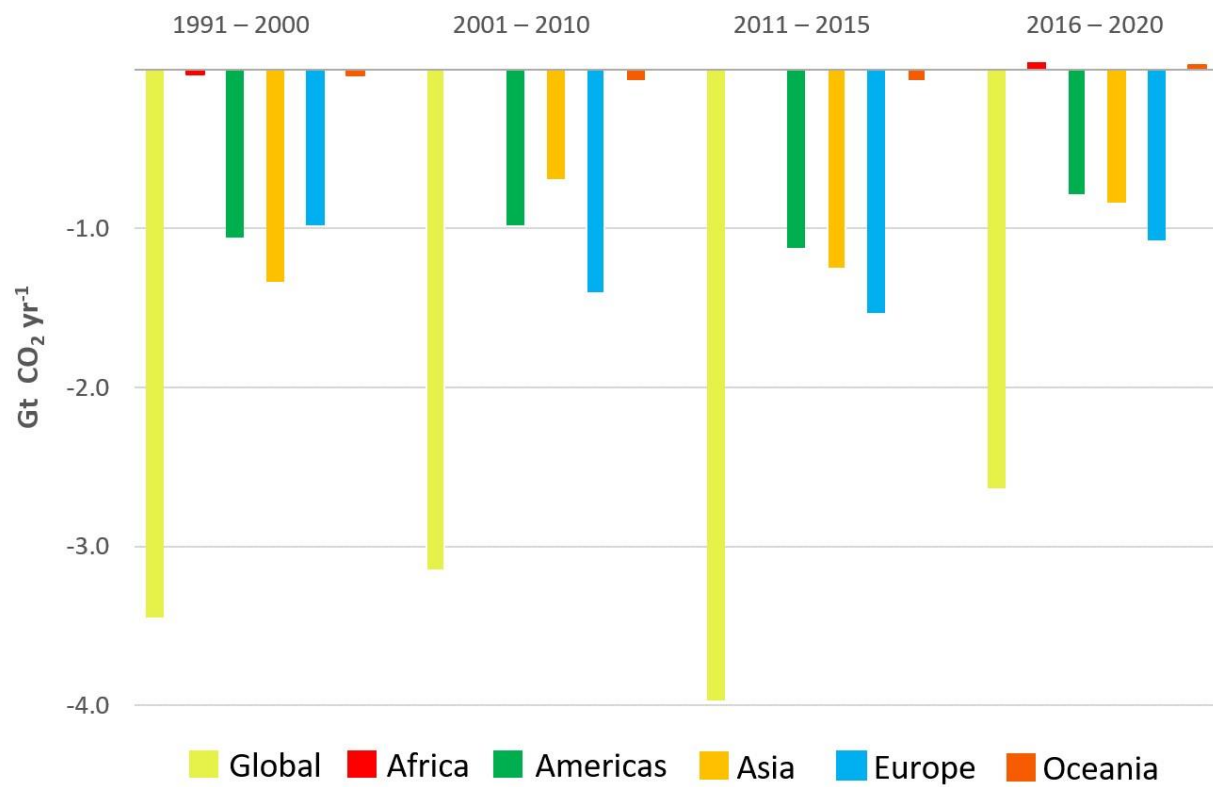
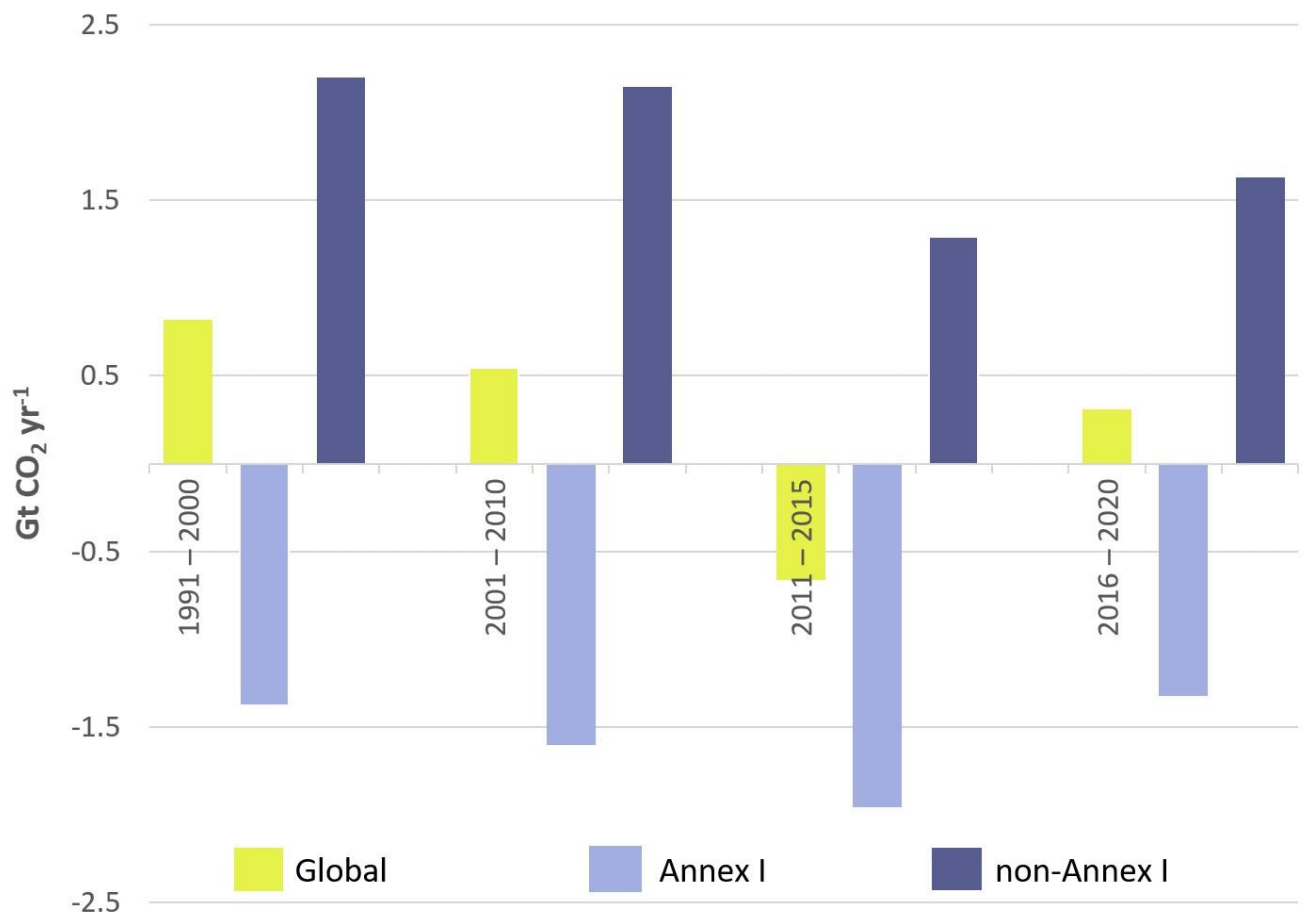


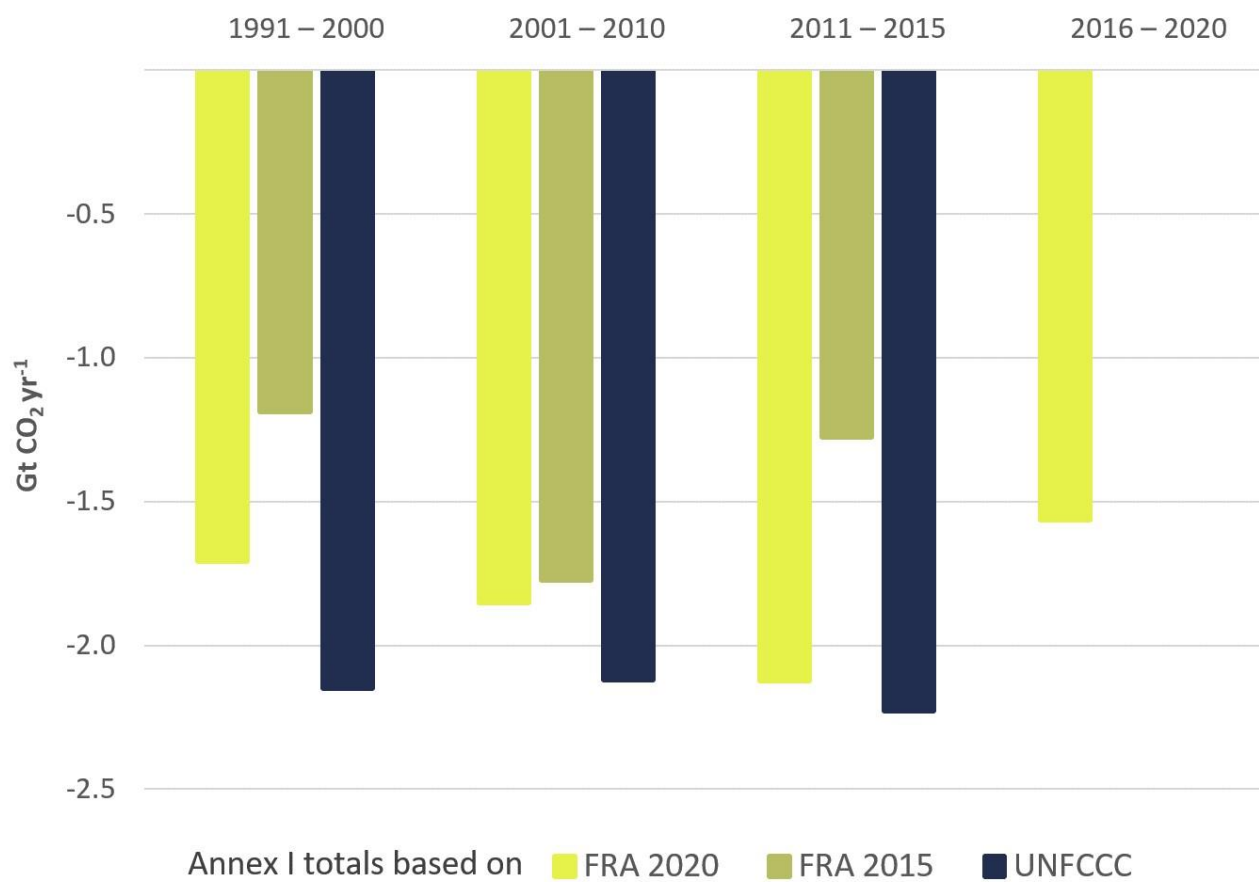
Figure 2. Estimates of emissions from net forest conversion (NFC) based on FRA 2020 for global (acid green) and regional (Africa = red; Americas = green; Asia = gold; Europe = sapphire; Oceania = orange) totals, in Gt CO₂ yr⁻¹.



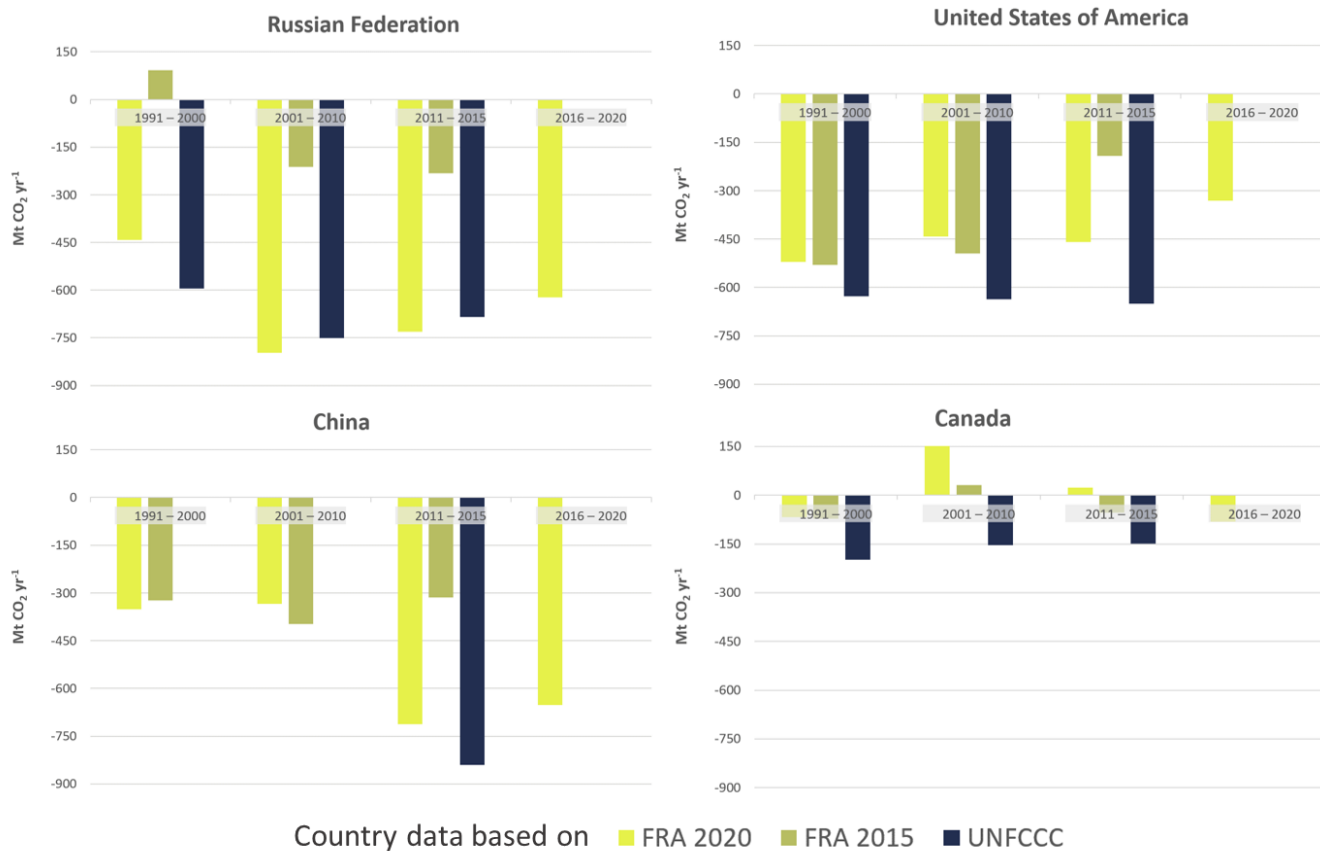
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2 **Figure 3. Estimates of the emissions/removals on forest land (FL) based on FRA 2020 for global (acid green) and regional**
3 **totals (Africa = red; Americas = green; Asia = gold; Europe = sapphire; Oceania = orange), in Gt CO₂ yr⁻¹.**
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3 **Figure 4. Estimates of total emissions/removals from forests (ER), based on FRA 2020, for global (acid green), Annex I**
4 **(lavender) and non-Annex I (purple navy) totals, in Gt CO₂ yr⁻¹.**
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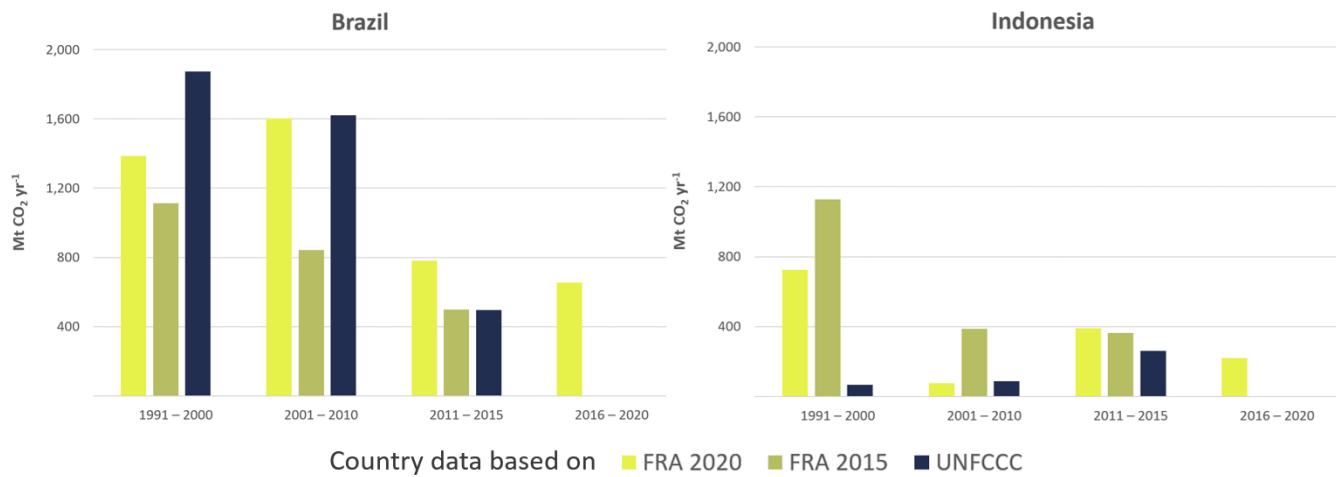


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2 **Figure 5. Comparison of estimates of emissions/removals on forest land (FL) for Annex I totals, in Gt CO₂ yr⁻¹, based on FRA**
3 **2020 (acid green) and FRA 2015 (olive green), to the Annex I totals reported by countries to UNFCCC (cadet blue).**
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Country data based on FRA 2020 FRA 2015 UNFCCC

Figure 6. Comparison of estimates of emissions/removals on forest land (FL) for Russian Federation (top left), USA (top right), China (bottom left) and Canada (bottom right), in Mt CO₂ yr⁻¹, based on FRA 2020 (acid green) and FRA 2015 (olive green), to country data reported to UNFCCC (cadet blue).



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3 **Figure 7. Comparison of estimates of emissions from net forest conversion (NFC) for Brazil (left) and Indonesia (right), in**
4 **Mt CO₂ yr⁻¹, based on FRA 2020 (acid green) and FRA 2015 (olive green), to country data reported to UNFCCC for**
5 **deforestation (cadet blue).**
6