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# Carbon Emissions and Removals by Forests: New Estimates 1990-2020

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**Abstract.** Trends in global, regional and national $CO_2$ emissions and removals from forest for the period 1990-2020, are estimated for the first time using data from the Forest Resources Assessment (FRA) 2020, providing new information with respect to the previous FRA 2015. Estimates indicate significant reduction of deforestation emissions over the study period, albeit more slowly than previously assessed, from an average of 4.3 Gt $CO_2$ $yr^{-1}$ during 1991-2000, to an average of 2.9 Gt $CO_2$ $yr^{-1}$ during 2016-2020. Remaining forest land was a significant net carbon sink globally and over the entire period, albeit decreasing in strength, from -3.4 Gt $CO_2$ $yr^{-1}$ in 1991-2000 to -2.5 Gt $CO_2$eq $yr^{-1}$ during 2016-2020. The overall net contribution of forests to atmospheric $CO_2$ (i.e., the combined effect of deforestation and forest emissions/removals) was an overall emission source of roughly 0.4 Gt $CO_2$ $yr^{-1}$ on average during 1991-2020, more than one-third less than previously estimated. Remarkably, the new data also suggest an overall net sink of about -0.7 Gt $CO_2$ $yr^{-1}$ during 2011-2015, never reported before. Forest emissions/removals data independently reported by countries to the United Nations Framework on Climate Change were in excellent agreement with the FAO estimates over the entire period 1990-2020, confirming a large sink on forest land estimated for 2011-2015. Data are made available as open access via the Zenodo portal (Tubiello, 2020), with DOI 10.5281/zenodo.3941973.

## 1 Introduction

The Food and Agriculture Organization of the United Nations (FAO) Forest Resources Assessment (FRA) collects, analyzes and disseminates, at regular intervals, a wealth of forest statistics describing the status of forests at country, regional and global level (http://www.fao.org/forestry/fra/fra2020/en/) (FAO, 2020b). Among many different uses, the FRA data are a critical input into estimates of forest carbon fluxes for global carbon cycle modeling (e.g., Friedlingstein et al., 2019; Houghton et al.,

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2012). To this end, they are the basis for FAO's own estimates of greenhouse gas emissions and removals from forest land, disseminated in FAOSTAT (FAO, 2020a; Tubiello et al., 2019), which regularly inform IPCC reports (e.g., Smith et al, 2014; Arneth et al., 2019) and users worldwide. Previous estimates based on the FRA 2015 (FAO, 2015; Federici et al., 2015; Houghton and Nassikas, 2017; Grassi et al., 2018) had found deforestation emissions decreasing from 1990 to 2015, from about 4.5 (1991-2000) to 3.0 (2011-2015) Gt $CO_2$ $yr^{-1}$. Likewise, they described a net forest carbon sink decreasing in strength over time, from an average of -2.7 (1991-2000) to -2.0 (2011-2015) Gt $CO_2$ $yr^{-1}$.

This paper provides new updates of emissions and removals of $CO_2$ from forests and deforestation emissions based on the new 2020 FRA and FAO estimation methods, including an analysis of new trends, documenting changes with previous estimates and preforming a comparison to independent country data reported to the United Nations Framework Convention on Climate Change (UNFCCC).

## 2 Material and Methods

Estimates of $CO_2$ emissions and removals from forest land were computed following the carbon stock change method of the 2006 IPCC (2006) guidelines, Vol. 2 and 3, at Tier 3, approach 1 (Federici et al., 2015; FAO, 2020a). Nearly complete time-series of forest land area and carbon stock in living biomass information for the years 1990, 2000, 2010, 2015 and 2020 were used as input into the FAO estimations. Forest land area was further stratified in two sub-categories: *Naturally regenerating Forest* and *planted forest*. When computing land area changes, these were tracked separately, in order to improve the computations of gross area change compared to the use of data on Forest land only.

We simplified the methods developed in Federici et al. (2015) in order to work only with FRA data, i.e., without interpolating between FRA years –as this would require assumptions on temporal forest dynamics not included in the FRA data. To this end, as show in more detail below, annual average emissions/removals within any FRA period (i.e., 1991-2000; 2001-2010; 2011-2015; 2016-2020) were computed as annual average fluxes from differences of relevant area or carbon stock information, as follows (see also Fig. 1).

$$FL\_Tot_{pi} = (B_i - B_{i-1}) * -\frac{44}{12} * 10^{-3} / D \quad (1)$$

$$NFC_{pi} = (B_{i-1})/(A_{i-1}) * \sum j \, \{Min\left[(A_{i,j} - A_{i-1,j}), 0\right]\} * -\frac{44}{12} * 10^{-3} / D \quad (2)$$

$$FL_{pi} = FL\_Tot_{pi} - NFC_{pi} \quad (3)$$

Where:

- *FL_Tot* is the overall carbon flux from forest change, expresses in Gg $CO_2$ $yr^{-1}$;
- *NFC* is net deforestation, expresses in Gg $CO_2$ $yr^{-1}$;
- *FL* is net emissions/removals on (remaining) forest land, expresses in Gg $CO_2$ $yr^{-1}$; and

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- $B_i$ is the carbon stock in living biomass at FRA year *i*, expresses in Mt C;
- $A_i$ is the forest land area at FRA year *i*, expresses in k ha;
- $A_{i,j}$ is the forest land area of category *j* = naturally regenerating, planted, at FRA year *i*; expressed in k ha.
- *i* = 1990, 2000, 2010, 2015, 2020 is the FRA year;
- *pi* =1991-2000; 2001-2010; 2011-2015; 2016-2020 is the corresponding FRA period;
- *D* is the length of the period *pi*, i.e. either 5 or 10 years; and
- Multiplication by - $44/12 * 10^{-3}$ was used to convert from Mt C to Gg $CO_2$ as well as to express a positive carbon stock change as a negative emission (removal) to the atmosphere, and vice-versa.

Finally, R code was run across the entire FRA 2020 data to ensure full equivalence of (1)-(3) with the more complicated equations developed in Federici et al. (2015).

### 2.1 Data Availability: Structure of the FAOSTAT datasets on emissions-forest land and online access

Results from the emissions estimates and associated biomass and area information were computed for 205 countries and territories. Statistics are disseminated in the FAOSTAT Emissions Land Use/ Forest Land domain, over the period 1990–2020 (FAO, 2020a), and cover forest land area, area of deforestation, biomass stock, and emissions/removals for total forest, on forest land proper, and from deforestation. The data is also provided as open access via Zenodo (Tubiello, 2020), with DOI 10.5281/zenodo.3941973.

### 2.2 Limitations and uncertainty

The FAO emissions estimates only include the first two of the six carbon pools identified by the IPCC guidelines: aboveground and belowground biomass, dead wood, litter, soil organic carbon, harvested wood products. Such incompleteness is expected to have an impact on the magnitude of the estimated C stock changes, but not on their direction, i.e., indicating a net sink or a net source. We included only carbon in living biomass because coverage of the other statistics was not of the same coverage by country and over time, requiring substantial more gap filling and thus increasing uncertainty. In addition, the use of net area change, even if performed separately on naturally regenerating and planted forest, is an underestimate of actual gross change. In addition, equation (2) assumes C loss in deforestation based on average carbon stock density of the entire forest, which is likely an underestimate whenever the deforested area is covered by primary or other natural forests.

The implication is that, while estimates of total forest flux to or from the atmosphere are correct, within the uncertainty of biomass carbon stock estimates reported to the FRA—estimates corresponding to the two sub-components, i.e., deforestation emissions, are likely and consistently underestimates. Conversely, forest land emissions/removals may be over or under-estimates, depending on specific cases.

Uncertainty of the emissions estimates depends directly on the uncertainty in area and carbon stock estimates reported by countries to the FRA. It can be assumed that the latter are fairly high, in general about 50% for carbon stock density (which is

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the primary variable measured, from which total carbon stock is obtained by are multiplication) and, in line with IPCC default assumptions, about 20% for area statistics. It follows that, assuming normal distributions and thus applying simple error propagation formulas, equations (1)-(3) imply that our estimates have uncertainties (expressed as relative errors) in the order of 70%.

Finally, it should be noted that the total carbon flux computed herein is entirely dependent on the FRA reporting process, and it may not be representative of the full range of forest carbon fluxes covered in other, more complete studies on the role of forests, natural and managed, within the terrestrial carbon cycle.

## 3 Results

For each UN Member State a time series of annual net $CO_2$ emission/removal from forest, divided into net deforestation fluxes, net forest land emissions/removals, and their aggregate, were computed over the period 1990-2020. The dataset, disseminated in FAOSTAT (FAO, 2020a) makes values available by country and by standard FAO regional aggregations, including Annex I and non-Annex I parties to UNFCCC. The emissions data are complemented by FRA 2020 data on forest land area and biomass stock, as well as by the net area changes underlying deforestation fluxes. An exact replicate of the data used for this paper is available at Zenodo (Tubiello, 2020), with DOI 10.5281/zenodo.3941973.

### 3.1. Total forest flux to the atmosphere

Results for the four FRA 2020 periods: 1991-2000, 2001-2010, 2011-2015, 2016-2020, were summarized by UNFCCC annex, regionally and globally (Tab. 1).

The FAO estimates show that forests (including deforestation losses and emissions/removals on remaining forest lands) acted globally as a net small source of $CO_2$ emissions to the atmosphere over 1991-2020, averaging 0.4 Gt $CO_2$ $yr^{-1}$, nearly one-fourth less than the FAO estimates based on FRA 2015. The small global source was the result of a large net sink in Annex I countries (-1.5 Gt $CO_2$ $yr^{-1}$) counterbalanced by a large net source in non-Annex I countries (1.9 Gt $CO_2$ $yr^{-1}$).

Two notable new findings emerged from a more detailed analysis focusing on trends over time (Fig. 2). First, the decreasing trend in non-Annex I sources and the increasing trend in Annex I sinks seen during 1990-2015 reversed itself in 2016-2020, with non-Annex I sources increasing from 1.3 to 1.6 Gt $CO_2$ $yr^{-1}$, while Annex I sinks decreased in strength from -2.0 to -1.3 Gt $CO_2$ $yr^{-1}$. Secondly, and remarkably, forests acted as a net overall sink of atmospheric $CO_2$ during the period 2011-2015, averaging 0.7 Gt $CO_2$ $yr^{-1}$. This overall sink has never been estimated before. By comparison, FAO estimates based on FRA 2015 for 2011-2015 had indicated a source of 1.1 Gt $CO_2$ $yr^{-1}$ (Tab.1).

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### 3.2 Deforestation

Results show that global deforestation fluxes to the atmosphere were significant during 1990-2020, averaging 3.7 Gt $CO_2$ $yr^{-1}$, confirming previous estimates. Unlike for total forest fluxes, deforestation was almost entirely determined by dynamics in non-Annex I countries, contributing more than 90% to the total (Tab. 1).

In terms of temporal trends, the new estimates confirm previous findings over the period 1990-2015, i.e., showing a decrease of average deforestation rates globally from 4.3 to 3.3 Gt $CO_2$ $yr^{-1}$ (about -20%, whereas the FRA 2015 had indicated a -40% decrease) , and then further down to an average of 2.9 Gt $CO_2$ $yr^{-1}$ during 2016-2020. The regional distribution of deforestation in 2016-2020 saw the Americas and Africa nearly equal major contributors (1.3 and 1.1 Gt $CO_2$ $yr^{-1}$, respectively), yet with markedly opposite trends. Compared to the earlier 1991-2000 period, deforestation emission in the Americas nearly halved, from 2.2 Gt $CO_2$ $yr^{-1}$, while in Africa they continued to increase, from earlier levels of 0.9 Gt $CO_2$ $yr^{-1}$. Asia was the third region in terms of deforestation emissions, with decreasing trends since 2010, i.e., from 0.6 Gt $CO_2$ $yr^{-1}$ (2011-2015) to 0.4 Gt $CO_2$ $yr^{-1}$ (2016-2020) (Fig. 3).

### 3.3 Emissions and removals on forest land

Results show that remaining forest land (i.e., net of deforestation) continued to function as a sink of atmospheric $CO_2$ over the entire 1991-2020 period, averaging -3.3 Gt $CO_2$ $yr^{-1}$. Unlike deforestation fluxes, the forest flux was roughly equally divided between Annex I (-1.8 Gt $CO_2$ $yr^{-1}$) and non-Annex I countries (-1.5 Gt $CO_2$ $yr^{-1}$) (Tab. 2). Compared with previous findings based on the FRA 2015, the new estimates were on average 1.0 Gt $CO_2$ $yr^{-1}$ (or 35%) stronger, due to larger computed sinks in Europe (dominated by Russian Federation) and Asia (China).

In terms of temporal trends, the new FAO estimates show a decrease in the world total forest land sink over the study period, with average rates going from -3.3 to -2.6 Gt $CO_2$ $yr^{-1}$, i.e., about a 20% decrease. In fact, the new estimates also reveal a significant albeit brief reversal during the period 2011-2015, where the forest land sink showed a marked increase in strength with respect to the 1991-2010 period, reaching on average annual rates of -4.0 Gt $CO_2$ $yr^{-1}$.

Regionally, the global sink, averaged over 1990-2020, was nearly equally split between Europe, the Americas and Asia, within a narrow range of -1.0 to -1.2 Gt $CO_2$ $yr^{-1}$, and with Europe having the largest contribution among these. Africa was the only region with positive estimated forest land emissions (albeit small, compared to the sinks), since the year 2000 (Fig. 4). Indeed, annual average emissions increased very significantly from 2001-2010 to 2011-2015, i.e., from 1.4 to 38 Mt $CO_2$ $yr^{-1}$, and the again to 43 Mt $CO_2$ $yr^{-1}$ in 2016-2020, or more than a 15-fold increase in forest degradation in this region over the last twenty years (degradation defined following Federici et al. 2015, as positive emissions over forest land, or loss of carbon stock).

### 4. Discussion

The recent release of the new FRA 2020 data allowed for a revision of earlier FAO estimates of forest emission and removals of $CO_2$ to and from the atmosphere, highlighting that in the most recent decade forests have contributed very little to net

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atmospheric emissions. By combining information on the two periods 2011-2015 and 2016-2020 to obtain for the first time a picture of the 2011-2020 decade, it follows that in 2011-2020 the net contribution of forests to the atmosphere were virtually zero (less than 200 Mt $CO_2$ yr$^{-1}$), resulting from the balance of much larger fluxes opposite in sign but similar in strength and with very large uncertainty (about 70% as discussed), i.e., deforestation fluxes (3.1 Gt $CO_2$ yr$^{-1}$) and emissions removals from remaining forest land (-3.3 Gt $CO_2$ yr$^{-1}$). This confirms and further quantifies a diminishing trend in the overall contribution of forests over the period 1991-2010, which was also seen in previous estimates using the FRA 2015 (Federici et al. 2015), albeit the latter were on average four times larger than those presented here. The main reason for this difference was identified in stronger forest sinks estimated with new FRA 2020 compared to FRA 2015 data, respectively for Europe (+ 0.7 Gt $CO_2$ yr$^{-1}$) and Asia (+ 0.6 Gt $CO_2$ yr$^{-1}$).

Finally using the new data, our estimates allow to make the first assessment of trends in both deforestation and forest emissions/removals over the last twenty years, by decade (i.e., 2011-2020 compared to 2001-2010). Results indicate a decrease of deforestation emissions by 15% and at the same time a small 5% decrease in the strength of the forest land sink.

The remarkable feature of the new estimates presented herein is undoubtedly the large estimated sink on forest land in the period 2011-2015, i.e., a forest land sink of -4.0 Gt $CO_2$ yr$^{-1}$. This forest land sink is the major reason for the overall net negative flux previously highlighted in the results section. Notable contributors to the 2011-2015 forest land sink were the Russian Federation, USA, China, Indonesia and India, which all had stronger uptakes compared to the previous 2001-2010 period, as well as much stronger estimated sinks compared to the FRA 2015.

A discussion on forest carbon emissions cannot be complete without an attempt to address the issue of anthropogenic versus natural fluxes, itself linked to definitions of 'managed' vs. 'unmanaged' forest, of relevance to climate change policy and action (e.g., Grassi et al., 2018 and 2018; Friedlingstein et al., 2019; Petrescu et al., 2019).

While equations (1)-(3) above do not separate between anthropogenic and natural fluxes, it can be noted that forest land area reported by countries to FAO is understood in principle to be managed (e.g., see http://www.fao.org/economic/ess/ess-home/questionnaires/en/)[1]. In practice, it is likely that at least portions of the forest land area reported by countries to the FRA may nonetheless be 'unmanaged'. To this end, the overall flux term computed with equation (1) is a mix of anthropogenic and natural fluxes. At the same time, the deforestation term computed in (2) can be considered 100% anthropogenic, since land use change typically requires human intervention. As a result, the emissions/reductions on forest land computed in (3) as a residual must also be a mix of anthropogenic and natural fluxes, thus representing an overestimate of anthropogenic emissions and removals on forest land. Additional analysis aimed at teasing out the anthropogenic component on forest land would involve consideration of trends in planted forests, as done in Federici et al. (2015). However these efforts are hindered by lack of further disaggregated carbon stock information between naturally regenerating and planted forests.

[1] The FAO definitions of forest land comprise areas under forestry production, forest conservation including natural parks, and in general any area regulated administratively in term of destination and use.

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**4.1 Comparisons with country reporting to the UNFCCC**

In order to assess in practice how much of the FRA-derived fluxes could be considered anthropogenic, we resorted to simple comparisons of our estimates with the anthropogenic emissions data reported by countries to UNFCCC, as accessed at the UNFCCC data portal (UNFCCC, 2020) and complemented with information from national Biennial Update Reports (BURs). While data from Annex I countries is fairly complete over the period 1990-2017, data from non-Annex I parties is sparse, although becoming increasingly available through BURs.

First, we looked at reported emissions/reductions on forest land reported by Annex I Parties. In the aggregate, e.g. summing up all countries data, our estimates were, on average over the period 1991-2020, within 14% (relative absolute error) of the UNFCCC country data. Specifically, we estimated an average sink of -1.9 Gt $CO_2$ $yr^{-1}$ vs -2.2 Gt $CO_2$ $yr^{-1}$ of Annex I country reporting (conversely, previous FRA 2015 estimates had indicated a 33% weaker sink). The new FAO estimates were particularly well aligned with country reporting for the period 2011-2015, i.e., within 5%, or -2.1 Gt $CO_2$ $yr^{-1}$ vs -2.2 Gt $CO_2$ $yr^{-1}$ of Annex I reporting. Previous estimates based on the FRA 2015 had instead indicated a 40% weaker sink (Fig. 5).

In order to gain further insight into these comparisons, we also separately analyzed data on forest land reported by individual countries, focusing on those reporting large sinks, i.e., Russian Federation and USA among Annex I parties, China (2018) among non-Annex I parties (Fig. 6). We also looked to deforestation figures for Indonesia (2018) and Brazil (2019), also non-Annex I parties (Fig 7).

Comparisons of forest land emissions/reductions for the Russian Federation between confirmed the overall agreement found for Annex I parties, as well as highlighted the considerable improvements made compared with FRA 2015. On average over the period 1990-2015, our new estimates of forest sinks in the Russian Federation were within 5% of the country data, while FRA 2015 had underestimated it by nearly 90%. Close agreement with country data was particularly good after 2000, i.e., an average estimated sink of -800 Mt $CO_2$ $yr^{-1}$ versus country data of -750 Mt $CO_2$ $yr^{-1}$ for the period 2001-2010, and estimates of -730 Mt $CO_2$ $yr^{-1}$ versus -680 Mt $CO_2$ $yr^{-1}$ for the period 2011-2015. Albeit estimates for the 1991-2000 sink were less precise than later periods, they were nonetheless much closer (25% relative error) to the country reported data than the earlier FAO estimates based on FRA 2015, which were off by over 100%.

Comparisons of the FAO estimates with country data for the USA were also encouraging, albeit showing larger differences than for the case of the Russian Federation. On average over the period 1991-2010, the new FAO estimates were within 25% of the country data (29% for FRA 2015). Importantly, estimates of the sink during 2011-2015 were 29% of the country data (but 80% for FRA 2015), with FAO estimating -460 Mt $CO_2$ $yr^{-1}$ and country data indicating a sink of -650 Mt $CO_2$ $yr^{-1}$.

A final important comparison useful to assess the anthropogenic component of the sink on forest land was performed with China, also a major contributor. Data for China were taken directly from its recent BUR (China, 2018), where average data for the period 2011-2015 were provided for total LULUCF. We assumed that China LULUCF data were a good proxy for forest land data, considering that, according to FAOSTAT estimates of LULUCF emissions (FAO, 2020a), deforestation was not present in this period while cropland and grassland emissions/removals–the other main component of LULUCF emissions

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within a national inventory—were small. With these assumptions, we found that for the period 2011-2015 the new FAO estimates of a forest land sink in China were within 20% of country reported data (but 70% using FRA 2015), i.e., -710 Mt $CO_2$ $yr^{-1}$ compared to country data of -840 Mt $CO_2$ $yr^{-1}$.

Additionally, we compared FAO estimates of deforestation emissions with country data, focusing on large emitters Brazil and Indonesia, for which BUR data existed. Data were obtained from Brazil (2017) and Indonesia (2019). Deforestation data for Brazil were directly available in the country report. For Indonesia, we took LULUCF emissions related to land use conversion to cropland and grassland—assuming, in line with current understanding of deforestation trends in this country, that this was a good proxy for deforestation, i.e., most conversion to cropland and grassland originated from forest land.

For Indonesia, the new FAO estimates (as well as those based on the FRA 2015) had greatly overestimated country reported data for 1991-2000, i.e., by factors of over 10. Conversely, for 2001-2015, they were on average within 25% of country data, or 180 Mt $CO_2$ $yr^{-1}$ vs country data of 165 Mt $CO_2$ $yr^{-1}$ (FRA 2015 estimates were 50% larger). Finally in terms of new information, for 2016-2020, the new estimates showed a decrease of nearly 50% in deforestation emissions with respect to the previous 2011-2015 period.

For Brazil, FAO estimates over 1991-2015 of deforestation emissions were within 10% of nationally reported data, i.e., 1.4 vs. 1.5 Mt $CO_2$ $yr^{-1}$, whereas FRA 2015 estimates were 40% smaller. More in detail by decade, FAO estimates were 1.4 vs 1.9 Gt $CO_2$ $yr^{-1}$ (1991-2000) and 1.6 Gt $CO_2$ $yr^{-1}$ vs 1.6 Gt $CO_2$ $yr^{-1}$ (2001-2010). The previous, FRA 2015-based estimates were 40% lower than country reported for these same periods. Conversely and remarkably, the new FAO estimates suggested more than 50% higher deforestation than reported by the country for the period 2011-2015, consistent with suggestions made in the literature that deforestation emissions may have been higher in this period than initially estimated by the country.

The findings above point to two main conclusions. First, the good agreement between the FAO estimates and country reports implies that the definition of forest land use underlying both FAO and UNFCCC reporting was consistent, i.e., all managed and hence the emissions were considered all anthropogenic. When this alignment in forest land use definitions was not present, as in the case of Canada, significant differences between FRA and country data were found (Fig. 6).

Second, country reports are consistent with and thus support FAO estimates of a large anthropogenic sink on forest land for the period 2011-2015, leaving open the possibility, put forward by the new FAO estimates and in need of verification in coming years, that the world forests were a small sink, rather than a source, of atmospheric carbon during this period.

## 5. Conclusions

The new FAO estimates of $CO_2$ emissions/removals from forest land were updated based on the most recent FRA 2020 data. Over the period 1990-2020, they confirmed well-known country, regional and global trends, providing additional detail to specific dynamics while extending information to the period 2016-2020. Importantly, they allowed for the first complete analysis of trends in the most recent decade, 2011-2020. The new estimates confirm and further quantify decreases over time in global deforestation emissions, to below 3 Gt $CO_2$ $yr^{-1}$ globally in the second half of the decade, highlighting important, opposite regional trends in Latin America and Africa, with the former seeing marked reductions while in the latter emissions have continued to grow. At the same time, the FAO estimates have identified a particularly strong carbon sink on remaining forest land during 2011-2015, consistent with country reporting but never previously detected with this magnitude. Overall and aside for the 2011-2015 sink, the new estimates confirm and extend current knowledge (Smith et al., 2014; IPCC SRLCC, 2020; Friedlingstein et al., 2019). Our findings confirm that forests retain a significant role for mitigating climate change. During the period 1991-2020, natural forests lost annually more than 2% of their biomass C stocks, corresponding to a mitigation potential of roughly 3 Gt $CO_2$ $yr^{-1}$ when future C stock losses from deforestation are avoided.

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## Tables

Table 1. **FAO estimates of total forest fluxes (FL_Tot), deforestation (NFC) and emissions/removals on forest land (FL), in Gt $CO_2$ $yr^{-1}$, for the period 1991-2020, for global, Annex I and non-Annex I totals. FAO estimates using FRA 2020 (this paper) and FRA 2015 are given for comparison.**

| | *FRA_2020* | | | *FRA_2015* | | |
|---|---|---|---|---|---|---|
| | *FL_Tot* | *NFC* | *FL* | *FL_Tot* | *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* | | | |
| | | | | | | |
| ***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* |

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Table 2. **Proportion of area of relevant CCI-LC pixels corresponding to land cover *grassland***

| | *FRA_2020* | *FRA_2015* | *UNFCCC_Annex I* |
|---|---|---|---|
| *2000* | *-1.7* | *-1.2* | *-2.1* |
| *2010* | *-1.9* | *-1.8* | *-2.1* |
| *2015* | *-2.1* | *-1.3* | *-2.2* |
| *2020* | *-1.6* | *0.0* | *0.0* |
| *AVERAGE 1990-2015* | *-1.8* | *-1.4* | *-2.2* |

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**Figures**

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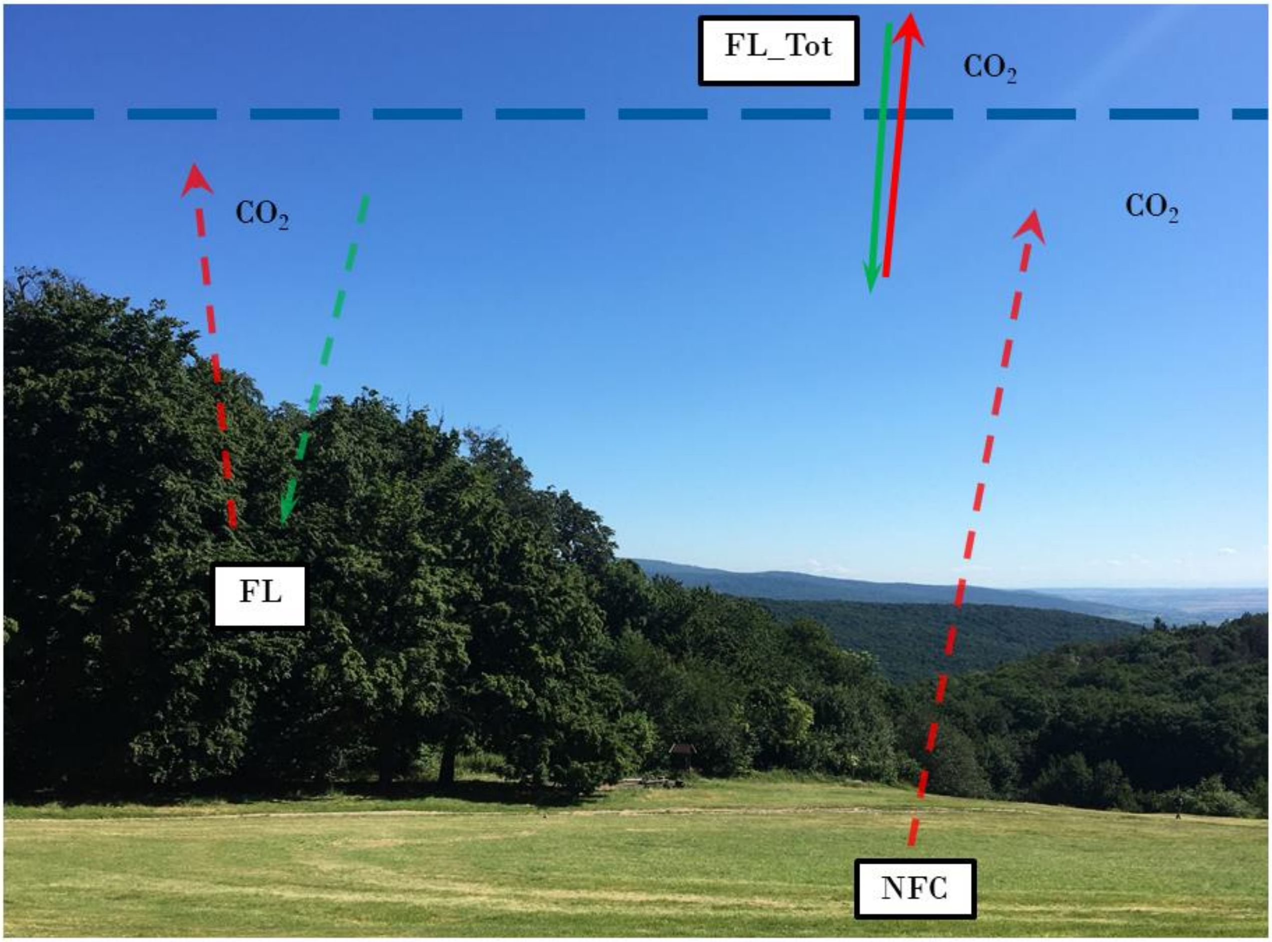


335 **Figure 1. The three main fluxes considered in this paper, consisting of overall forest fluxes to and from the atmosphere (FL_Tot), deforestation (NFC) and emissions/removals on forest land (FL). Photo copyright: Francesco N Tubiello.**

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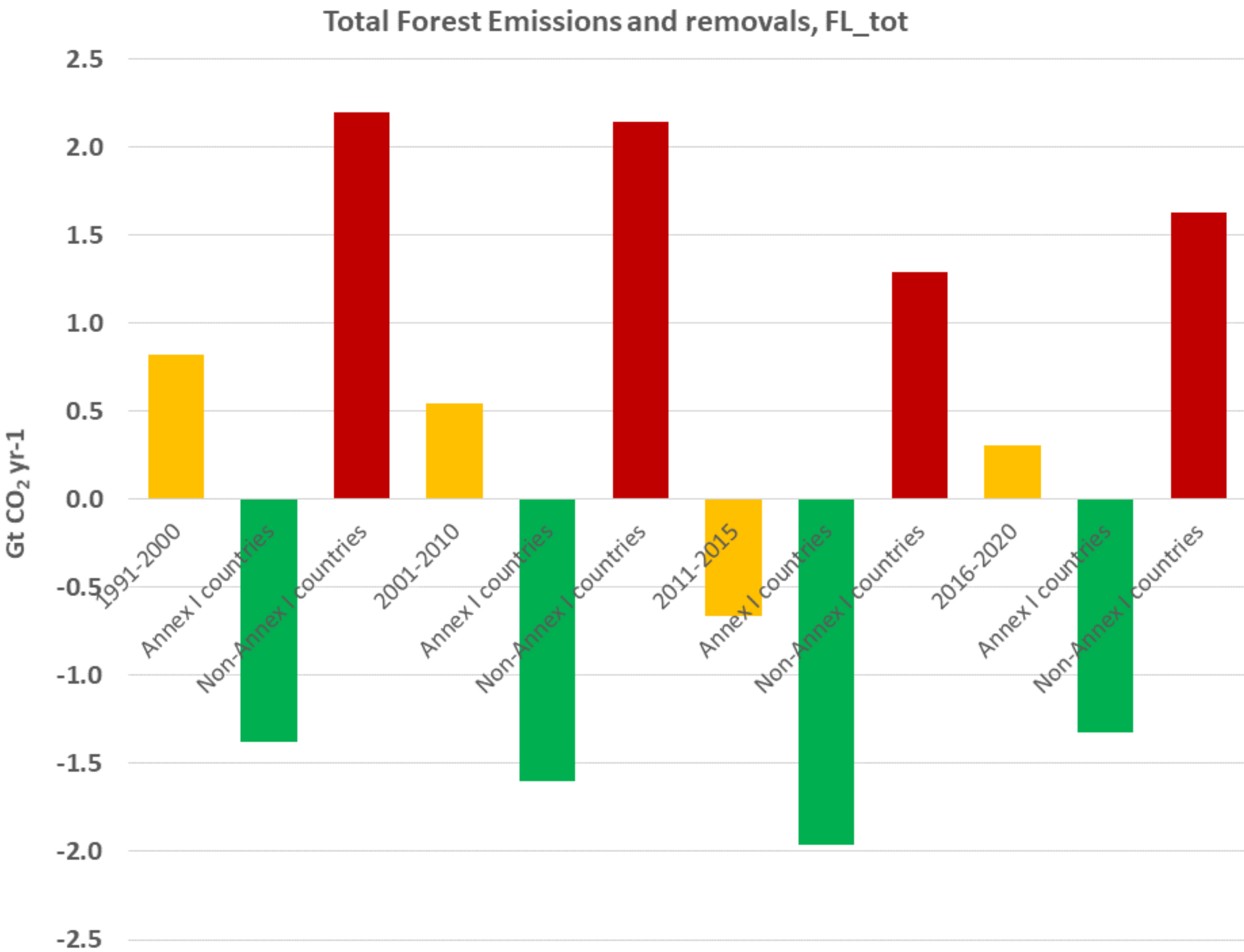


**Figure 2. FAO estimates of total forest fluxes (FL_Tot) for global, Annex I and non-Annex I totals, in Gt $CO_2$ $yr^{-1}$, for the period 1991-2020. FAO estimates using FRA 2020 (this paper) and FRA 2015 are given for comparison.**

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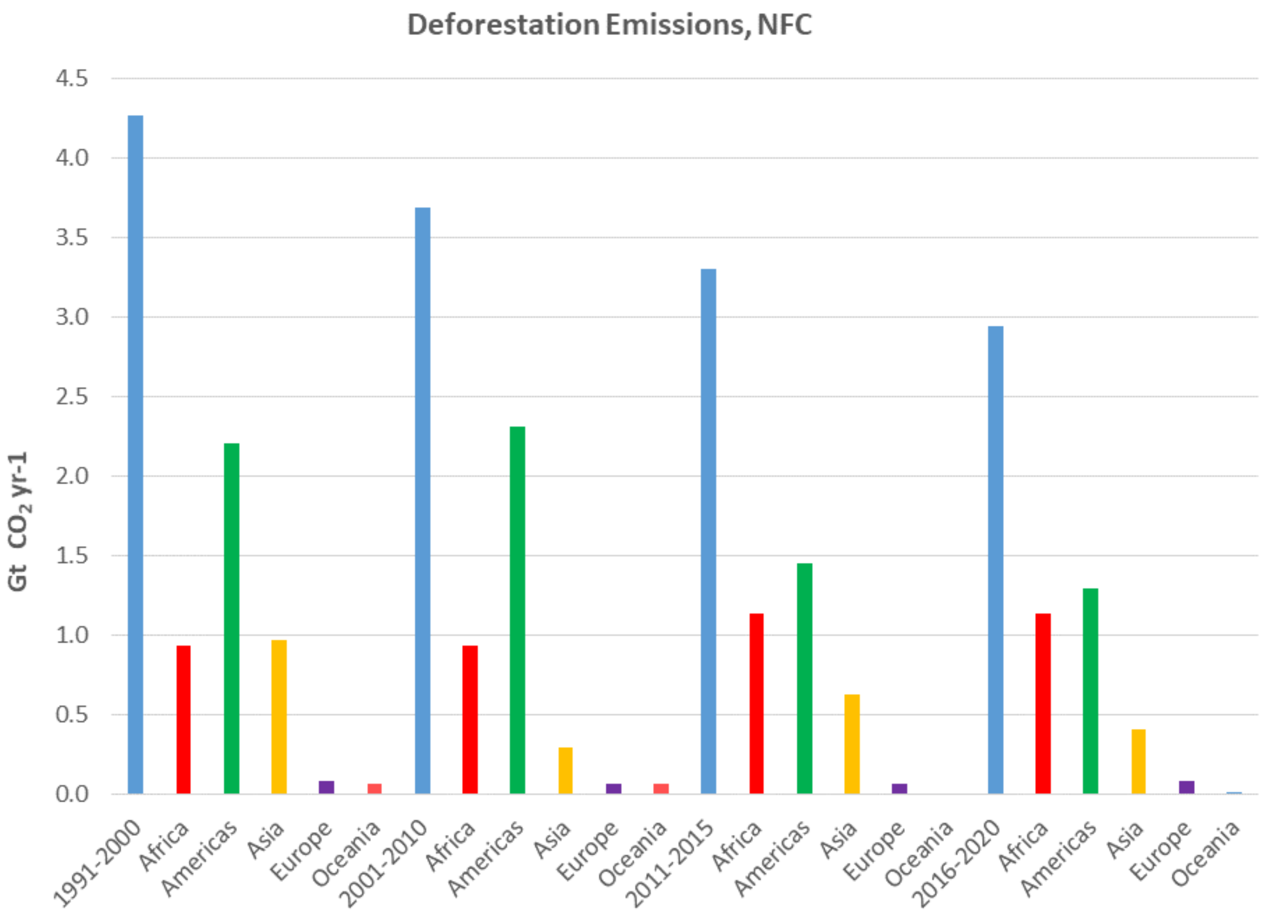


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**Figure 3. FAO estimates of deforestation emissions (NFC) for global and regional totals, in Gt $CO_2$ $yr^{-1}$, for the period 1991-2020. FAO estimates using FRA 2020 (this paper) and FRA 2015 are given for comparison.**

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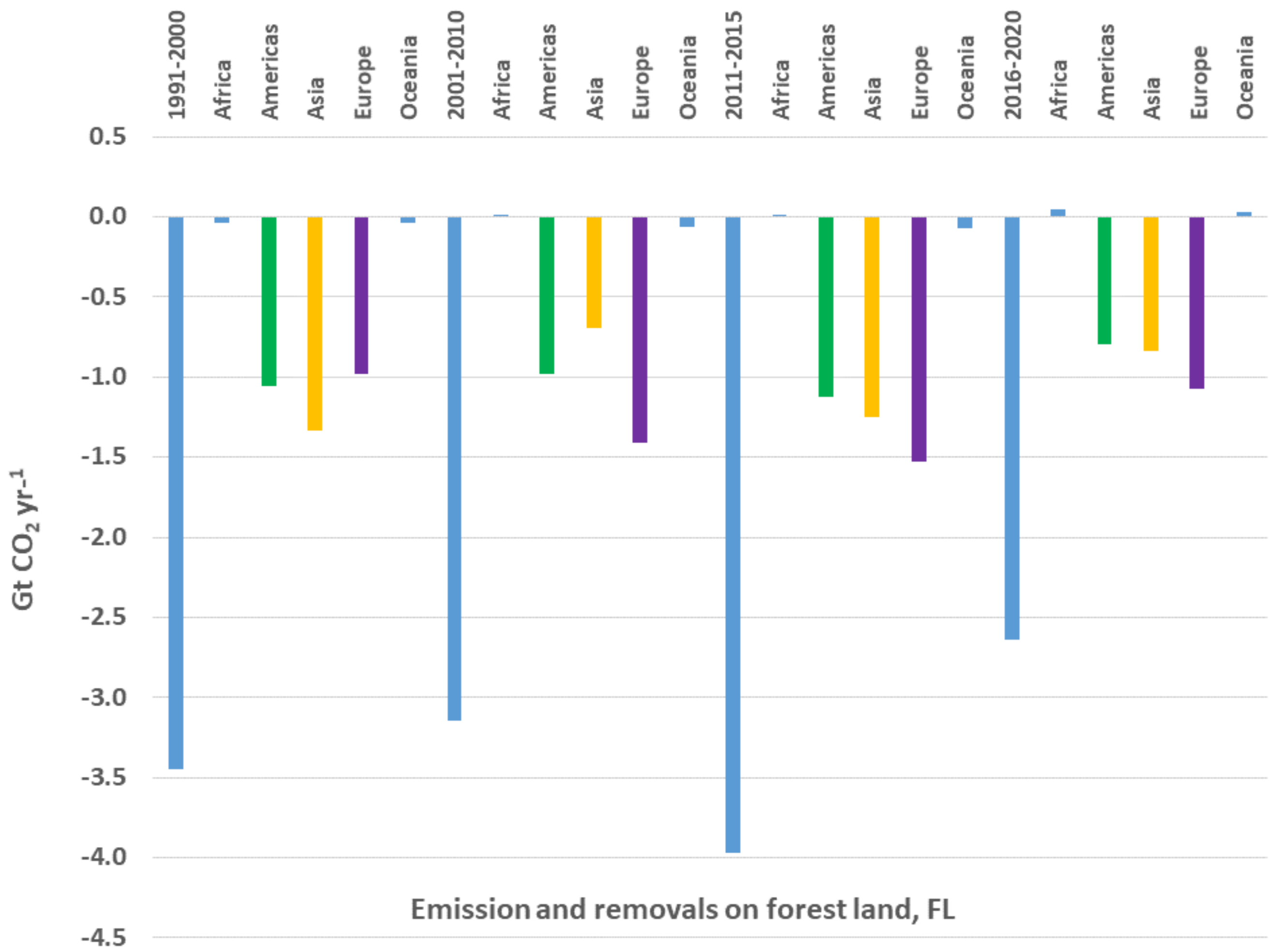


**Figure 4. FAO estimates of emissions/removals (FL) for global and regional totals, in Gt $CO_2$ $yr^{-1}$, for the period 1991-2020. FAO estimates using FRA 2020 (this paper) and FRA 2015 are given for comparison.**

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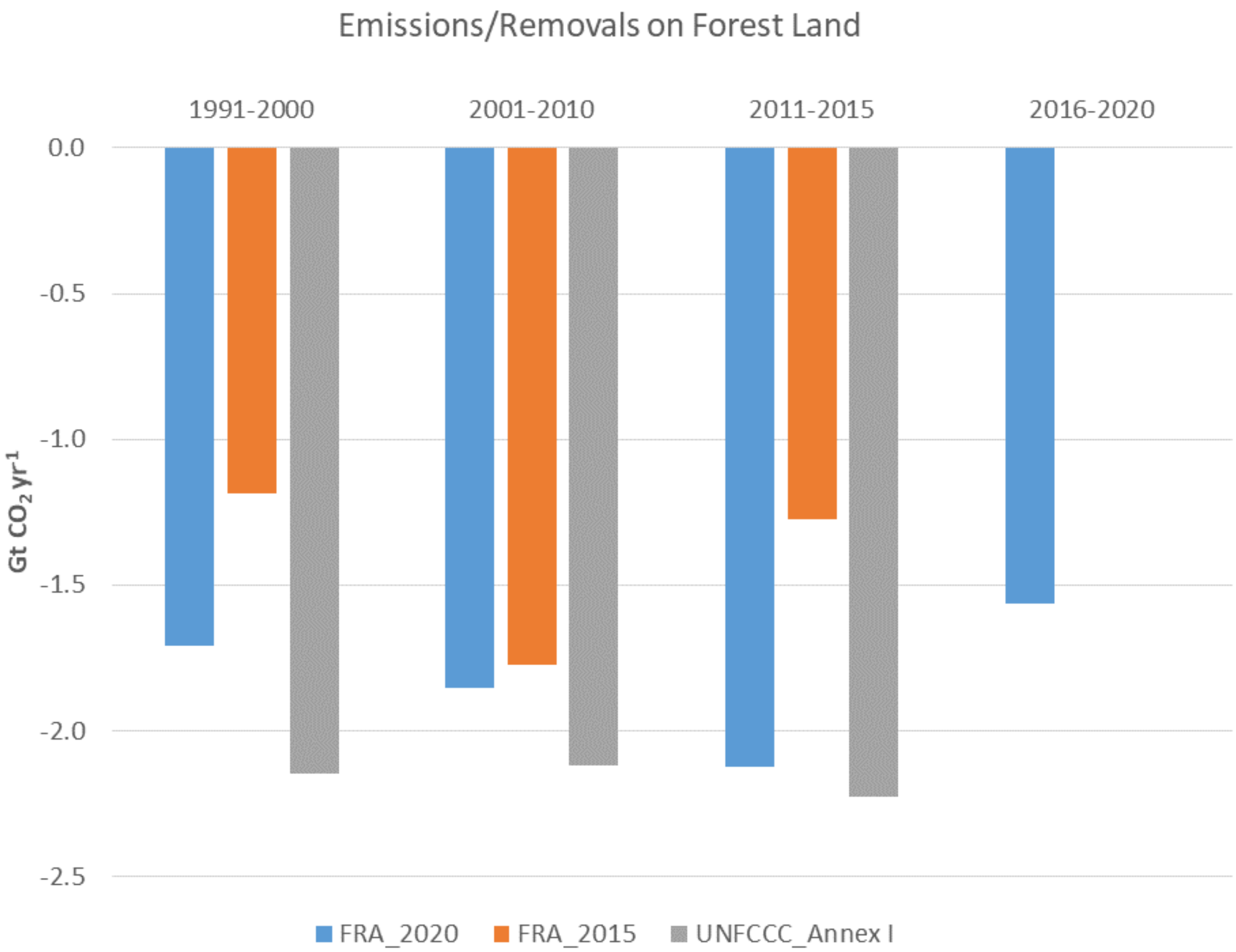


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**Figure 5. FAO estimates of emissions/removals (FL) for Annex I totals, in Gt $CO_2$ $yr^{-1}$, for the period 1991-2020. FAO estimates using FRA 2020 (this paper) and FRA 2015 are compared to country data reported to UNFCCC.**

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**Figure 6. FAO estimates of emissions/removals (FL) for Russian Federation, USA, China and Canada, in Mt $CO_2$ $yr^{-1}$, for the period 1991-2020. FAO estimates using FRA 2020 (this paper) and FRA 2015 are compared to country data reported to UNFCCC.**

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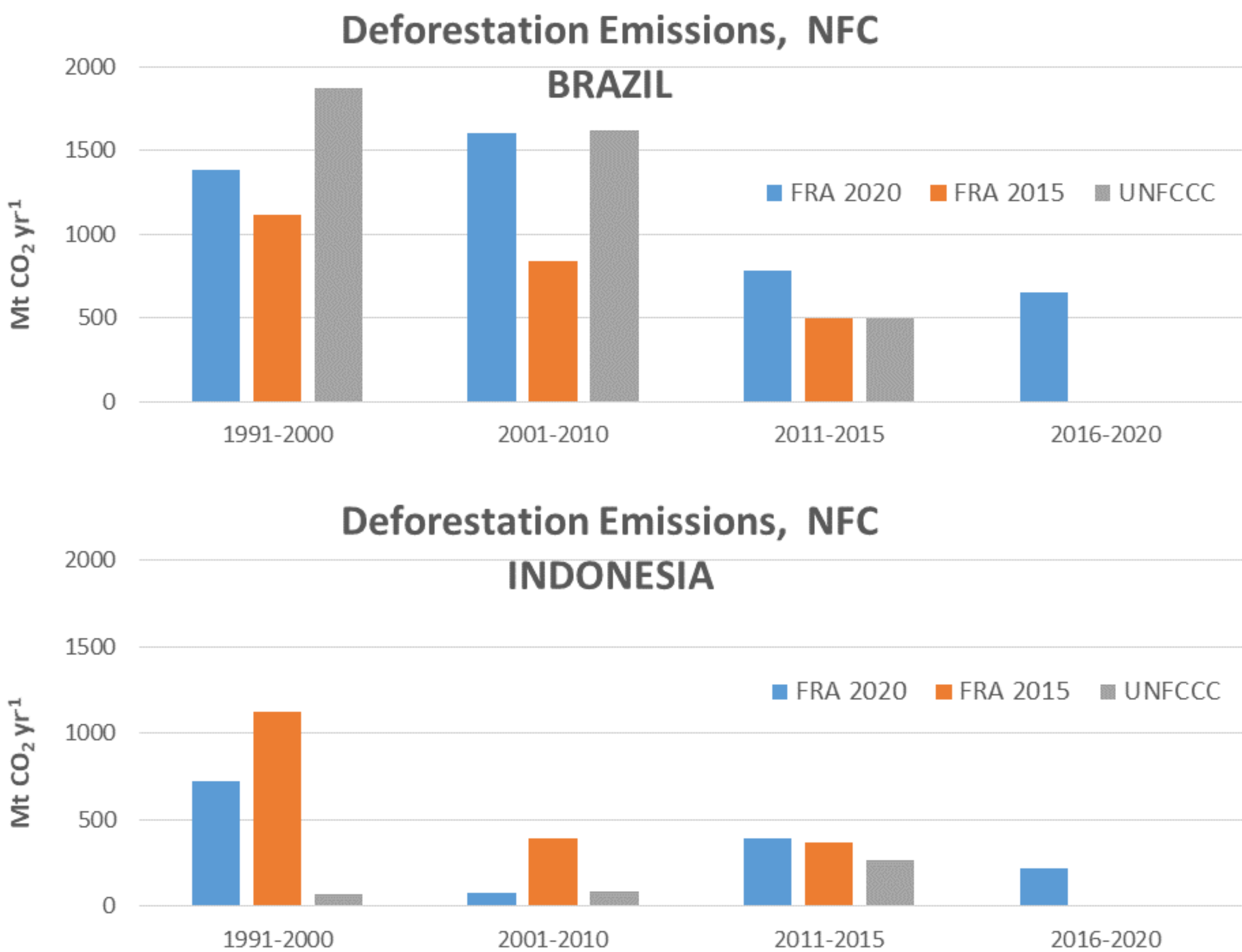


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**Figure 7. FAO estimates of deforestation (NFC) for Brazil and Indonesia in Mt $CO_2$ $yr^{-1}$, for the period 1991-2020. FAO estimates using FRA 2020 (this paper) and FRA 2015 are compared to country data reported to UNFCCC.**