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

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Abstract. NTrends in ational, regional and global , regional, and national CO_2 emissions and removals from forests were estimated , for the period 1990–2020,, using as input the are estimated by FAO and disseminated in FAOSTAT. using We document a major product update, based on the new country reports data from tpublished byof the Global Forest Resources Assessment (FRA) 2020, which replaces and updates previous information published under the FRA 2015, based on country reports, providing new information with respect to the previous FRA published in 2015. The FAOSTAT new FAO estimates, based on a simple carbon stock change approach, provideupdate published information on net emissions and removals from forests in relation to, in total as well as by component processesestimates were derived separately for two components: a) emissions from deforestationnet forest conversion; and b) emission and removals from remaining forest lands, including new forests resulting from natural expansion or afforestation. The estimatesResults indicate a significantshowconfirmed a significant reduction of the emissions fromin global net deforestation emissions from net forest conversion, a proxy for deforestation, over the study period, , though at . However, the emission reduction is slower rates than previously assessed, i.e., from a mean n average of 4.3 in the 1991–2000 to 2.9 Gt CO_2 yr^{-1} during 1991–2000, to an average of 2.9 Gt CO_2 yr^{-1} during 2016–2020 in 2016–2020. . At the same time, Excluding deforestation, forest land Excluding deforested areas, fForest land was a significant net carbon sink globally andglobally, but over the entire period, albeit decreasing in strength, over the study period, from -3.4 Gt CO_2 yr^{-1} in 1991–2000 to -2.5 Gt CO_2eq yr^{-1} during 2016–2020. In total,Combining emissions from net forest conversion with forest landremovals on forest land, ourthe FAOSTAT estimates indicatedd that globally forests were (and their losses) were generally and globally a small net source of CO_2 of emissions of roughly to the atmosphere on average during 1990–2020, with- mean net emissions of 0.4 Gt CO_2 yr^{-1} on average during 1990–2020 over the entire study period.. Remarkably,Yet for the brief the new estimates also suggest a globalperiod 2011-2015, The exception was the brief period 2011–2015, when forest land removals counterbalanced emissions from net forest conversion, resulting in forests acting

globally as a global net sink of about -0.7 Gt CO_2 yr^{-1} during 2011–2015 , a dynamic whichwhich was neverhas not beennot reported before in the literature. 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., less than 0.2 Gt CO_2 yr^{-1}. This near-zero balance was nonetheless the result of large global fluxes of opposite sign, namely net forest conversion emissions of 3.1 Gt CO_2 yr^{-1} counterbalanced by net removals on forest land of -3.3 Gt CO_2 yr^{-1}. Finally, we compared our estimates with Forest emissions and removals data independently reported by countries to the United Nations Framework on Climate Change, indicating were in closeexcellent agreement between FAO and country emissions and removals estimates with the new FAO estimates over the entire period 1990–2020study period. Data from this study are openly available via the Zenodo portal (Tubiello, 2020), with DOI 10.5281/zenodo.3941973, as well as on the FAOSTAT Emissions database..

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 CO_2 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 drainage of peatlands, generating roughly 4-5 Gt CO_2 yr^{-1} in recent decades (e.g., Tubiello, 2019). Additional important anthropogenic emissions and removals of CO_2 are located directly on forest land, in relation to processes linked to forest management or degradation.

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There is nonetheless significant disagreement between carbon cycle models on the one side, and national greenhouse gas inventories (NGHGI) on the other, on the quantification of the combined emissions and removals of CO_2 from all these land processes, though it is being increasingly shown that most differences are due to boundaries and definitional issues (e.g., Grassi et al., 2018; 2021). Greatly simplifying and limiting our scope to forests, terrestrial carbon cycle models have tended to focus on the CO_2 emissions from deforestation and forestry activities (land use change processes defined under the term E_{LUC}), while NGHGI have typically added removals on forest land beyond those generate by forestry practices, which the models tend not to consider anthropogenic. These forest removals in NGHGI counterbalance the positive emissions, resulting in near-zero estimated total net contributions of forests to the atmosphere (Grassi et al., 2018). Beyond the critical issues of the differences in boundaries and definitions between the two approaches, which are addressed elsewhere (e.g., Grassi et al., 2021), there is a significant need to improve the underlying activity input data used by both approaches. To this end, the The Food and Agriculture Organization of the United Nations (FAO) Global Forest Resources Assessment (FRA) collects, analyszes and disseminates, at regular intervals, a wealth of country-based forest statistics through its Global Forest Resources Assessment 2020 (FRA 2020), describing the status of forests with data at country, regional and global level (http://www.fao.org/forestry/fra/fra2020/en/) (FAO, 2020a). Among many different uses, FRA activity data of forest land area and carbon stock serve asare a critical inputs into for estimates of forest carbon fluxes by FAO (Federici et al., 2015; FAO, 2020b) and other major international efforts -for global carbon cycle modellingmodelling (e.g., Friedlingstein et al., 2019; IPCC, 2019; Houghton and Nassikas, 2017Houghton et al., 2012; Federici et al., 2015) and at . To this end, they are also the basis offor the FAO STAT estimates of greenhouse gas (GHG) emissions and removals from forest land disseminated in FAOSTAT (Tubiello et al., 2015; FAO, 2020b). The FAO estimates, accessible freely to users worldwide, have regularly featured in , which regularly inform IPCC assessment reports and other relevant scientific studies (e.g., Smith et al, 2014; IPCC, 2019;), studies (e.g. Houghton and Nassikas, 2017; Grassi et al., 2018) and users worldwide. FAO estimates Previous FAOSTAT estimates based on the previous FRA 2015 (Federici et al., 2015) (dataFAO, 2016) had documented a decrease of net forest conversionfound 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 on forest land, decreasing in strength over the same periodime, from an average of -2.7 (1991-2000) to -2.0 (2011–2015) Gt CO_2 yr^{-1}.

This paper describes the forest statistics available at FAO and discussedprovidesto estimate newupdated FAO STATestimates of emissions and removals of CO_2 from forests that, being -and net deforestation emissions based on a simple though powerful (and replicable) carbon stock change method, generate data that can serve as boundary conditions to help evaluate more complex terrestrial carbon model results and NGHGI data. -the new 2020 FRA 2020.data . OurThe analysis highlights new trends based on the use of FRA 2020 input data, , documentings the differences with respect to the previous use of FAO estimates based on FRA 2015. Finally, it -and compares results to national independent country data independently reported by countries to the United Nations Framework Convention on Climate Change (UNFCCC).

2 Material and Methods

The eEstimates of CO_2 emissions and removals from forestst land were computed following the established FAOSTAT made by FAO and published in FAOSTATmethodology (Federici et al., 2015; FAO 2020ba) are computed by applying . The methodology applies a simplifiedthe carbon stock change method of based on the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006, Federici et al., 2015; FAO, 2020a). -to input data on . timeT-series data of forest landarea and carbon stock in living biomass for the years 1990, 2000, 2010, 2015 and 2020 from country reports submitted under , derived for this update from the FRA 2020Previous estimates covered the period 1990-2015, using as inputs activity data from the FRA 2015 (Federici et al., 2015) were used as input into the FAOSTAT estimates. To this end, it should be noted thatThis work extends the FAO estimates of emissions and removals to -the FRA 2020 data2020, by adding new input data for the period 2015-2020, while incorporating any revision -may replace entirely those previously published under FRA 2015, rather than merely updating data for the more recent yearsin time series that may have occurred in the FRA 2020 with respect to FRA 2015. In describing the methods used in this work, we also discuss their limitations and uncertainties and the scope for comparing FAO estimates to UNFCCC country data.

2.1 Gap-filling

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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*; and carbon stock in above and below-ground living biomass. Data cover the period 1990-2020.We gap-filled ~~the few~~ missing ~~data from the original FRA 2020 dataset as follows. For~~ carbon stock ~~data~~ data when needed, by using ~~, we used~~ relevant regional averages of ~~above and below-ground~~ biomass stock density (carbon stock per unit forest land area), multiplied by~~to gap-fill missing country values~~ country forest land area. ~~For forest land area data, w~~Additionally, we checked the consistency of ~~consistency of country~~forest land area values ~~with those provided for the two sub-categories *Naturally regenerating* area of *Planted forest* area, i.e., by ensuring that they would~~ against ~~-sum to the value of the parent category~~its two sub-components. In the few cases when such consistency was violated, we ~~considered data on planted forest area more reliable than the other sub-category and~~ re-computed ~~the~~ *naturally regenerating forest* area ~~component~~ as the difference between ~~the areas of~~ *forest land* and *planted forest* area.~~.~~ The ~~data so derived were~~slightly revised dataset was used as input into the emissions~~FAOSTAT~~ calculations. It is ~~. They are~~ openly available via the Zenodo portal (Tubiello, 2020), with DOI 10.5281/zenodo.3941973, as well as via~~in~~ the FAOSTAT database (FAO, 2020a). ~~EachThe time series data for forest area were complete, but the carbon stock data had some gaps which were filled by FAO estimates to obtain a globally complete dataset for both variables and all FRA reporting years. for the sake of consistency, all data employed here came from FRA 2020 as FRA assessment may provide newly revised data for the whole time series, hence FRA 2020 entirely updates the FRA 2015 and extends it to 2020. FRA 2020 data on the forest land area are further stratified in two sub-categories: area of *Naturally regenerating* and area of *Planted forest*. P When computing area changes, these were tracked separately, in order to improve the computations of area change compared to the use of forest land area only. Following Federici et al. (2015), the decline in net forest area – resulting from the combination of losses due to forest conversion and from gains due to afforestation or natural expansion over any given period – is used herein as a proxy for deforestation.~~

~~Next we present a number of relevant definitional issues and discuss uncertainties, limitations and differences with respect to processes under the UN Framework Convention on Climate Change (UNFCCC).~~

2.2 Forest~~Land Use~~ Definition ~~definitions~~

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~~used to collect data from countries via the FRA process and the FAO Land Use Questionnaire~~. 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 ~~Such data are disseminated on the FRA portal as well as on the FAOSTAT Land Use database (FAO, 2020b). The areas of *forest land* are defined by FAO as tree-covered areas that meet~~ three basic bio-physical ~~parameters~~conditions are met, namely: i) minimum tree height of 5 m at maturity; ii) overall crown cover greater than 10%; and iii) minimum 0.1 ha in extension. ~~-(complete definitions can be found at~~ for complete

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definitions see, e.g., the FAO Land Use questionnaire, ~~the FRA portal or in FAOSTAT~~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, although the uncertainty underlying reported national forest data is often incomplete. Recent comparisons of land use with land cover information from remote sensing suggest differences of up to 20% at regional level, largely due to the difficulty of mapping land cover characteristics to land use status (FAO, 2020c). It may be noted that for well-defined forest land areas, uncertainties in national forest inventories are nonetheless typically 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 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 the world's forest land area in many countries is administratively regulated. Finally, we note that the FAO forest land area considered herein does not track separately, as done instead in UNFCCC reporting, the two- sub-components *forest land remaining forest land* (FL-FL) and newly converted forest land. This is often overlooked in the literature, where FAO estimates of forest land emissions and removals may be incorrectly compared to UNFCCC data for FL-FL (e.g., Petrescu et al., 2020). ~~the forest land definition used by countries for reporting to UNFCCC within their national GHG inventories (NGHGI) may differ from FAO's, for instance in the values of the minimum forest area thresholds. Also, NGHGIs may further subdivide *forest land* area into separate accounts for *forest land remaining forest land* (FL-FL) and new forest land, a feature that is not covered in the FAO definitions. It is important to highlight that, while being a land use definition, *forest land* for FAO includes both managed and unmanaged areas. Furthermore, 'managed' area may comprise active forestry production as well as areas for conservation, restoration, tourism, etc. At the same time, we note that most forests nowadays are under some administrative regulation in most countries, and hence many countries consider a large majority of their forest lands as managed. Nonetheless, the forest land definition used by countries for reporting to UNFCCC within their national GHG inventories (NGHGI) may differ from FAO's, for instance in the values of the minimum forest area thresholds. Also, NGHGIs may further subdivide *forest land* area into separate accounts for *forest land remaining forest land* (FL-FL) and new forest land, a feature that is not covered in the FAO definitions.~~

~~Secondly, *net forest conversion* is defined herein as the negative difference in forest land area between successive time periods. In practice, it represents the net loss of forest land area net of gains that may have taken place over the same period, considering that gross gain and loss area components are not tracked separately in the FAO data. As an effort towards capturing some of the possible gross changes in forest area, our computations track net forest conversion separately for the two forest subcategories *naturally regrowing forest* (including both primary and secondary forest) and *planted forest*. This separate~~

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accounting aims at reducing the possible masking of area losses in naturally regrowing forests by concomitant area expansions in plantation forests. A final consideration concerns the drivers of land use changes, i.e., whether they are anthropogenic or natural. While it is noted that the data on *net forest conversion* cannot be sub-classified as either anthropogenic or natural, we suggest they are largely an indication of the former, and that net of the limitations highlighted above, the can be used as a proxy for human-driven deforestation. To this end, we note that land use classifications are based on human agency, including as a driver of changes in land use typology. Specifically, in cases of forest land area losses due to natural causes, human intervention is typically required to determine a land use change, for instance through the establishment of non- forest activities, chiefly agriculture, or for building new infrastructure, which would then prevent the subsequent natural forest regrowth and recovery.

Conceptually, the computation of *net forest conversion* adopts the so-called IPCC 'Approach 1' for land use area representation. In terms of comparison to data reported to UNFCCC by countries that also apply Approach 1 to their land use statistics, the FAO *net forest conversion* data would roughly correspond to the sum of forest land use area changes from forest land to other land uses. More generally, forest land use change data reported to the UNFCCC may differ, since countries may be able to measure gross losses and gains of forest area via more accurate national forestry inventories, and in addition they may be able to better characterize which land use changes were driven by anthropogenic or natural causes.

2.3 Emissions and Removals

The FAOSTAT estimates presented herein provide information on total net emissions and removals from forests, in total as well as by component processes. We simplified the methods developed in Federici et al. (2015)and conducted the analysis without interpolating between FRA years as this would require assumptions on temporal forest dynamics that are not available in the FRA data. To this end, we computedFollowing previous work (Federici et al.., 2015), total net emissions/removals from forests, *ER*, were computed as the carbon stock change in living forest biomass over time, and split into two distinct component fluxes: a) net forest conversion, *NFC*; and b) forest land, *FL* estimates as annual average carbon fluxes from the differences of relevant forest area or carbon stock information for the FRA 2020 periods 1991–2000; 2001–2010; 2011–2015; and 2016–2020, as follows (see also Fig. 1). Specifically, fFor each country *a* and total carbon stock B_a (limited to carbon in above and below living biomass), the total forest emissions/removals, ER_a, were computed as a simple carbon stock change, as follows:

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

Where biomass stock information was derived from the FRA 2020 as indicated in the previous section, and t_i = 1990, 2000, 2010, 2015, 2020 represent FRA yearssuccessive periods in the FRA 2020 time series. The minus sign was used to adhere to the convention of considering emissions as positive fluxes to the atmosphere, corresponding to decreases in forest carbon stock— and vice-versa to consider removals as negative fluxes, i.e., –negative–from the atmosphere into forest land,

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corresponding to increases in forest carbon stock. We note that the estimates in equation (1) are robust as well as easily replicable by anyone having access to FRA data. At the same time, it is noted that the FAO carbon stock change estimates include only two of the five carbon pools typically reported by countries according to IPCC. This difference may affect the magnitude of the estimated C stock changes, although likely not the sign, because of biophysical linkages across carbon pools. The net forest signal to the atmosphere, ER, was split ~~Also shown in equation (1), these total emissions/removals were split~~ into two mutually exclusive components, specifically emissions from *net forest conversion*, NFC, ~~-~~and emissions/removals from *forest land*, FL~~.~~ ~~The net signal to the atmosphere is thus determined by the contribution of these two processes~~ (Fig. 1).

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2.3.1 *Emissions from Net Forest Conversion*

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For each ~~the same~~ country *a*, total carbon stock B_a, and time period t_i ~~in equation (1)~~, the emissions from *net forest conversion*, $NFC_a(t_i)$ in equation (1)~~,~~ were computed as the positive carbon flux to the atmosphere associated with~~to~~ net forest land area ~~net~~ losses, ~~the latter~~ tracked separately for sub-categories *naturally regenerating*~~*rowing*~~ *forest*, ANR_a, and planted forest, APL_a as follows~~-~~:

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

Thus net forest conversion tracks losses of both primary and secondary forest areas, as well as those in planted forest areas. It should be noted that in cases when net forest land area change is positive, indicating net area gains, NFC is zero by definition and the relevant emissions/removals are instead accounted for on forest land (see next section). ~~In the previous section we have already addressed potential differences and limitations characterizing these FAO estimates to data submitted to the UNFCCC by countries, linked to differences in national forest definitions, measurement techniques and level of data aggregation. Additional limitations apply to equation (2) in terms of assumptions and resulting uncertainties. First, there is currently poor understanding of the uncertainty in national forest land area data. Recent comparison of land use with land cover information from remote sensing suggests uncertainties of up to 20%, quite in line with what the IPCC guidelines indicate as default uncertainty for FAOSTAT activity data. It may be noted that uncertainties in national forest inventories are typically an order of magnitude smaller but apply to gross area differences. For lack of additional knowledge, we applied the same uncertainty to all area data used in equation (2), as well as to biomass density data in equation (2). Simple propagation of the component uncertainties results in an uncertainty in NFC emissions of roughly 50%. We furthermore apply this uncertainty to all components of (1), for coherence. This is consistent with values used for land use change emissions estimates in recent IPCC reports (IPCC, 2019) and carbon cycle literature (Friedglinstein et al., 2020). In addition to the numerical uncertainty arising from the input data, the~~ A number of limitations apply to the computation of emissions in (2), First, results are ~~-is furthermore~~ limited by the lack of ~~forest category-specific~~ carbon ~~density~~stock data by forest sub-component~~in the FRA 2020~~, resulting in the need to apply a single value for both naturally regenerating~~rowing~~ forest and planted forest. Considering that

~~generally carbon density can be expected to be higher in natural forests than in plantations, and that~~ the majority of forest area losses in the FRA 2020 ~~data~~ pertain~~refer to~~ to the natural forest component, however, ~~we suggest that~~ the use 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 expected to be higher in natural forests than the average biomass stock (which also includes carbon stock in plantations), implying that the NFC emissions computed in (2) are likely underestimates. Furthermore, we note that equation (1) above does not depend on the availability of carbon stock values by forest sub-component. ~~, and in addition we conclude that the NRC emission in (2) are likely underestimates.~~ A second important limitation to equation (2) is that forest losses are computed net of forest area gains taking place over the same period. The underlying activity data used as input do not in fact allow separate tracking of gross gains and losses. Thus in terms of comparison to UNFCCC, FAO *net forest conversion* data would roughly correspond to the sum of UNFCCC-reported land use changes from forest land to non-forest land, for those countries using the so-called ‘IPCC approach 1’ to land use representation, which like our estimates relies on net area changes. By contrast, use of more accurate national forestry inventories, with more detailed identification of gross area fluxes, would generate larger differences between FAO estimates and the corresponding UNFCCC country data for this category. Finally and importantly, estimates in equation (2) are limited by the underlying uncertainty in the activity data. Simple error propagation of the component uncertainties in area and carbon stock discussed in the previous section give an uncertainty in NRC emissions of roughly 50%. This is consistent with values used for land use change emissions estimates published in recent IPCC reports (IPCC, 2019) and in relevant carbon cycle literature (Friedlingstein et al., 2019). For coherence, we applied this uncertainty value to ER and FL estimates. ~~Finally, with the above definitions in mind, and within the differences highlighted with regards to land accounting approaches and differences in national forest definitions, the FAO *net forest conversion* emission estimates in (2) correspond to the sum of those reported by countries in their NGHGIs with regards to land use changes from forest land to non-forest land.~~

2.3.2 *Emissions and Removals on Forest Land*

~~Finally, f~~or any~~the same~~ country *a*, total carbon stock B_a, and time period t_i in equations (1) and (2) above, the emissions/removals on~~from~~ *forest land*, $FL_a(t_i)$, were computed ~~as the net carbon flux to or from the atmosphere associated to dynamic on forest land, i.e., from a combination of carbon stock changes and forest area increases on forest land between successive FRA periods. While Federici et al. (2015) had computed these dynamics explicitly, we compute them herein more simply, though equivalently to the previous approach,~~ as the residual between total forest carbon stock change and net forest conversion, as follows:

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$$FL_a(t_i) = ER_a(t_i) - NFC_a(t_i) \qquad (3)$$

The emissions/removals computed in (3) represent the net carbon flux to or from the atmosphere located within the boundaries of forest land area, arising from a combination of carbon stock and forest area changes between successive FRA periods. These changes in principle may arise from both anthropogenic and natural causes, including legacy effects of deforestation prior to the study period, afforestation, forest management, climate signals, as well as the impacts on plant growth of nitrogen deposition and increased atmospheric CO_2 concentrations. As discussed above, we associated an uncertainty level of 50% to estimates in equation (3), consistently with those computed for the emissions from net forest conversion and in line with the uncertainty used in the literature.

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

~~as the net carbon flux to or from the atmosphere associated to dynamic on forest land, i.e., from a combination of carbon stock changes and forest area increases on forest land between successive FRA periods. While Federici et al. (2015) had computed these dynamics explicitly, we compute them herein more simply, though equivalently to the previous approach. A number of considerations apply to the estimates in (3).~~

2.4 Comparisons to UNFCCC data

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

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To this end, we used country data accessed at the UNFCCC data portal (UNFCCC, 2020) and complemented with information from national Biennial Update Reports (BURs). While data from Annex I countries are fairly complete over the period 1990–2018, data from non-Annex I countries are sparse, although becoming increasingly available through BURs. Given these data limitations, a full comparison was possible only for Annex I countries for the FRA periods 1990–2000; 2001–2010; and 2011–2015. First, we compared results of equation (3) with aggregate Annex I reporting of emission/removal for the category '4.A Forest land' (UNFCCC, 2020). To gain further insights, we also separately analysed emissions/removals on forest land reported by individual countries in their national GHG inventories (NGHGIs), focusing on those reporting large sinks, i.e., Canada, Russian Federation and the United States of America among Annex I parties, and China among non-Annex I parties. We also compared our results for net forest conversion to available non-Annex I country data from Brazil and Indonesia, representing large emission sources, according to FAOSTAT estimates respectively the first and third emitters in this category (FAO, 2020b). Unfortunately, no BUR submissions have been made so far by the Democratic Republic of Congo—the second largest emitter from deforestation according to FAOSTAT data—which therefore could not be included in this comparison exercise. Data for NAI countries were sourced from China's second Biennial Update Report (2018), Brazil's third Biennial Update Report (2019) and from Indonesia's second Biennial Update Report (2018).

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First, as for the other estimates in this work, they represent net fluxes, arising from the combinations of many possible dynamics, from forest area expansion at constant carbon density, to increases in carbon density at constant forest land area, and combinations thereof, in either forest subcategory. While in principle it is possible to further disaggregate into forest subcomponents, as done in Federici et al. (2015), the use of a single value for carbon stock is a greater limitation than for net forest conversion, so that we do not include it in our results, but only offer a few remarks in the discussion section. Second, it is relevant to note that, when net forest conversion is non-zero, a direct consequence of the underestimation of NRC is that FL is likely overestimated as a source and underestimated as a sink.

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

$$NFC_{i-p} \quad _{i-1} \quad _{i-1} \sum \quad _{i,j} \quad _{i-1,j} \frac{}{12} - * 10^3 =) /) * j \{Min [-),0]\} * - / D \quad (2)$$

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

Where:

- *FL_Tot* is the overall forest carbon flux from forestarea , expressed in Gg CO_2 yr^{-1};
  - *NFC* is the (negative) net forest conversion, herein a proxy for emissions from deforestation, din Gg CO_2 yr^{-1};
    - *FL* is net emissions/removals on forest land (excluding deforestation),expressed in Gg CO_2 yr^{-1}; and
  - B_i is the carbon stock in living biomass (above and belowground) at FRA reporting year *i*, expressed in Mt C;
  - A_i is the forest land area at FRA year *i*, expressed in k ha;
  - $A_{i,j}$ is the area of forest category (*j* = Naturally regenerating forest, Planted forest,) at FRA 2020 year *i*; in k ha.
  - *i* = 1990, 2000, 2010, 2015, 2020 is the FRA reporting year;
  - *i-p* =1991 – 2000; 2001 – 2010; 2011 – 2015; 2016 – 2020 are the corresponding FRA 2020 periods;

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- D is the length of the FRA lag interval $i-p$, i.e. either 5 or 10 years; and

Values are multiplied by - 44/12 * 10^3 to convert from Mt C to Gg CO_2 as well as to express a positive change in carbon stock as a negative emission (i.e. removal or sink) to the atmosphere, and vice-versa.

In our estimates, deforestation occurs when the changes in the area of Naturally regenerating forest and Planted forest, computed separately for each FRA interval (5 or 10 years), sum to a net negative balance. In this respect, the concept of deforestation used here (i.e. net deforestation) is not entirely coincident to the definition of deforestation in the IPCC guidelines (2006), i.e. as any forested land converted to non-forested land. Likewise, the net emissions/removals on forest land from the calculations above, do not entirely correspond to the category Forest land under the UNFCCC reporting (UNFCCC, 2020).

FAOSTAT estimates are expressed in Gg CO2. For the sake of readability of results, this paper presents however regional and global values in Gt (giga tonnes) CO2 and country results in Mt (mega tonnes) CO2. Within the differences highlighted above, with regards to land accounting approaches and differences in national forest definitions, the FAO emissions/removals on *forest land* largely correspond conceptually to those used by countries in their reporting to the UNFCCC with respect to land use. At the same time, it is noted that

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2.1 Structure of the FAOSTAT datasets on emissions-forest land and online access

The computed emissions estimates and associated area information statistics are disseminated in the FAOSTAT Emissions Land Use/ Forest Land domain, over the period 1990–2020 (FAO, 2020b) for 220 countries and territories. Data include, by country and year, forest land area and area of deforestation (in 1000 ha), the emissions/removals on forest land and the emissions from deforestation (net negative forest conversion) (in Gg of CO_2). The carbon stock in living biomass (in Mt C) is available under the FAOSTAT database, Inputs/Land Use (FAO, 2020c). The dataset makes values available by country, by standard FAO regional aggregations and special groups, including the Annex I and non-Annex I to UNFCCC.

Where data for a country were not available for any FRA assessment, the data of the previous FRA assessment have been applied without any extrapolation, as well as without any interpolation for those data missing between 2 available FRA assessments.

2.2 **Limitations and uncertainty**

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For several reasons, the FAOSTAT emissions estimates presented here are likely to underestimate both emissions and removals. First , the FAO estimateswe include only two out of the five carbon pools identified by the IPCC guidelines (2006), that is the typically reported by countries. aboveground and belowground - biomass while excludingThis difference may affect the dead wood, litter, and soil organic carbon. Such incompleteness is expected to have an impact on the magnitude of the estimated C stock changes between FAO and UNFCCC data, , but although generally not on their likely not signthe sign (i.e., source or sink),, i.e., indicating a net sink or a net sourcebecause these processes are linked biophysically. We included only carbon in living biomass because data for the other pools were less complete and would have required substantial gap-filling and thus increasing uncertainty. Second, the use of net forest area change, even if performed separately on naturally regenerating and planted forest, is likelyalso contributing to underestimate the actual gross forest change (both deforestation and forest expansion). MoreoverFinally, equation (2) assumes C losses in deforestation based on average carbon stock density of the entire forest, which is probably an underestimate whenever the deforestation occurred onwas primary or other natural forests with higher carbon stocks than average.

The implication of these factors is that, while the estimates of total forest carbon flux to or from the atmosphere are correct — within the uncertainty of the biomass carbon stock values that are reported to the FRA — the estimates corresponding to the two sub-components, i.e., net deforestation emissions and forest land net sink, are probably underestimated in the case of naturally-growing forests. systematically underestimated.

The uncertainty of the emissions estimates depends directly on the uncertainty in area and carbon stock values that countries reported to the FRA 2020. The latter uncertainty can be assumed about 50 %. Carbon stock density is the variable measured and reported by countries and from which we derived the total carbon stock areain equations (1-2) multiplying by the forest area. In line with the IPCC default assumptions, the uncertainty is instead about 20 % for the 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.

Finally, it should be noted that the total forest carbon flux computed herein is based on the use of two attributes and istherefore not comparable with the results from studies considering the full range of forest carbon fluxes. GHG

In most country reports to FRA, forest carbon stock refers to the entire forest land area reported to FAO (i.e. without differentiating between primary, naturally regenerated and planted forest categories). The above means that estimates reported are are not always fully comparable with National GHG inventories reported to UNFCCC, because of possible differences in the pools and the area included (some National GHG inventory may report GHG fluxes on less area that FAO-FRA 2020, but they often include non-biomass pools).

2.54 Structure of the FAOSTAT datasets on emissions-forest land and online access

The FAO emissions and removals estimates and associated area information statistics are disseminated in the FAOSTAT Emissions Land Use/ Forest Land domain as yearly statistics, over the period 1990–2020 (FAO, 2020b), for 220 countries and territories. Annual averagemean fluxes are obtained by dividing the outcomes of (1)-(3) by the relevant time-period underlying FRA intervals, i.e., by 5 or 10 years. They therefore refer to the following periods: 1991–2000; 2001–2010; 2011–2015; and 2016–2020. For completeness, values for the year 1990 were set equal to the averages computed for 1991–2000, and the full period of analysis was referred to as 1990-2020. Data include, by country and year, forest land area and area of net forest conversiondeforestation (in 1000 ha), the emissions/removals on forest land and the emissions from net deforestation (net negative forest conversion; emissions/removals on forest land; and total emissions/removals from forests) (in Gg of CO_2). The carbon stock in living biomass (in Mt C) is available under the FAOSTAT database, Inputs/Land Use (FAO, 2020c). Data are disseminated The dataset makes values available by country, by standard FAO regional aggregations and special groups, including the Annex I and non-Annex I country grouping relevant to UNFCCC reporting.

3 Results

We present below the main findings of aAnnual CO_2 emissions/removals estimates from forest, divided into net emissions from net forest conversiondeforestation, net forest land emissions/removals, and their aggregate, total emissions and removals from forest, are disseminated in FAOSTAT (FAO, 2020b) forfor the period 1990–2020, computed for more than 200 countries and territories, based on equations (1)-(3) above. Emissions and removals are expressed in annual means (Gt CO_2 yr^{-1}) relative to the relevant FRA period. Results are

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We present below the main findings presented at global levelsummarized , by Annex I and non-Annex I countries and (also available in FAOSTAT as special regional groups), by standard FAOSTAT region, and globallywhere relevant. Results are presented for the four periods: 1991–2000, 2001–2010, 2011–2015, 2016–2020. Annex I and non-Annex I countries,and compared with the results based on Differences with estimates based on earlier FRA 2015 input data are also discussed, where of interest.and reported earlier

3.1. Total forest carbon flux to the atmosphere

FAOSTAT estimates based on FRA 2020 data show that forests acted globally as a net, albeit source of CO_2 emissions to the atmosphere over 1990 the 2020 period, averaging 0.4 Gt CO_2 yr^{-1}(including deforestation losses and emissions/removals on forest lands). This was which is significantly less than reported earlier.estimated earlier the (Table 1). The small global source was the result of a net

~~sink mostly in UNFCCC Annex I countries (-1.5 Gt CO_2 yr^{-1}) counterbalanced by a largerslightlylarger 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, both reversing 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 due to the decreased deforestation, averaging nearly -0.7 Gt CO_2 yr^{-1}. This net overall sink has never been estimated before by FAOSTAT. By comparison, FAO estimates based on FRA 2015 for the corresponding 2011–2015 period indicated a source of 1.1 Gt CO_2 yr^{-1} (Table 1).~~

3.12 ~~Deforestation~~Emissions from Net Forest Conversion

Results show that ~~global~~ carbon ~~net deforestation~~ fluxes ~~of carbon~~ to the atmosphere from *net forest conversion* were significant ~~during 1990–2020,~~, with world-total ~~averaging~~ means of 3.7 Gt CO_2 yr^{-1} for the period 1990—2020~~, confirming previous estimates~~, and . ~~Unlike for total forest carbon fluxes, deforestation was~~ almost entirely ~~determined by dynamics~~located in non-Annex I countries, which contributeding more than 90 % ofto the world total (Table 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 and associatedassociated emissions globally.~~the global mean decreased by 20% from 1990 to 2015, -from 4.3 to 3.3 Gt CO_2 yr^{-1}, less than -(previously estimated over the same period using the FRA 2015 (-~~about a 20 % decrease, there where the estimates based on the FRA 2015 had indicated a~~ 40 %~~ decrease~~). It decreased ~~, and then further down to an average of~~ by another 10% to 2.9 Gt CO_2 yr^{-1} during 20166—2020. ~~The regional distribution of deforestation in~~ For the period 20166—2020,~~ saw~~ the Americas and Africa were nearly ~~nearly~~ equal ~~major~~ contributors ~~(1.3 and 1.1 Gt CO_2 yr^{-1}, respectively)~~, but ~~yet~~ with markedly opposite trends c. Compared to the period~~first~~ 19911—2000. Specifically with respect to the two time periods, e ~~FRA 2020 period, deforestation~~ emission in the Americas nearly halved, from 2.2 to 1.3 Gt CO_2 yr^{-1}, while ~~in Africa~~ they ~~continued to~~increased in Africa ~~increase~~, from ~~earlier levels of~~ 0.9 Gt to 1.1 CO_2 yr^{-1}. Asia was the third region in terms of ~~deforestation~~ emissions from net forest conversion, ~~with associateassociated emissions decreasing., from~~showing a slight decrease, from -0.6 Gt to 0.4 CO_2 yr^{-1} over the same time periods ~~(2011 – 2015) to 0.4 Gt CO_2 yr^{-1} (2016 – 2020)~~ (Fig. 23).

3.23 Emissions and removals on forest land

~~Results show that~~Emissions/removals on forest land ~~after deducting the net deforestation continued to function as~~showed a net sink ~~of atmospheric CO_2~~ over the entire period 1990–2020 ~~period~~, ~~averaging~~ with a mean removal of -3.3 Gt CO_2 yr^{-1} globally.~~.~~ ~~Unlike deforestation fluxes, t~~Thise forest carbon flux was nearly ~~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}) (Table 1). Additionally, we computed that tThe ~~1~~ new FAO~~STAT~~ estimates

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indicated a stronger forest sink than previously estimated using FRA 2015 data,are i.e., on average 1.0 Gt CO_2 yr^{-1} and about (-35 %) stronger, than previous findings based on the FRA 2015, mostly due to larger computed estimated sinks in Europe (dominated by trends in Russian Federation) and Asia (China).

In terms of temporal trends, our estimates based on FRA 2020 data show a decrease in theAt the same time, the world totalestimated global forest land sink weakened in strength over the study period, with average rates goingthe world total mean decreasing from -3.3 to -2.6 Gt CO_2 yr^{-1}, i.e., about a 20 % decrease from 1990 to 2020due to decliningdeclining afforestation rate. In fact, the new estimates also reveal a significant albeit brief reversal during tThe period 20111–2015 represented an exception to this decreasing trend, , where theshowing the strongest forest land sink showed a marked increase in strength with respect to theover the study period 1991–2010 period, reaching an averagewith mean world total annual rates of -4.0 Gt CO_2 yr^{-1}.

Regionally, the global sink, averaged over the entire pIn terms of regional distribution and averaged over the period 1990—2020, was nearly equally split between Europe, the Americas and Asia nearly equally contributed to the estimated forest land removals, within a narrow range of -1.0 to -1.2 Gt CO_2 yr^{-1}, and with Europe (, including the Russian Federation), , being having the largest contributorion among these regions. Conversely, forest land in Africaa was the only region with was a source to the atmosphere, with mean emissions increasing significantly from 2000 to 2015, i.e., from 1.4 to 43 Mt CO_2 yr^{-1} (Fig. 3). By associating net forest land emission to forest degradation, as done in Federici et al. (2015), our results suggest over a 15-fold increase in forest degradation in Africa over the last twenty years. net forest land emissions (albeit small, compared to the sinks), in all more recent periods (2001–2010; 2011–2015; and 2016–2020) (Fig. 4)(degradation defined following Federici et al. 2015, as netnet emission over forest land, or a net loss of carbon stock).

, leading to the conclusion that those forest lands are subject to degradation of their C stocks. Indeed, annual average emissions increased significantly from 2001—2010 to 2011—2015, i.e., from 1.4 to 38 Mt CO_2 yr^{-1}, and thenthen further 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 netnet emission over forest land, or a net loss of carbon stock).

3.3 Total emissions and removals from forests

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FAOSTAT Our estimates based on FRA 2020 data show that the net effects of emissions from net forest conversion and removals on forest land were s acted globally as a small net, albeit source of CO_2 emissions to the atmosphere, with a world total mean over 1990–the 2020 period, averaging of 0.4 Gt CO_2 yr^{-1}1 over the 1990–2020 period. This new estimated value was(including deforestation losses and emissions/removals on forest lands). This was which is significantly less than reported earlier based on FRA 2015 data, estimated earlier the (Table 1). It is further of interest to note thatThe the estimated small global source was the result of a balance of larger fluxes: a net- sink on forest land, largely located in mostly in UNFCCC Annex I countries (-1.5 Gt

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CO_2 yr^{-1}), -counterbalanced by a ~~largerslightlylarger~~ net emission source from net forest conversion, mainly in non-Annex I countries (1.9 Gt CO_2 yr^{-1}).

~~Two notable new findings emerged from a~~ A more detailed analysis focusing on trends over time (Fig. 4~~2~~) ~~.~~ revealed two notable new findings of our analysis with respect to previous results. ~~(Fig. 2).~~ First, the period 2015-2020 saw a reversal of the decreasing trend in non-Annex I sources and the increasing trend in Annex I sinks seen for the period~~during~~ 1990 to —2015. Specifically, ~~, both reversing in 2016 – 2020, with~~ non-Annex I sources from net forest conversion ~~i~~began to increase again in 2016-2020,~~ing~~ from 1.3 to 1.6 Gt CO_2 yr^{-1}, while ~~, while~~ Annex I sinks on forest land began decreasing~~ed~~ in strength, from -2.0 to -1.3 Gt CO_2 yr^{-1}. Second, ~~ly,~~ and remarkably, forests acted as a net overall sink of atmospheric CO_2 during ~~the period~~ 2011~~1~~ –2015 ~~due to the decreased deforestation,~~, -averaging nearly -0.7 Gt CO_2 yr^{-1}, largely a result of decreased emissions from net forest conversion in this period. ~~.~~ This net overall sink has never been estimated before in the literature ~~before by FAOSTAT~~. ~~By comparison~~For instance, FAO had previously estimated for the same period,~~s~~ based on FRA 2015 input data, ~~for the corresponding 2011–2015 period indicated~~ a net emission source of 1.1 Gt CO_2 yr^{-1} (Table 1).

~~**4. Discussion**~~

~~The recent release of the new FRA 2020 data allowed for a revision of earlier FAO estimates of forest emissionsemissions to and removals from the atmosphere of CO_2,suggesting that in the most recent decade forests have contributed very little to atmospheric $CO_2$$CO_2$ concentration. We combined information reported by countries to FRA 2020 on the two periods 2011–2015 and 2016–2020 to obtain for the first time a picture of the 2011–2020 decade. Our findings indicate that in 2011 – 2020 the net contribution of forests to the atmosphere wasas less than 0.2 Gt CO_2 yr^{-1}, resulting from the emissions from large carbon. More specifically, the emissions from deforestation were 3.1 Gt CO_2 yr^{-1} whereas the net /removals from by forest land were -3.3 Gt CO_2 yr^{-1}, OurWhen comparing the net forest flux if the 2011-2020 to the previous decade, our 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 due to decreased pace of natural expansion and afforestation. alsoAlthough data limitations and quality remain issues to be addressed to achieve an accurate assessment of the forest contribution to atmospheric CO_2 concentration, results but also~~

~~The new FAOSTAT estimates also show that over the earlier period 1991 –2010 forests were a net source of emissions. This confirms and further quantifiesies what was also seen in previous estimates using the data reported to FRA 2015 (Federici et al. 2015) although those earlier results were on average four times larger than those presented here. The main reason for this difference was identified in stronger forest sinks estimated with the new FRA 2020 data compared to FRA 2015, respectively for Europe (+ 0.7 Gt CO_2 yr^{-1}) and Asia (+ 0.6 Gt CO_2 yr^{-1}).~~

~~The main finding of the new estimates presented herein is undoubtedly the large estimated sink on forest land over the period 2011–2015, i.e., a forest land sink of -4.0 Gt CO_2 yr^{-1}. This sink is the major reason for the overall net negative carbon flux~~

previously highlighted in the results section. Notable contributors to the 2011–2015 FAO estimates for 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 carbon fluxes, itself linked to the definitions of 'managed' vs. 'unmanaged' forest, of relevance to climate change policy and action (e.g., Grassi et al., 2018 and 2020; Petrescu et al., 2020). 20
While equations (1)-(3) above do not separate between anthropogenic and natural carbon fluxes, it can be noted that the stocks in deforestation emissions reported for here results mostly in from managed forestforests only (e.g., see http://www.fao.org/economic/ess/ess-home/questionnaires/en/)[1].

3.44.1 ComparisonsRegional c with country reporting to the UNFCCC

Forest Land

As discussed in the methodology section, we first compared our estimates of emissions/removals on forest land to To assess quality of the quality of FAO flux estimates, 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 are fairly complete over the period 1990–2018, data from non-Annex I countries are sparse, although becoming increasingly available through BURs. Given these data limitations, a full comparison was possible for the FRA periods 1991–2000; 2001–2010; and 2011–2015 (Fig. 5 to Fig 7)..

First, we looked at the emissions/removalsremovals on forest land reported by Annex I Parties, comparing our results withdata reported by -Annex I reporting of emission/removalcountries, i.e., for the category "4.A Forest land" in their national GHG inventory (UNFCCC, 2020). In the aggregate, e.g., summing up all country ies data and averaging over the period , our estimates were, on average over the entire period 1990–2020, with equal sign andour estimates agreed in both sign and magnitude within 14 % (relative absolute error) withof the UNFCCC country data (14 % relative absolute error). Specifically, we estimated an averageour estimates indicated a mean sink of -1.9 Gt CO_2 yr^{-1} vs -2.2 Gt CO_2 yr^{-1}- reportedof Annex I country reporting. Using , while the earlier estimates based on the FRA 2015 in earlier work (Federici et al., 2015) had given -ahad indicated a 33 percent % smaller sinkweaker sink (Table 2). The new FAOSTATOur estimates were particularly well aligned

[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 terms of destination and use.

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with country reporting for the period 20101–2015, i.e., within 5 %percent, predicting a sink on forest land ofor -2.1 Gt CO_2 yr^{-1} vs -2.2 Gt CO_2 yr^{-1} of Annex I reportingreported. As in the previous case, earlier sink estimates based on the FRA 2015 were 40 % smaller Previous estimates based on the FRA 2015 for the same period reported instead a 40 percent weaker sink (Fig. 5).

To gain further insights, we also separately analyzed data on forest land reported by individual countries in their national GHG inventories (NGHGIs), focusing on those reporting large sinks, i.e., Canada, Russian Federation and the United States of America (USA) among Annex I parties, and China among non-Annex I parties (Fig. 6). In Inthe latter group, we also compared our results to the data to UNFCCC from Brazil and Indonesia (Fig. 7), focusing in this case instead on two net sources.large emitters

Comparisons of estimated forest land emissions/removals on forest land removals for specific countries with large reported sinks the Russian Federation confirmed the good overall agreement found for Annex I parties in aggregate. For instance, oOn average over the period 1990–2015, our estimates of forest land sinks forin the Russian Federation were within 5 % of those reported by the country eNGHGI. AThe NGHGI data agreement with NGHGI data was particularly goodeven closer after the year 2000, i.e., for the period 2001–2010 an average estimated our estimates indicated a mean sink on forest land of -800 Mt CO_2 yr^{-1} versus NGHGINGHGI country data of -750 Mt CO_2 yr^{-1} for the period 2001–2010, and a mean sink estimates of -730 Mt CO_2 yr^{-1} versus -680 Mt CO_2 yr^{-1} for the period 20111–2015 (Fig. 66).

Comparisons of the FAO estimates forwith the USA NGHGINGHGI datawere also encouraging, albeit withshowing larger differences than found for the Russian Federation. On average over the period 19911–2010, the FAOSTAT estimates were were of awithin 25 % smaller sink on forest land compared toof the NGHGI countryINGHGI data. Importantly, estimates of the sink duringAveraged over the period 20111–2015 our estimates were 29 % of the NGHGI data,NGHGI with FAO estimatingsmaller than the country data, or -460 Mt CO_2 yr^{-1} and NGHGINGHGI data indicating a sink of -650 Mt CO_2 yr^{-1}, respectively(Fig. 6).

Another important comparison useful to assess the anthropogenic component of the sink on forest land was We performed comparisons for China, also a major contributor to the global sink, using. dData for China were taken directly from the country's the Ssecond recent Biennial Update Report to the UNFCCC (2018), to extend our analysis to non-Annex I countries reporting large sinks on forest land. S, where averagepecifically, we used national data on total removals from LULUCF data for for the period 2011–2015 are available for total LULUCF. We assumed concluded that China LULUCF data were a good proxy for forest land data, considering that — deforestation: 1) zero emissions from net forest conversion were indicated in the same BURwas not present in this period; and 2) , emissions from while cropland and grassland emissions/removals —the other main component of LULUCF emissions within a national inventory — are usuallywere likely small, as indicated by independent emissions estimates published in FAOSTAT (FAO, 2020b). Within these assumptions, ~~we found that for the period 2011–2015~~ our~~the FAO~~ estimates of a ~~forest land~~ sink on forest land in China for the period 2011–2015 agreed well with country data (~~were~~ within 20 % of country data ~~NGHGI data,~~), i.e., -710 Mt CO_2 yr^{-1} compared to -840 Mt CO_2 yr^{-1} reported to UNFCCC (~~(~~Fig. 6).

~~Finally, our results showed in~~Conversely, our estimates of emissions/removals on forest land did not agree well to those reported by Canada. Our results indicated ~~-~~a net~~forest~~ source on forest land, declining ~~over the periods 2001–2010 and 2011–2015~~from 2000 to 2015, whereas the NGHGI country data reported a progressively smaller~~reducing~~ sink over the same period (Fig. 6). Specifically f~~F~~or the period 2011~~1~~–2015, our estimates ~~reported a~~indicated a weak net source, ~~i.e.~~ about 23 Mt CO_2 yr^{-1}~~.~~, compared to ~~about~~ a net sink of -150 Mt CO_2 yr^{-1} in ~~of~~ the country ~~NGHGI~~ data. Finally, our ~~Our~~ estimates for the most recent ~~-~~period, 2016~~6~~–2020, for which however there is no available NGHGHI data yet from the country, ~~also indicate~~began to show a sink on forest land, of -80 Mt CO_2~~2~~ yr^{-1}~~yr-1~~, thus indicating a possible ~~progressively~~ alignment ~~ingnet~~ with NGHGI data in recent years. A possible reason for the discrepancies found in this case may relate to differences in land use definitions, particularly those related to managed forest land. For the purpose of the NGHGI~~GHG inventory~~, in fact, ~~Canada delineates~~ the area of managed forests defined by Canada ~~(forest under direct human influence) which~~ is ~~about~~ 65 % of the total forest land area reported to FAO (Canada's 7th National Communication and 3rd Biennial Report, 2017; Ogle et al., 2018). ~~This is likely the main reason for the discrepancies found with our estimates, which were larger than for the other countries (Fig. 6).~~ .

Net forest conversion

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We also ~~also~~ compared ~~FAOSTAT~~ estimates of emissions from net forest conversion with data reported to UNFCCC ~~fromNGHGI Brazil and Indonesia through their BUR~~. As discussed in the methodology section, FAO estimates of emissions from net forest conversion are proxies for deforestation emissions data. The two countries for which relevant data were available were Brazil and Indonesia. ~~More specifically, data were obtained from the BrazilBrazil's third Biennial Update Report (2019) and from the IndonesiaIndonesia's second Biennial Update Report Indonesia (2018) (Fig. 7). In general FAO estimates of deforestation should be an underestimate of NGHGI values since the latest are based on gross deforestation while FAO data estimates the net deforestation.net deforestation only.~~ For ~~Deforestation data for~~ Brazil, we compared our estimates of net forest conversion directly to deforestation emissions from ~~were directly available in~~ the country's BUR. For Indonesia, we ~~took~~ compared our estimates to ~~LULUCF~~ sum of LULUCF emissions arising from land use change~~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.,~~ land ~~most~~ converted~~sion~~ to cropland and grassland in Indonesia originated largely from loss of forest land area. ~~Deforestation data for Brazil were directly available in the BUR.~~

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For Indonesia, for the period 1991–2000, ~~the FAOSTAT~~our estimates of emissions from net forest conversion ~~differ~~ greatly overestimated country data ~~from the NGHGIdata~~for deforestation, ~~in the BUR for 1991–2000, i.e.,~~ by over a factor ~~s~~ of ~~over~~ 10 (Fig. –7). Conversely, for the more recent period 2011~~01~~–2015, they were on average within 25 % of country

~~NGHGI~~NGHGI data, ~~or~~ specifically 180 Mt CO_2 yr^{-1} vs country data of 165 Mt CO_2 yr^{-1}. ~~Finally in terms of new information, for 2016–2020, the FAOSTATFAO estimates showed a~~Our estimates further suggested a 50% decrease in emissions from net forest conversion ~~of nearly 50 % with respect to the 2011–2015 period~~in the period 2016-2020, for which however BUR data are not yet available (Fig. 7).

For Brazil, our estimates ~~over the entire 1991–2015~~ were in good agreement (within 10 %) ~~-of NGHGI~~ country ~~NGHGI~~ data over the period 1990 to 2015, i.e., on average 1.4 vs. 1.5 Mt CO_2 yr^{-1} reported data (Fig. 7). More in detail by decade, ~~FAO~~ our estimates were 1.4 vs 1.9 Gt CO_2 yr^{-1} during 1991–~~1–~~2000 and ~~both~~ 1.6 vs 1.6 Gt CO_2 yr^{-1} over 2001~~1~~–2010. ~~While~~ Conversely, for the period 2010–2015, our~~FAO~~ estimates of emissions from net forest conversion were ~~suggested a much~~ significantly~~-~~ higher ~~deforestation (about 50 % more)~~ than reported in the BUR~~in the NGHGI for the period 2011–2015.~~, ~~consistently with suggestions made in the literature that deforestation emissions may have been higher in this period than initially estimated by the country (Fig. 7).~~

~~These findings point to two main conclusions. First, the good agreement between the FAOSTAT estimates and country reports implies that the definition of forest land use underlying both FAO and UNFCCC reporting was consistent. 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 FAOSTAT estimates of a large anthropogenic sink on forest land for the period 2011–2015, leaving open the possibility, put forward by the new 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.~~

4. Discussion

The availability of new forest area and carbon stock data from the FRA 2020 enabled a new analysis of the role of forests in generating CO_2 emissions and removals at country, regional and global level, during the period 1990–2020. In particular, the new information allowed us, for the first time in the literature, to estimate emissions and removals relative to the most recent decade, covering the period 2011–2020. Our findings indicate that in the decade just concluded the net contribution of forests to the atmosphere, representing the combination of emissions from net forest conversion and removals on forest land, was very small, i.e., an overall emission source of less than 0.2 Gt CO_2 yr^{-1}. It nonetheless resulted from the balance of large global fluxes of opposite sign, namely mean net forest conversion emissions of 3.1 Gt CO_2 yr^{-1}, counterbalanced by mean net removals on forest land of -3.3 Gt CO_2 yr^{-1}. Both fluxes, and hence the overall net near zero balance for forests, were shown to be in very good agreement with the data reported by countries in national GHG inventories, and in line with independent findings by Grassi et al. (2021). At the same time, the consistency of our estimates with those of terrestrial carbon cycle models were limited to the anthropogenic carbon flux from foreststo the atmosphere (i.e., IPCC, 2019). Results further showed that, with respect to the previous decade 2001–2010, emissions from net forest conversions had decreased by 15 %, while removals on forest land had decreased by 5 %. Further analysis of the underlying FRA 2020 data (not shown) indicated that such decreases were due to a reduced pace of natural expansion and afforestation in Annex I countries, which have functioned historically (1990-2020) as forest sinks, as well as a decrease in forest loss in non-Annex I countries, which have represented the bulk of deforestation. The new estimates also show that over the earlier period 1991–2010 forests were a smaller net source of emissions than previously calculated (Federici et al. 2015). largely due to much stronger sinks on forest land estimated using the new FRA 2020 as opposed to FRA 2015 data, respectively for Europe (+ 0.7 Gt CO_2 yr^{-1}) and Asia (+ 0.6 Gt CO_2 yr^{-1}).

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The main new finding of this work is the large estimated sink on forest land over the period 2011–2015, averaging -4.0 Gt CO_2 yr^{-1}, causing the overall net negative carbon flux from forests highlighted in the results section. Notable contributors to this forest land sink were the Russian Federation, USA, China, Indonesia and India, which all had stronger carbon uptake compared to the previous 2001–2010 period. Comparisons with country data reported to the UNFCCC support our estimates, indicating that they represent an improvement compared to previous results. In particular, the good agreement between our new estimates and country NGHGI data on emissions/removals on forest land and emissions from net forest conversion suggests that the definition of forest land area underlying both FAO and UNFCCC reporting was consistent across the countries considered, i.e., they considered most of the forest land area reported to FAO as managed for UNFCCC purposes—confirming the analysis provided in the methodological section of this paper. This implies that, limited to the countries tested and within the range of limitations discussed earlier in this paper, the estimates of emissions and removals from forests provided in this paper can be considered largely anthropogenic. Finally, the good agreements found between our estimates and country reports support the finding of a large anthropogenic sink on forest land for the period 2011–2015, leaving open the possibility, 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. In fact, the discussed progressive reduction of the overall forest source observed across the two most recent decades is consistent with the appearance of a net overall forest sink in recent years.

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5. Data availability

The emissions and removals dData, alongside with input activity data of forest land area and carbon stock, are is disseminated in FAOSTAT (FAO, 2020b). An exact replica of the data used for this paper is available at Zenodo (Tubiello, 2020), with DOI 10.5281/zenodo.3941973. provided as open access via Zenodo (Tubiello, 2020), with DOI 10.5281/zenodo.3941973.

6. Conclusions

EThe new FAOSTAT estimates of CO_2 emissions and /removals from forests land were updated based on the most recent FRA 2020 data and by applying a simple yet robust, transparent and easily replicable carbon stock change approach. Over the period 1990–2020, they results confirmed well-known country, regional and global trends, providing additional detail to specific dynamics while extending existing information to the period 20166–2020. Importantly, the new estimates allowed to characterize for the first time 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., less than 0.2 Gt CO_2 yr^{-1}. This near-zero balance was nonetheless the result of large global fluxes of opposite sign, namely net forest conversion emissions of 3.1 Gt CO_2 yr^{-1} counterbalanced by net removals on forest land of -3.3 Gt CO_2 yr^{-1}.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 net deforestation emissions, to below 3 Gt CO_2 yr^{-1} globally in the second half of the decade. The new FAOSTATFAO estimates highlighted opposite regional trends in Latin America and Africa, with the former seeing marked reductions while in the latter the emissions from deforestation have continued to grow. At the same time, these estimates have identified a particularly strong carbon sink onforest 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; Friedlingstein et al., 2019; IPCC, 2019). During the period 1991–2020, natural forests lost annually more than 2 percent 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 and forest degradation are avoided. Our findings also confirm that forests continue being a net, albeit small sink of emissions and thus have a significant role for mitigating climate change.

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Author contributions.

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

Disclaimer. The views expressed in this publication are those of the authors and do not necessarily reflect the views or policies of FAO.

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Tables

Table 1. EEstimates ~~-~~of ~~total forest carbon fluxes (FL_Tot),~~ total emissions and removals from forests (ER), net forest conversion~~deforestation~~ (NFC) and emissions/removals on forest land (FL) ~~, in Gt CO_2 yr^{-1}, for the period 1990 – 2020, for global~~for World, Annex I and non-Annex I totals~~. FAOSTAT~~, based on ~~estimates using~~ FRA 2020 ~~(ibidemibidem)~~ and FRA 2015 ~~data~~ (Gt CO_2 yr^{-1}). ~~**(Federici et al., 2015(FAO, 2016) are comparedcompared.**~~

	FRA 2020			FRA 2015		
	~~FL_Tot~~ ER	NFC	FL	~~FL_Tot~~ 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			
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. Estimates of emissions/removals on f~~Comparison of f~~orest land ~~carbon flux~~ for Annex I countries, ~~-~~based on FRA 2020 and ~~(ibidem),~~ FRA 2015, compared to ~~(Federici et al., 2015FAO, 2016) and~~ country data reported to UNFCCC (Gt CO_2 yr^{-1}). ~~(2020)~~

	~~Annex I totals~~		
-	~~FRA_2020 (ibidem)~~	~~FRA_2015 (Federici et al., 2015)~~	~~UNFCCC (2020)~~
Annex I total emissions/removals~~Gt CO_2~~			
-	**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	~~0.0~~	~~0.0~~
AVERAGE 1991~~0~~–2015	**-1.8**	**-1.4**	**-2.2**

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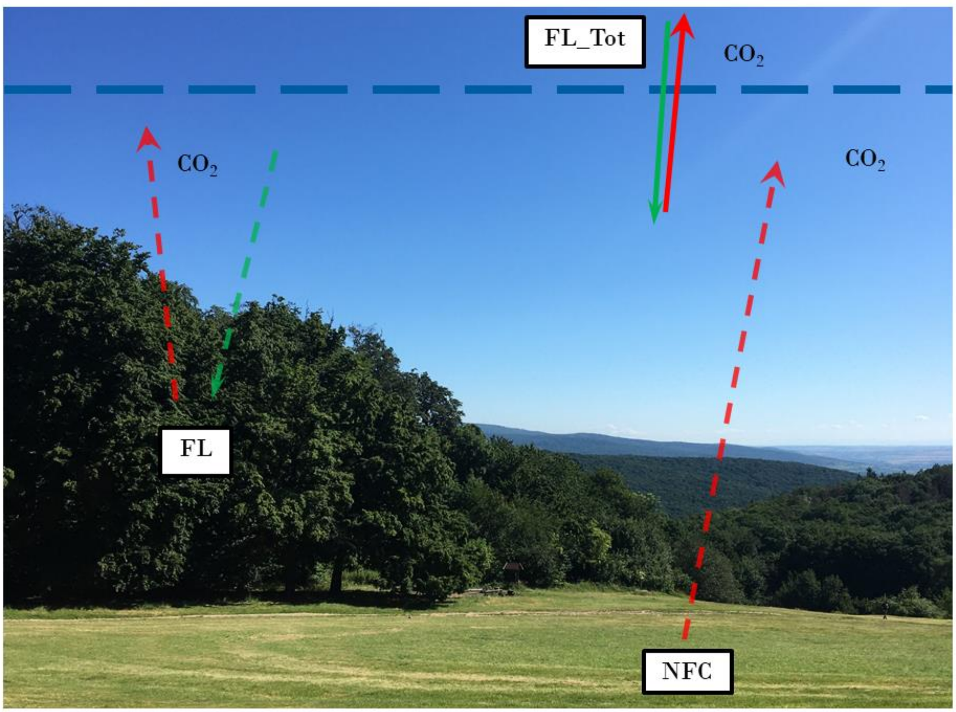
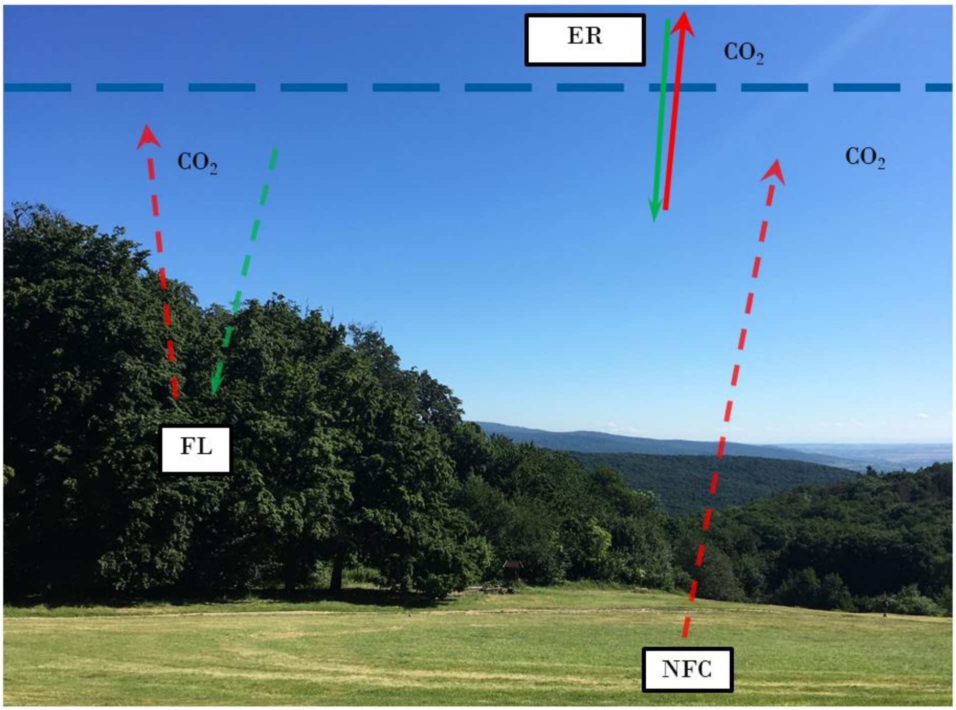
Figures


FL_Tot
CO$_2$
CO$_2$
CO$_2$
FL
NFC



ER
CO_2
CO_2
CO_2
FL
NFC

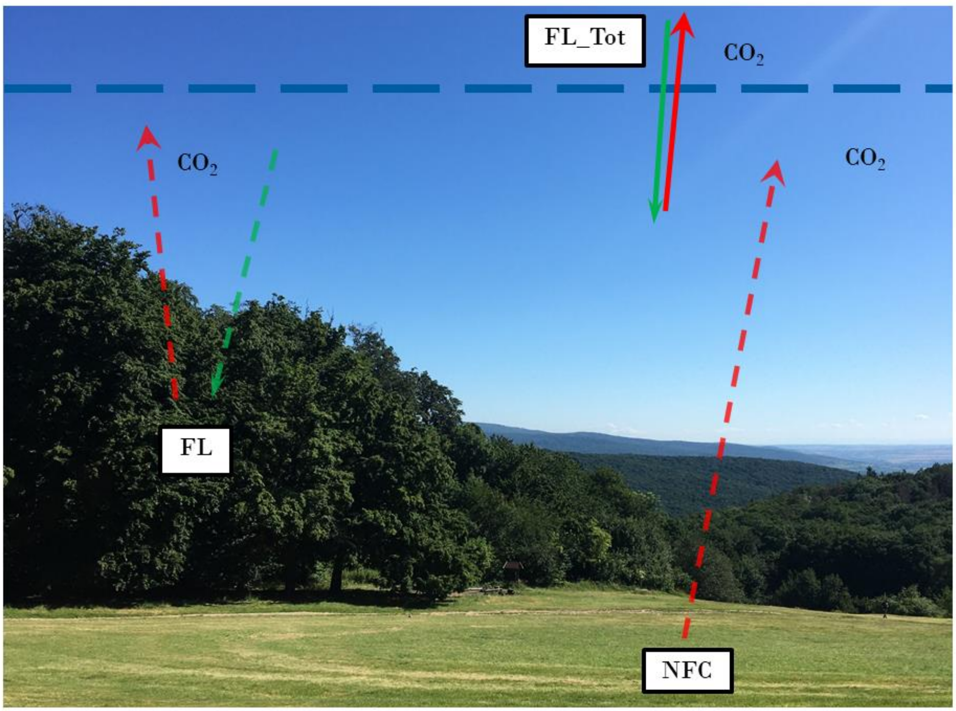
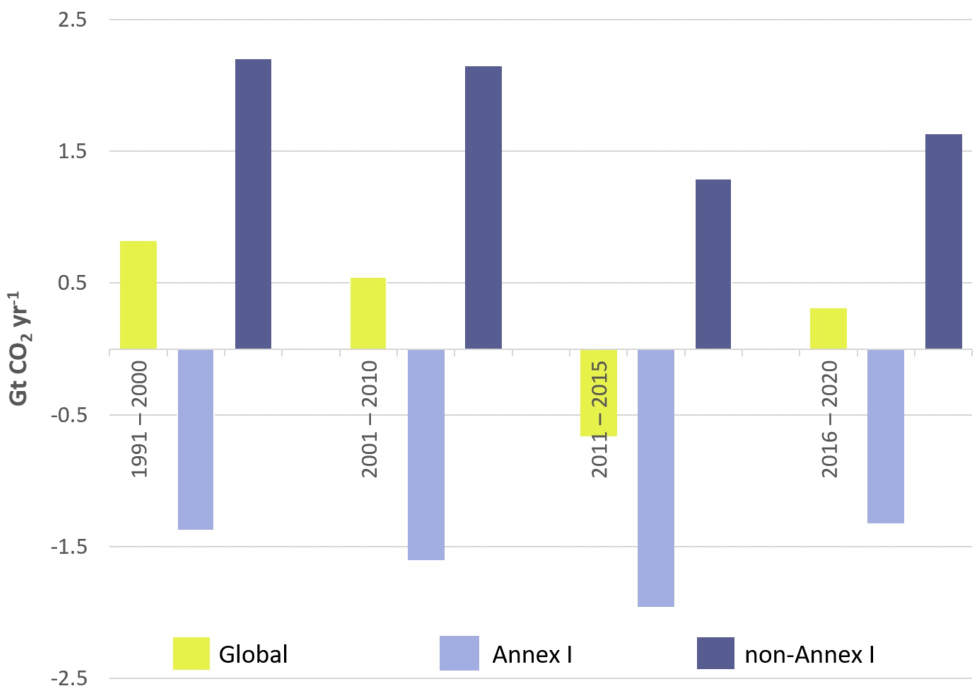


Figure 1. The three main carbon fluxes considered in this paper, consisting of emissions from ~~overall carbon forest fluxes to and from the atmosphere (FL_Tot), deforestation~~ net forest conversion (NFC), ~~and~~ emissions and ~~/~~removals on forest land (FL~~FL~~) and their aggregate, representing total net emissions/removals from forests (ER).~~.~~ Photo copyright: Francesco N. Tubiello.


Gt CO_2 yr[-1]
2.5
1.5
0.5
-0.5
-1.5
-2.5
1991 – 2000
2001 – 2010
2011 – 2015
2016 – 2020
Global
Annex I
non-Annex I

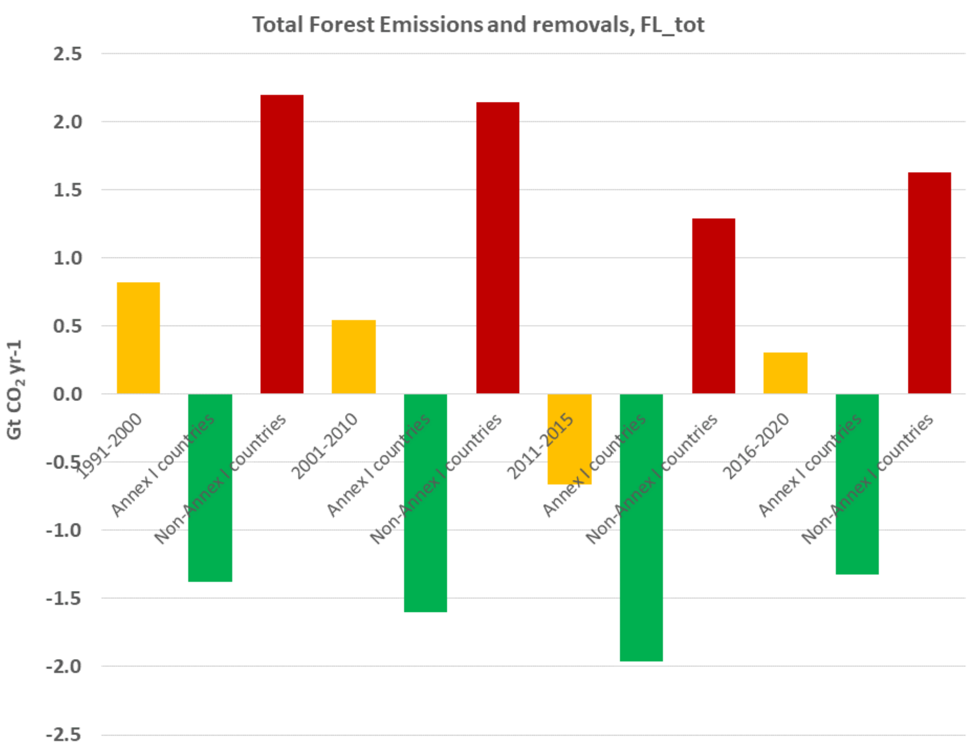
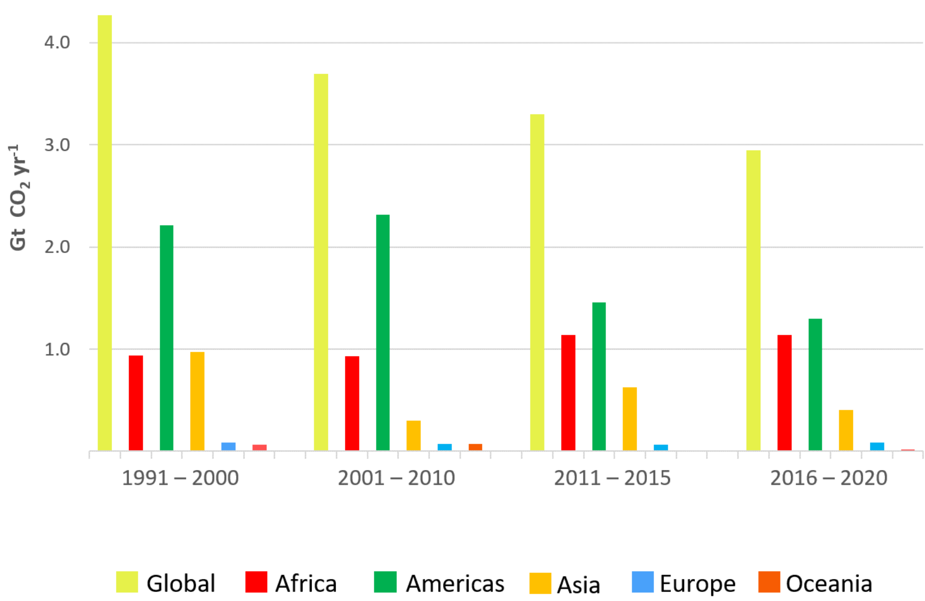


Figure 2. Estimates of total carbon forest fluxes (FL_Tot) based on FRA 2020 (ibidem) for the global (acid green), Annex I (lavender) and non-Annex I (purple navy) totals, in Gt CO_2 yr^{-1}, averaged over the periods 1991–2000; 2001–2010; 2011–2015;ibidem and (FAO, 2016–2020.)


4.0
3.0
2.0
1.0
Gt CO2 yr-1
1991 – 2000
2001 – 2010
2011 – 2015
2016 – 2020
Global
Africa
Americas
Asia
Europe
Oceania

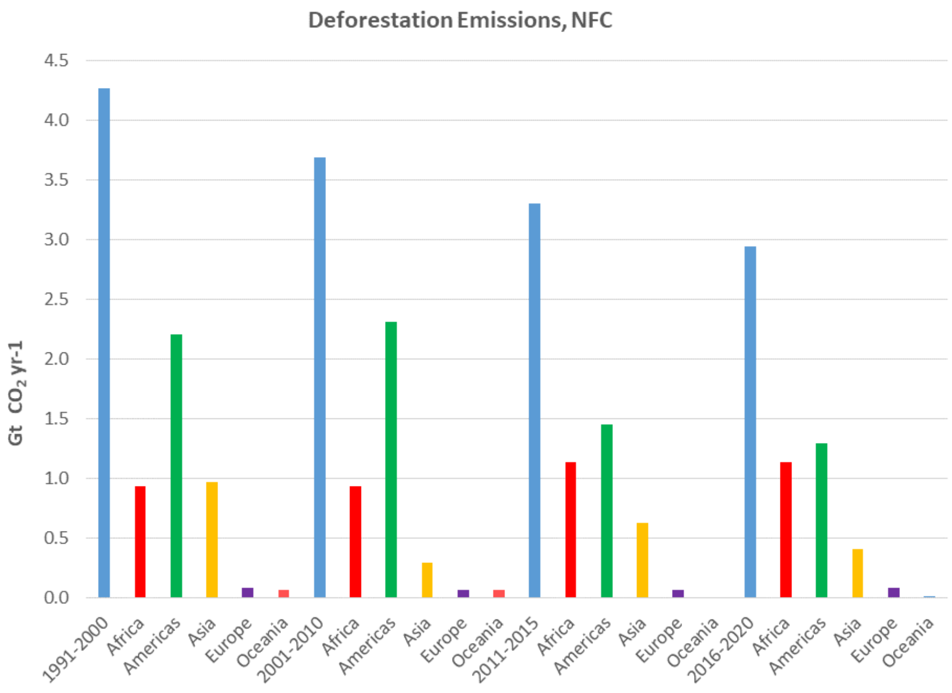
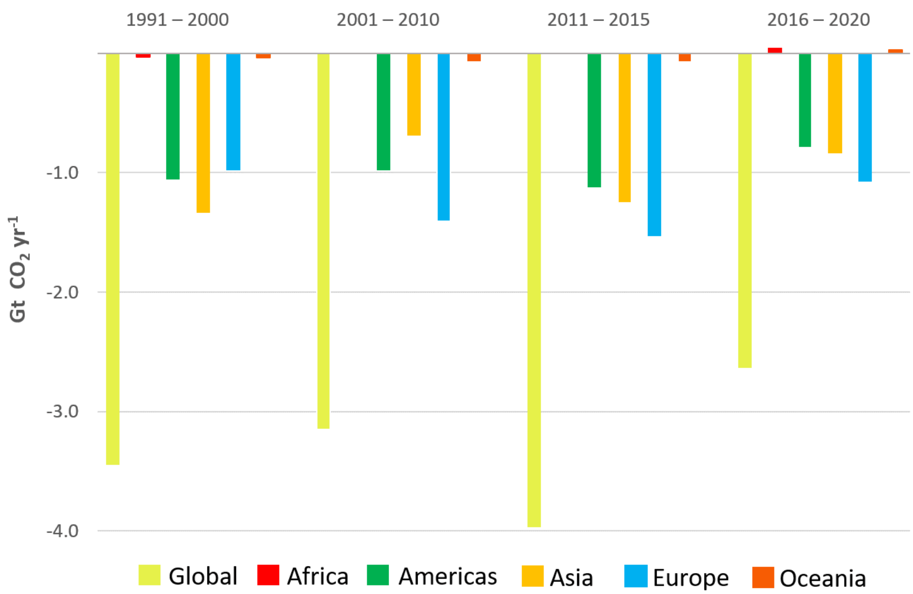


Figure 23. Estimates regional of emissions from net forest conversiondeforestation (NFC) based on FRA 2020 (ibidem) for globalglobal (acid green) and regional (Africa = red; Americas = green; Asia = gold; Europe = sapphire; Oceania = orange) totals, in Gt CO_2 yr^{-1}., averaged over the periods 1991–2000; 2001–2010; 2011–2015; ibidem and (FAO, 2016–2020.)


1991 – 2000
2001 – 2010
2011 – 2015
2016 – 2020
Gt CO2 yr-1
-1.0
-2.0
-3.0
-4.0
Global
Africa
Americas
Asia
Europe
Oceania

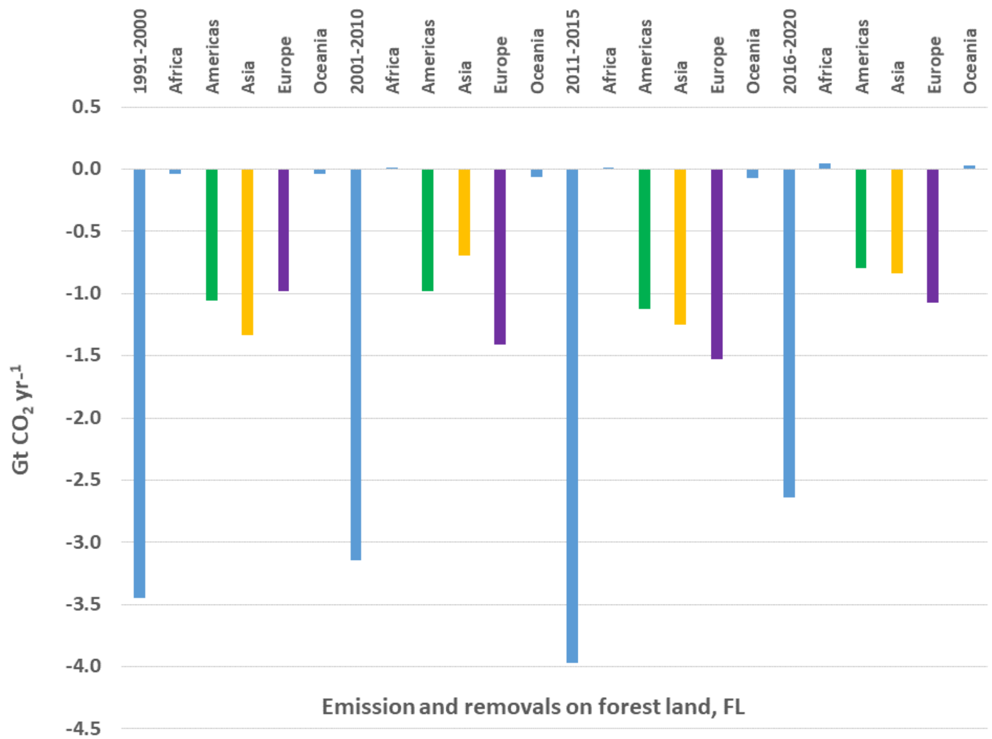


Figure 3~~4~~. Estimates of the emissions/removals on forest land (FL~~FL~~) based on FRA 2020 ~~(ibidem)~~ for global~~global~~ (acid green) and r~~r~~egional totals (Africa = red; Americas = green; Asia = gold; Europe = sapphire; Oceania = orange), in Gt CO_2 yr^{-1}.~~, averaged over the periods 1991–2000; 2001–2010; 2011–2015;ibidem and (FAO, 2016–2020.)~~

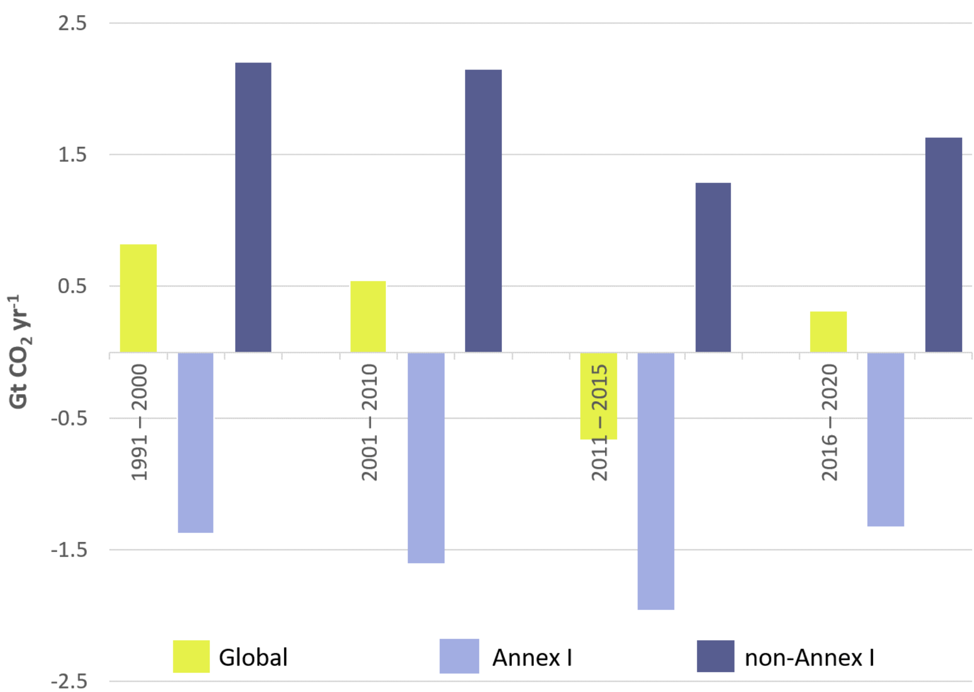
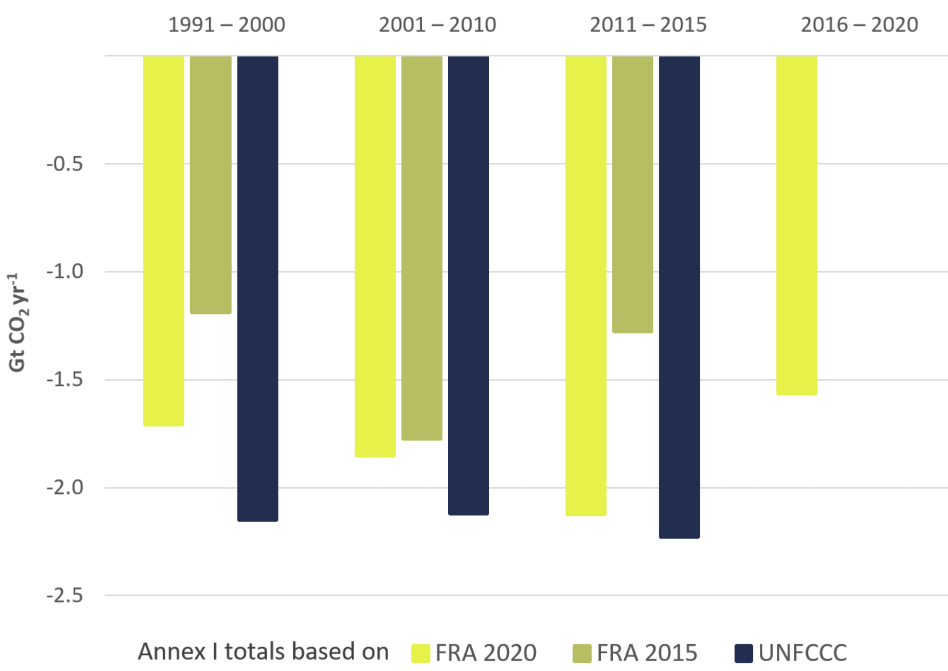


Figure 4. Estimates of total emissions/removals from forests (ER), based on FRA 2020, for global (acid green), Annex I (lavender) and non-Annex I (purple navy) totals, in Gt CO_2 yr^{-1}.


1991 – 2000
2001 – 2010
2011 – 2015
2016 – 2020
-0.5
-1.0
-1.5
-2.0
-2.5
Gt CO_2 yr^{-1}
Annex I totals based on
FRA 2020
FRA 2015
UNFCCC

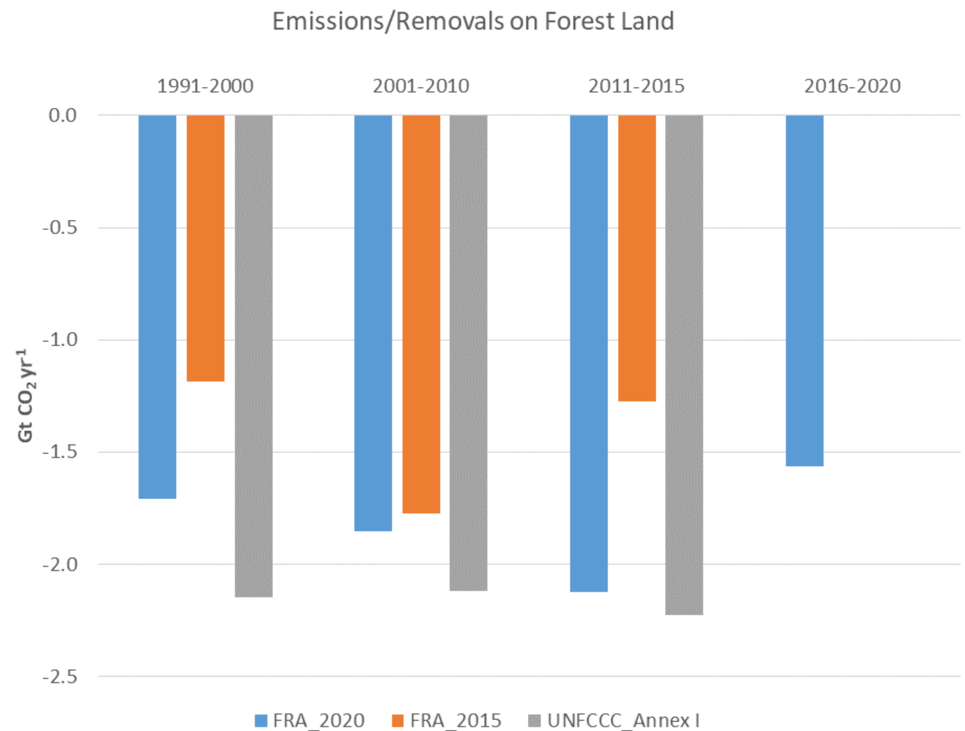


Figure 5. Comparison of estimates of emissions/removals on forest land (FLFL) for Annex I totals, in Gt CO_2 yr^{-1}, from estimates based on FRA 20200 (ibidem) (acid green) and , from earlier estimates based onibidem FRA 2015 (Federici et al., 2015) (olive green), and fromto the sum of data that Annex I countries totals reported by countriesreported to UNFCCC (2020)(cadet blue). Totals are averaged over the periods 1991–2000; 2001–2010; 2011–2015; andFAO, 2016–2020.)

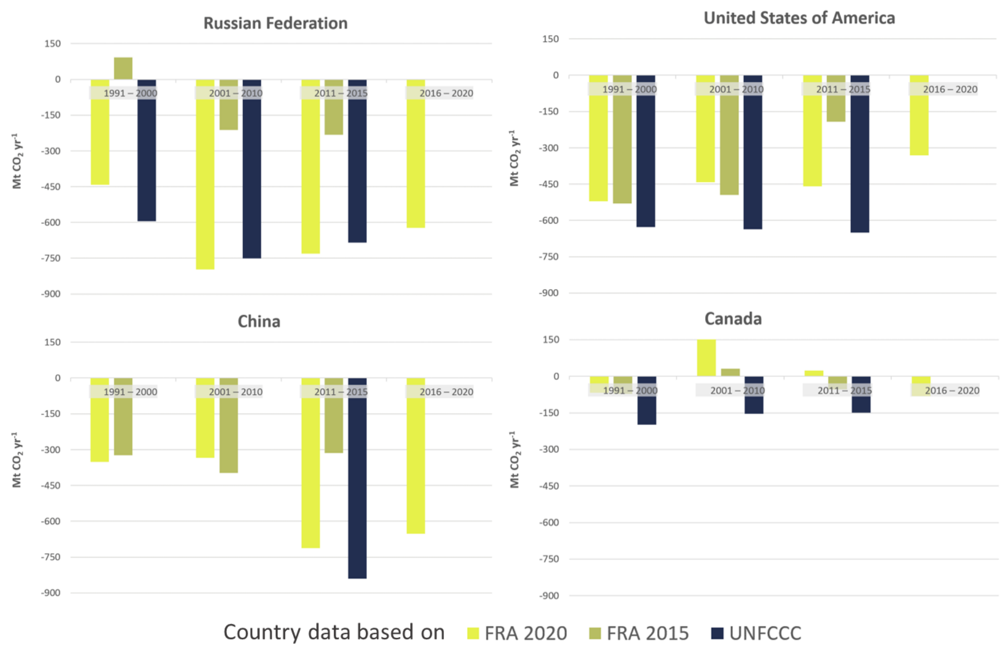
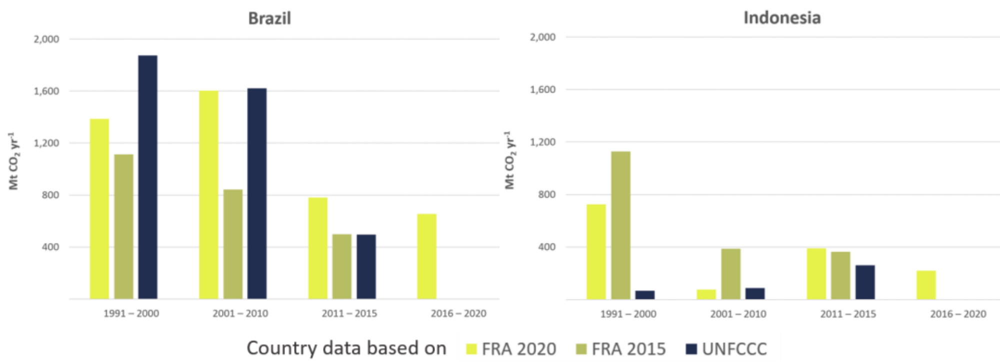
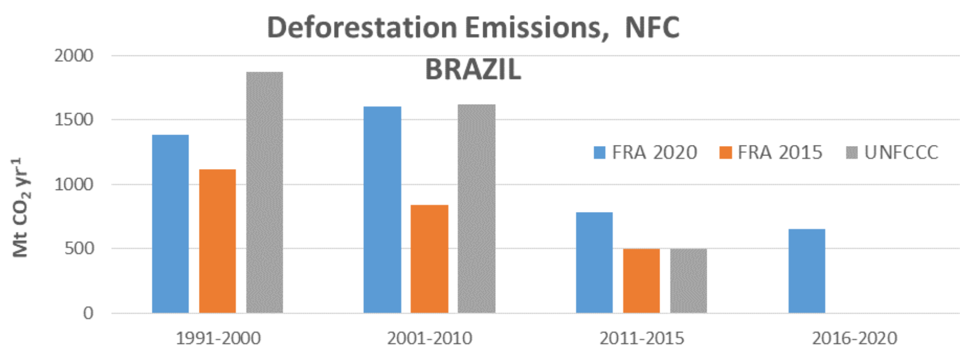

Russian Federation
United States of America
China
Canada
Mt CO_2 yr^{-1}
150
0
-150
-300
-450
-600
-750
-900
1991 – 2000
2001 – 2010
2011 – 2015
2016 – 2020
Country data based on
FRA 2020
FRA 2015
UNFCCC

Figure 6. **Comparison of ~~e~~Estimates of emissions/removals on forest land (FL~~FL~~) for Russian Federation (top left), USA (top right), China (bottom left) and Canada (bottom right), in Mt CO_2 yr^{-1}, ~~from estimates~~ based on FRA 2020 ~~(ibidem)~~(acid green) and ~~, from earlier estimates based on~~ FRA 2015 ~~(Federici et al., 2015)~~ (olive green), to~~and from~~ country data reported to UNFCCC ~~(2020)~~ (cadet blue). ~~Totals are averaged over the periods 1991–2000; 2001–2010; 2011–2015; and ibidem(FAO, 2016–2020).~~**


Brazil
Indonesia
2,000
1,600
1,200
800
400
Mt CO2 yr-1
1991 – 2000
2001 – 2010
2011 – 2015
2016 – 2020
Country data based on
FRA 2020
FRA 2015
UNFCCC


Deforestation Emissions, NFC
BRAZIL
2000
1500
1000
500
0
Mt CO2 yr-1
FRA 2020
FRA 2015
UNFCCC
1991-2000
2001-2010
2011-2015
2016-2020

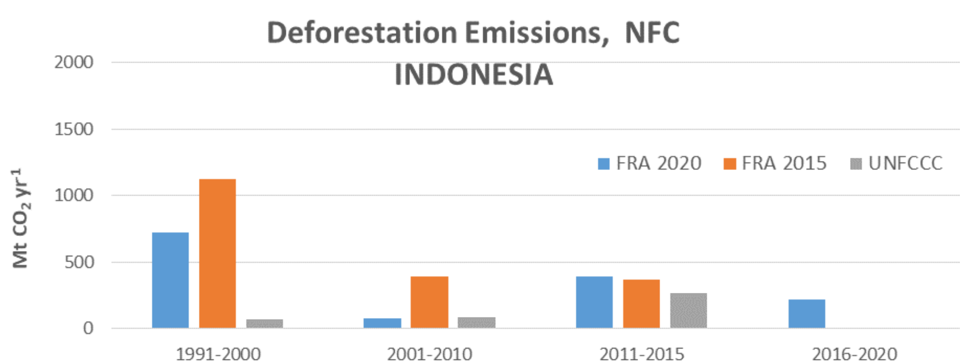

Deforestation Emissions, NFC
INDONESIA
2000
1500
1000
500
0
Mt CO2 yr-1
FRA 2020
FRA 2015
UNFCCC
1991-2000
2001-2010
2011-2015
2016-2020

Figure 7. Comparison of ~~the emissions~~ estimates of emissions from ~~deforestation~~ net forest conversion (NFC) for Brazil (left) and Indonesia (right), in Mt CO_2 yr^{-1}, ~~from estimates~~ based on FRA 2020 ~~(ibidem)~~ (acid green) and~~,~~ ~~from earlier estimates based on ibidem~~FRA 2015 ~~(Federici et al., 2015)~~(olive green), ~~and fromFAO, 2016)~~to country data reported to UNFCCC for deforestation ~~(2020)~~(cadet blue). ~~Totals are averaged over the periods 1991–2000; 2001–2010; 2011–2015; and 2016–2020.~~