Forest Ecology and Management 352 (2015) 89–98

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

New estimates of CO_2 forest emissions and removals: 1990–2015 ☆

Sandro Federici [a], Francesco N. Tubiello [a,b,*], Mirella Salvatore [a], Heather Jacobs [a], Josef Schmidhuber [b]

[a] Climate, Energy and Tenure Division, Food and Agriculture Organization of the United Nations, Via Terme di Caracalla, Rome 00153, Italy
[b] Statistics Division, Food and Agriculture Organization of the United Nations, Via Terme di Caracalla, Rome 00153, Italy

ARTICLE INFO

Article history:
Received 2 January 2015
Received in revised form 16 April 2015
Accepted 22 April 2015
Available online 7 September 2015

Keywords:
Forest
CO_2 emissions
CO_2 removals
Deforestation
Forest degradation
REDD+
Carbon
Stock change
FAOSTAT
FRA

ABSTRACT

Using newly available data from the 2015 Forest Resources Assessment (FRA), we refined the information, currently available through the IPCC AR5 and FAOSTAT, on recent trends in global and regional net CO_2 emissions and removals from forest land, including from net forest conversion (used as a proxy for deforestation) and forest remaining forest. The new analysis is based on the simplified forest carbon stock method of the FAOSTAT Emissions database, equivalent to a Tier 1, Approach 1 IPCC methodology, limited to biomass carbon stocks. Our results indicated that CO_2 emissions from net forest conversion decreased significantly, from an average of 4.0 Gt CO_2 yr^{-1} during 2001–2010 to 2.9 Gt CO_2 yr^{-1} during 2011–2015. More than half of the estimated reductions over the last five years, some 0.6 Gt CO_2 yr^{-1}, took place in Brazil. Detailed analyses further indicated that remaining forests continued to function as a net carbon sink globally, with an average net removal of −2.2 Gt CO_2 yr^{-1} during 2001–2010, and −2.1 Gt CO_2 yr^{-1} during 2011–2015. Annex I Parties represented the bulk of this sink, contributing 60% of the total in 2011–2015, down from 65% in 2001–2010. Compared to previous FAOSTAT assessments for the period 2001–2010, based on the 2010 FRA and published in the IPCC AR5, the use of FRA 2015 data led to estimates of net forest conversion that were consistent with previous ones (4.0 vs. 3.8 Gt CO_2 yr^{-1}), while the estimated forest sinks were 22% larger (−2.2 vs. −1.8 Gt CO_2 yr^{-1}). The net contribution of forests to anthropogenic forcing based on FRA2015 data was thus smaller than previously estimated by the IPCC AR5. Finally, we separated for the first time net emissions and removals from forest land into a sink component and a degradation component. Results indicated that, contrary to CO_2 emissions from deforestation, CO_2 emissions from forest degradation increased significantly, from 0.4 Gt CO_2 yr^{-1} in the 1990s, to 1.1 Gt CO_2 yr^{-1} in 2001–2010 and 1.0 Gt CO_2 yr^{-1} in 2011–2015. Emissions from forest degradation were thus one-fourth of those from deforestation in 2001–2010, increasing to one-third in 2011–2015.

1. Introduction

The Food and Agriculture Organization of the United Nations (FAO) makes available online data on forests, originally submitted by its Member States and analyzed through the Global Forest Resource Assessment (FRA) (MacDicken, 2015). FRA data, available over the period 1990–2015, include, among others, estimates of forest area and of carbon stocks in aboveground and belowground biomass carbon pools. The latter data categories are needed in standard carbon cycle computations of forest dynamics, in line with methods provided in the 2006 IPCC Guidelines for National GHG Inventories (IPCC, 2006). Since 2012, FAO has used FRA data to estimate net CO_2 emissions and removals associated with C stock changes of the biomass C pools, related to forest land and net forest conversion, the latter used as a proxy for net deforestation (FAOSTAT, 2015; FAO, 2014). The FAO data, considered equivalent to a Tier 1, approach 1 estimate using the carbon stock difference method of the IPCC guidelines, were published in the IPCC AR5 (Smith et al., 2014).

The FRA is the only global database that provides the value and historical trend of C stock changes in forest for each country, using official data provided by countries to FAO. An additional repository of data on forest carbon dynamic is the database of the UN Framework Convention on Climate Change (UNFCCC), which contains data submitted by its Parties (http://unfccc.int/national_reports/items/1408.php).

There are important differences between the FRA and UNFCCC. First, the UNFCCC database currently does not cover all UN

☆ This article is part of a special issue entitled "Changes in Global Forest Resources from 1990 to 2015".

* Corresponding author at: Food and Agriculture Organization of the United Nations, Via Terme di Caracalla, Rome 00153, Italy.

E-mail address: francesco.tubiello@fao.org (F.N. Tubiello).

http://dx.doi.org/10.1016/j.foreco.2015.04.022
0378-1127/© 2015 Published by Elsevier B.V.

Member States. In coming years, new country submissions of Biennial Update Reports[1] to UNFCCC by non-Annex I Parties[2] will increase coverage, while adding valuable information on management practices, area, carbon stocks and their changes.

Second, even though UNFCCC requires its Parties to provide data on forest land that are consistent with those they submit to FAO[3], often the data provided to FAO are numerically different from those submitted to UNFCCC, stemming from discrepancies in forest definitions applied[4], and from the fact that different national focal points are responsible for FAO and UNFCCC submissions.

The FAOSTAT Emissions database is one of three independent sources used in the recent IPCC Fifth Assessment Report (AR5) to estimate anthropogenic GHG emissions and removals from Agriculture, Forestry and Other Land Uses (AFOLU) (Tubiello et al., 2015). In particular, for CO_2 emissions and removals from forest, FAOSTAT provided estimates of net forest carbon stock change at national, regional and global levels to the IPCC AR5. Using data from the FRA 2010 (FAO, 2010), and with reference to the period 2001–2010, FAO estimated average decadal CO_2 emissions from deforestation of 3.8 Gt CO_2eq yr^{-1} and a net carbon sink in forest land of −1.8 Gt CO_2eq yr^{-1}. Additional GHG emissions from terrestrial C pools estimated by FAO to the IPCC AR5, but not discussed herein, included emissions from drained peatlands (0.9 Gt CO_2eq yr^{-1}) and from biomass fires (0.3 Gt CO_2eq yr^{-1}).

This paper provides FAOSTAT updates of CO_2 emissions and removals from forests, based on FRA 2015 data. Furthermore, this paper introduces an improved methodology to assess separately, within the forest domain, net CO_2 emissions from forest degradation and net CO_2 removals from forest re-growth, thus providing for the first time in the literature, an assessment of both of these important terrestrial carbon fluxes.

2. Materials and methods

FAOSTAT estimates of CO_2 emissions and removals from forest were computed following the carbon stock difference equation of the 2006 IPCC Guidelines, using FRA country information on forest area and carbon stock density[5] as input. This was considered equivalent to an IPCC Tier 1, approach 1 method (FAO, 2014). In fact, the stock difference method is not the IPCC default[6], because its application requires the use of statistically consistent time-series of national forest inventory data, which are not typically available in all countries. The FRA however provides exactly this type of information, including forest area activity data and carbon stock-change factors by country, making the application of stock difference equations within FAOSTAT much simpler than the gain-loss method. More specifically, we used FRA data for the years 1990, 2000, 2005, 2010, and 2015, including total national *forest area*, *A*, and its three subcategories: *primary forest*, *other naturally regenerated forest*, and *planted forest*; as well as total *woody biomass carbon stock*, *B* (defined as above and below-ground biomass)[7]. FRA data also included some information on carbon stocks in litter, deadwood and soils. Coverage by country was rather incomplete however, so that this information was not used herein.

FRA 2015 data presented country data gaps on forest area by subcategory, especially for the first two mentioned above, and on woody biomass. These data gaps were filled as follows. For forest area, missing total forest area data were linearly extrapolated or interpolated using existing FRA data, as needed. When the proportion of forest area among sub-categories was missing we used information on shares by forest subcategory from neighboring countries with similar forest conditions, and applied these shares to total forest area. For total woody biomass, we used the relevant sub-regional weighted average value[8], and multiplied it by the total country forest area.

All data were linearly interpolated to obtain a yearly time series over the period 1990–2015. As described below in more detail, annual data were used as input to compute net CO_2 emissions and removals on *forest*, including forest land area (hereafter referred to as *forest land*) and forest area converted to other land uses (hereafter referred to as *net forest conversion or deforestation*). The terminology used herein is in line with the relevant database categories of the FAOSTAT Emissions database—Land use (http://faostat3.fao.org/browse/G2/*/E). It may be considered consistent with REDD+, albeit representing an over-simplification of current GHG national reporting practice[9].

2.1. Derived input data

Annual data needed as input into the FAOSTAT stock difference methodology were derived from FRA2015, by country and over the period 1990–2015, including:

- *Forest area*, $A_i(t)$. Total forest area A, disaggregated into two forest strata *i* as follows:
  - *Natural forest area*, defined as the sum of FRA area data for sub-categories *primary forest* and *other naturally regenerating* forest; and
  - *Planted forest area,* taken directly from the FRA.

The above aggregation of *natural forest* was made to ensure that net area losses of primary to secondary forest, a typical outcome of forest resources exploitation, would not be counted as forest area change. Thus the associated carbon losses were counted as forest degradation rather than deforestation. At the same time, separating this stratum from *planted forest* was necessary in order to identify areas and associated CO_2 emissions from deforestation of *natural forest*, separately from those associated to afforestation with plantations.

- *Woody biomass carbon stock density*, *b*. Computed as *B/A*, where *B* was the FRA national total woody biomass carbon stock and *A* the total national forest area. FRA biomass data were provided

[1] Biennial Update Reports contain, among other information, a GHG Inventory for forest land, and an annex on the implementation of REDD+ activities: forest conservation, sustainable forest management, enhancement of carbon stocks, reducing emissions from deforestation and forest degradation.

[2] Annex I Parties include the 24 original OECD members, the European Union, and 14 countries with economies in transition. While non-Annex I Parties have currently no legal commitment to reducing their greenhouse-gas (GHG) emissions, Annex I Parties committed to returning their GHG emissions to 1990 levels by the year 2000, under UNFCCC Article 4.2 (a) and (b), and accepted emissions targets for the period 2008–12 under Article 3 and Annex B of the Kyoto Protocol.

[3] UNFCCC decision 16/CMP1, para16; 2/CMP8 Annex I para1f; 12/CP7 Annex, para n.

[4] FAO member countries must report to FRA using the FAO forest definition (i.e., minimum area 0.5 ha, minimum cover 10%, minimum height 5 m), while they can report to UNFCCC using their national forest definitions, which may differ from FAO's. Furthermore, reported FRA data cover the entire national forest area, as they must include unmanaged forest land. By contrast, UNFCCC submissions may be limited to managed forest land.

[5] Defined as carbon stock per hectare of total biomass (above-and below-ground).

[6] The IPCC default method is the "gain-loss" method, requiring information on net forest growth rates, harvest data and estimated losses from disturbances.

[7] FRA data by country are available at http://www.fao.org/forestry/fra/67090/en/.

[8] FAO sub-regions and number of countries (in parenthesis) with no national value in FRA: Eastern Africa (1), Western Africa (2), North America (2), Central America (1), Caribbean (13), South America (3), South-Eastern Asia (3), Western Asia (6), Northern Europe (3), Southern Europe (1), Australia and New Zealand (1), Melanesia (2), Micronesia (1), Polynesia (5).

[9] In GHG national inventories, net emissions associated with deforestation are reported in the new land category to which forest was converted. By contrast, assessing net emissions and removals from *deforestation* and from *forest land* separately, as well as reporting their sum as net emissions and removals from *forest*, is relevant to REDD+.

only for total forest, hence no further stratification between the two above forest strata was made. Rather, each was assigned with the same value *b*, with limitations discussed below.

2.2. Stock difference equations

We estimated annual C stock change, limited to changes in carbon in woody biomass, and thus net CO_2 emissions and removals, over the period 1990–2015, associated with the following *process types*: (i) net forest area loss with associated net C stock loss (reported under *net forest conversion* or *deforestation*); and (ii) net forest area gain with associated net C stock gain; and (iii) net changes in C stock density over the forest land area. The last two process types were reported together under *forest land*)[10]. The stratification of the forest area and equations applied followed the IPCC (2006) guidelines and are summarized for convenience in Table 1 and 2.

In general, net C stock change was computed by applying:

- Approach 1 (IPCC, 2006, Ch. 3, Vol. 4) for land representation. Only net forest area changes were considered, since FRA data did not allow for quantification of gross area changes.
- IPCC stock-difference equation (IPCC, 2006; equation 2.5, Vol. 4) for the calculation of average C stock density change.

More specifically, net CO_2 emissions and removals[11] were computed for each of the two forest strata *i* (*natural forest* and *planted forest*) each of the three process types *j* and for each year *t*, as follows (see also Table 2):

$$netCO_2emission_{i,j}(t) = a_{i,j}(t) * CSCF_j(t) * -\frac{44}{12} * 10^{-3} \qquad (1)$$

where:

netCO₂emission is expressed in Gg CO_2 (or equivalently, kt CO_2);

$a_{i,j}(t)$ is the area underpinning the process type *j* in strata *i*, at year *t*, expressed in ha (see below);

$CSCF_j(t)$, or carbon stock change factor, is the woody biomass carbon stock density change relative to process type *j*, estimated at time *t*, expressed in metric tonnes C ha^{-1}. The factor 44/12 converts C to CO_2; 10^{-3} converts metric tonnes to Gg. The minus sign allows to assign emissions (positive sign) to carbon stocks losses, and removals (negative sign) to carbon stocks gains.

For each of the forest strata *i* defined above, the area $a_{i,j}(t)$ was defined as follows:

$$a_{i,j}(t) = \begin{cases} SFA_i(t) \\ FAC_i(t) \end{cases} \qquad (2)$$

where $SFA_i(t)$ is the *stable forest area* of strata *i* at time *t*, defined as the forest area remaining forest between two successive years ($t-1$) and *t*:

$$SFA_i(t) = \text{Min}\,[A_i(t), A_i(t-1)] \qquad (2a)$$

And $FAC_i(t)$ is *forest area change* of strata *i* at time *t*:

$$FAC_i(t) = [A_i(t) - A_i(t-1)] \qquad (2b)$$

The latter was recorded as *net forest area increase,* when $FAC_i(t) > 0$, and as *net forest conversion,* used herein as a proxy for *deforestation,* when $FAC_i(t) < 0$.

Therefore the following area identity holds for each of the forest strata and each time *t*:

[10] Including in principle C stock changes in both primary and other naturally regenerating forests, since FRA C stock values are averaged over the total forest.

[11] The term removal herein refers to removal of carbon from the atmosphere and its storage into forest woody biomass.

Table 1
Subdivisions of Forest land categories and forest strata used in the FAOSTAT methodology.

Forest	Forest land	Natural forest	Stable forest area in the inventory year (SFA_1) New net forest area in the inventory year (FAC_1)
		Planted forest	Stable forest area in the inventory year (SFA_2) New net forest area in the inventory year (FAC_2)
	Net forest conversion	Natural forest	Net deforestation in the inventory year (FAC_3)
		Planted forest	Net deforestation in the inventory year (FAC_4)

$$\textit{Forest land}\ \text{area}: A_i(t) = SFA_i(t) + \text{Max}[FAC_i(t), 0]; \qquad (3)$$

$$\textit{Deforestation}\ \text{area}: \text{Min}[FAC_i(t), 0] \qquad (4)$$

For each of the process type *j* defined above, the carbon stock change factor $CSCF_j(t)$ was computed as follows:

$$CSCF_j(t) = \begin{cases} b(t) - b(t-1); & for\ j = SFA; \\ b(t-1); & for\ j = FAC < 0 \\ b(t); & for\ j = FAC > 0 \end{cases} \qquad (5)$$

Note that under Eq. (5), the carbon stock density of deforested land, as well as the previous woody biomass carbon stock density of land that was converted to forest, are both assumed to be zero. Similarly, the woody biomass carbon stock density of new forested land is assumed to be that of the remaining forest. This is a consequence of the methodology applied herein, leading to either under and over estimates of carbon stock changes reported for natural forest and planted forest under *net forest conversion* and under *forest land*, depending on national forest circumstances. Errors however cancel out once estimates are summed up for the category *forest*, since the net C stock change calculated for *forest* corresponds exactly to the difference in the woody biomass C stocks reported by countries under FRA, and thus are not a source of bias at the level of total forest area.

2.3. Definition of net emissions from forest degradation

Using Eqs. (1)-(3) and (5), net CO_2 emissions and removals estimated over *forest land* area at country level, *netCO₂emission* (t) corresponded to net annual decreases or increases in forest woody biomass C stock density. Irrespective of the underlying processes, which could not be further analyzed using FRA data, whenever *netCO₂emission* $(t) > 0$, we counted net forest emissions as *forest degradation*. Similarly, whenever *netCO₂emission* $(t) < 0$, we counted them as net forest removals. This allowed us to separate estimates of net forest sinks at global and regional level into a degradation component and into a net removal component.

3. Uncertainties and limitations

Uncertainties in the estimates of CO_2 emissions and removals discussed herein stemmed from the methodology applied, and depended on the availability and quality of FRA data submitted by countries to FAO.

3.1. Methodological uncertainties

Our estimates were limited to only two carbon pools, above- and below-ground biomass, out of six pools identified by the IPCC guidelines: above- and below-ground biomass, dead wood,

Table 2
Equations applied for estimating the components A and CSCF of Eq. (1).

Subdivision			A	CSCF
Forest land	Natural forest	Stable forest area in the inventory year (SFA_1)	Min[A(t),A(t−1)]	CSCF = b(t) − b(t−1)
		New net forest area in the inventory year (FAC_1)	Max[A(t)–A(t−1),0]	CSCF = b(t)
	Planted forest	Stable forest area in the inventory year (SFA_2)	Min[A(t),A(t−1)]	CSCF = b(t) − b(t−1)
		New net forest area in the inventory year (FAC_2)	Max[A(t)-A(t−1),0]	CSCF = b(t)
Net forest conversion	Natural forest	Net deforestation in the inventory year (FAC_3)	|Min[A(t)-A(t−1),0]|	CSCF = b(t−1)
	Planted forest	Net deforestation in the inventory year (FAC_4)	|Min[A(t)-A(t−1),0]|	CSCF = b(t−1)

litter, soil organic carbon, and harvested wood products. This likely impacted the magnitude of estimated net C stock change, as the inclusion of other C pools would probably have increased the magnitude of estimated changes, but not their direction of change, i.e., the identification of a net sink or a net source, since the dynamics of C pools are strictly linked. Soil carbon pools in forest over drained organic soils represent a notable exception, since they may be characterized by long-term C losses even as carbon biomass and litter pools increase.

By excluding dead wood, litter and soil organic carbon, FAOSTAT estimates of net CO_2 emissions and removals were likely under-estimates of actual net CO_2 emissions. By analysing UNFCCC country submissions, we assessed the magnitude of this underestimate to be as large as one-third of the potential C stock change from all pools. CO_2 Emissions from deforestation are possibly further underestimated, since they were based on net, rather than gross, deforested area.

Additional methodological uncertainties were linked to the use of average C stock densities, i.e., not differentiated by forest strata. This would lead to an over or under-estimation of net emissions and removals for forest strata with C density significantly above or below the average values. Because the information on C density is however correct when considered over the sum of forest and deforested areas, these errors cancel out at the level of total net C stock change of *forest.*

Finally, our estimates included CO_2 gas only. Including CH_4 and N_2O emissions would have increased our emission estimates, especially in countries where forest fires play a significant role in deforestation and forest degradation. Analyses we performed with the FAOSTAT Emissions database, however, showed that such additional non-CO_2 emissions were typically one order of magnitude lower than the CO_2 estimated values.

3.2. Uncertainties associated with FRA data

Additional uncertainties stemmed from: (i) Heterogeneity in country data quality; and (ii) FRA data projections within given FRA cycles.

The latter type of uncertainty was related to the fact that, for any FRA cycle, the last years of data are in fact projections rather than actual measurements. The impact of this on estimated emissions and removals was evaluated herein by comparing results for years 2009–2010, which were projections in FRA 2010 data, revised using actual measurements in FRA 2015. This was a simplified exercise, recognizing that periods longer than two years may in fact represent projections in any given FRA cycle, and acknowledging that uncertainties may grow by comparing periods further apart in time. Our analyses comparing net CO_2 emissions and removals for 2009–2010 made with FRA2015 to FRA2010, indicated small relative effects on global *deforestation* estimates (−0.6%), including for non-Annex I Parties (−5.8%), and large relative effects in Annex I Parties (+43.8%), although it should be considered that in the latter case absolute values were very small. Similarly, we found small effects on estimates of global *forest* net C stock change (+13.4%), including for Annex I (+10.2%) and non-Annex I Parties (+20.4%).

Regarding the quality of country data, FRA 2005 estimated uncertainties of growing stock at ±8% for industrialized countries (Annex I) and ±30% for non-industrialized countries (non-Annex I). The uncertainty of biomass density for estimating C stock losses from net deforestation was larger, and was set by expert judgement at ±80%. Uncertainties for wood density data were estimated in the range 10–40%. Additionally, FAOSTAT estimates uncertainties of area data at ±10% in general, and possibly as low as ±3% in industrialized countries. Additional uncertainties were linked to the use of conversion factors needed to estimate total living biomass stocks from nationally reported wood volumes. These factors include a biomass conversion and expansion factor (BCEF = 1.3), a root-to-shoot ratio (R:S = 0.2), and a biomass-to-carbon conversion factor (CF = 0.5). The IPCC associates uncertainties of ±30% to these factors. The resulting overall uncertainty[12] at global level, computed by applying relevant 2006 IPCC equations for error propagation, was about ±30% for CO_2 emissions from *deforestation* and ±15% net CO_2 emissions and removals from *forest land*. It should be noted that FRA applies the conversion factors described above equally across all countries. This simplification introduced additional uncertainties, which we did not know how to quantify.

4. Results and discussion

Updated annual net CO_2 emissions and removals from *forest* and from its two sub-components *forest land* and *net forest conversion* (*deforestation*), were computed and made available via the FAOSTAT database (http://faostat3.fao.org/faostat-gateway/go/to/download/G2/GF/E)[13]. Results were summarized globally and disaggregated by Annex I and non-Annex I Parties as averages for the periods 1991–2000, 2001–2010, 2011–2015, and 1991–2015 (Table 3). Only mean values were reported.

4.1. Global trends

Results indicated that over the period of study, 1991–2015, *forest land* was a net source of CO_2 emissions globally, averaging 1.52 Gt CO_2 yr^{-1}. These corresponded to emissions from

[12] From IPCC 2006: Lack of knowledge of the true value of a variable that can be described as a probability density function (PDF) characterising the range and likelihood of possible values. The uncertainty in the mean (e.g. the uncertainty associated with the calculation of the average biomass C density across the country) is estimated as plus or minus *k* (or approximately 2) multiples of the standard error divided by the sample mean times 100, where the standard error is the sample standard deviation divided by the square root of the sample size. The uncertainty in the individual (e.g. the uncertainty associated with the use of the average biomass C density for estimating C stock losses of a single unit of land) is estimated as plus or minus *k* (or approximately 2) multiples of the sample standard deviation divided by the sample mean times 100. Both calculations are based on an assumption of a normal distribution, and k is obtained from the student's t-distribution.

[13] The *Forest* sub-domain in FAOSTAT contains data by country, with a range of regional aggregations, including Annex I and non-Annex I groups. Data for download are net CO_2 emissions/removals in $GgCO_2$; C stock change in GgC; implied emission factors; and area.

Table 3
Estimates of annual net CO_2 emissions and removals from forest (woody biomass C stock changes only). Mean values only are reported.

Subdivision			1991–2000	2001–2010	2011–2015	1991–2015
			t C (thousand)			
Total Forest	Total	Annex I	*−981,451.76*	*−1,096,888.72*	*−1,158,287.58*	*−1,063,025.76*
		non-Annex I	*2,675,855.92*	*2,809,900.98*	*1,949,565.06*	*2,583,693.79*
		Global	*1,694,404.17*	*1,713,012.26*	*791,277.48*	*1,520,668.03*
	Natural forest	Annex I	*−494,133.03*	*−527,360.69*	*−773,006.17*	*−563,227.53*
		non-Annex I	*3,093,295.83*	*3,477,942.01*	*2,479,090.54*	*3,123,887.64*
		Global	*2,599,162.81*	*2,950,581.32*	*1,706,084.38*	*2,560,660.11*
	Planted forest	Annex I	*−487,318.73*	*−569,528.03*	*−385,281.41*	*−499,798.23*
		non-Annex I	*−417,439.91*	*−668,041.03*	*−529,525.48*	*−540,193.84*
		Global	*−904,758.64*	*−1,237,569.06*	*−914,806.90*	*−1,039,992.08*
Forest land	Total	Annex I	*−1,206,517.43*	*−1,459,683.16*	*−1,285,657.13*	*−1,323,611.66*
		non-Annex I	*−1,781,025.72*	*−777,879.76*	*−862,408.08*	*−1,196,043.81*
		Global	*−2,987,543.15*	*−2,237,562.92*	*−2,148,065.21*	*−2,519,655.47*
	Natural forest	Annex I	*−713,692.06*	*−872,441.74*	*−888,801.61*	*−812,213.84*
		non-Annex I	*−1,335,910.28*	*−85,900.98*	*−285,925.07*	*−625,909.52*
		Global	*−2,049,602.34*	*−958,342.72*	*−1,174,726.68*	*−1,438,123.36*
	Planted forest	Annex I	*−492,825.37*	*−587,241.42*	*−396,855.51*	*−511,397.82*
		non-Annex I	*−445,115.44*	*−691,978.78*	*−576,483.01*	*−570,134.29*
		Global	*−937,940.81*	*−1,279,220.20*	*−973,338.53*	*−1,081,532.11*
Net forest conversion	Total	Annex I	*225,065.67*	*362,794.45*	*127,369.54*	*260,585.90*
		non-Annex I	*4,456,881.65*	*3,587,780.74*	*2,811,973.14*	*3,779,737.60*
		Global	*4,681,947.32*	*3,950,575.18*	*2,939,342.69*	*4,040,323.51*
	Natural forest	Annex I	*219,559.03*	*345,081.05*	*115,795.44*	*248,986.32*
		non-Annex I	*4,429,206.12*	*3,563,842.99*	*2,765,015.61*	*3,749,797.16*
		Global	*4,648,765.15*	*3,908,924.04*	*2,880,811.06*	*3,998,783.47*
	Planted forest	Annex I	*5,506.64*	*17,713.39*	*11,574.10*	*11,599.59*
		non-Annex I	*27,675.53*	*23,937.75*	*46,957.53*	*29,940.45*
		Global	*33,182.17*	*41,651.14*	*58,531.63*	*41,540.03*

deforestation of 4.04 Gt CO_2 yr^{-1}, counterbalanced by net removals in *forest* of −2.52 Gt CO_2 yr^{-1} (Table 3) Importantly, global emissions from *forest degradation* were also estimated, for the first time in the literature, at 0.80 Gt CO_2 yr^{-1} on average over 1991–2015. This implies that the actual forest sink was −3.32 Gt CO_2 yr^{-1}.

Historical trends were particularly significant (Table 4). Net emissions from deforestation decreased over the period 1991–2015, from an average of 4.68 Gt CO_2 yr^{-1} in 1991–2000, to 3.95 in 2001–2010 and then to 2.94 Gt CO_2 yr^{-1} in the last five years 2011–2015. The most recent rates represented a reduction of over one-fourth over the preceding decade.

During the same time periods, net emissions from forest degradation increased three-fold, from 0.35 on average during 1991–2000, to 1.15 in 2001–2010 and 0.99 Gt CO_2 yr^{-1} in 2011–2015. It should be noted that sudden shifts in CO_2 emissions from *deforestation* to forest *degradation* were observed in some countries with significant forest area, after the year 2000. In such cases, aggregating net CO_2 emissions at the level of *forest* would be preferable in order to provide for unbiased trends.

Finally, alongside the estimated increases in forest degradation, and mostly due to a decrease in non-Annex I Parties sink strength, the global net forest sink decreased, from −2.99 on average during 1991–2000, to −2.24 in 2001–2010 and then to −2.15 Gt CO_2 yr^{-1} in 2011–2015.

As a result of the above, *forest* was a net source of CO_2 into the atmosphere over the entire period of study, albeit one that significantly decreased over time (Table 4). Average CO_2 emissions from *forest* slowed from rather steady rates of 1.70 Gt CO_2 yr^{-1} over the period 1991–2010, to roughly half this value, or 0.79 Gt CO_2 yr^{-1}, in 2011–2015.

Table 4
Summary estimates of annual net CO_2 emissions and removals for forest, showing deforestation and forest land contributions, limited to woody biomass C stock changes. The latter is further separated into a forest degradation component and a net CO_2 removal component.

	Average annual Gt CO_2 yr^{-1}		
	1991–2000	2001–2010	2011–2015
net CO_2 sink in forest land	−2.99	−2.24	−2.15
net CO_2 removals in forest land	*−3.34*	*−3.38*	*−3.14*
net CO_2 emissions from forest degradation	*0.35*	*1.15*	*0.99*
CO_2 emissions from net deforestation	4.68	3.95	2.94
Forest total net CO_2 source	1.69	1.71	0.79

4.2. Annex I and non-Annex I Parties and regional trends

Disaggregation by country groups added significant insight into largely different trends between Annex I and non-Annex I Parties. On average during the entire study period of 1991–2015, *Forest* was a net source in non-Annex I Parties, averaging 2.58 Gt CO_2 yr^{-1}, while it generated net CO_2 removals in Annex I Parties, with an average of −1.06 Gt CO_2 yr^{-1}. *Natural forest* and *planted forest* contributed equally to the estimated overall net CO_2 removal in Annex I Parties. In non-Annex I Parties, *natural forest* were a significant net source (3.12 Gt CO_2 yr^{-1}), largely due to *deforestation*, while *planted forest* acted as a net sink (−0.54 Gt CO_2 yr^{-1}) (Table 3).

Deforestation took place mainly in *natural forest* in non-Annex I Parties, emitting on average 3.75 Gt CO_2 yr^{-1}, while deforestation rates in Annex I Parties were minimal, at 0.26 Gt CO_2 yr^{-1}.

Decreases in deforestation rates in non-Annex I Parties followed the global trends reported above. In addition, net CO_2 emissions from *forest degradation* were almost entirely located in non-Annex I Parties, which were responsible for as much as 90% of the total net CO_2 emissions from degradation estimated herein.

Over the period 1991–2015, *planted forest*, representing 7% of total forest area, accounted for a global average sink that was comparable to the sink in *natural forest* (−1.08 vs. −1.44 Gt CO_2 yr^{-1}) (Table 3). The sink in planted forests was driven by continuous increases in total area.

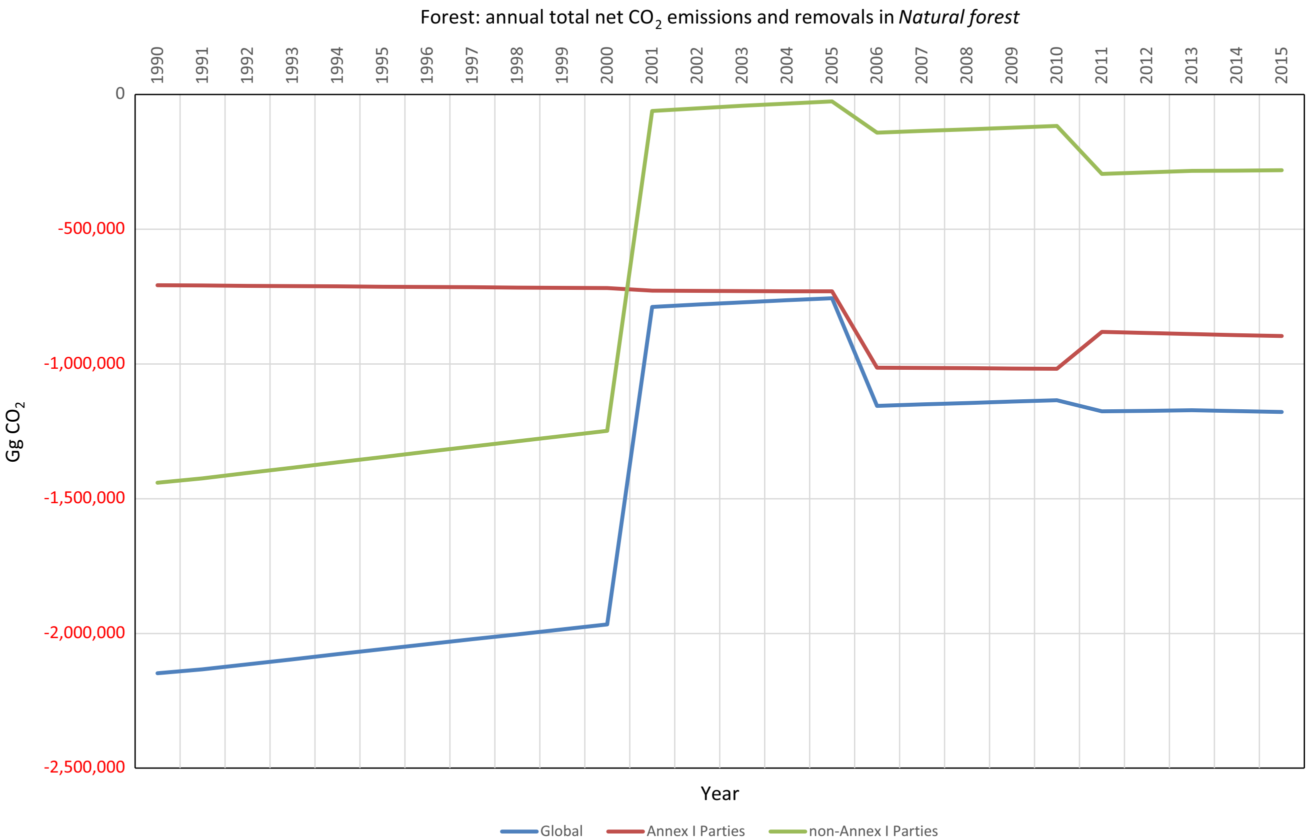

Fig. 1. Annual total net CO_2 emissions and removals in the *Natural forest* subdivision of category *Forest land*.

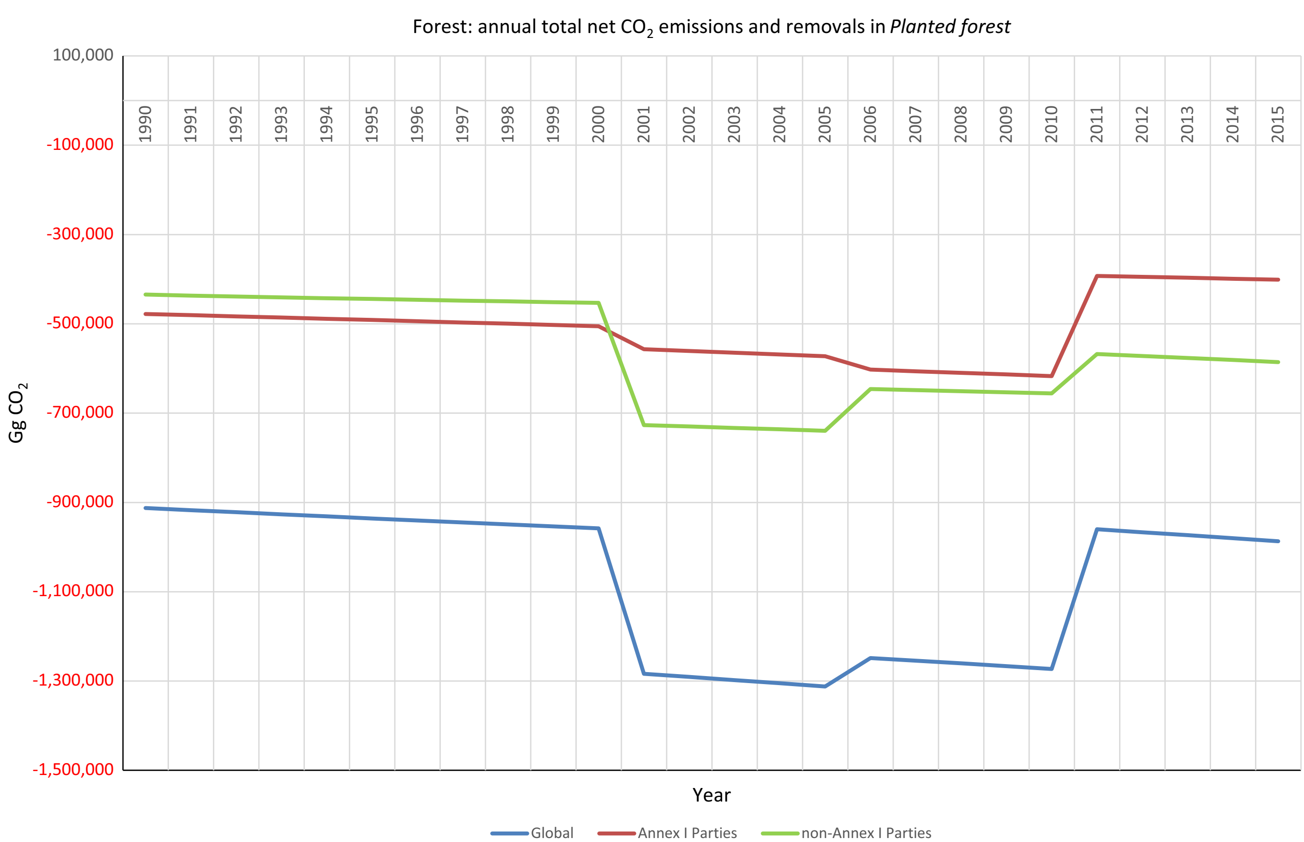

Fig. 2. Annual total net CO_2 emissions and removals in the *Planted forest* subdivision of category *Forest land*.

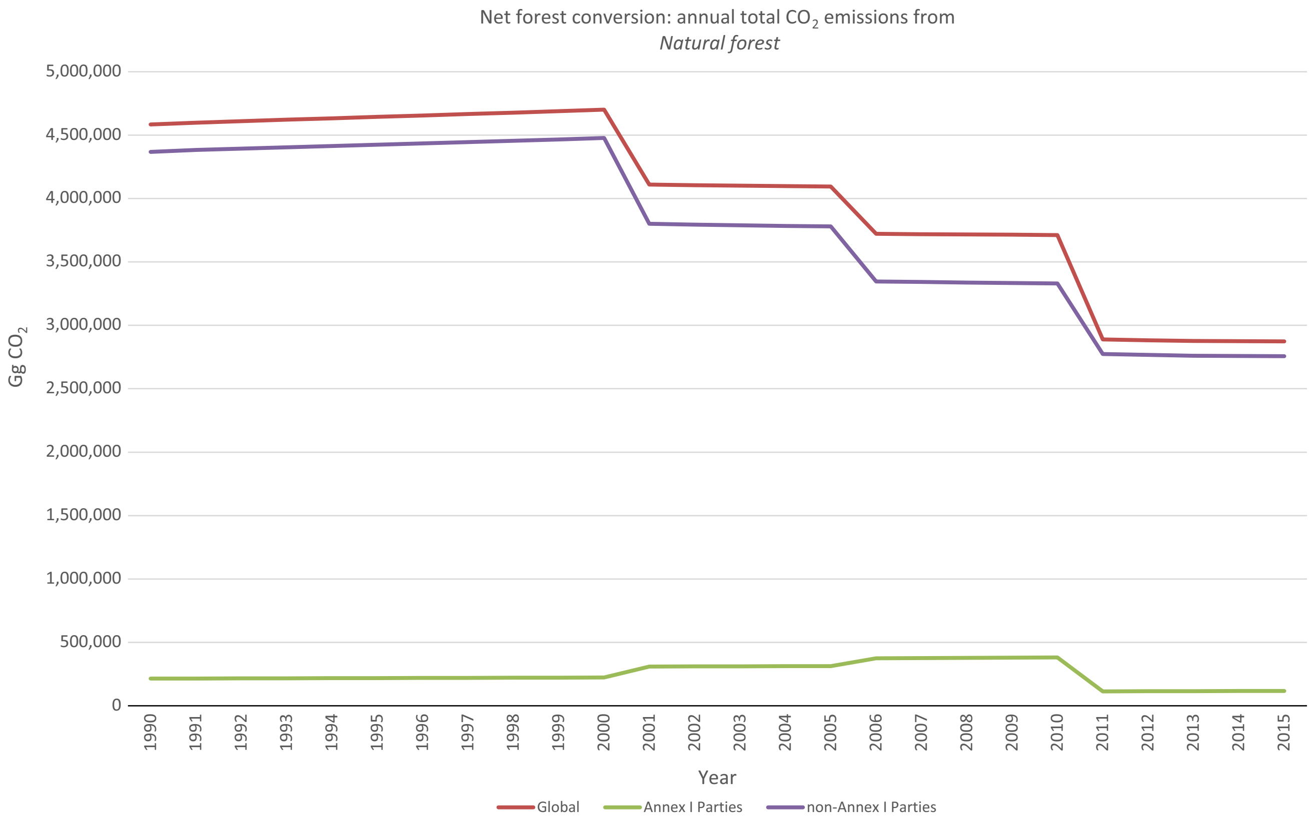

Fig. 3. Annual total CO_2 emissions in the *Natural forest* subdivision of category *Net Forest Conversion*.

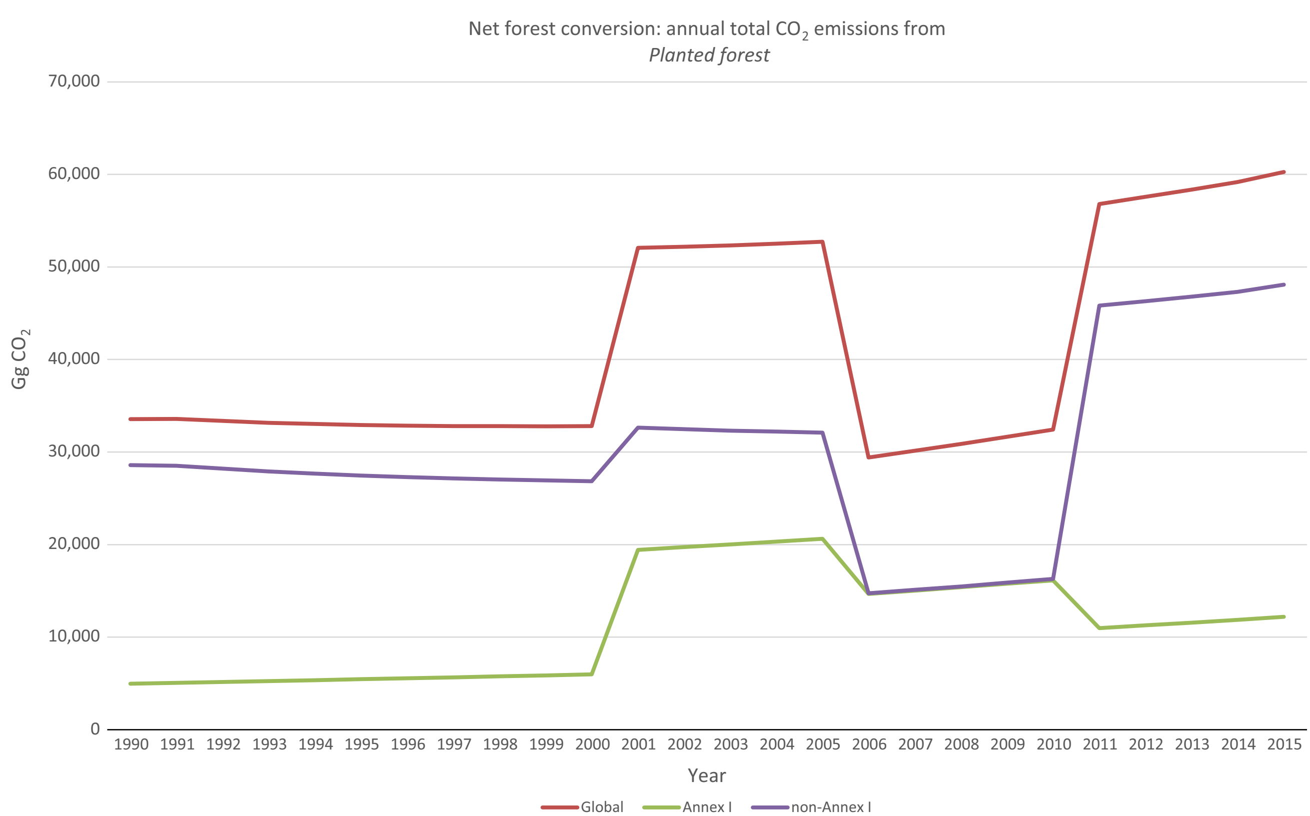

Fig. 4. Annual total CO_2 emissions in the *Planted forest* subdivision of category *Net Forest Conversion*.

Forests in Annex I Parties represented 52% of the global estimated carbon sink, consistently with their share of global forest area coverage (45%), and increases in biomass C density, from 44.9 t C ha^{-1} in 1990 to 48.2 t C ha^{-1} in 2015, accounted for 87% of the forest sink. The remaining 13% of the sink was linked to increases in forest area, from 1.81 to 1.84 billion hectares in 1990 and 2015, respectively.

By contrast, the net sink in non-Annex I Parties was determined exclusively by forest area expansion from 1991 to 2015. Indeed, despite overall area decreases in non-Annex I Parties of some 154 million ha, area gains of 104 million ha were observed in some countries, established through natural forest expansion (56 million ha) and afforestation (48 million ha). By contrast, biomass C stock density decreased, from 97.5 in 1990 to 96.3 t C ha^{-1} in 2015.

4.3. Critical national trends

Net CO_2 emissions and removals for *natural forest* were computed annually in order to assess critical dynamics (Fig. 1). Large discontinuities in the order of 1 Gt CO_2 yr^{-1} were observed across years 2000 and 2001, in non-Annex I Parties, while smaller discontinuities were observed in Annex I Parties, across the years 2005 and 2006. Remarkably, they were largely determined by trends in a few countries. In fact, the large discontinuity in non-Annex I Parties trends was due to one country alone (Indonesia). Its forests were estimated to be a significant net sink before the year 2000, becoming a large net source afterwards. The smaller discontinuity in Annex I Parties between 2005 and 2006 was characterized by large increases in forest sinks after 2006. This trend was determined by three countries: Australia, where forests were a net source before 2005 but became a net sink afterwards; Canada, where the net source in forest land was halved after 2005, and the Russian Federation, where the net sink almost doubled after 2005.

For *planted forest*, the estimated annual net uptake of CO_2 decreased in Annex I Parties during 2011–2015, due to significant decreases in newly planted area, i.e., from an average of 2 Mha yr^{-1} prior to 2010 to 1 Mha ha yr^{-1} during 2011–2015 (Fig. 2). In

Table 5
Twenty-five year long-term average analysis of forest net carbon emissions and removals from FAOSTAT, compared to Annex I and available non-Annex I Parties submissions to UNFCCC (woody biomass C stock changes only).

	Comparison between FRA and UNFCCC data (% difference)	FAOSTAT data	GHG data (non-Annex I Parties)	GHG Inventory (Annex I Parties)
		This analysis	UNFCCC website	
		Average 1991–2010 – Gg CO_2 net emissions		
Grand total	−3.46%	−2,557,116	−2,648,718	
Total non-Annex I Parties	7.93%	−1,215,833	−1,126,553	
Total Annex I Parties	−11.88%	−1,341,283		−1,522,165

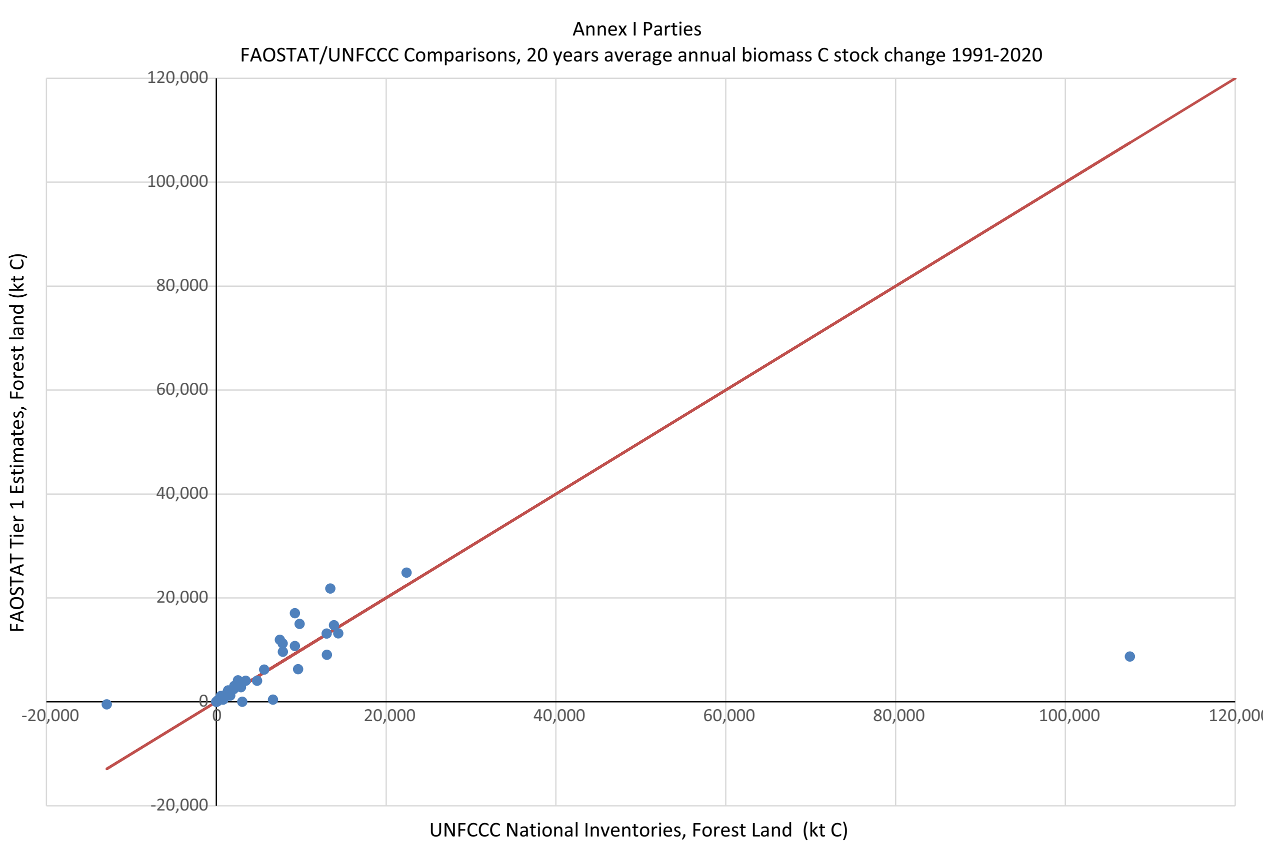

Fig. 5. Comparisons of net CO_2 emissions and removals from *Forest land* in Annex I Parties. FAOSTAT estimates vs. UNFCCC reports.

non-Annex I Parties, by contrast, the net carbon sink of *planted forest* continued to increase over the entire analysis period, due to increased area.

Our annual estimates clearly indicated the critical role of *deforestation* in *natural forest* of non-Annex I Parties, with a minor contribution from *planted forest* (Figs. 3 and 4). Similarly to previous cases, observed discontinuities were determined by only two countries, as follows:

- Decreases by almost two-thirds of net deforestation in Indonesia after 2000.
- Decreases by almost one-third of net deforestation in Brazil after 2005.
- Decreases by almost one-half of net deforestation in Brazil after 2010.

4.4. Comparisons of FAOSTAT estimates and UNFCCC data

We compared 1991–2015 global averages of FAOSTAT estimates for *forest land*[14], limited to countries with forest area larger than 1 Mha, to similar data reported by countries to the UNFCCC[15] (Table 5).

We found that FAOSTAT estimates were within 5% of UNFCCC data, thus statistically similar, given the large uncertainties discussed previously. Disaggregation between Annex I and non-Annex I Parties also showed good agreement. Specifically, for non-Annex I Parties, FAOSTAT estimated a sink 4% larger than implied by UNFCCC data. For Annex I Parties, FAOSTAT estimated a sink 12% smaller than implied by UNFCCC data (Fig. 5). Results for the Russian Federation were responsible for most of the difference observed between the two data sources. This country reported a rather stable forest area and forest C stock to FRA, resulting in minor net CO_2 removals. By contrast, its UNFCCC data indicated a large net carbon sink, of some 400 Mt CO_2 yr^{-1} on average.

5. Conclusions

5.1. Main findings

Our analysis quantified the global relevance of forest-related CO_2 emissions and removals, making available estimates based on official country data and international methodologies. Our findings quantified for the first time the overall net forcing of forests on the atmosphere over the period 1991–2015, (1.52 Gt CO_2 yr^{-1}), highlighting the significant role of deforestation as a net source (4.04 Gt CO_2 yr^{-1}), and the importance of remaining forests as net sink (−2.52 Gt CO_2 yr^{-1}). Furthermore, this study quantified global CO_2 emissions form forest degradation, alongside those from deforestation, providing a useful basis for quantifying emission sources under REDD+. The value estimated for forest degradation over 1990–2015, 0.80 Gt CO_2 yr^{-1}, was about one-fourth of deforestation emissions. Importantly, while emissions from deforestation significantly decreased in non-Annex I Parties over time, e.g., from 4.68 in 1991–2000 to 2.94 Gt CO_2 yr^{-1} in 2011–2015, emissions from forest degradation increased three-fold, from 0.35 in 1991–2000 to 0.99 Gt CO_2 yr^{-1} in 2011–2015.

Despite the simplified carbon stock change methodology applied in this study, it is worth noting that the estimates of global CO_2 emissions from *deforestation* provided herein were fully consistent with those summarized by the IPCC AR5 WGI (4.03 ± 2.93 Gt CO_2 yr^{-1}). The latter were based on a range of modelling techniques, including some using FRA data in conjunction with more complex bookkeeping methods (i.e., Houghton et al., 2012).

5.2. Suggested methodological and data improvements

The quality of FAO estimates for *forest* discussed herein could benefit from a number of improvements in FRA reporting. These include:

1. Enhanced country data to cover carbon stock gains and carbon stock losses separately, and disaggregated by forest type.
2. Improved coordination at national level, especially between FRA and UNFCCC focal points, to ensure consistency, completeness and accuracy of reported information.

Looking forward to the 2020 FRA, with respect to point 1 above, significant possible improvements would be the inclusion of data on woody biomass stocks by forest strata,, i.e. primary forest, other naturally regenerated forest, and planted forest, allowing for computation of different carbon stock densities and thus a more precise estimation of CO_2 emissions and removals. Separation of losses from harvesting of industrial round-wood and fuel-wood would also be extremely useful to permit implementation using the gain-loss method.

Further improvements to enhance progress toward a harmonized and complete dataset of regional and global C balance estimates of *forest*, while recognizing the difficulty of gathering such information, would be data on forest disturbance, as well as better data on C stock gains associated with stock increments, ideally disaggregated by strata. We further note that, although the new FRA 2015 questionnaires requested *information on gross forest expansion* (topic 1.6) and *information on gross deforestation* (FRA topic 1.7), few countries reported such information. Improved reporting of gross area changes is very difficult, yet it would be needed to increase the accuracy of computations of annual C stock changes associated with forest area changes.

Importantly, countries should be given an opportunity, depending on their capacity and timing of forest survey/census cycles, to communicate updated forest data to FAO between FRA reporting periods, in order to avoid incongruities between actual national data and FRA projections, especially for the last two years of a given FRA cycle.

Finally, consistency between FRA and UNFCCC data should be improved. FRA questionnaires could explicitly ask countries to report to the two UN agencies the same set of values on forest area and area change, volume increment, harvesting quantities, growing stock, other C stocks, etc.

5.3. Mitigation potential of forests

Forests can play a significant role in the mitigation of climate change. Mitigation through *forest* may be achieved either reducing net C stock losses or increasing of long-term average C stocks.

According to the 2015 FRA data, natural forests lost their biomass stocks at a rate of 2.5% per year during the period 1991–2015. Our estimates helped to clarify that, if reversed, this would correspond to a REDD+ mitigation potential of about 4 Gt CO_2 yr^{-1} from avoided deforestation and 1 Gt CO_2 yr^{-1} from avoided forest degradation. Additional mitigation potential would have to be achieved through new afforestation of degraded lands.

[14] *Net forest conversion* could not be directly compared with data on gross deforestation reported to the UNFCCC

[15] For Annex I Parties, data were taken from their 2014 national GHG Inventory, Common Reporting Format (CRF) Table 5A: biomass net C stock change (cell M10): http://unfccc.int/national_reports/annex_i_ghg_inventories/national_inventories_submissions/items/8108.php. For non-Annex I Parties, data were taken from their most recent National Communications (http://unfccc.int/ghg_data/items/3800.php), category "Changes in Forest and Woody Biomass Stocks".

Therefore, future FRA efforts should focus on providing more detailed information on forest types, strata, and C stocks, in order to allow for better quantification of such significant potential.

Acknowledgments

The Climate, Energy and Land Tenure Division, the Forestry Division and the Statistics Division of FAO supported this work under the MAGHG Project. Generous funding was provided by Norway and Germany, via Trust Funds GCP/GLO/GER/286 and GCP/GLO/NOR/325. We thank A. Gordon, F. Grita, S. Murzilli and G. Barbaglia of the FAO Statistics Division for providing essential data and IT support. We are thankful to K.G. MacDicken of the FAO Forest Management Division for providing us with the FRA 2015 data and for many helpful suggestions and insights. We thank two anonymous reviewers for their useful comments, which significantly improved this manuscript.

References

FAO, 2010. Global Forest Resources Assessment 2010, FAO Forestry Paper 163, Rome, <http://www.fao.org/forestry/fra/fra2010/en/>.

FAO, 2014. Agriculture, Forestry and Other Land Use Emissions by Sources and Removals by Sinks: 1990–2011 Analysis. FAO Statistics Division Working Paper Series, 14/01. UN FAO, Rome, Italy, <http://www.fao.org/docrep/019/i3671e/i3671e.pdf>.

FAOSTAT, 2015. FAOSTAT online database at <http://faostat3.fao.org/faostat-gateway/go/to/browse/G2/*/E>.

Houghton, R.A., House, J.I., Pongratz, J., van der Werf, G.R., DeFries, R.S., Hansen, M.C., Le Quéré, C., Ramankutty, N., 2012. Carbon emissions from land use and land-cover change. Biogeosciences 9, 5125–5142. http://dx.doi.org/10.5194/bg-9-5125-2012.

IPCC, 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme. In: Eggleston, H.S., Buendia, L., Miwa, K., Ngara, T., Tanabe, K., (Eds), IGES, Hayama, Japan, <http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html>.

MacDicken, K.G., 2015. Global Forest Resources Assessment 2015: What, why and how? Forest Ecology and Management. 352, 3–8.

Smith, P., Bustamante, M., Ahammad, H., Clark, H., Dong, H., Elsiddig, E.A., Haberl, H., Harper, R., House, J., Jafari, M., Masera, O., Mbow, C., Ravindranath, N.H., Rice, C.W., Robledo Abad, C., Romanovskaya, A., Sperling, F., Tubiello, F., 2014. Agriculture, Forestry and Other Land Use (AFOLU). In: Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Farahani, E., Kadner, S., Seyboth, K., Adler, A., Baum, I., Brunner, S., Eickemeier, P., Kriemann, B., Savolainen, J., Schlömer, S., von Stechow, C., Zwickel, T., Minx, J.C., (Eds.), Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Tubiello, F.N., Salvatore, M., Ferrara, A.F., House, J., Federici, S., Rossi, S., Biancalani, R., Condor Golec, R.D., Jacobs, H., Flammini, A., Prosperi, P., Cardenas-Galindo, P., Schmidhuber, J., Sanz Sanchez, M.J., Srivastava, N., Smith, P., 2015. The contribution of agriculture, forestry and other land use activities to global warming, 1990–2012. Glob. Change Biol. http://dx.doi.org/10.1111/gcb.12865.