GHG fluxes from forests: An assessment of national reporting and independent science in the context of the Paris Agreement

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Policymaker Summary

The Paris Agreement suggests several ambitious global mitigation goals: to hold the increase in global average temperature to well below 2°C (pursuing 1.5°C), to reach global peaking of greenhouse gas (GHG) emissions as soon as possible, and achieve a balance between anthropogenic emissions and removals in the second half of this century. These goals require a significant contribution from forests—not only through reducing deforestation in the tropics, but also by increasing the global sink capacity of forests.

Objectives of the study

Assessing the contribution of forests to global mitigation efforts requires understanding of both *national* GHG inventories (GHGIs), on which Nationally Determined Contributions (NDCs) are based, and results from independent scientific studies focused on *global* estimates of fluxes from forests. The data, information and methodologies used by national governments to report emissions and removals may differ from that used in independent scientific studies. This assessment seeks to:

a) Clarify what forest-related emissions and removals are (and are not) included in national GHGIs;

b) Compare national reporting to independent scientific studies, and provide an explanation of why and how they differ;

c) Provide recommendations on how additional transparency could improve understanding of the forest contribution to the global carbon budget.

The study is considered a first step in better understanding differences in estimates of forest-related GHG fluxes, to provide a basis for considerations of improvements in country-level reporting and global scale assessments—as both provide critical information towards delivering on Paris Agreement goals.

Coverage of GHG fluxes in national GHG inventory reporting on forests

National GHGI reporting under the United Nations Framework Convention on Climate Change (UNFCCC) aims to provide information to assess the overall effects of measures taken by each Party and the cumulative impacts (UNFCCC Article 7). The Paris Agreement also created a transparency framework (Article 13) that includes national GHGIs, with the objective of building mutual trust and confidence and to provide a clear understanding of climate change action. National GHGIs will be critical for providing transparency on progress toward achieving NDCs and to inform global stocktaking efforts.

National GHGIs contain *anthropogenic* emissions and removals and are used to quantify the mitigation efforts of each country. Non-anthropogenic emissions and removals are not included in national GHGIs, and to do so would complicate the assessment of net emission reductions achieved by mitigation actions.

The managed land proxy: IPCC Guidelines for national GHGIs apply a concept called the *managed land proxy* as a first order separation of anthropogenic and non-anthropogenic emissions and removals. The rationale for this approach is that the preponderance of anthropogenic effects occurs on managed lands. This proxy has been introduced to overcome the challenge of separating human-induced from natural effects, absent practicable methodologies to do so. Areas of land considered "managed" are defined by national governments, and should follow IPCC guidance which states that managed land is *land where human interventions and practices have been applied to perform production, ecological or social functions*. Consequently, GHGIs do not include estimates of GHG fluxes from areas that are designated as "unmanaged." Specific emissions and removals that would be excluded from a GHGI, to the extent they occur on unmanaged land, include:

a) carbon sinks, with the most significant fluxes due to accumulation of carbon in dead organic matter (e.g. black carbon from fire, organic matter in peat soil), regrowth after disturbances, forest expansion on unmanaged lands because of treeline shifts due to climate change, and fertilization effects due to increased atmospheric CO_2 or atmospheric N deposition;

b) emission sources, including wildfires and other disturbances (such pest outbreaks), mortality caused by climate change and associated impacts on peat lands from permafrost thaw.

These emissions and removals can be potentially significant, and may explain some of the apparent disparities between GHGI reporting to the UNFCCC and independent scientific studies.

Capacity for reporting: Generally speaking, all 43 Annex I (developed) countries have well-established national systems that employ technical experts and researchers within government departments or agencies. Such countries have submitted, to date, national GHGI reports annually from 2003 to 2016 (i.e. 14 per country, covering the period since 1990), National Communications every four years (i.e. six from each country), and two biennial reports (i.e. in 2014 and 2016, or two per country). All such reports are reviewed by technical experts coordinated by the UNFCCC secretariat, and the review reports published on the UNFCCC website. This annual reporting and review process has resulted, in most cases, in dedicated teams in developed countries assigned to these tasks that have been working for many years through iterative improvements of their respective national GHGIs.

For non-Annex I (developing) countries, capacity to measure and monitor forest-related fluxes is uneven. For some, GHGIs are compiled by external consultants. Developing countries have historically reported much less frequently, in less detail and historically have not been subject to expert assessments. Most developing countries have submitted only two national communications, and just 32 (out of 153 non-Annex I Parties) have submitted their first Biennial Update Report (BUR), despite a UNFCCC decision that non-Annex I Parties should submit a first BUR by December 2014.

GHGIs of developing countries have not benefitted from sustained feedback through international reviews that help country teams to address these issues. This increases the risk of technical shortcomings that can lead to significant errors and/or omissions in estimating GHG fluxes. Further, data sources and methodologies may not be well documented and definitions may be applied inconsistently across time and across data sources.

An analysis of reporting by 20 non-Annex I countries (with significant forest cover) suggests that reporting on deforestation is relatively complete. However, there are large uncertainties in the reporting categories of "forest remaining forest" and "non-forest to forest". Many developing countries do not have sufficient data to provide robust estimates on whether processes are leading to a long-term decline in carbon stocks of forests (degradation), which may be a significant source of emissions. There are also issues in identifying what area is "managed" versus "unmanaged", and in quantification (often leading to omission) of more complex forest dynamics (e.g. forest regrowth, shifting cultivation). Reporting on pools beyond biomass (e.g. deadwood, litter and soil) is a challenge for many developing countries that do not have regular National Forest Inventory (NFI) cycles, as data on such pools may be old or non-existent. The omission of non-CO_2 gases (common in non-Annex I GHGIs), particularly from forest fires, may also be significant for some countries.

Another source of uncertainty is the use by many developing countries of the older IPCC 1996 Guidelines for GHGIs—which do not allow for an understanding of which forest transitions or pools are covered, unless additional information is provided. However, the situation is changing—developing countries are encouraged to use the IPCC 2003 Good Practice Guidance, and BUR requirements and the International Consultation and Analysis (ICA) process (a technical analysis of BURs by a team of experts), plus an increasing interest in REDD+, are beginning to produce more frequent reporting by developing countries. These external analyses and assessments are expected to help improve national GHGIs of developing countries.

Completeness of reporting: National GHGIs should include all anthropogenic emissions and removals, but in practice they are not necessarily complete. There are several carbon stock change processes not fully captured by GHGIs of both developed and developing countries. Some are fluxes caused partially by indirect impacts of human activities e.g. permafrost thaw, CO_2 fertilization and nitrogen deposition, temperature variations and droughts. This may be because they are not well understood scientifically or because they occur on land classified as unmanaged.

The impact of natural disturbances often averages out across long time periods. Annually they may cause large variations in the anthropogenic GHG balance of a country. IPCC guidelines are that countries include emissions and subsequent removals associated with natural disturbances on managed land in their national GHGI *reporting*. However, when assessing performance relative to a national target (*accounting*), countries may wish under certain circumstances to exclude a portion of emissions and removals associated with disturbances on the basis that the magnitude of disturbance events may overcome the capacity of humans to take them under control and limit their impact. The Paris Agreement has not yet established guidance on how countries may account for natural disturbances in the context of NDCs although rules have been established under the Kyoto Protocol.

The summary table below is the authors' best selection of the most significant anthropogenic emissions and removals that may not be included in the current status of development of counties GHGIs.

Table 1: GHG forest fluxes that are not required (or may not be included) in current national GHGIs

Should be included in GHGIs	Not required in GHGIs
• GHG emissions and removals in managed lands for which not enough data yet exist (especially developing countries) • Fluxes related to non-living biomass pools (deadwood, litter and soil) • Emissions from drained organic soils • Impacts of CO_2 and N fertilization in managed lands • Emissions and subsequent removals associated with natural disturbances on managed land, including those which are out of human control	• Changes of the C stock equilibrium in unmanaged forest land due to changes in the natural disturbances regime • The natural sink in unmanaged peatlands • CO_2 and N fertilization in unmanaged lands • GHG from fires on unmanaged land

Other fluxes may also be significant, including the Impact of permafrost melting; N_2O emissions from mineralization of soil organic matter where not associated with a net soil organic carbon change; CH_4 emissions from termites and from ruminants, where not part of husbandry systems; and net C stock accumulation in the black carbon pool originating from fires in managed and unmanaged lands. Quantifications of emissions and removals for these fluxes are not well known and are not forest-specific but may help close gaps between inventory data and science studies, although their inclusion may not be a requirement for GHGIs.

Comparing GHGI reporting to independent scientific studies

There is a growing body of publicly available independent data with estimates of GHG fluxes from forests and land to the atmosphere. These include studies of land cover change and fire from remote sensing sources; carbon densities data from various sources; top down global models that estimate emissions and removals combining remotely sensed and ground collected data; and studies that attempt to estimate the impact of fertilization and other components of the terrestrial carbon budget. These studies are often not directly comparable with country reporting to the UNFCCC, nor among themselves—but form the basis of IPCC Assessment Reports (ARs).

IPCC Assessment Reports and country GHGI reporting

The objective of the IPCC's AR process is to provide "a clear and up to date view of the current state of scientific knowledge relevant to climate change". In doing so it reviews scientific literature for its *global* assessment of the physical science basis of climate change (Working Group I) and options for mitigating climate change (Working Group III). The IPCC Task Force on National GHG Inventories has been established to develop internationally agreed methodologies to estimate *national* GHG emissions and removals. These different objectives imply differences between the data, information, and methodologies used in the AR process compared to the guidance used by governments in developing national GHGIs.

The main source of difference between independent scientific studies and national GHGI reporting is the treatment of anthropogenic emissions and removals. Whereas national GHGIs apply the *managed land proxy*, estimates from global model approaches often take a different approach to separate management effects from indirect (or natural) impacts, and include different processes, definitions, and approaches to calculate global emissions and removals from forests. In particular, IPCC AR5 distinguishes emissions and removals due to: (a) land use change, including changes in land cover and certain 'management' processes (such as harvesting and replanting) and (b) the "residual terrestrial sink", estimated by the difference of the other terms of the global carbon budget, and generally assumed to be a 'natural' response of forests and other lands to the fertilizing effects of increased levels of CO_2 and N in the atmosphere and the effects of climate change.

Table 2 compares global estimates of anthropogenic and natural land-related CO_2 fluxes to the aggregate anthropogenic fluxes from land use from national reporting. From Table 2 emerges an *apparent* significant discrepancy between what independent scientific sources estimate as net "anthropogenic" terrestrial emissions and what countries reports for "managed land" (under land use, land-use change and forestry, or LULUCF).

Table 2: Annual GHG fluxes from land: first-order comparison of independent scientific studies versus national reports

Study	**Period**	**Estimate of anthropogenic fluxes (Gt C/y)**	**Residual Terrestrial sink (Gt C/y)**
IPCC AR5, Volume I	(2000-2009)	1.1 $\pm$ 0.8 net land use change (using Houghton bookkeeping model*)	-2.6 $\pm$ 1.2
Le Quéré et al 2015	(2000-2009)	1.0 $\pm$ 0.5 net land use change	-2.4 $\pm$ 0.8
Country reports** (INDC, UNFCCC, FAO)	(2000-2010)	0.2 $\pm$ 0.4*** Whole LULUCF	Not estimated

* Houghton, R. A. *et al.* Carbon emissions from land use and land-cover change. *Biogeosciences* **9**, 5125-5142 (2012).

** From Grassi G., Dentener F. (2015) Quantifying the contribution of the Land Use sector to the Paris Climate Agreement; EUR 27561; doi 10.2788/096422

*** *The +/- is based on an expert-judgment selection of alternative countries' data.*

To investigate further the apparent discrepancies, Table 3 provides estimates of fluxes associated with: (a) "land converted to other land uses" (i.e. land use change, mostly represented by tropical deforestation) and/or deforestation; (b) "land remaining in the same land use" or "forests remaining forests" (in country reporting, mostly represented by removals reported by developed countries); and (c) "land converted to forest land".

The results suggest a partial reconciliation of the discrepancies:

(i) Emissions from deforestation reported by countries (≈0.92 Gt C/yr) reflect reasonably well estimates of land use changes (essentially deforestation) by independent scientific studies (in the table above, ≈1.0-1.1 Gt C/yr). The relatively small difference may be associated with differences between global models vs. country reports in terms of methods used and pools, gases, and processes included.

(ii) Global models tend to estimate forest-related emissions based on net forest area and assume that, unless harvested, forests remaining forests are carbon neutral. Consequently, a large part of the sink that most Annex I countries report under "land remaining under the same land use" (including the large sink in temperate and boreal F→F areas, around -0.53 Gt C/yr) is implicitly included in the "residual sink" by global models (-2.6 Gt C/yr). The same may partly apply also for Non Annex I countries. This means that countries consider this sink at least *partly* human-induced (because reported under "managed land") while global models consider it "natural".

The fact that the forest sink reported by countries is much smaller than the "residual sink" estimated by global top down studies may be explained by several factors, including: (a) uptake in unmanaged land not reported by countries (because considered non-anthropogenic); (b) omissions of fluxes (e.g. regrowth in tropical forests, sink in grassland soils and wetlands, etc.) or pools in managed lands; (c) other factors that are not well understood or captured by the GHGI methodology (e.g. fertilization effects) and therefore not included in national reports. In addition, the residual (terrestrial) sink is a difference in global budget terms and not a direct estimation of GHG fluxes and therefore other factors may explain the disparity with national reports.

Table 3: Comparison of annual GHG fluxes (Gt C/yr) from national reports, disaggregated between 'Land use change' and 'Land other than land use changes'

Study	**Coverage**	**Land use change, or deforestation**	**F→F or L→L**	**NF→F**
Country reports (2000-2010)	All countries	≈ 0.92 deforestation	≈ -0.48 L→L (includes F→F) ≈ -0.75 F→F	≈-0.27
	Annex I	0.04 deforestation	-0.53 F→F, mainly removals from temperate and boreal forests	-0.03
	Non-Annex I (≈ tropics)*	≈ 0.88 deforestation	≈ -0.22 F→F	≈ -0.24
Federici et al 2015 (2000-2010)[1]	Global	1.1 net deforestation**	-0.6 NF→F and F→F (including 0.3 GtC/yr of forest degradation)	

[1] This study derives net C stock changes in F→NF and in NF→F + F→F, by assigning net C stock changes to net area changes reported by countries to FRA for three forest types: *Primary forest, Other naturally regenerating forests* and *Plantations*. For each country, total net C stock change of F→NF and NF→F + F→F corresponds to the net C stock change reported by countries to FRA.

Pan et al. 2011		2.8 tropical gross deforestation	--4.2 NF→F and F→F, excluding unmanaged forests in Canada (118 Mha), Alaska (51 Mha) and West/Central Asia (53 Mha)	
Achard at al 2014 (2000-2010)	Tropics only	0.88 gross emissions using remote sensing data (includes forests and other wooded land)	-0.10 removals from forest regrowth	
Baccini et al 2012[2] (2000-2005)		0.89 net deforestation** and shifting cultivation (excluding soils)	0.09 net emissions from industrial logging and fuelwood harvest	
Harris et al 2012 (2000-2005)		0.81 gross deforestation using remote sensing data		

* In non-Annex I country reports to UNFCCC using the 1996 IPCC Guidelines is often very difficult to distinguish between F→F and L→F. Numbers in this table should be considered a first estimate.
** Net deforestation estimates include a portion of fluxes from the NF→F category.

Even though it appears that global estimates of emissions from deforestation by independent studies match well with aggregated forest emissions from national GHGI reporting, this may not indicate accuracy by either source of information. It is possible that global or pan-tropical aggregates are averaging out actual differences in estimations. Studying these differences could lead to improvements on both sides of the comparison. For example, in addition to the definition of "anthropogenic" that lead to differences in national and aggregate estimates of forest-related GHG fluxes, the following may also result in quantified differences (and are elaborated in Section 3.3 of the report):

- **Forest definition**: Differences may include parameter values (e.g. minimum area, height, crown cover, etc.); use of land *cover* versus land *use*; or the exclusion of some types of tree cover (e.g. agricultural production systems).

- **Activity data**: In the case of land-use changes, these data are normally provided in hectares. Forest definition and the differentiation between managed and unmanaged land are two factors that can substantially influence activity data. Additional reasons for differences include: spatial resolution; remote sensing analysis approach; temporal resolution; or sampling vs. wall-to-wall coverage.

- **Emission factors:** Emission factors may vary based on which pools are included, as well as whether national estimates or default values are used. They may also vary based on the stratification used (given emissions and removals are affected by climate, soil, vegetation, management practices), or the methods used to calculate them.

Conclusions

The goals agreed in Paris cannot be met without a significant contribution from forests. Understanding forest-related GHG fluxes, however, can be challenging. Independent scientific studies—which are the basis of the IPCC's periodic Assessment Reports aimed at providing global flux estimates, including from the land sector—

[2] Estimate based on the Baccini et al. 2012 analysis as re-assessed in "Progress Towards A Consensus on Carbon Emissions from Tropical Deforestation", by Woods Hole Research Center and Winrock International (2012), and information from IPCC WG3 AR5 Figure 11.8.

often use different definitions and methodologies than those included in the IPCC Guidelines for National GHG Inventories, whose aim is to provide internationally agreed, standardized guidance to countries in preparing their national GHG inventories. This can result in differing quantifications of anthropogenic emissions and removal from forest lands.

A significant difference between independent scientific studies and national reporting is the methodology used to distinguish anthropogenic from natural sources of emissions and removals. Other differences may arise due to differences in forest definition, sources of activity data, emission factors, or the use of models to produce global, regional and/or biome results. Coverage of pools and greenhouse gas source categories may also not be the same when comparing scientific papers with national reports, but also when making comparisons between scientific papers. When comparing estimates from scientific journals to those in national GHGI reports, therefore, issues that need to be considered include:

- approaches to separate natural from human induced fluxes,
- estimation methods used,
- differences in forest definition,
- pool coverage,
- whether regrowth is included,
- whether and how natural disturbances are included.

Estimates from studies published in scientific journals and national GHGI reports *are both the result of* science-based methods, and can in principle be reconciled, or the differences understood. It is important to understand where differences among estimates that seemingly should agree are coming from. Once understood, the numbers should agree to within the quantified uncertainties. Likely sources of differences include methodological approaches and assumptions and inclusiveness of some of the fluxes.

The periodic "global stocktake" called for by the Paris Agreement will require tracking of the role of forests in achieving the 2 °C or 1.5 °C goal. This requires robust country estimates, and in this context it is important to achieve greater comparability between scientific studies and national reports. In order to make such comparisons, each source of information would need to provide transparent documentation on how estimates were derived.

Starting from the scientific side there should be greater awareness of the information contained in national reports and the possibilities of using it. Providing information disaggregated by national boundaries and by administrative region will be helpful, and it will be useful to consider IPCC definitions when considering pool coverage. Scientific papers that provide information compatible with IPCC inventory methods should be communicated to IPCC via the Emissions Factor Database. The scientific community could also help to distinguish and clearly document those fluxes that are outside of the GHGI framework but are nonetheless of substantial importance for tracking the global carbon budget in the context of the Paris Agreement.

From the national GHG inventory side there is considerable scope for improving forest-related estimates of GHG fluxes that would enhance the understanding of countries' NDCs, as well as overall progress towards the global goals contained in the Paris Agreement. There should be greater awareness of scientific work that is consistent with IPCC methods that can be used for independent verification. This awareness should be further encouraged by the inventory review and assessment process. Countries not having country specific data should use IPCC default methods to extend the range of carbon pools covered. Countries which have significant areas of unmanaged land may wish to include information on emissions and removals on these lands even though they are not included in national greenhouse gas inventories. Countries need to continue to improve transparency of information reported to allow, as far as practicable, for replicability of GHG estimates. Spatial boundaries and statistical estimation methods should be clear, so comparisons can be made as closely as possible. More recent IPCC guidance (at least 2003 Good Practice Guidance) should be used, consistent with encouragement in COP decisions.

Finally, the IPCC in future AR or Special Reports may provide clarification of differences such as those highlighted in this report. Where possible, it may also consider greater consistency between definitions and methods used when estimating forest-related GHG fluxes for Working Group I and III reports and comparability with guidance provided by the IPCC Task Force on GHG Inventories.

Contents

List of acronyms

AGB	Aboveground biomass
AR5	5th Assessment Report (of the IPCC)
BC	Black carbon
BGB	Belowground biomass
BUR	Biennial Update Report
COP	Conference of the Parties
DOM	Dead organic matter
DW	Dead wood
EF	Emission Factor
ESA	European Space Agency
EU	European Union
F	Forest
FAO	Food and Agriculture Organization (of the United Nations)
FRA	Forest Resources Assessment of FAO
FREL	Forest reference emission level
GHG	Greenhouse gas
GHGI	Greenhouse gas inventory
ha	Hectare
HWP	Harvested wood product
ICA	International Consultation and Analysis
IPCC	Intergovernmental Panel on Climate Change
L	Litter
LULUCF	Land use, land-use change and forestry
MRV	Measurement, reporting and verification
N	Nitrogen
NDC	Nationally determined contribution
NF	Non-forest
NFI	National forest inventory
REDD+	Reducing emissions from deforestation, reducing emissions from forest degradation, conservation of forest carbon stocks, sustainable management of forests, and the enhancement of forest carbon stocks
SOM	Soil organic matter
UNFCCC	United National Framework Convention on Climate Change
WG	Working Group

1. Introduction: Objectives of the Study

Countries agreed at the 21st Conference of Parties (COP21) of the United Nations Framework Convention on Climate Change (UNFCCC) in Paris in December 2015 on a number of climate change mitigation goals: to hold the increase in global average temperature to well below 2°C, to reach global peaking of greenhouse gas (GHG) emissions as soon as possible, and to achieve a balance between anthropogenic emissions and removals in the second half of this century. These goals will require a significant contribution from forests[3][4]—not only through reducing deforestation in the tropics, but also by maintaining and increasing the global sink capacity of forests, including through increasing forest area, improved forest management, restoring degraded forest lands, and improved use of wood products.

GHG exchanges between the land and the atmosphere are generated by anthropogenic and natural processes. For the land sector, national GHG inventories (GHGIs) are intended to focus on *anthropogenic* emissions and removals rather than non-anthropogenic GHG exchanges between the land and the atmosphere. Thereby GHGIs seek to capture the impact of human actions on atmospheric GHG concentrations, as a basis for quantifying the human induced mitigation potential of each country, and allow the tracking of mitigation achieved through policies and measures implemented. In the context of the Paris Agreement, national GHGIs are critical for providing transparency on progress toward achieving nationally determined contributions (NDCs).

While national GHGIs should include all anthropogenic emissions and removals, in practice they are not necessarily complete. Developed countries report and are reviewed annually, and have relatively complete GHGIs; however, developing countries have historically reported much less frequently, and in less detail, and their reports historically have not been subject to expert assessments. However, the operationalization of Biennial Update Report[5] (BUR) requirements and the International Consultation and Analysis[6] (ICA) process, plus the increasing interest in REDD+, are beginning to produce more frequent reporting by developing countries and, over time, the external analysis and assessments are expected to help improve the GHGIs.

Some fluxes that can be affected by indirect impacts of human activities e.g. permafrost thaw, CO_2 fertilization and nitrogen deposition, temperature variations or droughts may not be fully captured by, or included in, GHGIs. This may be because they are not well understood scientifically, occur on "unmanaged" land (see section 2.2), or because the use in GHGIs of parameters based on historical data will not (until they are updated or periodically recalibrated) capture dependence on changing climate and environmental conditions, such as greater atmospheric CO_2 concentration.

In addition to national GHGI reporting, there is a growing body of independent research produced by the scientific community that seeks to quantify GHG fluxes from forests. These include studies of land cover change and fire; forest carbon densities; global models that estimate emissions and removals by combining satellite and ground data; and studies that estimate the impact of fertilization and other components of the terrestrial carbon budget.

[3] Houghton et al, A role for tropical forests in stabilizing atmospheric CO_2, Nature Climate Change, December 2015.
[4] IPCC, 2014: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, page 151.
[5] In 2010, Parties to the UNFCCC decided that developing countries should submit BURs containing updates of national GHGIs every two years and National Communications every four years. In 2012 the COP adopted guidelines for the BURs and decided that non-Annex I Parties should submit their first BUR by December 2014; as of May 2016, 32 have done so. For more information on BURs, see: http://unfccc.int/national_reports/non-annex_i_parties/biennial_update_reports/items/9186.php
[6] Also in 2010, Parties decided to conduct international consultation and analysis (ICA) of BURs; the modalities and guidelines were adopted the following year and include a technical analysis of each BUR by a team of technical experts. As if May 2016, 22 countries have undergone the technical analysis. For more information on the ICA process, see: http://unfccc.int/national_reports/non-annex_i_parties/ica/items/8621.php

This assessment seeks to:

d) Clarify what forest-related emissions and removals are (and are not) included in national reporting, in particular through GHGIs;
e) Compare national reporting to independent scientific studies, and provide an explanation of why and how they differ;
f) Provide recommendations on how additional transparency could improve understanding of the role of forests in the global carbon budget.

This study should be considered as a first step towards a better collective understanding of the forest-related information available to assess progress toward delivering on the goals of the Paris Agreement, as well as potential improvements in country-level reporting.

2. National GHG inventory reporting

2.1. The context and objectives of national reports

The ultimate objective of the UNFCCC is to *stabilize GHG concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system* (UNFCCC Article 2). Reporting requirements of the UNFCCC aim to provide the Conference of the Parties with information to *assess the overall effects of the measures taken [by each Party] pursuant to the Convention … as well as their cumulative impacts and the extent to which progress towards the objective of the Convention is being achieved* (UNFCCC Article 7).

More recently, the Paris Agreement established a transparency framework (Article 13) whose objectives are to *build mutual trust and confidence and to promote effective implementation* and *to provide a clear understanding of climate change action* and *to provide a clear understanding of climate change action* including *clarity and tracking of countries' progress towards achieving their nationally determined contributions* (NDCs), and to inform the global stocktaking. Under the framework, countries regularly provide national GHG inventory reports, prepared using good practice methodologies accepted by the Intergovernmental Panel on Climate Change (IPCC) and agreed upon by the Conference of the Parties serving as the meeting of the Parties to the Paris Agreement. Therefore Parties report to the UNFCCC (not the IPCC), but to do this, they are required to use methodological guidelines that IPCC has developed for this purpose.

The Paris Agreement's Global Stocktake

The Paris Agreement creates a process through Article 14 to take stock periodically of the implementation of the Agreement and to assess the collective progress towards achieving its objectives, which include holding the increase in global temperature to well below 2^{o}C (Article 2), reach global peaking as soon as possible, and achieve a balance between anthropogenic sources and removals by sinks in the second half of this century (Article 4). It states that this should be done in light of the best available science. The first official stocktake will be in 2023 and every 5 years thereafter, with a first 'facilitative dialogue' to take place in 2018, informed by a Special IPCC report on the assessment of impacts of a 1.5C rise in global warming and related global greenhouse gas emission pathways.

All signatories to the UNFCCC (197 Parties have ratified the Convention, including 196 countries plus the European Union) are required to report greenhouse gas (GHG) emissions and removals through submission of national GHG inventories (GHGI). As just identified, GHGIs are produced using methodologies provided by the

IPCC. These inventory methodologies were produced in 1996 with important updates in 2000, 2003, 2006 and 2013[7]. They are developed and extensively reviewed by international scientists and government experts.

All countries are requested by the UNFCCC to submit National Communications reports (which contain GHGI information) every four years, and developed countries in addition are requested to submit *annual* GHGIs. More recently (in 2012), the Conference of the Parties (COP) decided that developing countries (with flexibility for Least Developed Countries) should submit GHGI information every two years as part of their BURs. GHGIs cover a range of economic sectors (e.g. energy, industrial processes, agriculture and land use, and waste).This report focuses on emissions and removals from forests, which is part of the land use sector.

Although capacity for estimating forest fluxes is uneven among countries and this can create variable coverage within national GHGIs, the IPCC Guidelines do allow countries to start with more simple methods using default factors (Tier 1) and continue to improve by developing country specific factors (Tier 2) or to use modeling approaches (Tier 3) as they improve and more accurately report all anthropogenic emissions and removals.

The scope of national GHGIs is to estimate anthropogenic emissions and removals. Inclusion of non-anthropogenic sources of emissions and removals in GHGIs would complicate the assessment of net emission reductions achieved by mitigation actions and the quantification of emissions and removals associated with policies and measures. However, available science does not allow for full separation between anthropogenic and non-anthropogenic emissions by sources and removals by sinks in the land use sector, which has led the IPCC to adopt (in its Guidelines for national GHGIs) the managed land proxy.

2.2. The managed land proxy

IPCC Guidelines for national GHGIs apply a concept called the *managed land proxy* as a first order separation of anthropogenic and non-anthropogenic emissions and removals. *The key rationale for this approach is that the preponderance of anthropogenic effects occurs on managed lands.* This proxy was introduced to overcome the challenge of providing a practicable and broadly applicable methodology to separate direct human-induced effects from indirect human-induced and natural effects. According to the IPCC Guidelines, managed land is *land where human interventions and practices have been applied to perform production, ecological or social functions. All land definitions and classifications should be specified at the national level, described in a transparent manner, and be applied consistently over time*[8]. The IPCC revisited the managed land proxy at an expert meeting in 2009 which noted that whilst work on alternatives should continue, *the managed land proxy is currently the only widely applicable method to estimate the separation between anthropogenic and natural fluxes.*[9]

Consequently, GHGIs do not include the estimate of GHG fluxes from areas that countries designate as "unmanaged." Once human intervention occurs in an unmanaged land and results in anthropogenic GHG fluxes,

[7] There are IPCC Guidelines and Good Practice Guidance for National GHG Inventories; from here on in the report we simply refer to "IPCC Guidelines".
[8] See Vol 4, chapter 1, page 1.4 of the IPCC 2006 Guidelines for National Greenhouse Gas Inventories.
[9] See http://www.ipcc-nggip.iges.or.jp/public/mtdocs/pdffiles/0905_MLP_Report.pdf, according to which *While several concerns and deficiencies of the managed land proxy were identified, none of the alternatives considered at the meeting proved to be sufficiently well developed (for all Tier levels required) to justify an IPCC recommendation for change in the default estimation approach, thus the meeting concluded that the managed land proxy is currently the only widely applicable method to estimate the separation between anthropogenic and natural fluxes. Participants also recognised that with increasing impacts of climate change (an indirect human-induced cause) the managed land proxy could in the future include an increasing proportion of natural and indirect human contributions to the reported emissions and removals. Therefore work needs to continue to identify and test approaches to separating (factoring-out) anthropogenic impacts from others. The meeting briefly reviewed a number of proposed alternatives to the managed land proxy and considered they still needed further development before they can be assessed for use by the IPCC. These methods need to be reviewed with regard to their methodological implications, data requirements and compatibility with the inventory principles.*

the land should be thereafter considered a managed land[10]. Comparison between GHGI and independent scientific studies for countries with significant unmanaged forest area need to take this into account. Table 1 shows which of the top ten countries by forest area have distinguished between managed and unmanaged forest.

Table 1: Managed and Unmanaged Lands in top 10 forested countries and the EU by area

Country	Total forest area as reported in GHGI (M ha)	Forest area considered managed (M ha)	% Unmanaged
Russia (CRF, 2015)	778	664	15%
Brazil[1]	512	380	26%
Canada (NIR, 2015)	348	232	33%
United States (NIR, 2015)	302	293	3%
China (NC, 2012)	195	195[2]	0%
European Union	165	161	2%
DRC (3rd NC, 2015)	150	150[2]	0%
Australia (CRF, 2015)	103	103	0%
Indonesia (BUR, 2016)	Area estimates not provided		
Peru (3rd NC, 2016)	74	49	34%
India (BUR, 2015)	70	70[2]	0%

[1] Brazil reports emissions from forest loss for all lands and, when loss occurs, assumes it to be anthropogenic and therefore is categorized as managed; removals from forests that remain as forests are only reported from secondary forests and from other forests on managed land (defined as indigenous lands and lands included in the National System of Protected Areas).
[2] Many developing countries, including China, DRC, India and Indonesia do not refer to either managed or unmanaged land in their National Communications and appear to imply all forests are included in the reporting.

Specific emissions and removals related to forests that would be excluded from a GHGI *to the extent that they occur on unmanaged* land include:

c) **Carbon removals**, such as carbon sequestration from forest growth and re-growth after disturbance, sequestration from new forest expansion due to climate change-induced treeline shifts; fertilization effects due to increased atmospheric CO_2 or atmospheric N deposition; and accumulation of carbon in dead organic matter (e.g. organic matter in peat soil, black carbon from fire);

d) **GHG emissions,** including from wildfires and other disturbances (such as pest outbreaks), mortality caused by climate change and associated impacts on peat lands from permafrost thaw.

These emissions and removals can be potentially significant, and may explain some of the apparent disparities between GHG reporting to the UNFCCC and independent scientific studies (see Section 3). Several examples of emissions and removals on unmanaged lands are included in Table 2 below.

[10] For example, deforestation (but not temporary forest loss due to natural disturbances such as fire and flooding) occurring in unmanaged land is mostly direct human-induced and therefore should be captured in GHGI reporting.

Table 2: Examples of emissions and removals on unmanaged lands

Country examples	Canada	Canada does not include in its GHGI emissions from fires on unmanaged land, which data for 2001 to 2011 suggest accounts for 42 to 76% of total area affected by fires (see Case Studies: Canada, Section X.X); using an average 132 tCO_2e/ha[11] suggests emissions of around **43 to 254 $MtCO_2e/yr$** in unmanaged areas during this time period. Removals from expected regrowth following such disturbances on unmanaged lands are also not included in the GHGI.
	Russia	Kurgova et al, 2010[12] estimate an annual sink of **-0.4 Gt CO_2eq** (in the SOM pool of abandoned agricultural land under natural conversion to forest) which Russia considers as unmanaged forest[13].
	Brazil	Brazil's BUR suggests that gross forest-cover loss is detected (and reported) for *all* lands. Removals are estimated from all secondary forests, as well as, from primary forests on managed lands; Brazil's BUR suggests that the potential sink associated with carbon stock accumulation on unmanaged forest land caused by N and CO_2 fertilization effect is excluded.
Regional examples	Canada, Russia and the US	GHG fluxes from peatlands that are considered unmanaged are likely significant; currently they are a net sink and may help explain a portion of the "missing sink" (see Section 3.2). However, with a warming climate, these areas may turn to a source if water levels decrease (due to higher evaporation or lower precipitation) or permafrost thaws[14], or may increase their sink capacity from a longer growth season or fertilization effects (N or CO_2)[15]
	Unmanaged Boreal and temperate forests	According to Luyssaert et al[16] these forests sequester about -1.3 + 0.5 Gt of C per year. The authors indicate that over 30 percent of global forest area is unmanaged[17] primary forest and contains the remaining old growth forests. Half of the primary forests (covering 600 million ha) are located in boreal (near the Arctic) and temperate regions in the Northern Hemisphere. Some these areas are likely to be included in the GHGIs as for instance the forest areas under conservation.
	Unmanaged tropical forests	One report[18] estimates the sink of "intact" tropical forest at 1.19 Gt C. It is not straightforward, to compare this with forest area reported as unmanaged in GHGIs, as the application of the managed land proxy may not correspond to the same areas considered intact even though it is likely that most of the intact forest is not subject to direct anthropogenic impacts.

[11] This figure is from Canada's FMRL submission (2011), as the wildfire emission factor used to calculate the "background level of natural disturbance", and is derived from Canada's 2011 NIR.

[12] I.N. Kurganova, V.N. Kudeyarov andV.O. Lopes De Gerenyu, 2010. Updated estimate of carbon balance on Russian territory. Tellus, Volume 62, Issue 5, pages 497–505, November 2010

[13] Because such forest expansion occurs on unmanaged land, the GHGI inventory does not report associated emissions and removals although it reports the area subject to this expansion.

[14] Swindles, G. T. et al. The long-term fate of permafrost peatlands under rapid climate warming. Sci. Rep. 5, 17951; doi: 10.1038/srep17951 (2015) http://www.nature.com/articles/srep17951. In such paper the authors report a reduction in carbon accumulation (i.e. a GHG source) in peatlands on permafrost that is subsequently followed by a new phase of carbon accumulation after the peat bog collapses and is transformed in a arctic fen with thaw pools

[15] Charman, D. J. et al. Drivers of Holocene peatland carbon accumulation across a climate gradient in northeastern North America. Quaternary Science Reviews Volume 121, 1 August 2015, Pages 110–119. doi:10.1016/j.quascirev.2015.05.012. http://www.sciencedirect.com/science/article/pii/S0277379115002115

[16] Luyssaert S, Schulze E-D, Bőrner A, Knohl A, Hessenmőller D, Law BE, Ciais P and Grace J. Old-growth forests as global carbon sinks. Nature 2008, 455, 213-5.

[17] For Luyssaert et al the term unmanaged means forest not subject to any commercial exploitation activity, which does not coincide with the IPCC definition if the country includes forest management activities other than commercial exploitation to qualify land as managed (e.g. protected areas). Since most of the areas indicated by Luyssaert occur in Canada, Russia and United States, the area reported by the countries as unmanaged forests is probably a subset of the unmanaged area of Luyssaet.

[18] Global Forest Monitoring from Earth Observation. Edited by Frederic Achard and Matthew C. Hansen; 2012 - Role of Forests and Impact of Deforestation in the Global Carbon Cycle, Richard A. Houghton.

Large differences in reported fluxes may arise if land which is remote (and therefore not subject to significant human intervention) is treated in the same way as land that is subject to significant intervention. For example, the DRC's GHGI does not separate out unmanaged lands, but it includes gross removals of -322 and -205 million tCO_2e/yr in approximately 160 million ha in 2000 and 2010. A significant increment factor for regrowth seems to have been applied, although much of these large areas are inaccessible and should therefore have been treated as unmanaged lands (where forests are largely in equilibrium and the use of increment factors is inappropriate).

2.3. GHGI capacity in developed and developing countries

Generally speaking, all 43 Annex I (developed) countries have provided national GHGI reports annually from 2003 to 2015, have submitted National Communications every four years (i.e. six such reports from each country), and two biennial reports to date (2014 and 2016). They are reviewed by technical experts coordinated by the UNFCCC, and the review reports are published on the UNFCCC website.

In 2010 the COP decided[19] that non-Annex I (developing) countries are to submit National Communication reports every four years (taking into account flexibility for Least Developed Countries) and Biennial Update Reports every two years. As of May 2016, most developing countries have submitted two national communications (since entering the UNFCCC in the 1990s), including several large forest countries such as Bolivia, Colombia, the Democratic Republic of Congo, India, and Indonesia. Twenty-two out of 153 developing countries have submitted three reports (including Brazil and Peru) and only Mexico has submitted a 4th and 5th report. As of May 2016, 32 non-Annex I countries, or about one-fifth of developing countries, have submitted their first BUR—this includes large forest countries such as Brazil, Colombia, India, Indonesia, and Peru.

Table 3: Number of National Communications by Developing Countries[20]

Submitted Report	No. of Developing countries
Initial National Communications	147
Second National Communications	122
Third National Communications	22
Fourth National Communications	1
Fifth National Communications	1

For most developed countries (and some developing countries), data reported on forests are generated by well-established national systems (often designed for reasons other than measuring carbon fluxes) that typically employ technical experts and researchers within government departments or agencies. Their national forest monitoring systems collect data regularly as part of national statistical processes.

For developing countries, capacity has historically been very uneven. GHGIs have often been compiled by external consultants without necessarily generating lasting capacity. Also, GHGI compilation has not benefitted from sustained feedback through international reviews. By contrast developed countries report annual GHGI to the UNFCCC and therefore typically set up dedicated teams for this task that have been working for many years through iterative improvements and drawing on an international review process.

[19] See Decision 1/CP.16 para 60.
[20] Countries are continuously submitting National Communications; the tallies are as of May 11, 2016 and taken from: http://unfccc.int/national_reports/non-annex_i_natcom/submitted_natcom/items/653.php

As a consequence, many developing countries' GHGI have shown technical shortcomings that can lead to significant errors and/or omissions in estimating GHG fluxes. Further, data sources and methodologies may not be well documented and definitions may be applied inconsistently across time and across data sources. The situation is changing—for example, the robustness of several developing countries' GHGIs (e.g. Brazil, Chile) can be considered as well within the range of Annex I GHGIs.

Developing countries have recently committed to regular GHGI reporting, through the BURs, and begun to develop capacities with encouraging early results. One recent study[21] explored MRV capacity development across 12 countries and concluded that significant progress could be observed, providing reassurance regarding the soundness of development agencies' significant investments in MRV. Another study[22] explored progress in 99 countries over the last ten years and found that good or very good forest area change monitoring had increased from 69% to 83%. Similarly, diffusion of good to very good forest inventory capacities had increased from 38% to 66%. Much of the observed progress may be driven by increased donor support in the REDD+ context and the same level of progress does not necessarily apply to other parts of the GHGI.

2.4. Completeness of reporting

Within managed lands, all emissions and removals related to forests should be reported by countries. However, there are instances where anthropogenic forest-related GHG fluxes on managed lands may be missing from currently reported GHGI data. This is particularly true for those developing countries that lack capacity to report on all emissions and removals. The sub-sections below analyze areas where GHGI reporting currently tends to be incomplete.

2.4.1. Reporting on forest-related categories

Forest-related emissions and removals are estimated and reported in GHGIs in the following categories[23]: (a) Forest land to Non-Forest land (F→NF), such as F→Cropland, or F→Grassland; (b) Non-Forest land to Forest land (NF→F); and (c) Forest land remaining Forest land (F→F). National reports are not always comprehensive in reporting these categories.

Table 4: Number of countries reporting on forest-related transitions, based on country reports to UNFCCC

	F→F	F→NF	NF→F
Annex I[1] (41)	41	36[2]	37[3]
Non-Annex I (153)			
≈ 20 non-Annex I forest countries analyzed – listed below[4]	≈15	19[5]	≈14
other Non-Annex I	60% still use IPCC 1996 Guidelines which does not classify transitions in this way – see text		

[21] *Assessing progress in MRV capacity development: experience with a scorecard approach*. Neeff T, Somogyi Z, Schultheis C, Mertens E, Rock J, Brötz J, Dunger K, Oehmichen K, Federici S (in press, available online). Climate Policy.
[22] *Assessing change in national forest monitoring capacities of 99 tropical Countries*, Erika Romijn, Celso B. Lantican, Martin Herold, Erik Lindquist, Robert Ochieng, Arief Wijaya, Daniel Murdiyarso, Louis Verchot. Forest Ecology and Management, 352 (2015) 109–123.
[23] According to approaches 2 and 3 of the more recent version of the IPCC Guidelines and Good Practice Guidance.

[1]Annex I excluding Malta (with negligible forest) and Monaco (with no forest) and including Kazakhstan; information from 2015 GHGI submissions to UNFCCC (for the year 2013), except few countries (Belarus, Canada, Switzerland and USA, from GHGI 2014, for the year 2012)
[2]Not reporting: Belarus, Cyprus, Kazakhstan, Lithuania, Turkey; the United States includes only soil emissions, with the other pools of F→NF included F→F category
[3]Not reporting: Belarus, Cyprus, Kazakhstan, United States; however, the United States includes estimates for NF→F in the F→F category
[4]Information from National Communications and BURs; countries analyzed to approximate reporting of developing countries includes: Brazil, Indonesia, DRC, Bolivia, Mexico, Colombia, Argentina, Angola, Peru, Myanmar, Venezuela, Mozambique, Thailand, India, Paraguay, China, Madagascar, Cambodia, Vietnam, Laos; information is from National Communications, BURs, INDCs, or REDD+ Reference Level (FREL) submissions. These countries were selected based on a combination of top countries in terms of forest cover and countries where enough information was available.
[5]Not clearly reporting: India

Completeness varies between developed and developing countries. For Annex I the reporting is almost complete, except in few countries (including Belarus, Kazakhstan and Turkey) due to lack of activity data. In the case of the United States' GHGI an important transparency issue is that almost all carbon stock changes from land use change from/to forest are reported within the category F→F[24].

For the 20 non-annex I forest countries analyzed, reporting appears almost complete for deforestation (F→NF), although the quality of reporting is still being established via the International Consultation and Analysis process). The greatest uncertainties are likely to be related not to deforestation, but to forest remaining forest and to the identification and quantification of complex forest dynamics (e.g. forest regrowth, shifting cultivation). Another source of uncertainty is the use of the IPCC 1996 Guidelines (by some of these 20 countries), which does not allow an unequivocal classification of areas in the three forest transitions of table X[25], unless additional information is provided. To enhance transparency of future reported information, the use of more recent IPCC Guidelines (or at least 2003 Good Practice Guidance) is encouraged, consistent with Annex III to decision 2/CP.17.

Forest degradation is generally understood to be a decrease in carbon stocks in forests across time without a corresponding land use change; for example, a conversion of primary forest to secondary forest in land remaining in forest land use[26], or natural forest to forest plantations[27], or an increase in wood harvesting rates in managed (secondary or planted) forest. It may be a significant source of net emissions, particularly in developing countries[28], but is not always well estimated or reported in GHGIs as part of forest remaining forest.

Even though it may appear that countries report on "forests remaining forests" (per Table X), many developing countries do not have sufficient data to provide robust estimates of the actual net C stock balance, and consequently on whether processes leading to long-term decline in carbon stocks are occurring in forest remaining forest. While many developed countries have repeated national forest inventory (NFI) cycles that allow for quantified estimates of net decreases across time of carbon stocks in forest land, many developing countries have difficulties and not necessarily the resources needed to conduct repeated NFIs, and therefore data are often unavailable. Such time series data are necessary to estimate forest degradation, unless a country

[24] The United States intends to separate out such categories over time; its draft 2016 GHGI begins to do so, reporting NF→F separately.
[25] The IPCC 1996 Guidelines includes the following categories: 5A Change in Forest and Other Woody Biomass Stocks (which includes F→F or NF→F, although limited to forest plantations, as well as emissions and removals from other wooded lands that do not meet the forest definition); 5B Forest and Grassland Conversion (which may be assumed to be dominated by deforestation); 5C Abandonment of Managed Land (which may reflect more or less anthropogenic NF→F, also as natural forest expansion on previously managed lands).
[26] Primary forests are naturally regenerated forests of native species, where there are no clearly visible indications of human activities and the ecological processes are not significantly disturbed. Where there are clear visible indications of human activities, naturally regenerating forests are considered secondary forests. Secondary forests have a long run average C stock lower than primary forests.
[27] Planted forests often have a long run average C stock lower than natural forests.
[28] FAO's Forest Resource Assessment shows that degradation (defined as a net C stock loss across a 5 year period) largely occurs in developing countries.

has adequate management data, e.g. information on primary, secondary, and planted forests for disturbances and changes in the disturbances regime, legal and illegal logging rates and changes in such rates, as well as estimates of the age class distribution, or the biomass density distribution, and of annual net increment rates, and changes in such rates.

Degradation is a REDD+ activity but is less widely covered than deforestation in reference level submissions. For example, while Brazil, Paraguay and Peru reported on the F→F category in the GHGIs, in their REDD+ Reference Emission Level (FREL) submission, these countries currently exclude degradation, suggesting they are currently unable to provide what they consider to be sufficiently robust estimates of historical or actual degradation at this time. A number of countries are beginning to experiment with different options to measure net emissions from degradation typically using high resolution remote sensors or proxies based on drivers, but this remains an emerging field—driven in large part by countries pursuing REDD+ programs. In 2014 GFOI, GOFC-GOLD and ESA held a workshop on approaches to monitoring forest degradation for REDD+[29] which reviewed the techniques available.

Unless the necessary data streams are in place, countries' GHGIs also often give relatively little attention to estimating carbon removals from forest regrowth[30]. Per unit area, forest regrowth has much slower impact on the annual carbon balance than deforestation or most kinds of forest degradation and it may therefore be less of a focus in GHGI design. However, while forests regrow gradually, possibly over many years, the accumulated removals of the total area regenerating at any time may be significant[31].

The lack of information and knowledge on regrowth is, perhaps, best illustrated by submissions of REDD+ FRELs. Nearly all focus on deforestation (typically based on gross loss of forest cover). A few include forest degradation (largely focused on estimating gross carbon loss from timber harvesting only). Hardly any consider growth (F→F) or regrowth (NF→F). Ignoring regrowth, however, may overestimate the net emissions that result from forest cover loss by classifying all cleared lands as deforested (i.e. with permanent loss of forest cover). In most countries at least some cleared areas are eventually fallowed, enabling forest regrowth. In their respective REDD+ FREL submissions, Brazil and Indonesia have both applied an estimate of 'gross deforestation' that corresponds to a gross forest cover loss and currently disregard any forest regrowth that may occur after the forest clearance events. And while some of that regrowth may be eventually cleared, or cycle back and forth between field and forest, the long run-averaged carbon content of such areas would nevertheless be higher than assumed in a calculation of gross deforestation emissions.

2.4.2. Reporting on C Pools

Another reason countries may not report completely in their national GHGIs is the omission of certain carbon pools. IPCC Guidelines require national GHGIs to report on significant emissions or removals from five pools: aboveground biomass (AGB), belowground biomass (BGB), deadwood, litter[32], and soil organic matter (SOM). Harvested wood products compose an additional, man-made, pool. National reporting and independent scientific studies normally include biomass pools; other pools are included to varying degrees. The IPCC Guidelines provide methods to estimate all pools, including default factors[33], and therefore country reporting should be comprehensive. However, in practice not all countries report comprehensively (see Table 5).

[29] See http://www.gfoi.org/wp-content/uploads/2015/03/GFOI-GOFCGOLD_RDExpertWS2_Report.pdf
[30] Throughout the paper the term "regrowth" refers to both carbon accumulation in F→F and NF→F.
[31] Furthermore, the rates of CO_2 accumulation may be quite high in the initial decade or two of regrowth, e.g. Poorter et al. 2015 (http://www.nature.com/doifinder/10.1038/nature16512). Also, the area covered may be very large, as illustrated by Brazil's TerraClass data on regrowth of deforested areas in the Amazon (http://www.inpe.br/cra/projetos_pesquisas/terraclass2014.php).
[32] Dead wood and litter are often grouped together in a C pool named: dead organic matter (DOM), reducing the number of carbon pools to four.
[33] Noting that under default assumptions dead wood and litter, as well as SOM in mineral soils, are assumed not to change for forest remaining forest.

Especially for developing countries that do not have regular NFI cycles, the data on some pools may be old or non-existent. Deadwood, litter, and soil, in particular, are pools that are not as well reported as others, and often the net C stock change is assumed to be insignificant or, consistent with methodologies in IPCC Guidelines (at Tier 1 level), such pools may be assumed to have no net C stock changes in F→F.

Table 5: Coverage of pools in national GHGI reporting, based on country reports to UNFCCC (see Table 4 on forest transitions). Figures in parenthesis are approximate because the pools included are often not explicitly specified.

		Carbon pools			
		Biomass	Dead organic matter	Mineral soil	Organic soil
Annex 1 countries* (41)	F→F	41	25	18	17
	NF→F	37	26	32	15
	F→NF	35	32	33	11
≈ top 20 forest Non-Annex 1		20	(3)	(7)	(2)

*Annex I excluding Malta (with negligible forest) and Monaco (with no forest)

Coverage of pools is more complete for Annex 1 countries. The lower coverage of mineral soil in F→F reflects the difficulty to estimate detectable soil C stock changes in this category. Organic soils are less reported than other pools because significant areas may not exist in some countries. For non-Annex 1 countries, the situation is much less certain: beyond biomass, it is often unclear which pools are included. Based on information collected, most non-Annex 1 countries do not report non-biomass pools. The harvested wood product (HWP) pool is now reported by the vast majority of Annex I countries through IPCC default or country-specific decay rates, while all non-Annex I countries apply a default assumption that all carbon biomass harvested is oxidized in the removal (harvest) year[34].

The table below summarizes the potential impact of excluded pools on deforestation flux estimates compared to the case where only AGB is estimated. For more information on how the impacts were estimated, see the Supplementary Information.

Table 6: Maximum potential scale of missing carbon pools compared to C stock losses from the aboveground biomass pool for deforestation estimates

Missing pool	**Potential impact on quantified estimate**	**Comment**
BGB	Up to 35% of biomass	If the full carbon content of BGB is assumed to be released to the atmosphere with deforestation, IPCC root-to-shoot ratios suggest that the resulting quantification of emissions could increase by 20% to 55% depending on the ecosystem—for tropical rain forests a representative value for the root-to shoot ratio is 0.37, and tropical dry forests, can have a value as high as 0.56.
DW and L	Up to 100% of biomass	C stocks in DW and L in boreal forests can be of the same magnitude as AGB C stock, and may be released to the atmosphere similarly to AGB depending on the type of disturbance. In temperate and tropical forests, the importance of DW and L is smaller. Overall, in Annex I countries DW and L represent on

[34] The 1996 IPCC Guidelines (Vol. III, p.5.17, Box 5).

		average about 15% of the total sink in F→F and NF→F and 35% of total emissions in F→NF
SOM in mineral soils	Large variability (however, according to IPCC default methods it may be around 10% across the entire conversion process[35])	Need more consistent data on carbon stocks of soils, and on soil carbon *changes* with land use transitions. In Annex I countries mineral soils represent on average about 5-10% of the total flux in the various forest transitions, but this contribution varies considerably among countries being larger in tropical countries.
Organic soils	From 30-40[36]%	Emissions/removals from organic soils occur across long time periods, so that their exclusion may have a relatively small impact on the annual[37] GHG balance of a specific unit of land deforested). Impact is highest in tropical moist deep drained land, and will be increased by fire.

2.4.3. Reporting on gases

National GHG inventories are required to report on all GHGs (CO_2, CH_4 and N_2O). The main source of non-CO_2 emissions from forests is fire[38]: in Annex 1 countries, where the reporting of forest fires may be considered complete for the vast majority of countries, non-CO_2 represent about 10-12% of total CO_2-equivalent fire emissions. Relative to the total forest fluxes, the importance of non-CO_2 GHG is smaller, i.e. in Annex 1 countries, non-CO_2 represent about 2-3% of total CO_2-equivalent forest sink, with country differences mainly explained by the relative importance of fires. Therefore, CO_2 represents the vast majority of forest-related net emissions.

In non-Annex 1 countries the situation is less clear. The vast majority of countries do not report specific information on non-CO_2 gases, and in this case it can be assumed that only CO_2 is reported from fire (e.g. fire often occurs as part of a land use change, e.g. F→NF, and the loss in biomass reported). Only a few countries (including Brazil, India, Indonesia, DRC) explicitly include non-CO_2 emission from fires, although for the same country the coverage sometimes differs for different reports (e.g. Brazil reports all GHG in the National Communication, but only CO_2 in the REDD+ FREL; Indonesia reports all GHG in the second national Communication, but only CO_2 in the BUR and its REDD+ FREL). As explained above, the omission of non-CO_2 GHG is relevant only where forest fires are important in the overall GHG budget.

2.4.4. Other processes that may not be reported

There may be other carbon stock change processes that are not included in national GHGI reports. Below are short summaries of these potential additional gaps that may occur in national reporting. More detailed discussions of each of the topics below are included in the Supplementary Information document.

Legacy: The term legacy refers to emissions/removals (CO_2, and for SOM also N_2O) occurring in years subsequent to a disturbance that has caused an abrupt change in C stocks (e.g. accumulation of DOM stocks due to pest, or of HWP due to harvesting) or a change in management/disturbance regime that determines an increase of the long run average C stock (e.g. by extending the harvesting cycle) of the forest. Legacy emissions/removals would be constant across time under a constant level of management and background level of disturbance. In these cases, estimating emissions by assuming instantaneous oxidation of C losses would yield

[35] IPCC default establishes a conversion period of 20 years.
[36] Calculated summing up annual net GHG fluxes reported in Chapter 2 of the 2013 IPCC Wetlands Supplements for Boreal and Tropical forests and compared to the ABG stock reported for boreal and tropical forest in table 4.12 of Volume 4 of the 2006 IPCC Guidelines
[37] However, across time and across the entire country, depending on the total area of forested and deforested land drained, the GHG flux may be an order of magnitude larger than that of the AGB.
[38] In the case of fuelwood, carbon stored in biomass is reported as harvest loss and non-CO_2 gases from burning are reported under energy in the GHGI.

the same annual emissions/removals as explicit consideration of legacy effects. However, in practice these assumptions are unlikely to occur and legacy effects will need to be taken into account to estimate emissions, removals and carbon stocks over a given time period, since these may differ significantly from the long run average. Legacy in emissions is likely to be more relevant in forests where decay and accumulation processes are slower, as in boreal forests. For instance, Canada reports that legacy emissions offset 90-94% of the net increment. The temporal dynamics linked to legacy effects can be better represented by more detailed modeling and methodologies, such as IPCC Tier 3 methodological levels[39]. Long time series of data (as long as the effect of the disturbance or of the change in management or disturbance regime) are needed to properly estimate legacy emissions/removals. For such reason many Annex I Parties' GHGIs are prepared from datasets that contain data from the 1970s. The relative shortage of historical data in developing countries makes a proper quantification of legacy emissions/removals challenging and may have an impact on the level, but possibly also on the trends, of reported GHG emissions/removals.

Age class: Age class is a type of legacy effect and refers to when disturbances or management at the landscape or stand level cause a loss of biomass with a rejuvenation of individual trees all at about the same age and an abrupt accumulation of C stocks in the dead organic matter pools (i.e. DOM, SOM, and HWP) which then decay. If left undisturbed, the landscape equilibrium will eventually be re-established; however, there will for some time be a perturbation in the level of stocks and emissions and removals. If the forest is repeatedly harvested there may never be equilibrium over any given period although there will be an average level of carbon storage in the forest landscape. Assumptions made about the effect of age class on GHG fluxes, or the methodology used to calculate the C stock changes (e.g. constant factors *versus* the use of models that calculate C stock changes on the basis of annual data inputs) can result in significant differences in estimates of emissions and removals, particularly in terms of timing—when fluxes actually occur versus when they would be reported, and also in terms of total amount if conditions change over time. In general, developed country GHGIs largely capture the impacts of age class, whereas many GHGIs of developing countries do not. Global studies tend not to consider, or not fully consider, the impact of age class distribution because of the absence of a global dataset—although the Hansen et al. (2013) dataset, visualized on the Global Forest Watch (GFW) web platform, may in the future provide relevant data when the time series is long enough to reconstruct tree cover removal and regrowth dynamics of forest land.

CO_2 fertilization: Increasing atmospheric CO_2 can increase C uptake, and possibly long run C stocks, but the magnitude and the spatial distribution of these impacts are still debated[40]. National inventory reports may include fertilization effects if they use a stock difference method (i.e. comparing direct measurements of forest carbon stock from two different points in time). Other methods to estimate removals often use standardized yield tables that do not include the possible impact of CO_2 fertilization, thereby potentially underestimating growth while others may use models that predict CO_2 fertilization effects. In either case, however the expected magnitude is likely small in comparison to the level of uncertainties related to data itself.

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[39] As defined by the IPCC Guidelines, Tier 3 methodological levels use higher order methods, including models and inventory measurement systems tailored to address national circumstances, repeated over time, and driven by high-resolution activity data and disaggregated at sub-national level. These higher order methods provide estimates of greater certainty than lower tiers. Such systems may include comprehensive field sampling repeated at regular time intervals and/or GIS-based systems of age, class/production data, soils data, and land-use and management activity data, integrating several types of monitoring. Pieces of land where a land-use change occurs can usually be tracked over time, at least statistically. In most cases these systems have a climate dependency, and thus provide source estimates with interannual variability.

[40] Korner, C., Morgan, J., Norby, R., 2007. CO_2 fertilization: when, where, how much? In: Canadell, J.G., Pataki, D., Pitelka, L. (Eds.), Terrestrial Ecosystems in a Changing World. The IGBP Series. Springer-Verlag, Berlin, Heidelberg, pp. 9–21; Morgan, J.A., Pataki, D.E., Korner, C., Clark, H., Del Grosso, S.J., Grunzweig, J.M., Knapp, A.K., Mosier, A.R., Newton, P.C.D.; Niklaus, P.A., Nippert, J.B., Nowak, R.S., Parton, W.J., Polley, M.R., Shaw, M.R., 2004. Water relations in grassland and desert ecosystems exposed to elevated atmospheric CO_2. Oecologia 140, 11–25.

Nitrogen (N) deposition: Improved N bio-availability after deposition of atmospheric N, on its own and interactively with the CO_2 fertilization effect, is an important C sink process in N-limited regions. This N originates from the combustion of fossil fuels, biomass burning or from the volatilization of N from organic or inorganic sources in agricultural N fertilization. The impacts of N fertilization on forests from deposition is probably most important in Europe and the Eastern US because of the large quantities of atmospheric N and and because many of those forests are N limited. Globally, N deposition may have accounted for about -0.19 to -0.25 GtC year^{-1} of the -0.2 to -1.4 Gt C/yr net terrestrial C sink during the 1980s and 1990s[41]. In the future, further enhancement of the terrestrial sink will probably shift away from N fertilization because the expected larger future growth of the CO_2 forcing effect and the negative effects on additional N depositions in regions already N saturated[42]. Some models indicate that temperature effects are likely to overwhelm effects of increased N deposition[43]. However, a recent paper that modelled 68 forest sites' flux data estimated that 19% (+/- 29%) of the observed increases in C sink were due to N deposition effects on biomass, with larger effects in temperate and tropical forest[44].

Permafrost thaw: There is little quantified information on the impacts of permafrost thaw *in forest land* as distinct from all lands, making it difficult to estimate the scale of this process for just forests. With regard to land in general (some of which will include forest land), studies suggest the northern permafrost zone contains anywhere from around 1,500 to 1,700 Gt of carbon[45], one-fifth of which is in peatlands[46]. However, while the IPCC's 5th Assessment Report (AR5)[47] states that there is *high confidence* warming is causing reductions in permafrost extent there is *low confidence* on the magnitude of carbon losses. Schaefer et al (2012) estimate that thawing permafrost could emit 43 to 135 Gt CO_2e by 2100, and 246 to 415 Gt CO_2e by 2200 (as CO_2 and methane emissions). While academic literature suggests a gradual and prolonged release of GHG emissions from permafrost *soils* in a warming climate, permafrost carbon dynamics are poorly understood[48] and the literature is unclear on whether the Arctic is a sink or source with the loss of sea ice, decomposing permafrost and increasing tundra fires if one takes into account increased photosynthetic activity (i.e. increased carbon uptake from new Arctic vegetation[49] and longer growing season) and potential peat accumulation, which may also occur in a warming climate[50].

Black carbon: The continuum of combustion products from vegetation fires such as char, ash, soot and charcoal are commonly referred to as black carbon (BC), and are all resistant to further biological or chemical decay. Hence, BC appears to have a significant half-life, in the order of thousands of years and is thus the most stable biomass-derived material in the biospheric C cycle. It tends to accumulate in soils and other terrestrial and marine sediments and to act as a removal (sink) of carbon from the more rapid bio-atmospheric carbon cycle to

[41] Nadelhoffer, K.J., Emmett, B.A., Gundersen, P., Kjonaas, O.J., Koopmans, C.J., Schleppi, P., Tietema, A., Wright, R.F., 1999. Nitrogen deposition makes a minor contribution to carbon sequestration in temperate forests. Nature 398, 145–148.
Sabine, C.L., Heimann, M., Artaxo, P., Bakker, D.C.E., Chen, C-T.A., Field, C.B., Gruber, N., Le Quere, C., Prinn, R.G., Richey, J.E., Romero, P., Sathaye, J.A., Valentini, R., 2004. Current status of past trends of the global carbon cycle. In: Field, C., Raupach, M. (Eds.), Global Carbon Cycle, Integrating Humans, Climate and the Natural World. Island Press, Washington, D.C., pp. 17–44.
[42] J. G. Canadell · M. Kirschbaum · W. A. Kurz · M.J. Sanz · B. Schlamadinger · and Y. Yamagata. 2007. Factoring out natural and indirect human effects on terrestrial carbon sources and sinks. Environmental Science & Policy, 10: 370–384
[43] G. Bala, N. Devaraju, R. K. Chaturvedi, K. Caldeira, and R. Nemani. 2013. Nitrogen deposition: how important is it for global terrestrial carbon uptake? Biogeosciences, 10, 7147–7160.
[44] Fleischer, K., et al. (2015), Low historical nitrogen deposition effect on carbon sequestration in the boreal zone, J. Geophys. Res. Biogeosci., 120, 2542–2561
[45] UNEP: *Policy Implications of Warming Permafrost* by Schaefer et al (2012); Swindles, G. T. et al. 2015; Schurr et al 2015; Tarnocai et al 2009
[46] Swindles, G. T. et al. 2015
[47] Chapter 6, section 6.4.3.4 (page 526) and FAQ 6.1 "Could Rapid Release of Methane and CO_2 from Thawing Permafrost or Ocean Warming Substantially Increase Warming?"
[48] Schuur E. A. G. et al. 2015. Climate Change and the Permafrost Carbon Feedback. Nature 520, 355–364)
[49] Parmentier F. - J. W. et al, 2013. The impact of lower sea-ice extent on Arctic greenhouse-gas exchange. Nature Climate Change 3, 195-202
[50] Charman, D. J. et al., 2015. *Drivers of Holocene peatland carbon accumulation across a climate gradient in northeastern North America*, Quaternary Science Reviews 121 (2015) 110-119

the slower (long-term) geological carbon cycle[51]. Forbes et al in 2006 estimated a rate of formation of BC equivalent to 4-5% of biomass burnt in forest fires and a 2013 estimate of the formation of BC from forest fires is from 0.56 to 0.74 Mt C[52]/yr[53]. The key question is whether the rate of annual BC formation exceeds the amount of C released from the large pool of BC that is already accumulated in terrestrial and marine ecosystems. BC comprises up to 40% of the organic C in terrestrial soils and 12-31% of the very large pool of organic C in deep ocean sediments (further, radiocarbon ages of BC in soils is in excess of thousands of years). On the other hand BC appears to have a significant effect on radiative forcing and albedo[54] which could have a local warming effect.

Natural disturbances: Although the impact on the GHG balance of natural disturbances in managed land may be assumed to average out across long time periods under constant environmental conditions, annually they may cause large variations in the anthropogenic GHG balance of a country. The IPCC Guidelines are that countries include emissions and subsequent removals associated with natural disturbances on managed land in their national GHGI *reporting.* However, when assessing performance relative to a national target (*accounting*), countries may wish under certain circumstances to, in addition to applying the managed land proxy, to be able to exclude a portion of emissions and subsequent removals associated with disturbances on the basis that the magnitude of disturbance events may overcome the capacity of humans to take them under control and limit their impact. An approach to do this has been agreed for use under the Kyoto Protocol for its second commitment period, which requires inventory reporting of disturbance emissions for transparency. The Kyoto rules also require evidence of action taken to limit such occurrences, and disallow exclusion of emissions if the disturbance is followed by land-use change. While the Paris Agreement has not yet established any specific rules or guidance on how countries may account for natural disturbances in the achievement of their NDC, it recognizes that existing methods and guidance should be taken into account[55].

Table 7: Potential impact of various processes that may not be included in GHGI reporting

Process	Potential impact on quantified estimate	Comment
Legacy	Up to 90%-100% of net increment[56]	Not considering legacy effects may result in an underestimate of emissions/removals; assuming instantaneous changes may determine whether the reported value is an under- or overestimate of the true value. Legacy in emissions is likely to be more relevant in forest where decay and accumulation processes are slower, as in the boreal forest
Age class	10%[57]-40%[58] of net C stock change in F→F	Not considering the age class of forests may result in either an underestimate or an overestimate of the true value

[51] e.g., Graetz, R.D. and Skjemstad, J.O. (2003). The charcoal sink of biomass burning on the Australian continent. CSIRO Atmospheric Research Technical Paper; no 64; Schmidt, M.W.I (2004). Carbon budget in the black. Nature; 427:305-306; Druffel, E.R.M. (2004). Comments on black carbon in the global carbon cycle. Marine Chem.; 92:197-200.
[52] Being C fraction around 0.6 according to Sediment Records of Biomass Burning and Global Change (Nato ASI Subseries I:)Jun 29, 2013 by James S. Clark and Helene Cachier.
[53] Bond, T. C., et al. 2013. Bounding the role of black carbon in the climate system: A scientific assessment. Journal of Geophysical Research: Atmospheres 118 (11): 5380–5552.
[54] Ibid.
[55] Article 4, para 14 of the Paris Agreement.
[56] From Canada's GHGI.
[57] Range of variation of net increment across a 24-year time series of the UK GHGI using a predictive model based on age class distribution and yield curves.

CO2 fertilization	At global scale, 1-2 Gt/yr May explain 50% of the Siberian sink, but only as much as 10% of the European sink[59]	Ciais et al[60] using a combination of biogeochemical modeling, atmospheric measurements and forest inventories estimates CO_2 fertilization could explain as much as 100% of the biospheric tropical sink which, with large uncertainties, is estimated to be of similar magnitude as emissions from deforestation, or 1–2 GtC/yr
N deposition	Estimates highly uncertain ~0.2 Gt/yr (or around 19% of the C sink)	Nitrogen fertilization is probably most important in Europe and the Eastern U.S. because of the large quantities of N deposition and because many forests are in N limited conditions.
Permafrost thaw	Unknown in forested lands	There is high uncertainty of emissions from permafrost thaw and no estimates for permafrost in only forested areas.
Black carbon	-	Annual production from forest fires around 0.9 – 1.2 Mt BC, high uncertainty on annual emissions from BC oxidation
Natural disturbance	Variable, depending on country	Currently Australia[61] is the only country removing a portion of emissions/removals from natural disturbances from its GHGI; in 2014 this resulted in reported emissions from forest fires dropping from ~459 to 92 MtCO2eq.

2.5. Summary of what's in (and what's out) of GHGIs

The purpose of GHGIs is to report information on anthropogenic emissions and removals within national boundaries. To achieve this, countries estimate emissions and removals following the methodological guidance that IPCC has been producing from 1996 onwards and the UNFCCC's reporting guidelines. Countries' have committed to **include all anthropogenic emissions and removals in their reports,** which is part of the total flux to and from the atmosphere within the national boundary.

What is included in national GHG inventories

If a country follows IPCC Guidelines, all emissions and removals associated with net C stock changes in all C pools of managed forest lands should be estimated. This includes forest growth and biomass turnover and mortality, harvesting and fuelwood collection, natural disturbances (e.g. fires and pest), decay of dead organic matter and soil organic matter, production of wood products and emissions from drained organic soils. At Tier 1 changes in dead wood, litter and organic carbon in mineral soil pools in forest remaining forest[62] are not estimated. The net emissions and removals of CO_2, and categories of CH_4 and N_2O associated with net C stock changes are reported and summed up to the national total amount of anthropogenic net emissions. Important sources of uncertainties are related to what can be considered directly human induced within F→F and to the identification and quantification of the complex forest dynamics beyond deforestation.

[58] Range of variation of net increment across a 24-year time series of the Russian GHGI using a predictive model based on age class distribution and chrono-sequences.
[59] Sabine, C.L., Heimann, M., Artaxo, P., Bakker, D.C.E., Chen, C-T.A., Field, C.B., Gruber, N., Le Quere, C., Prinn, R.G., Richey, J.E., Romero, P., Sathaye, J.A., Valentini, R., 2004. Current status of past trends of the global carbon cycle. In: Field, C., Raupach, M. (Eds.), Global Carbon Cycle, Integrating Humans, Climate and the Natural World. Island Press, Washington, D.C., pp. 17–44.
[60] Ciais, P., Janssens, I., Shvidenko, A., Wirth, C., Malhi, Y., Grace, J., Schulze, E.-D., Heimann, M., Phillips, O., Dolman, A.J., 2005. The potential for rising CO_2 to account for the observed uptake of carbon by tropical, temperate, and boreal forest biomes. In: Griffiths, H., Jarvis, P.G. (Eds.), The Carbon Balance of Forest Biomes. Taylor & Francis, Oxford, UK.
[61] Australia is understood to be preparing a GHGI report including separately identified disturbance emissions.
[62] These pools are assumed to remain constant at Tier 1. Default values are provided to estimate emissions associated with transition to other land uses.

What may not be included in national GHG inventories

As discussed above, GHG fluxes that occur on unmanaged lands (and therefore assumed not to be a result of an anthropogenic activity) are not reported in GHGIs. For managed lands, national reports may vary in their completeness, with some pools and gases reported less comprehensively than others. In forests, above and below ground biomass are the most likely pools to be included, others less so. Table 8 is the authors' best estimate of the most significant anthropogenic emissions and removals that may not be included in the current status of development of counties GHGIs.

Table 8: GHG forest fluxes that are not required (or may not be included) in current[63] national GHGIs

Should be included in GHGIs	Not required in GHGIs
• Non-living biomass pools (SOC DW, L) assumed constant at Tier 1 in forest remaining forest. These pools should be estimated at Tier 1 in land conversions from and to Forest, and at higher Tiers for forest remaining. • Emissions from drained organic soils—more likely to be included than previously, following publication of IPCC's 2013 Wetland Supplement • CO_2 and N fertilization in managed lands if gains and losses method or models are used that do not incorporate those effects. • Managed lands for which not enough data yet exist to estimate GHG emissions and removals (especially in developing countries) • All emissions and subsequent removals associated with natural disturbances on managed land, including those which are out of human control[64]	• Perturbations of the C stock equilibrium in unmanaged forest land due to changes in the natural disturbances regime • The natural sink in unmanaged peatlands • CO_2 and N fertilization in unmanaged lands • GHG from fires on unmanaged land

Some other fluxes may also be significant, including:

- Impact of permafrost melting;
- N_2O emissions from mineralization of soil organic matter where not associated with a net SOC change;
- CH_4 emissions from termites and from ruminants, where not part of husbandry systems.
- Net C stock accumulation in the black carbon pool originating from fires in managed and unmanaged lands.[65]

Quantifications of emissions and removals for these fluxes are not well known and are not forest-specific but may help close gaps between inventory data and science studies. Their inclusion may not be a requirement for GHGIs.

[63] The table is based on the current status of GHGIs; however, as explained in the text, these are expected to improve over time and, as such, the assessment may change in the future.
[64] Although in accounting they may be excluded.
[65] Kuhlbusch, T. A. J., and P. J. Crutzen (1995), Toward a global estimate of black carbon in residues of vegetation fires representing a sink of atmospheric CO_2 and a source of O2, Global Biogeochem. Cycles, 9(4), 491–501, doi:10.1029/95GB02742. – *Sink estimated in the order of 0.05-0.27 Gt C yr^{-1}*

3. Comparing GHGI reporting to independent scientific studies

3.1. The context of independent scientific studies

Independent scientific studies of carbon fluxes from forests and land are published by somewhat distinct research communities using three different approaches: top-down atmospheric models, bottom-up terrestrial biosphere models, and estimates of GHG fluxes from land use or land cover change. These studies are often not directly comparable with country reporting to the UNFCCC, nor among themselves, although in some cases comparability may be increased by looking at components of the estimates. While we call such studies independent, they may sometimes use national reporting data; similarly, national reporting may use information from scientific studies.

There are other differences between independent scientific studies and national GHGI reporting. The former may focus more on new results, the latter on consistency over time. Requirements differ as well—for example, international reporting must follow internationally agreed methodologies, and national reports need take into account national decisions (e.g. that define forests or land use, which may affect the allocation of emissions and removals between forest and non-forest categories). Independent scientific studies also adopt different forest definitions and may not align with national distinctions or definitions such as anthropogenic versus non-anthropogenic GHG fluxes. Independent scientific studies and national GHGI reporting are all subject to peer review, although the review process differs[66]. There may also be differences in data access and in technical expertise. These differences cumulatively help explain why a variety of approaches are applied, resulting in a range of estimates of GHG fluxes between forests and the atmosphere.

BOX: IPCC AR5 vs. country GHGI reporting

The objective of the IPCC's Assessment Report (AR) process is to provide "a clear and up to date view of the current state of scientific knowledge relevant to climate change". In doing so it reviews scientific literature, what this report refers to as "independent scientific studies", for its *global* assessment of the physical science basis of climate change (Working Group I) or options for mitigating climate change (Working Group III). The IPCC's Task Force on National GHG Inventories (TFI) was established to develop internationally agreed methodologies to estimate *national* GHG emissions and removals. These different objectives have meant that there are differences among the data, information, and methodologies used in the assessments made by the IPCC's AR process as compared to the IPCC Guidelines developed by the TFI and used by national governments to report national GHGIs to the UNFCCC.

The main source of difference between the methods to estimate forest net emissions included in Assessment Reports and those in country reporting to UNFCCC concerns the treatment of anthropogenic emissions and removals (other differences are covered in Section 3.3). As explained in section 2.2, the IPCC Guidelines for national GHGIs apply the concept of *managed land* as a *proxy for anthropogenic effects,* because the preponderance of anthropogenic effects occurs on managed lands. Areas of land considered "managed" are defined by national governments (subject to IPCC guidance[67]), with each land use disaggregated between "land converted to other land uses" (e.g. L→F, typically in the last 20 years) and "land remaining under the same land

[66] Scientific papers may be rejected because of review outcomes and the analysis provided by the reviewers is not published. Information reported to the UNFCCC is never rejected and the complete analysis made by reviewers is published. Consistency of information submitted to the UNFCCC with other national datasets is a relevant issue for GHGI review that is not generally taken into consideration in the review of scientific studies.

[67] Managed land is land where human interventions and practices have been applied to perform production, ecological or social functions. All land definitions and classifications should be specified at the national level, described in a transparent manner, and be applied consistently over time (IPCC 2006 GL, vol 4, page 3.6).

use” (e.g. F→F). Estimates from global model approaches such as those used in IPCC AR5[68] (which draws from, e.g. Houghton et al., 2012[69]), and the Global Carbon Project[70] are based on a wide range of data sources, take a different approach to separate management effects from indirect (or natural) impacts, and include different processes, definitions, and approaches to calculate global emissions and removals from forests. IPCC's AR5 distinguishes between emissions and removals due to:

(a) Land use change* including fluxes based on changes in land cover (over a longer time period than GHGIs use as a default to distinguish between “land converted to other land uses” and “land remaining in a land use”). For instance, the Houghton bookkeeping approach tracks the CO_2 emitted to the atmosphere during and following specific management interventions, for example during deforestation, and over time due to the follow-up decay of soil and vegetation carbon in different pools, including wood product pools. Depending on the modeling capability, some forms of forest management such as wood harvest, shifting cultivation and forest regrowth may also be included; e.g. Houghton et al. considers degradation of forests (where a fraction of the trees is removed) and forest management (wood harvest with replanting). It also tracks the regrowth of vegetation and associated build-up of soil carbon pools after land-use change. The activity data underlying these estimates is derived from reports to the FAO, and include net land use changes in all forest and land areas rather than gross land use changes on “managed land”, as per methods provided by IPCC Guidelines.

(b) The “residual terrestrial sink”, estimated by the difference of the other terms of the global carbon budget (i.e. the total net CO_2 flux between the land and atmosphere minus “land use changes”). This residual sink is generally assumed to be a natural response of forests and other lands to the fertilizing effects of increased levels of CO_2 and N in the atmosphere and the effects of climate change (IPCC AR5, WGI Chapter 6), although it is acknowledged that some of it may be due to changes in management practice not considered by current models[71] and there are uncertainties associated with separating out oceanic fluxes.

***** *The term “land use change” is used by IPCC AR5 WG I (Table 6.1), while for the same estimate the IPCC AR5 WG III uses the term “Forestry and Other Land Uses.” Despite the differences between IPCC AR5 and country reporting noted above, the AR5 authors state that in both cases the estimate is consistent with the term “LULUCF”.*

3.2. Quantified comparisons between national reporting and independent studies

The table below compares global estimates of anthropogenic and natural land-related CO_2 fluxes. The Houghton bookkeeping model used in IPCC's AR5 report estimates anthropogenic fluxes based on changes in land use, and some forms of forest management that would occur within a land use category (wood harvest, shifting cultivation, and forest regrowth). As described in the box above, the “residual terrestrial sink” is generally assumed to be a ‘natural’ response of primary or mature regrowth forests to environmental change (e.g. climate change, fertilizing effects of increased CO_2 and Nitrogen deposition). By comparison, Grassi and Dentener (2015)[72] estimated the aggregate anthropogenic fluxes from land use from national reporting, primarily using INDC[73] or other data submitted to the UNFCCC (GHG inventories, BURs, National Communications), and FAO datasets (country reporting to FAO-FRA for forest lands and FAOSTAT GHG emissions database for non-forest lands) to gap-fill. An *apparent* significant discrepancy emerges from Table 9 between what independent

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[68] Ciais, P. *et al.* in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (eds T.F. Stocker *et al.*) 465-570 (Cambridge University Press, 2014).
[69] Houghton, R. A. *et al.* Carbon emissions from land use and land-cover change. *Biogeosciences* **9**, 5125-5142 (2012).
[70] Le Quéré, C. *et al.* Global Carbon Budget 2015. *Earth System Science Data* **7**, 349-396 (2015).
[71] Erb, K. H. *et al.* Bias in the attribution of forest carbon sinks. *Nature Climate Change* **3**, 854-856 (2013)
[72] Grassi G., Dentener F. (2015) Quantifying the contribution of the Land Use sector to the Paris Climate Agreement; EUR 27561; doi 10.2788/096422
[73] Intended Nationally Determined Contributions submitted to the UNFCCC prior to COP21 in Paris.

scientific sources (Houghton and Le Quéré et al.) estimate as net "anthropogenic" emissions (around 1.0-1.1 Gt C/y) and what countries reports for LULUCF "managed land" (about 0.2 Gt C/y).

Table 9: Annual GHG fluxes (Gt C/y) from land: first-order comparison of independent scientific studies versus national reports

Study	Period	Estimate of anthropogenic fluxes	Residual Terrestrial sink
IPCC AR5[74]	(2000-2009)	1.1 ± 0.8 net land use change (using Houghton bookkeeping model[75])	-2.6 ± 1.2
Le Quéré et al 2015	(2000-2009)	1.0 ± 0.5 net land use change	-2.4 ± 0.8
Country reports (INDC, UNFCCC, FAO FRA)	(2000-2010)	0.2 ± 0.4* whole LULUCF	Not estimated

*The +/- is based on an expert-judgment selection of alternative country data to make a comparison with national reporting.

To investigate further the apparent discrepancies in Table 9, the table below (Table 10) provides estimates of fluxes associated with: (a) "land converted to other land uses" (i.e. land use change, mostly represented by tropical deforestation) and/or deforestation; (b) "land remaining in the same land use" or "forests remaining forests" (in country reporting, mostly represented by removals reported by developed countries); and (c) "land converted to forest land".

The results shown in Table 10 in relation to Table 9 suggest a partial reconciliation of the above discrepancies. In particular:

(iii) Emissions from deforestation reported by countries (≈0.92 Gt C/yr) reflect reasonably well estimates of land use changes (essentially deforestation) by independent scientific studies in Table 3.1 (1.0-1.1 Gt C/yr). The relatively small difference may be associated with differences between global models vs. country reports in terms of methods used[76] and pools, gases, and processes included.

(iv) Global models tend to estimate forest-related emissions based on net forest area and assume that, unless harvested, forests remaining forests are carbon neutral. Consequently, a large part[77] of the sink that most Annex I countries report under "land remaining under the same land use" (including the large sink in temperate and boreal F→F areas, around -0.53 Gt C/yr) is implicitly included in the "residual sink" by global models (-2.6 Gt C/yr). The same may partly apply also for Non Annex I countries. This means that countries consider this sink at least *partly* human-induced (because reported under "managed land") while global models consider it "natural".

The fact that the forest sink reported by countries is much smaller than the "residual sink" estimated by global top down studies may be explained by several factors, including: (a) uptake in unmanaged land not reported by countries (because considered non-anthropogenic); (b) omissions of fluxes (e.g. regrowth in tropical forests, sink in grassland soils and wetlands, etc.) or pools in managed lands; (c) other factors that are not well understood or

[74] Ciais, P. *et al.* in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (eds T.F. Stocker *et al.*) 465-570 (Cambridge University Press, 2014).

[75] Houghton, R. A. *et al.* Carbon emissions from land use and land-cover change. *Biogeosciences* **9**, 5125-5142 (2012).

[76] E.g. as explained in the box above, independent studies typically estimate emissions from net land use changes (while countries' reports to UNFCCC typically refers to gross land use changes), and include forest degradation within "land use change" (while countries' reports to UNFCCC include degradation within F→F)

[77] As explained in the box above, *some* of the emissions/removals included by countries in F→F are included in "land use and land cover changes" by global models. However, a comparison of Fig. 11.7 of WGIII of IPCC AR5 (for OECD countries) with Annex I countries' reporting suggests that the *majority* of the sink in F→F in country reporting is not included in the "land use change" estimates reported by IPCC AR5.

captured by the GHGI methodology (e.g. fertilization effects[78]) and therefore not included in national reports. In addition, the residual (terrestrial) sink is a difference in global budget terms and not a direct estimation of GHG fluxes and therefore other factors may explain the disparity with national reports.

Table 10: Comparison of annual GHG fluxes (Gt C/yr) from national reports, disaggregated between 'Land use change' and 'Land other than land use changes'

Study	**Coverage**	**Land use change, or deforestation**	**F→F or L→L**	**NF→F**
Country reports (2000-2010)	All countries	≈ 0.92 deforestation	≈ -0.48 L→L (includes F→F) ≈ -0.75 F→F	≈-0.27
	Annex I	0.04 deforestation	-0.53 F→F, mainly removals from temperate and boreal forests	-0.03
	Non-Annex I (≈ tropics)*	≈ 0.88 deforestation	≈ -0.22 F→F	≈ -0.24
Federici et al 2015 (2000-2010)[79]	Global	1.1 net deforestation**	-0.6 NF→F and F→F (including 0.3 GtC/yr of forest degradation)	
Pan et al. 2011		2.8 Tropical gross deforestation	--4.2 NF→F and F→F Excluding unmanaged forests in Canada (118 Mha), Alaska (51 Mha) and West/Central Asia (53 Mha)	
Achard at al 2014 (2000-2010)	Tropics only	0.88 gross emissions using remote sensing data (includes forests and other wooded land)	-0.10 removals from forest regrowth	
Baccini et al 2012[80] (2000-2005)		0.89 net deforestation** and shifting cultivation (excluding soils)	0.09 net emissions from industrial logging and fuelwood harvest	
Harris et al 2012 (2000-2005)		0.81 gross deforestation using remote sensing data		

* In non-Annex I country reports to UNFCCC using the 1996 IPCC Guidelines is often very difficult to distinguish between F→F and L→F. Numbers in this table should be considered a first estimate.
** Net deforestation estimates include a portion of fluxes from the NF→F category.

Even though it appears that global estimates of emissions from deforestation by independent studies match well with aggregated forest emissions from national GHGI reporting, this may not indicate accuracy by either source of information. It is possible that global or pan-tropical aggregates are averaging out actual differences in estimations. Studying these differences could lead to improvements on both sides of the comparison.

[78] NFIs will capture this implicitly so GHGIs relying on NFI data, usually in the context of stock-change estimates, will do so also.
[79] This study derives net C stock changes in F→NF and in NF→F + F→F, by assigning net C stock changes to net area changes reported by countries to FRA for three forest types: *Primary forest, Other naturally regenerating forests* and *Plantations*. For each country, total net C stock change of F→NF and NF→F + F→F corresponds to the net C stock change reported by countries to FRA.
[80] Estimate based on the Baccini et al. 2012 analysis as re-assessed in "Progress Towards A Consensus on Carbon Emissions from Tropical Deforestation", by Woods Hole Research Center and Winrock International (2012), and information from IPCC WG3 AR5 Figure 11.8.

As an example, the case of Zambia is provided (see Table 11). The total emissions using UMD/Hansen activity data multiplied by Baccini emission factors (as provided by Global Forest Watch) nearly matches the historical emissions estimates provided by the Government of Zambia in its recent REDD+ FREL submission. However, the underlying data are quite disparate—Zambia estimates over three times the area of forest loss, but also estimates biomass in its forests to have over three times less carbon.

Table 11: Comparison of independent reports on deforestation in Zambia with national data

Zambia	Independent study	Country report*
Emissions	**25.4** $MtCO_2$/yr (2006-2014) (Hansen and Baccini)	**24.4** $MtCO_2$/yr (2006-2014)
Activity data	2001-2010 **65,000** ha/yr 2010-2014 **108,000** ha/yr (Hansen)	2000-2010 **250,000** ha/yr 2010-2014 **341,000** ha/yr
Emission factors	Range = **56 to 200** tC/ha (AGB) (IPCC default range)	5 strata, largest loss in strata with **18** tC/ha (AGB + BGB)

*Zambia's Forest Reference Emission Level submission (January 2016)

The Zambia situation may not be typical of countries with mostly moist tropical forests. Zambia has mostly dry forest which can be difficult to detect with remote sensing. Other characteristics, such as significant forest fragmentation, degraded forests or land use classifications that may result in forest definitions that differ significantly from tree cover, could also result in national GHG forest-related flux estimates that are not comparable to global studies (see Section 3.3 for further discussion of these issues). The possibility of such differences argue for country-level comparisons, particularly if country reporting is the basis for mitigation actions.

3.3. Reasons why independent studies differ from national reporting

In addition to the elements discussed in Section 2, which may apply to independent scientific studies as well as GHGIs, (e.g. GHGI focus on anthropogenic emissions and removals via the managed land proxy, lack of completeness, and use of methods to estimate emissions/removals that may not include certain carbon stock change processes, such as fertilization), there may be other reasons why there are quantitative differences in estimates. We discuss several of these below.

3.3.1. Forest definition

From a GHGI perspective, forest definitions relate primarily to the allocation of emissions and removals between forest and non-forest categories. Comprehensive national GHGIs include reporting across all land categories, they should not affect the total estimate of GHG emissions and removals reported by a country, although if a national GHGI devotes more resources to the forest sector, so that other land uses are not estimated as effectively, then different forest definitions can affect the inclusion of emissions and removals, or change the uncertainty with which they are included. Comparison of forest-related estimates amongst science studies, or between science studies and inventories, will be more meaningful if the consequences of differences in definition are recognized and taken into account. Differences include:

Parameter values used to define forest: Table 12 shows some parameter values and ranges associated with the UNFCCC and the FAO Forest Resource Assessment (FRA). Under the UNFCCC countries are expected to choose a value for each parameter and use it consistently over time, and to report on the national forest definition used.

Table 12: Parameters in forest definition of several international conventions

Parameter	UNFCCC	FRA
Minimum area	0.05-1.0 ha	0.5 ha
Minimum height	2-5 m	5 m
Minimum crown cover	10-30%	10%
Minimum time since conversion	Not available	~10 years
Minimum strip width	Not available	20 m
Other parameters covered in definition	Young stands, temporarily unstocked areas	Young stands, temporarily unstocked areas, predominant land use agroforestry

Land use and land cover definitions: With a *land cover definition*, land areas estimated to meet the other minimum requirements transfer in or out of forest status according to whether the percentage crown cover definition is satisfied. In the case of a *land use definition* even if tree cover is temporarily removed below the minimum percentage requirement (e.g. because of harvest or disturbance), land retains forest status provided regeneration (natural or by replanting) is expected to take place so that all minimum requirements will again be met, perhaps within a specified time period—and so long as a change to another land use has not taken place. The difference in practice is the temporarily unstocked areas consistent with the forest definition. Although the IPCC Guidelines call for land use definitions, scientific studies tend to rely on remotely sensed data and use land cover definitions. Countries that use remote sensing data as a basis for estimated activity data (see Section 3.3.2) may be using land cover change, in practice, as an approximation of land use change. A land use definition can be based on remotely sensed data and biophysical properties of the land, for example by determining if a change in tree cover below minimum thresholds is or is not accompanied by observation of substitute land uses like agriculture. Countries may have access to administrative and other national statistical data sources which can be used in making the distinction, provided they are accurate and kept updated. If this is not the case an additional source of confusion could be introduced.[81]

Exclusion of some types of tree cover: Forest definitions may exclude some types of land with tree cover, e.g. agricultural production systems.

The forest definition determines the boundary of the land that is monitored as forest. Estimation of the effect of forest activities is made more efficient by stratification to differentiate between forest ecosystems and management of disturbance regimes. Comparability between estimates made using the same forest definition does not necessarily require the same stratification scheme, although it is important that estimates are unbiased[82]. This entails use of a valid sampling procedure to estimate the properties of the strata. Examples include use of a higher-quality reference sample to deal with bias in classification algorithms used with remote sensing, and recognizing that plots gathered for research purposes may not be representative of the strata in which they occur.

[81] Such as when F->NF and NF->F simply result from an administrative reclassification of land instead of from a change in its biophysical characteristics.
[82] Technically this means that they are made using unbiased estimators, or statistical procedures that do not carry the expectation of bias

Table 13: Forest definitions used in selected scientific studies

Study	Forest definition
Achard at al 2014	Forests are stratified into 3 classes: i) >70% crown cover, ii) 30% to 70% crown cover, iii) other woody vegetation
Avitabile et al	N/A
Baccini et al 2012	FAO (by implication)
Federici et al 2015	FAO
Grace et al 2014	As classified by ESA
Hansen et al 2013	Tree cover over 5m height at various crown cover thresholds at the Landsat pixel scale (.09 ha)
Harris et al 2012	Forest cover is defined as 25% or greater canopy closure at the Landsat pixel scale (30 m x 30 m) for trees >5 m in height. Includes intact forests, plantations, or forest regrowth. Deforestation is defined as the reduction of canopy cover to below this 25% threshold
Pan et al 2011	FAO (including temporarily unstocked and plantations)
Saatchi et al 2011	>10% tree cover as defined by the MODIS vegetation continuous field product

3.3.2. Activity data

Activity data, according to the IPCC Guidelines, are defined as data on the magnitude of human activity resulting in emissions or removals taking place during a given period of time. In the case of land-use changes, these data are normally provided in hectares (e.g. hectares of land in a particular year that changed from forest to non-forest). Tradeoffs in the spatial resolution, frequency, and costs of data used to generate information about forests mean that there are limits on the detail and frequency at which countries can identify forest losses and gains. Remote sensing observations from optical satellites, often integrated with NFIs, lie at the heart of modern day forest monitoring for forest area change.

Forest definition (Section 3.3.1) and the differentiation between managed and unmanaged land (Section 2.2.1) are two factors that can substantially influence differences in reported activity data. Below are additional reasons why activity data may differ even when the same areal extent is being monitored—each topic is covered in further detail in the Supplementary Information document.

Spatial Resolution: Spatial resolution is important in cases where remote sensing data forms the main input for estimating forest area and area change. Landsat (30 m resolution) is most widely used because of free availability and the long historical archive. Other spatial resolution may be used from RapidEye (1-5 m resolution; may be of use in detecting degradation) to MODIS (250 to 500m resolution; high temporal resolution and useful spectral indices for detecting change; also freely available).

Remote sensing analysis approach used: To analyze forest change, two different approaches are used: the more traditional approach using sequential mapping of land classes and changes vs. a more recent "follow the pixel" approach (e.g. used by Hansen et al, 2013 and more recently at MapBiomas). The choice may significantly impact quantified results (see Supplementary Information for descriptions of these methods). There are trade-offs, however, in each approach—the former allows quantification of transition in multiple land use and land cover types, while the latter is currently limited (particularly for global analyses) to transitions from forest to non-forest[83], but allows for the use of all available data and, therefore, a more complete time series analysis. Visual interpretation of remote sensing products (e.g. using tools such as Collect Earth) may be used to derive activity data and may result in increased accuracy and lower costs, but requires human resources to interpret

[83] A single tree cover gain estimate is provided for the period 2000 to 2012

multiple points (particularly for larger territories), and may be used to obtain reference data that can be used with mapped data to produce unbiased estimators – see below.

Temporal resolution: Reliable estimates of carbon dynamics require detailed observations of change on an annual basis; missing a single year of observations can lead to substantial errors, especially in ecosystems with rapid forest regrowth. Although UNFCCC reporting is based on a one-year timeframe (for Annex 1 countries), estimation of annual activity data is likely to be reported on the basis of *average* rates of land-use conversion, as determined by measurements made at longer intervals. In contrast to measurement estimates made at longer time intervals, remote sensing approaches to monitor forest area change can be made annually and even sub-annually (e.g., Brazil's PRODES monitoring system, Hansen annual forest loss, GLAD weekly forest change alerts). Moscarro et al. (2015) conclude that higher temporal resolution remote sensing products improved carbon dynamics estimates and captured inter-annual variability in forest dynamics.

Sampling vs. wall-to-wall coverage: The difference between wall-to-wall mapping and sample data is not clear-cut. This is because statistically sound, sample based estimates (e.g. from NFIs) are well understood and the estimators used, if properly implemented, are unbiased. Remote sensing estimates, even if wall-to-wall may have bias entering through the classification algorithms[84]. For this reason it will often be most efficient in terms of resources for countries to use unbiased estimators which combine remote sensing and sample reference data. This issue was discussed in the context of global mapping at the 2015 GFOI-GOFC GOLD expert workshop on Using Global Datasets for National REDD+ Measuring and Monitoring[85]. This issue can help explain apparent differences between global mapping (usually wall-to-wall) and national estimates (usually sample-based), e.g. where certain types of tree cover are not included in national forest definitions.

Table 14: Approaches to estimating activity area in selected independent studies.

Study	Area estimation
Achard at al 2014	Sampling 4000 10x10 km sites based on interpretation of Landsat pixels
Baccini et al 2012	Taken from FRA 2010
Federici et al 2015	FRA 2015 subcategorized by primary forest, other naturally regenerated forest, and planted forest
Grace et al 2014	FAO, Hansen
Hansen et al 2014	Landsat data
Harris et al 2012	MODIS data calibrated with Landsat data (i.e., Hansen product prior to wall-to-wall Landsat)
Pan et al 2011	Various: national forest inventory data, FAO data and remote sensing
Saatchi et al 2011	MODIS
Tyukavina et al 2015	Sample-based approach using a stratified random sample, with strata derived from the wall-to-wall forest cover loss map of Hansen et al. (2013) to separate the gross loss of forest biomass into losses from natural forests and losses from managed forests including plantations, agroforestry systems and subsistence agriculture.

Activity Data for Forests Remaining Forests

In the case of forests remaining forests, where countries apply the gain-loss method of the IPCC Guidelines, biomass losses from wood harvest, fuelwood collection and natural disturbance must be subtracted from biomass gains from forest growth. Estimates for biomass losses used in national GHGIs for the category of forests remaining as forests rely primarily on information collected by national forest departments on extracted

[84] See for example *Remote Sensing Based Two-Stage Sampling for Accuracy Assessment and Area Estimation of Land Cover Changes* Heinz Gallaun *, Martin Steinegger, Roland Wack, Mathias Schardt, Birgit Kornberger and Ursula Schmitt Remote Sens. 2015, 7, 11992-12008; doi:10.3390/rs7091199
[85] See http://www.gfoi.org/rd/fourth-rd-expert-workshop/

wood volumes). Biomass loss from fuelwood collection, particularly for tropical countries where these losses can be substantial, relies almost exclusively on FAOSTAT data. In the case of monitoring natural disturbances, some developed countries use carbon budget models to simulate ecosystem response to natural disturbance, and are a well-established approach to estimating carbon fluxes at regional to national scales. For example, Canada's National Forest Carbon Monitoring Accounting and Reporting System (NFCMARS) uses the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3). Individual U.S. agencies monitor disturbances such as fire, hurricanes, insect damage and drought, but these data are not used explicitly in the U.S. forest inventory (the U.S. inventory uses the stock-change method).

3.3.3. Emission factors

Emission factors (EFs) quantify GHG emissions or removals (or C stock change) per unit activity per year. Usually, in the case of forestry and other land use, activity is measured by area, so EFs are expressed per unit area. Examples of EF include carbon densities before and after a transition from forest to another land use (in which case the difference is multiplied by the area transferred per year), or they may be a change in carbon density over time, which is multiplied by an area of forest in which the change is taking place. Emission factors corresponding to transitions between forest strata may be used to estimate emissions and removals associated with degradation. Emission factors are also used to quantify non-CO_2 GHG emissions, e.g. from fire. In integrated, IPCC Tier 3 models emission factors can be thought of more generally as model parameters – e.g. rates of transfer between pools – that are not a function of the activity data used to drive the model.

When establishing comparability between scientific studies or with inventory data, issues relevant to emission factors include:

Coverage: National inventories may measure emission factors for some pools and use default values for others. The pool for which emission factors are most often measured directly is above ground-biomass and frequently below-ground biomass is added using root-to-shoot ratios. Emissions factors for drained organic soils are important for some ecosystems, and for peat fires. Independent scientific studies may not be comparable to GHGIs if they do not have the same pool coverage (see Section 2.2.2 on completeness of reporting). The summary table at the end of this section provides a brief comparison of the various pool coverages of independent scientific studies.

Values: Langer et al[86] have compared IPCC default AGB values for use in forest land conversion with those from the Saatchi and Baccini datasets, and found on average the latter lower by 35% and 24% respectively; the difference falling to 13% and 1% respectively for intact forest landscapes. They conclude the IPCC defaults refer mainly to intact forest landscapes. Table 15 below compares some carbon densities corresponding to total biomass between independent studies and country-specific values.

Table 15: Average forest carbon density estimates (tC/ha) in above- and below-ground tree biomass for top ten tropical countries with highest emissions from deforestation.

Country	Saatchi et al. (2011)*	FAO FRA2015	Baccini et al. (2015)	Country FREL
Brazil	123 (110 – 136)	119	124 148 (Amazon)	152 (average for Amazon)

[86] *Can recent pan-tropical biomass maps be used to derive alternative Tier 1 values for reporting REDD+ activities under UNFCCC?* A Langner, F Achard and G Grassi, Environ. Res. Lett. 9 (2014) 124008 (12pp)

Indonesia	158 (143-172)	162	149	60-142** (EFs specific to forest type)
Colombia	141 (127-155)	151	132 156 (Amazon)	154 (Amazon biome)
Bolivia	94 (82-106)	78	104	
Madagascar	78 (71-84)	130	137	
DRC***	134 (120-144)	127	138	179 (dense forest class) 108.5 (secondary forest)
Peru	160 (145-174)	114	154	11-140 (EFs specific to forest type)
Mexico	52 (43-61)	63	75	19-42 (EFs specific to forest type) 4-6 (EFs other woody vegetation)
Malaysia	180 (164-196)	120	146	
Paraguay	27 (19-35)	No data reported	49	28-66 (EFs specific to forest type)

***** Numbers in parentheses for Saatchi et al. (2011) indicate uncertainty bounds.
** Aboveground biomass only.
*** Information from reference level submitted to the FCFP Carbon Fund

Time dimension: IPCC emission factors are based on historical data and this is often the case for country-specific emission factors, e.g. where these are established on the basis of historical surveys or statistically representative research plots. However, the real underlying relationship between area and emissions that is represented by an emission factor may be changing over time rather than static. When repeated surveys are used, such as periodic national forest inventories, any gradual change in emission factors e.g. due carbon fertilization, N deposition or temperature and rainfall trends will be taken into account. For this reason, emission factors based on historical data may need to be updated periodically to continue to represent conditions on managed land, and to represent the impact of new management practices.

If emission factors (e.g. rate of tree growth) are measured annually there may be considerable variation due to year-on-year variation environmental conditions (as opposed to long term trends discussed in the paragraph above). In this case measurements should be continued for a sufficient period to remove the inter-annual fluctuations. In the case of forests harvested for wood products (HWP) there may be a significant difference in emissions and removals according to whether the wood in HWP is assumed to be emitted instantaneously at the point of harvest, or whether the dynamics of product decay is considered explicitly

Space: Factors affecting the amount of GHG emissions/removals include climate, soil, vegetation, management practices (including those leading to degradation), so that the land needs to be stratified accordingly. Stratification increases sampling efficiency. EFs calculated for different levels of stratification allow estimation of equivalent GHG balances at the highest (least detailed) level of stratification.

Measurement of emission factors: Where emission factors are measured they should correspond to the activity data strata or drivers that they refer to. The sampling to achieve this should follow some accepted statistical scheme and an explanation be provided as to why the results are expected to be free of bias, and the expected uncertainty should be quantified. IPCC Guidelines suggest using an uncertainty range corresponding to the 95% confidence interval to do this.

Methods: EFs can be calculated as C stock changes or as GHG fluxes. C stocks are derived through inferences/models based on conversion and /or expansion factors and/or allometric equations from measurements (diameter, height, soil samples, DOM samples, above and below ground turnover, tree models). Consequently, the model applied to ground measurements for calculating C stocks may be a source of differences among EFs, although such source varies significantly among developing and developed countries[87], among tropical and boreal forests.

Table 16: Pool coverage and methods to calculate Emission Factors in various independent studies

Study	Pool coverage	EF method of calculation
Achard at al 2014	AGB expanded to total biomass	Drawn from merging of FAO ecosystem map, IPCC default data and Baccini and Saatchi maps
Avitabile et al	AGB	Fusion of Baccini (2012) and Saatchi (2011) maps using reference data points for bias correction
Baccini et al 2012	AGB	LiDAR calibrated with field data and upscaled using MODIS
Federici et al 2015	AGB expanded to total biomass	FRA 2015 data
Grace et al 2014	AGB expanded to total biomass; peat fires and HWP included using other available data assumptions	Saatchi biomass map
Harris et al 2012	AGB expanded to total biomass	Saatchi biomass map
Pan et al 2011	Total biomass, deadwood, soils	Various: National inventory data, national models, expansion factors, ecosystem and bookkeeping models
Saatchi et al 2011	AGB expanded to total biomass	Ground plots, Lidar

3.3.4. Uncertainties

Estimating GHG from forests and forest-cover change needs to deal with high uncertainties in underlying data. Forests are diverse environments, and many processes lead to land-use change. Available data are often imperfectly suited to GHG estimation. The upshot is that typically, the most important activity data in LULUCF GHG estimation are about 30% uncertain (see Table below).

Independent scientific studies employ diverse approaches for uncertainty analysis, while the IPCC Guidelines give national reports a common framework. However, some national reports (and independent scientific studies) can be incomplete in their treatment of uncertainties. Most independent scientific studies and national GHGI reports (particularly of developed countries) apply simulation and error propagation techniques, and quantify random errors, but only a few independent scientific studies and national reports quantify systematic errors. In practical terms the way forward is to use statistically valid sample reference data to provide estimates that, consistent with the IPCC's definition of good practice *are neither over-nor under-estimates so far as can be judged*. Considerable progress has been made in defining methods to achieve this, using reference data alone, or reference data and remote sensing data in combination as set out in the GFOI Methods and Guidance Document section 3.7 and the references therein[88].

Most developed countries, such as the United States and Canada, provide a high level of detail on a systematic approach to assess uncertainties in estimation. Brazil and Indonesia have undertaken initial steps towards

[87] Chave, J., et al . Tree allometry and improved estimation of carbon stocks and balance in tropical forests. Oecologia (2005) 145: 87–99. DOI 10.1007/s00442-005-0100-x
Holdaway, Robert J., Stephen J. McNeill, Norman W. H. Mason, and Fiona E. Carswell. 2014. Propagating Uncertainty in Plot-based Estimates of Forest Carbon Stock and Carbon Stock Change. Ecosystems in press. DOI: 10.1007/s10021-014-9749-5
[88] See http://www.gfoi.org/wp-content/uploads/2015/04/GFOIMGD_English.pdf . This material will be expanded when Version 2 of the MGD is published later in 2016.

building an approach for uncertainty analysis of their national GHG inventories. Most developing countries' national reports have high potential to improve uncertainty analysis in GHG estimation.

Typical uncertainties need careful analysis to measure 'significant' GHG reductions from reduced deforestation or other land-use changes. At a global level, scientific studies have uncertainties around 20%-30% for this metric. Indonesia's GHG inventory in the SNC implies uncertainties around 80%, Brazil's and DRC's GHG inventories do not report uncertainties for this metric.

Table 17: Uncertainties in selected independent scientific studies and national GHGI reports*

	Reported uncertainty		
	Forest conversion (area data)	GHG from F→NF	GHG from F→F
Achard et al 2014	+/-4-10% + bias 11.2% (95%)	+/- 30% (95%)	
Pan et al 2011		+/-16% (95%)	+/-21% (95%)
Hansen et al 2013	+/- 2% (95%)**		
USA's NIR 2015		FL->CL: -53% and +123%*** (95%)	-25.4% and +25.8% (95%)
Canada's NIR 2015	+/-30% (95%)	+/-17% (95%)	+/- 41% (95%)
Brazil's SNC (2010)	Only aggregate uncertainties reported		
Indonesia's SNC (2010)	+/-30% (no confidence level specified)	+/-81%** (no confidence level specified)	+/-56%** (no confidence level specified)
DRC's TNC (2015)	No uncertainty analysis undertaken		

*Either reported as such or implied by reported uncertainties; (XX%) stands for "around the mean with XX% confidence"
** Estimated based on values provided
***Large uncertainty due to changes in soil C.

4. Conclusions and Recommendations

The goals agreed in Paris in Dec 2015 to hold the increase in global average temperature to well below 2°C, reach global peaking of greenhouse gas (GHG) emissions as soon as possible, and achieve a balance between anthropogenic emissions and removals in the second half of this century cannot be met without a significant contribution from forests—not only through reducing deforestation in the tropics, but also by maintaining and increasing the global sink capacity of forests.

Understanding forest-related GHG fluxes, however, can be challenging. Independent scientific studies—which are the basis of the IPCC's periodic Assessment Reports aimed at providing global flux estimates, including from the land sector—often use different definitions and methodologies from those of the IPCC Task Force on GHG Inventories, which aims at providing internationally agreed, standardized guidance to countries in preparing their national GHG inventories (i.e. IPCC Guidelines for National GHG Inventories). This can result in differing quantifications of anthropogenic emissions and removal from forest lands.

GHG inventories report information on *national* anthropogenic GHG fluxes and so track the progress of each country in reducing emissions and enhancing removals. National GHGIs follow methodological guidance provided in the IPCC Guidelines, including use of an assumption that forest-related anthropogenic emissions and removals are those occurring on *managed land* defined by countries subject to consistent application of broad IPCC criteria. Countries may regard emissions and subsequent removals from large natural disturbances as non-anthropogenic even if they occur on managed land, and methods to do this have been agreed in the Kyoto Protocol context. However, countries are required to report such emissions and removals in their national GHGI.

There is considerable scope for improving forest-related estimates of GHG fluxes that would enhance the understanding of countries' NDCs, as well as overall progress towards the global goals contained in the Paris Agreement. Developing country inventory reports (with a few exceptions) tend to be less advanced than developed country reports. However, developing country inventory reports are now subject to technical assessment and analysis (under the agreed BUR process), and many are pursuing improved forest monitoring as part of emerging REDD+ efforts. The result has been observable improvements in the capacity of developing countries to monitor forests.

Increasing numbers of papers are published in scientific journals that estimate forest net emissions. The scale of such studies tends to be larger (e.g. global or regional, often for tropical forests) or smaller (i.e. type of forest, biome, stands) than national reports. This means that scientific studies and national reports may not be easily comparable because the national boundaries may not be identifiable or the definitions used may differ. Another significant difference between independent scientific studies and national reporting is the methodology used to distinguish anthropogenic from natural sources of emissions and removals. Independent studies also use varying sources of activity data—including global data sets (remote sensing or of statistical nature), national reports, or sometimes a combination of both—and combine these with emission factors from IPCC defaults, recent global or regional synthesis papers, or even models to produce global, regional and/or biome results. Coverage of pools and greenhouse gas source categories may also not be the same when comparing scientific paper with national reports, but also when making comparisons between scientific papers. Comparisons between national reports are facilitated to a degree by the use of common reporting format tables.

When comparing estimates from independent scientific studies (as is done in the IPCC's AR process) to those in national GHGI reports (that are prepared using the IPCC Guidelines for reporting), therefore, issues that need to be considered include: differences in defining what is anthropogenic, the estimation methods used, differences in forest definition, area coverage, pool coverage, whether regrowth or legacy emissions are included, how harvested wood products are treated, and whether and how natural disturbances are included.

Differential treatment in different studies and in national reports can complicate the aggregation or disaggregation necessary to make meaningful comparisons. However, estimates from studies published in scientific journals and national GHGI reports *are both the result of* science-based methods, and can in principle be reconciled, or the differences understood. It is important to understand where differences among estimates that seemingly should agree are coming from. Once understood, the numbers *should* agree to within the quantified uncertainties – otherwise, it is likely that the differences can be attributed to methodological differences or inclusiveness of some of the fluxes.

In order to make such comparisons, each source of information would need to provide transparent documentation on how estimates were derived. Such documentation is a requirement for national reports, and is itself the subject of review and assessment under UNFCCC processes, which typically continues to identify areas for improvement from most countries. Papers published in scientific journals are typically linked to a particular research question or agenda. They are, in almost all cases, peer reviewed. However, there is not the same continuous process in time for producing or updating those estimates as there is in national reports. Studies published in scientific journals sometimes investigate new techniques or methodologies that could require further development to be translated to widespread practice if they are to become operational in the context of national reports.

Better tracking of the role of forests in achieving the 2 °C or 1.5 °C target require greater comparability between scientific studies and national reports. This can be achieved from both sides:

- Starting from the scientific side there should be greater awareness of the information contained in national reports and the possibilities of using it. Providing information disaggregated by national boundaries and by administrative region will be helpful, and it will be useful to consider IPCC definitions when considering pool coverage. Scientific papers that provide information compatible with IPCC inventory methods should be communicated to IPCC via the Emissions Factor Database. The scientific community could also help to distinguish and clearly document those fluxes that are outside of the GHGI framework but are nonetheless of substantial importance for global monitoring purposes in the context of the Paris Agreement.
- Starting from the GHG inventory side, there should be greater awareness of scientific work that is consistent with IPCC methods that can be used for independent verification (in line with IPCC Guidelines). This awareness should be further encouraged by the inventory review and assessment process. Countries not having country specific data should make full use of IPCC default methods to include the full range of carbon pools (recognizing that some simplifying assumptions exist at Tier 1, as discussed above). Countries which have significant areas of unmanaged land may wish to include information on emissions and removals on these lands even though they are not included in national greenhouse gas inventories. Countries need to continue to improve transparency of information reported to allow, as far as practicable, for replicability of GHG estimates. Spatial boundaries and statistical estimation methods should be clear, so comparisons can be made as closely as possible.

Finally, the IPCC in future AR or Special Reports may provide clarification of differences such as those highlighted in this report. Where possible, it may also consider greater consistency between definitions and methods used when estimating forest-related GHG fluxes for Working Group I and III reports and comparability with guidance provided by the IPCC Task Force on GHG Inventories.