



Pantropical CO₂ emissions and removals for the AFOLU sector in the period 1990–2018

Sylvia S. Nyawira¹ · Martin Herold² · Kalkidan Ayele Mulatu³ · Rosa Maria Roman-Cuesta^{4,6} · Richard A. Houghton⁵ · Giacomo Grassi⁶ · Julia Pongratz^{7,8} · Thomas Gasser⁹ · Louis Verchot¹⁰

Received: 21 June 2022 / Accepted: 11 December 2023 / Published online: 20 February 2024
© The Author(s) 2024

Abstract

Transparent, accurate, comparable, and complete estimates of greenhouse gas emissions and removals are needed to support mitigation goals and performance assessments under the Paris Agreement. Here, we present a comparative analysis of the agriculture forestry and other land use (AFOLU) emission estimates from different datasets, including National Greenhouse Gas Inventories (NGHGs), FAOSTAT, the BLUE, OSCAR, and Houghton (here after updated H&N2017) bookkeeping models; Emissions Database for Global Atmospheric Research (EDGAR); and the US Environmental Protection Agency (EPA). We disaggregate the fluxes for the forestry and other land use (FOLU) sector into forest land, deforestation, and other land uses (including non-forest land uses), while agricultural emissions are disaggregated according to the sources (i.e., livestock, croplands, rice cultivation, and agricultural fires). Considering different time periods (1990–1999, 2000–2010, and 2011–2018), we analyse the trend of the fluxes with a key focus on the tropical regions (i.e., Latin America, sub-Saharan Africa, and South and Southeast Asia). Three of the five data sources indicated a decline in the net emissions over the tropics over the period 1990–2018. The net FOLU emissions for the tropics varied with values of 5.47, 5.22, 4.28, 3.21, and 1.17 GtCO₂ year⁻¹ (for BLUE, OSCAR, updated H&N2017, FAOSTAT, and NGHGs, respectively) over the recent period (2011–2018). Gross deforestation emissions over the same period were 5.87, 7.16, 5.48, 3.96, and 3.74 GtCO₂ year⁻¹ (for BLUE, OSCAR, updated H&N2017, FAOSTAT, and NGHGs). The net forestland sink was -1.97, -3.08, -2.09, -0.53, and -3.00 GtCO₂ year⁻¹ (for BLUE, OSCAR, updated H&N2017, FAOSTAT, and NGHGs). Continental analysis indicated that the differences between the data sources are much large in sub-Saharan Africa and South and Southeast Asia than in Latin America. Disagreements in the FOLU emission estimates are mainly explained by differences in the managed land areas and the processes considered (i.e., direct vs indirect effects of land use change, and gross vs net accounting for deforestation). Net agricultural emissions from cropland, livestock, and rice cultivation were more homogenous across the FAOSTAT, EDGAR, and EPA datasets, with all the data sources indicating an increase in the emissions over the tropics. However, there were notable differences in the emission from agricultural fires. This study highlights the importance of investing and improving data sources for key fluxes to achieve a more robust and transparent global stocktake.

Keywords Agriculture forestry and other land use (AFOLU) · Forestry and other land use (FOLU) · Agricultural emissions · Emissions · Sinks · Tropics

1 Introduction

Atmospheric concentrations of greenhouse gases have increased substantially since pre-industrial times. The rise in CO₂ is mainly associated with fossil fuel burning and contributions from the land sector (IPCC 2022), commonly referred to as ‘agriculture, forestry, and other land uses’ (AFOLU). AFOLU emissions result from changes in the natural fluxes of CO₂ and other non-CO₂ gases, largely methane (CH₄), and nitrous oxide (N₂O), through anthropogenic changes in land use/cover (e.g., conversion of forest lands and grasslands to cropland and pasture, afforestation), and management of croplands, forests, and wetlands. AFOLU activities lead to both sources and sinks of CO₂, mainly from forestry and land-use change, and to non-CO₂ emissions mainly from agriculture, e.g., CH₄ from livestock and rice cultivation, N₂O from manure storage, and cropland soils and biomass burning (Tubiello et al. 2013, 2014). Globally, the AFOLU sector was responsible for 13 GtCO₂ eq. year⁻¹ in 2019, which was about 22% of net anthropogenic greenhouse gas (GHG) emissions, with approximately half from agriculture and the other half from forestry and other land use activities (FOLU) (Pathak et al. 2022).

AFOLU emissions for different GHG gases (CO₂ and non-CO₂) are available through the Food and Agriculture Organization (FAO) Statistical database (Tubiello et al. 2013, 2014). In addition, global and national CO₂ emissions for the FOLU sector are also provided by bookkeeping models, i.e., BLUE, Houghton and Nassikas, and OSCAR models (Gasser et al. 2020; Hansis et al. 2015; Houghton et al. 2017), and the estimates have recently been updated for the Global Carbon Budget 2022 (Friedlingstein et al. 2022). Agricultural CO₂ and non-CO₂ emissions are available through the FAO database, Emissions Database for Global Atmospheric Research (EDGAR) (Crippa et al. 2019; Crippa et al. 2020), and the US Environmental Protection Agency (EPA) databases (US EPA 2019). Past comparative analyses showed reasonably good agreement among these data sources in the total gross emissions at the aggregated level for the tropical regions, but significant disagreements when disaggregating the emissions by sources, continents, and gases, particularly for the forest sector, with fire leading the differences (Roman-Cuesta, Herold, et al., 2016). In addition, emissions from the tropical regions have remained consistently higher compared to global estimates. For instance, for the FOLU sector, Roman-Cuesta et al. (2016a) reported emissions of ca. 6 GtCO₂ eq. year⁻¹ for the tropics (2000–2005), with this value being higher than the global AFOLU emission estimates of ca. 5.0 GtCO₂ eq. year⁻¹ in the Intergovernmental Panel for Climate Change (IPCC) AR5 synthesis report over the same period (Smith et al. 2014).

Besides these global datasets, article 14 of the Paris Agreement includes an enhanced transparency framework (ETF) to periodically track and review the progress of countries towards achieving their Nationally Determined Contributions (NDCs), and a periodic global stocktake process for assessing the countries’ collective progress towards achieving the long-term goals of the agreement (UNFCCC 2016). All parties to the United Nations Framework Convention on Climate Change (UNFCCC) are required to document the anthropogenic emissions and removals of different sectors and report these through the national greenhouse gases inventories (NGHGs). Recently, a dataset including compilation of individual NGHGs for the land use, land-use change and forestry (LULUCF)

sector has become available (Grassi et al. 2022b). Previous studies revealed conceptual inconsistencies between the scientific modelling assessments and countries in estimating the net anthropogenic land related CO₂ emission, with a gap of about 4 to 6.7 GtCO₂ year⁻¹ globally between the aggregated NGHIs and global model estimates (Grassi et al. 2018, 2021, 2023). The large differences are mostly due to different approaches in estimating the forest sink. While these two studies have made significant progress in reconciling the differences between global models and NGHIs, their focus was on forest-related emissions and sinks at the global level. In a recent study, differences between the NGHIs and FAOSTAT have also been assessed at the global and regional level (Grassi et al. 2022b), and the discrepancy between global models and NGHIs has been resolved at the country-level as well (Schwingshackl et al. 2022). However, there's still a need for a thorough comparative analysis of emissions in tropical regions that integrates all the latest available datasets. With all UNFCCC parties expected to adopt a harmonized reporting by 2024 under the Enhanced Transparency Framework (UNFCCC Secretariat 2020), such an analysis would not only be useful in identifying and understanding the causes of differences among the datasets but would also offer information on how countries can improve their reporting using the available datasets.

In this study, we present a comparative analysis of AFOLU emission estimates for the tropics for the period 1990–2018 using seven data sets: NGHIs, FAOSTAT, the BLUE, OSCAR and Houghton and Nassikas booking models (here after updated H&N2017), EPA, and EDGAR. Although the approach for our analysis is in some ways like that used in the comparative study by Roman-Cuesta et al. (2016b), our study goes a step further by including new databases (e.g., NGHIs), more updated global data sources, longer analysis periods, and disaggregated analysis for FOLU emissions. The objectives of the study are (i) to provide a comprehensive and updated analyses on the global and tropical regions aggregated and disaggregated AFOLU emissions from different data sets (i.e., at continental level and activity), (ii) assess the trend of the emissions, and (iii) understand the reasons for the differences between the datasets.

2 Methods

2.1 Study scope

Our study comprises a detailed analysis of global AFOLU datasets and estimates, with a focus on three tropical regions: Latin America (LAM), sub-Saharan Africa, and South and Southeast Asia. We chose to analyse the emissions for these regions because of the rapid land use change in the tropics and the increased reporting requirements on tropical countries under the Paris Agreement. In addition, the tropics have the largest emissions uncertainty and gaps, hence the need to understand the causes of differences between the available AFOLU data sources (Romijn et al. 2012, 2015). Such detailed comparisons already exist for other regions like Europe (Maria et al. 2020). We analysed the annual average emissions over three different time periods (1990–1999, 2000–2010, 2011–2018), which allowed for an assessment of how the reported emissions have changed over time. We focused on the period 1990–2018, because it was the period where emissions were available in most of the datasets. The average emissions over a given period was calculated by summing the annual emissions and dividing by the total number of years in that period. Our analysis includes net FOLU emissions, gross emissions from deforestation, net emissions or sinks from other

forestland activities (e.g., harvest), and other land uses. Net land use emissions consider the emissions by the sources and the removals by sinks in a final emission balance where the removals are discounted from the emissions. Gross assessments include the contributions of different sources and sinks to the net land use emissions. A key advantage of the gross assessments compared to net AFOLU emissions is that they offer direct information on the sinks and sources that can facilitate the development of more targeted measures and policies to enhance and promote mitigation (Deb Richter and Houghton 2011; Roman-Cuesta et al. 2016a), and provide a better indication of the climate benefits of forests.

2.2 AFOLU data sources

2.2.1 FAOSTAT

FAOSTAT covers agriculture, forestry, and other land uses and their associated emissions of CO₂, CH₄, and N₂O (Federici et al. 2015; Tubiello et al. 2013, 2021). FAOSTAT database includes emission estimates for 242 countries annually for the reference period 1961–2018 (agriculture) and 1990–2019 (FOLU), based on national activity submitted by countries and further compiled by FAO (Food and Agriculture Organization of the United Nations). Estimates are computed following Tier 1 methods and default factors of the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. FAOSTAT includes estimates of carbon emissions from net forest conversion, biomass fires, organic soils in cropland and grasslands, peatland drainage, and emissions from other forestland activities (Table 1). These estimates are based on national statistics. Forest carbon stock changes (both emissions and removals) have recently been updated based on the national-level FAO Forest Resources Assessment 2020 (FAO 2020a, 2020b).

2.2.2 Bookkeeping models

We used the three bookkeeping models that were part of the 2022 Global Carbon Budget: the OSCAR model, the bookkeeping of land use emissions (BLUE), and the Houghton and Nassikas model (updated H&N2017) (Gasser et al. 2020; Hansis et al. 2015; Houghton et al. 2017). The models are based on the original bookkeeping approach of Houghton (2003) that keeps track of the carbon stored in the vegetation and soils before and after a land-use change. The models use literature-based response curves to describe the decay of vegetation and soil carbon, including transfer of product pools of different lifetimes, as well carbon uptake due to regrowth. Bookkeeping models estimate emissions of CO₂ from deforestation, shifting cultivation, wood harvest, woody debris decay, biomass burning (deforestation and peatland fires), and soil organic matter (SOM) from cultivated soils.

The three bookkeeping models differ with respect to the land-use change data used to drive the model. The updated H&N2017 bases its estimates on the Forest Resource Assessment (FRA) of the FAO, which provides statistics on forest change and management at intervals of 5 years and is currently updated until 2020 (FAO 2020a). Changes in land use other than forests are based on annual national changes in cropland and pasture areas reported by FAO (FAOSTAT, 2021). BLUE uses the harmonized land-use change data LUH2-GCB2022 covering the entire 850–2021 period, which is an update to the previously released LUH2 v2h dataset (Hurtt et al. 2020). OSCAR was run with both LUH2-GCB2022 and FAO/FRA (as used in the updated H&N2017), where the drivers of the latter were linearly extrapolated to 2021 using their 2015–2020 trends. BLUE

Table 1 A summary of the characteristics of the four forestry and land use (FOLU) activity data sets analysed in the present study

	FAOSTAT ^a	BLUE	H&N2017 and OSCAR	NGHGIS ^b	EDGAR ^c	EPA ^d
Spatial disaggregation in present study	Country	Country ^e	Country	Country	Country	Country
Period available	1990–2019	1850–2020	1850–2021	2000–2020	1970–2015	1990–2030
Period in present study	1990–2018	1990–2018	1990–2018	2000–2018	1990–2015	1990–2015
Gross/net emissions	Gross except forest fluxes	Gross	Gross	Gross	Gross	Gross
Tier	1	3	3	1 or 2	1	1
Sector	Agriculture and FOLU	FOLU	FOLU	FOLU	Agriculture	Agriculture
Gas	CO ₂ , CH ₄ , N ₂ O	CO ₂	CO ₂	CO ₂	CO ₂ , CH ₄ , N ₂ O	CO ₂ , CH ₄ , N ₂ O

^a<https://www.fao.org/faostat/en/#data/GT/downloadedon27thApril2022>

^b<https://zenodo.org/record/6390739#.YmkC89pBw2y>

^chttps://edgar.jrc.ec.europa.eu/dataset_ghg60downloadedimJanuary2020

^d<https://www.epa.gov/global-mitigation-non-co2-greenhouse-gases/global-non-co2-ghg-emissions-1990-2030>

^e Also available at pixel level (0.25)

and updated H&N2017 models exclude land ecosystems' transient response to changes in climate, atmospheric CO₂, and other environmental factors, and the carbon densities are based on contemporary data from literature and inventory data. Since carbon densities remain fixed over time, the additional sink capacity that ecosystems provide in response to CO₂ fertilization and some other environmental changes is not captured by the models (Pongratz et al. 2014). Although the OSCAR model does account for the transient response associated with environmental changes, the emissions included here are only those associated with land-use change. Emissions from peat burning and peat drainage are added from external datasets (see Appendix C2.1 in Friedlingstein et al. 2022). We obtained the net FOLU emissions for the three bookkeeping models and annual gross fluxes of CO₂ (i.e., both sinks and sources) resulting deforestation, forestland, and other land use transitions for the three bookkeeping models. For the three models, annual emissions were available for 218 countries. The FOLU emissions used here are based on the 2022 Global Carbon budget (Friedlingstein et al. 2022).

2.2.3 National Greenhouse Gases Inventories (NGHGs) for the LULUCF sector

National Greenhouse Gas Inventories (NGHGs) presented here include estimates of LULUCF CO₂ emissions and sinks submitted to the UNFCCC. Figure 1 illustrates the conceptual differences between the NGHGs, the bookkeeping models, and FAOSTAT in terms of the processes accounted for and the area extent. The data were compiled from various submissions to UNFCCC, prioritizing the most recent and considering the completeness of the information (Grassi et al. 2022a; Grassi et al. 2022b). For non-Annex 1 countries, National Communications (NCs), Biennial Update reports (BURs), and nationally determined contributions were used in compiling the data. Only one submission was used in compiling the data national GHGs. While NCs are typically submitted every 4 years, BURs provide an update of the information presented in NCs, typically every 2 years.

The time of reporting varies for the different non-Annex 1 countries. To ensure a complete time series for the period 2000–2020, gaps were filled using standard statistical methods, with the aim to maintain the levels and trends of the underlying reported raw data (see Tables 4 and 5 of the online dataset in Grassi et al. 2022a, showing the original and gap-filled time series, respectively). However, most of the non-Annex 1 countries with the biggest emissions, including Brazil, Indonesia, and Democratic republic of Congo, reported relatively complete time series. The gap-filled data includes all land uses (i.e., forestland, cropland, grassland, wetlands, settlements, and other land) and covers 195 countries. Almost all Annex 1 countries report all land uses, while many non-Annex 1 countries report only on forestland and deforestation. Here, we used the NGHGI data compiled in Grassi et al. (2022b), which include a split of the net LULUCF flux into the categories of forest land, deforestation, organic soils, and other land use fluxes.

2.2.4 EDGAR

The Emissions Database for Global Atmospheric Research version 5 (EDGARv5.0) provides emissions of three main greenhouse gases (CO₂, CH₄, and N₂O) per sector at 0.1 deg × 0.1 deg grid maps and country level (Crippa et al. 2019, 2020). The EDGAR database for this version covers the energy, industry, transport, waste management, and agriculture (including agricultural soils, agricultural waste burning, enteric fermentation, manure management) sectors, mainly quantified using the IPCC 2006 guidelines for emissions

FOLU emissions

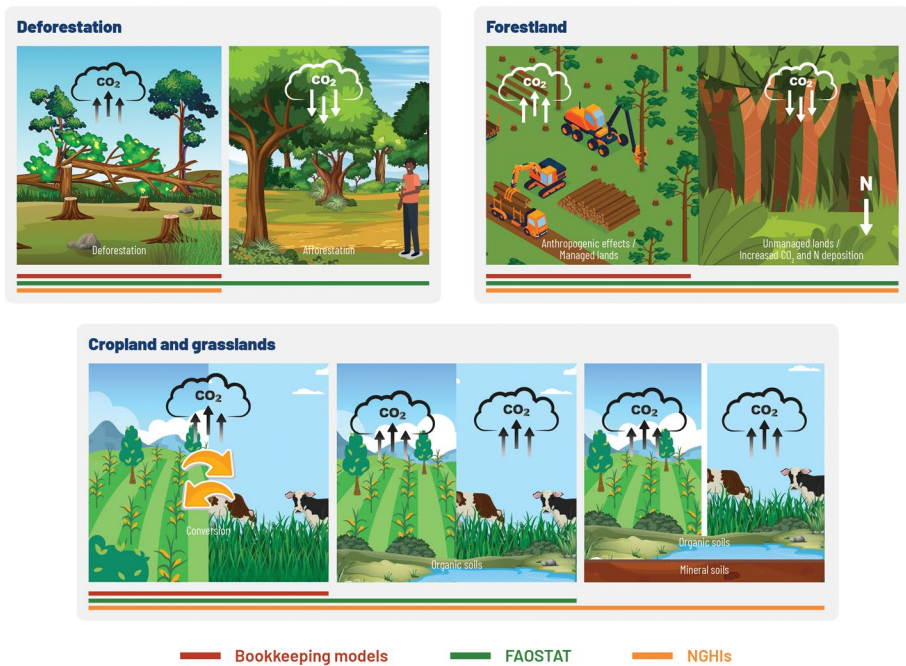


Fig. 1 A conceptual diagram indicating the key differences between the National Greenhouse Gases Inventories (NGHIs), the bookkeeping models and the FAOSTAT in their Forestry and Land Use (FOLU) emissions. Bookkeeping models and NGHIs provide gross emissions of deforestation, while FAOSTAT provides net emissions from forests, where emissions from deforestation are discounted with the gains from afforestation. Bookkeeping models consider as anthropogenic only direct human-induced fluxes on forestland, while NGHIs and FAOSTAT account for both the human-induced fluxes and the indirect effects resting from environmental changes, e.g., the CO₂ fertilization and nitrogen deposition. In addition, the extent of areas differs with NGHIs also including unmanaged lands. On cropland and grasslands, bookkeeping models only include fluxes from the land use conversion, FAOSTAT include only the fluxes from organic soils, while the NGHIs account for the fluxes from both mineral and organic soils

estimations. However, emissions of large-scale biomass burning in savannahs, forest fires, and sources and sinks from LULUCF are excluded in this version. EDGAR emission estimates are mostly calculated using activity data from FAO statistics. However, N₂O emission from fertilizer use and CO₂ from urea fertilisation are estimated using both the International Fertilizer Association (IFA) and FAO statistics data. Furthermore, CH₄ emissions from enteric fermentation for dairy and non-dairy cattle are calculated using Tier 2 emission factors. We downloaded the EDGARv5.0 (January 2020) emissions over the period 1990–2018 on an annual basis, at the country level (Table 1) (Crippa et al. 2019).

2.2.5 The US Environmental Protection Agency (EPA)

The EPA dataset contains global non-CO₂ projected emissions for the period 1990–2050 for the agriculture (livestock, cropland, rice cultivation, and biomass burning), energy, industrial processes, and the waste sectors. EPA provides future projections of non-CO₂ GHGs using a combination of country-reported inventory data and EPA-estimated

calculations consistent with the 2006 Intergovernmental Panel on Climate Change (IPCC) Guidelines for national GHGIs. The EPA data provides information that can be used to understand national contributions of GHG emissions, historical progress on reductions, and mitigation opportunities. The EPA data does not include estimates of FOLU activities. We downloaded annual agricultural emissions offered at a 1-year interval at country level and disaggregated by gas and emission sources from the recently updated data that was used in the 2015–2050 projections (Table 1) (US EPA 2019).

2.3 Estimating net and gross emissions and sinks

We analysed the data using two major categories: (1) forestry and other land use activities (FOLU) and (2) agriculture. We quantified the net FOLU and agriculture emissions by summing the emissions and sinks for all the activities in the respective category under Table 1. We compared the net FOLU, and agriculture emissions estimated from the different data sources at the global level and within the three continents in the tropical regions. To assess the trend of the emissions in the tropical regions, we calculated the average values for three different time periods (1990–1999, 2000–2010, and 2011–2018). Disaggregated values from the NGHGs were available in four time slices (2000–2005, 2006–2010, 2011–2015, and 2016–2020). For comparability with other data sets, the 2016–2020 emissions were included in the 2011–2018 period.

FOLU emissions from all the considered data sets only included CO₂ emissions and excluded non-CO₂ greenhouse gases. To gain an in-depth understanding of the emissions patterns and identify the possible causes of differences among the data sources, the FOLU emissions were further disaggregated into three categories: deforestation, forestland, and other land uses (emissions and sources). Emissions from organic soils were included in other land use emissions. Emissions for forest fires were included in the forestland category. Any other non-forest-related activities were categorized as other land-use emissions. FAOSTAT do not provide gross deforestation emissions fluxes, but instead include the net forest conversion emissions (i.e., from forest area losses minus area gains). For comparison purposes with the other data sources, the net forest conversion emissions for FAOSTAT were included in the deforestation category. The disaggregation of FOLU emissions into deforestation, forestland, and other land use was chosen for comparability of other data sets in the FOLU sector recently published national GHGIs (Grassi et al. 2022b).

Emissions from agriculture were separated into four categories based on the different sources, i.e., croplands, livestock, rice cultivation, and agricultural fires. CH₄ and N₂O emissions were converted to CO₂eq.

3 Results

3.1 FOLU emissions

3.1.1 Global and regional net emissions

Globally, all the data sources show that the net FOLU activities contributed to CO₂ emissions over the periods 1990 to 1999 (Table 2; Fig. 2). However, there was disagreement between NGHGs and the other data sources on the emissions for the period between 2000 to 2010 and 2011–2018, with the inventories indicating a net sink of

Table 2 The total net FOLU emissions in $\text{GtCO}_2 \text{ year}^{-1}$ for the tropical and other regions for the various data sources. The tropical regions include Latin America, sub-Saharan Africa, and South and Southeast Asia

Dataset	1990–1999			2000–2010			2011–2018		
	Tropics	Other	Total	Tropics	Other	Total	Tropical	Other	Total
Updated H&N2017	4.77	-0.98	3.79	4.40	-1.29	3.11	4.28	-1.10	3.18
OSCAR	4.92	0.63	5.55	5.42	0.12	5.54	5.22	-0.06	5.16
BLUE	5.18	1.55	6.73	5.93	0.49	6.42	5.47	0.43	5.90
FAOSTAT	3.71	-1.94	1.77	3.64	-2.20	1.44	3.21	-2.95	0.26
NGHGs				1.68	-3.00	-1.32	1.17	-3.20	-2.03

-1.32 and -2.03 $\text{GtCO}_2 \text{ year}^{-1}$ over the two periods, while the other data sources indicated a source (Table 2). Over the period 2011–2018, the updated H&N2017, BLUE, and OSCAR bookkeeping models estimated a net global source of 3.18, 5.16, and 5.90 $\text{GO}_2 \text{ year}^{-1}$, while the emissions from FAOSTAT were 0.26 $\text{GtCO}_2 \text{ year}^{-1}$. The total emissions for the tropics over the same period were 5.47, 5.22, 4.28, 3.21, and 1.17 $\text{GtCO}_2 \text{ year}^{-1}$ (for BLUE, OSCAR, updated H&N2017, FAOSTAT, and NGHGs). All the other data sources indicate a decline in the net global FOLU emissions over time.

Regional analyses showed that the largest contributions for the global FOLU emissions stemmed from the tropical regions of South and Southeast Asia, sub-Saharan Africa, and Latin America (Fig. 2; Table 2). Three of the data sources (updated H&N2017, FAOSTAT, and NGHGs) indicate that the large emissions in the tropics were offset by the forest sink in the non-tropical regions, leading to lower net emissions globally. However, the BLUE and OSCAR models generally estimated a source of CO_2 also for the non-tropical regions (Table 2). The updated H&N2017 model, FAOSTAT, and NGHGs indicate a decline in the net tropical emissions over the three

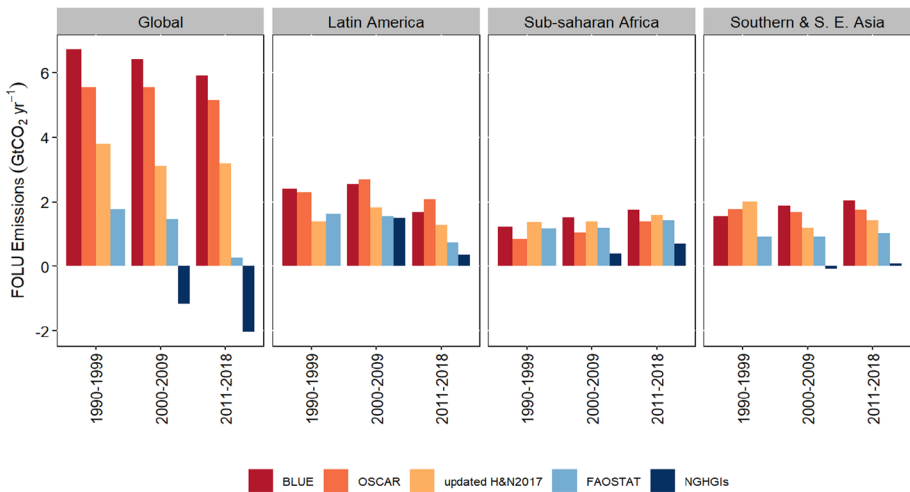


Fig. 2 Global and tropical regions net forestry and other land use (FOLU) emissions for the five data sources. BLUE, OSCAR, updated H&N2017, FAOSTAT, and NGHGs include emissions due to all forestry and land use activities, while the reported emissions in NGHGs vary depending on the countries

considered period, while the BLUE and OSCAR models indicate a decline in the emissions over the two recent periods (2000–2010 and 2011–2018). Consistent with the observed global patterns, the net emission estimates from the NGHGs are smaller than those from the other data sources in the three tropical regions (Fig. 2). Overall, there was generally a decline in the emissions over Latin America and an increase over sub-Saharan Africa, but the different datasets indicated different trends over South and Southeast Asia.

Further analyses showed substantial differences between NGHGs and other data sources at the sub-regional levels for the tropical regions. Within West and Southern Africa, the NGHGs indicated a small sink in CO₂, while the other four data sets indicated a source over the regions (Fig. S1). The bookkeeping models generally estimated an increase in the emissions over the East Africa region between 1990–1999 and 2000–2010 and a decrease in 2011–2018, while FAOSTAT and NGHGs indicated no change. An increase in the emissions over Central Africa was evident in all the data sources. As expected, South America is the main contributor of emissions in Latin America, with almost all the data sources estimating a decline in the emissions over the period 2011–2018 (Fig. S1). Emissions within Central America were relatively small. In addition, the Southeast Asia sub-region was the main source of emissions within South and Southeast Asia region. NGHGs indicated a sink in over the South Asia and Central America.

3.1.2 Disaggregated emissions and sinks

Global gross deforestation emissions (i.e., forest losses only) estimates from the three bookkeeping models (updated H&N2017, OSCAR, and BLUE) were higher than the estimates from NGHGs and FAOSTAT (Fig. 3a). The NGHGs and FAOSTAT indicated a decline in the global deforestation emissions, while the updated H&N2017 estimated no change in the emissions. The BLUE model indicated an increase in the emissions in the first two considered periods and decline over the period 2011–2018, while the OSCAR model indicated a small increase in the emissions over the same period. A similar trend was also observed in the total deforestation emissions for the tropical region (Fig. 3b). Overall, the global deforestation emissions over the recent period (2011–2018) were 6.90, 8.06, 5.23, 4.10, and 3.17, and 5.64 GtCO₂ year⁻¹ for BLUE, OSCAR, updated H&N2017, NGHGs, and FAOSTAT. The total tropical deforestation emissions were 5.88, 7.16, 5.48, 3.74, and 2.96 GtCO₂ year⁻¹ (BLUE, OSCAR, updated H&N2017, NGHGs, and FAOSTAT), which amounts to about 90 to 96% of the global deforestation emissions (Fig. 3).

Regional analyses indicated a decline in the deforestation emissions over Latin America and a slight increase over sub-Saharan Africa and South and Southeast Asia (Fig. 4). Within sub-Saharan Africa, the three data sources generally agreed on the trend of deforestation emissions for the different sub-regions (Fig. S2): An increase in the emissions was evident in Central Africa, while there was a decline in the emissions over Western Africa and very small changes over Eastern and Southern Africa. As expected, Central Africa had the largest deforestation emissions, because of the high forest cover and deforestation rate mainly in the Congo Basin. Similarly, deforestation emissions in Latin America were mainly from South America region, with the Central America emissions being substantially smaller (Fig. S3). The Southeast Asia sub-region contributed to nearly all the emissions in the South and Southeast Asia region (Fig. S4).

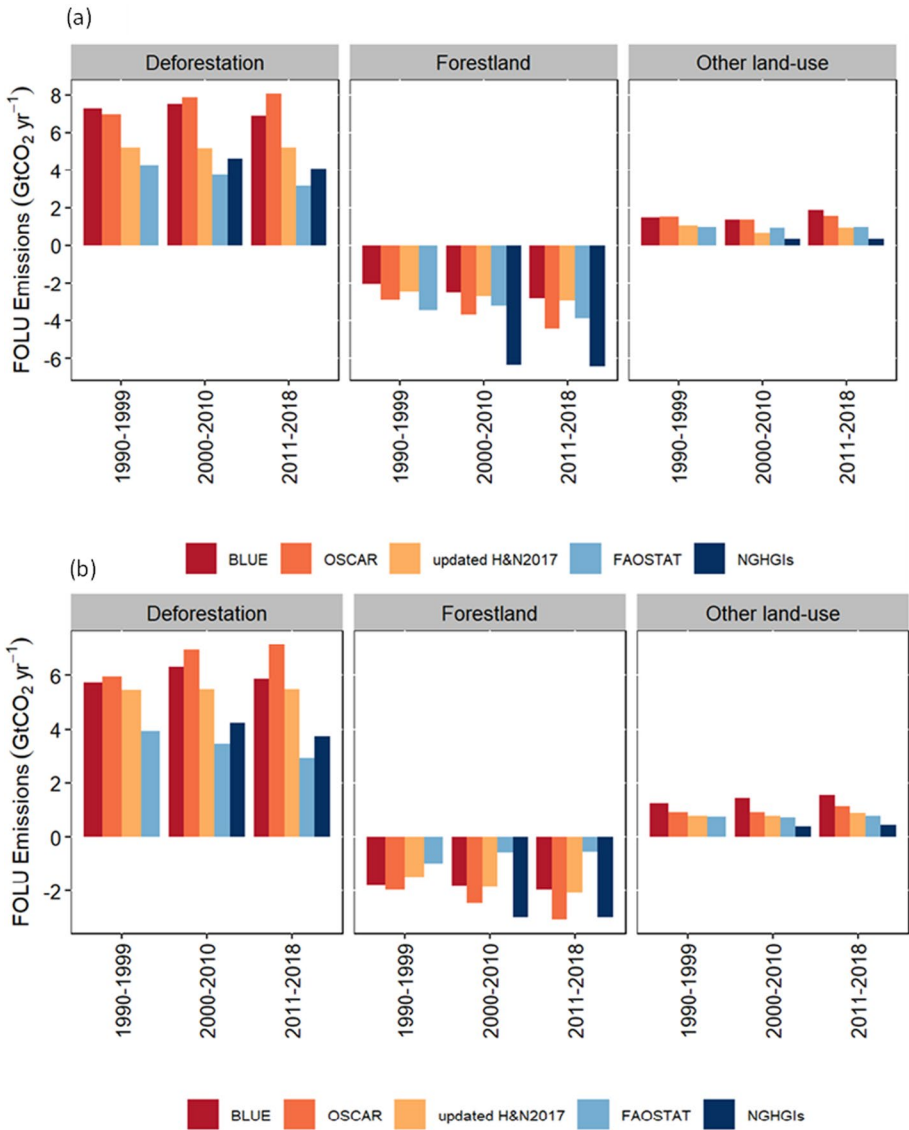


Fig. 3 **a** Global and **b** tropical region disaggregated emissions and sinks from deforestation, other forestland activities (e.g., harvest, reforestation, and fires), and other land use activities. Deforestation emissions for the three bookkeeping models (updated H&N2017, OSCAR, and BLUE) and NGHGIs represent the emissions associated forest losses only, while the emissions for FAOSTAT represent the net emissions from forest area losses discounted with the sink from forest area gains. The sum of the three components is equivalent to the total emissions represented in Figure 2

Other forestland activities (e.g., afforestation, reforestation, regrowth, and harvest) contributed to a global net sink in CO₂ across all the data sets over the considered periods (Fig. 3a). However, the sink in the NGHGIs was larger than that in FAOSTAT and the bookkeeping models estimates. The global forestland sink was -2.86, -4.45, -2.96, -6.44, and -3.89 GtCO₂ year⁻¹ (for BLUE, OSCAR, updated H&N2017,

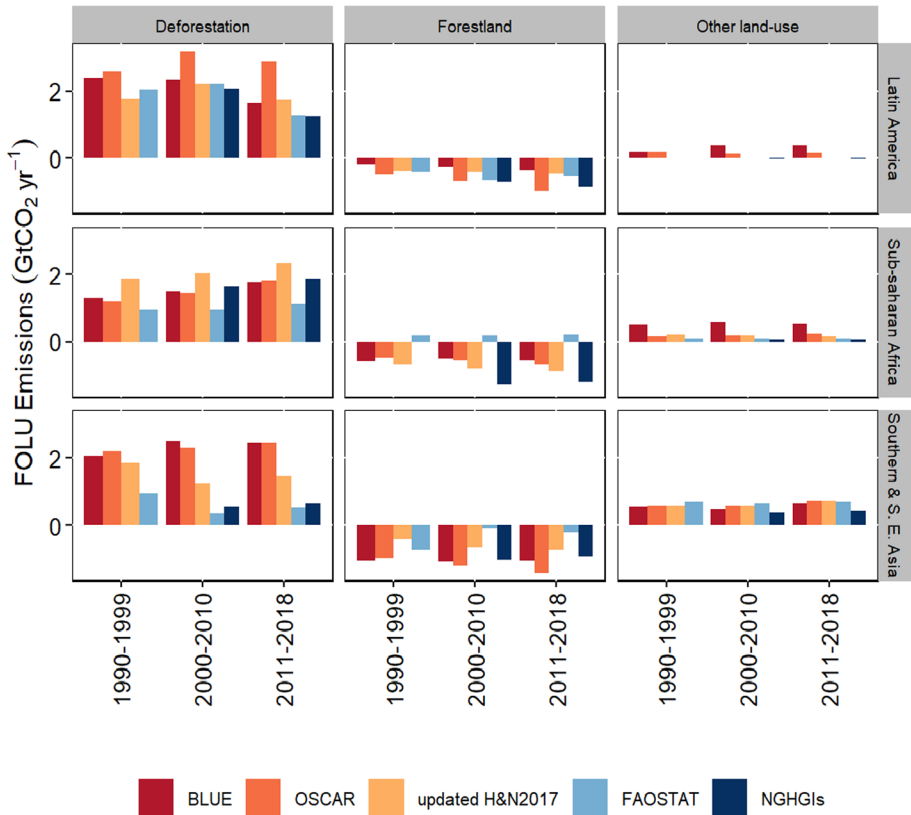


Fig. 4 Disaggregated emissions and sinks from deforestation, other forestland activities (e.g., harvest, reforestation, and fires), and other land use activities for Latin America, sub-Saharan Africa, and South and Southeast Asia. Deforestation emissions for the three book keeping models (BLUE, OSCAR, and updated H&N2017) and NGHGs represent the emissions associated forest losses only, while the emissions for FAOSTAT represent the net emissions from forest area losses discounted with the sink from forest area gains. The sum of the continental emissions is equivalent to the total tropical regional emissions represented in Fig. 3b

NGHGs, and FAOSTAT, respectively) over the period 2011–2018. The total net forest sinks for the tropical regions were -1.84 , -3.08 , -2.09 , -3.00 , and -0.53 GtCO₂ year⁻¹ (for BLUE, OSCAR, updated H&N2017, NGHGs, and FAOSTAT respectively). Hence, the tropical region contributed to about 13 to 47% of the global forest sink. Overall, an increase in the global forest sink was evident across all the datasets, but there were no notable changes in the tropics (Fig. 3).

All the data sources indicated a CO₂ sink in the forest over Latin America and South and Southeast Asia (Fig. 4). However, the NGHIs estimated a larger sink than the bookkeeping models and FAOSTAT. The data sets differed in sub-Saharan Africa with the NGHGs and the three bookkeeping models estimating a sink in CO₂ while FAOSTAT indicated a source. In terms of trend, the three data sources indicated a small increase in the forest sink over Latin America and a relatively small decline over sub-Saharan Africa and South and Southeast Asia (Fig. 4). The forestland sink was evident in the NGHGs, and bookkeeping model estimates

across all the sub-regions within sub-Saharan Africa (Fig. S2), with the largest sink being in Central Africa and Western Africa and the smallest over Southern Africa. FAOSTAT mostly showed a small source of CO₂ across the regions. As expected, the forest sink was larger over South America than Central America, with fewer differences between the data sources over South America (Fig. S3). The NGHGs and the bookkeeping models estimated a much larger forest sink over Southeast Asia compared to FAOSTAT (Fig. S4).

Other land use activities (e.g., non-forest related land use conversions, biomass burning, and peatlands drainage) contributed to emissions, with the total emissions being much smaller than that of deforestation across all the considered regions (Fig. 3). The total net global emissions from other land use activities were 1.87, 1.55, 0.92, 0.33, and 0.98 GtCO₂ year⁻¹ (for BLUE, OSCAR, updated H&N2017, NGHGs, and FAOSTAT, respectively) over the period 2011–2018. The tropical regions contributed largely to these emissions with values 1.56, 1.13, 0.88, 0.45, and 0.77 GtCO₂ year⁻¹ (for BLUE, OSCAR, updated H&N2017, NGHGs, and FAOSTAT) over the same period. For FAOSTAT, emissions from other land use activities were only from the organic soils (Table 3). At the global and tropical region level, emissions from organic soils were generally higher in FAOSTAT than in the NGHGs and in the average data estimates used in the bookkeeping models. All the data sets estimated higher emissions for the organic soils in the tropics compared to other regions. Regional analyses indicated no major changes in the total emissions from other land use activities over the considered time period. However, at the sub-regional level an increase in emissions over Western Africa and Eastern Africa and a decline of Central Africa were evident among most of the data sources (Fig. 4, S2, S3 and S4).

3.2 Agricultural emissions

3.2.1 Global and regional net emissions

Global values showed a good agreement in emissions from agriculture among the three data sources (Table 4; Fig. 5). All the sources indicated an increase in the agricultural emissions over time, with values of 5.89, 6.08, and 6.27 GtCO₂ eq. year⁻¹ (for FAOSTAT, EDGAR, and EPA, respectively) for the recent period (2011–2018). Global agricultural emissions were generally higher than the FOLU emissions (comparing total emissions in Tables 2 and 4). Analysis of the contribution of the different GHGs generally indicates

Table 3 Comparisons of emission estimates for organic soils for the tropical and non-tropical regions. The three book keeping models use the same source of dataset for organic soils emissions in calculating the total FOLU emissions

Dataset	1990–1999			2000–2010			2011–2018		
	Tropics	Other	Total	Tropics	Other	Total	Tropical	Other	Total
FAOSTAT	0.75	0.21	0.96	0.75	0.18	0.93	0.77	0.21	0.98
NGHGs	-	-	-	0.55	0.29	0.84	0.69	0.28	0.97
BLUE, OSCAR and H&N2017	0.59	0.30	0.89	0.50	0.27	0.77	0.57	0.28	0.85

Table 4 Contribution of CO₂, CH₄, and N₂O to the global and tropical regions agricultural emissions from FAOSTAT, EDGAR and EPA

	Global				Tropics			
	CO ₂	CH ₄	N ₂ O	Total	CO ₂	CH ₄	N ₂ O	Total
1990–1999								
FAOSTAT	-	2.95	2.22	5.17	-	1.50	0.86	2.36
EDGAR	0.71	2.93	1.50	5.14	0.56	1.54	0.62	2.72
EPA	-	2.96	2.60	5.56	-	1.72	1.30	3.02
2000–2010								
FAOSTAT	-	3.05	2.46	5.51	-	1.70	1.04	2.74
EDGAR	0.85	3.02	1.63	5.50	0.71	1.74	0.76	3.21
EPA	-	3.00	2.74	5.74	-	1.85	1.47	3.32
2011–2018								
FAOSTAT	-	3.18	2.71	5.89	-	1.87	1.21	3.08
EDGAR	1.04	3.25	1.79	6.08	0.88	1.94	0.87	3.69
EPA	-	3.21	3.06	6.27	-	2.06	1.64	3.70

higher methane emissions compared to carbon dioxide and nitrous oxide over all the considered time periods (Table 4).

Regional analyses indicate that the emissions were generally higher in South and Southeast Asia followed by Latin America and sub-Saharan Africa for EDGAR and FOASTAT (Fig. 5). The total emissions over the tropical regions were 3.08, 3.69, and 3.70 GtCO₂ eq. year⁻¹ for the period 2011–2018. Overall, the regions contributed to about 50–60% of the global agricultural emissions. All data sources indicate a slight increase in the emissions in all the three tropical regions. Sub-regional analyses showed a good agreement among the data sources in Latin America and South and Southeast Asia (Fig. S5). In contrast to the

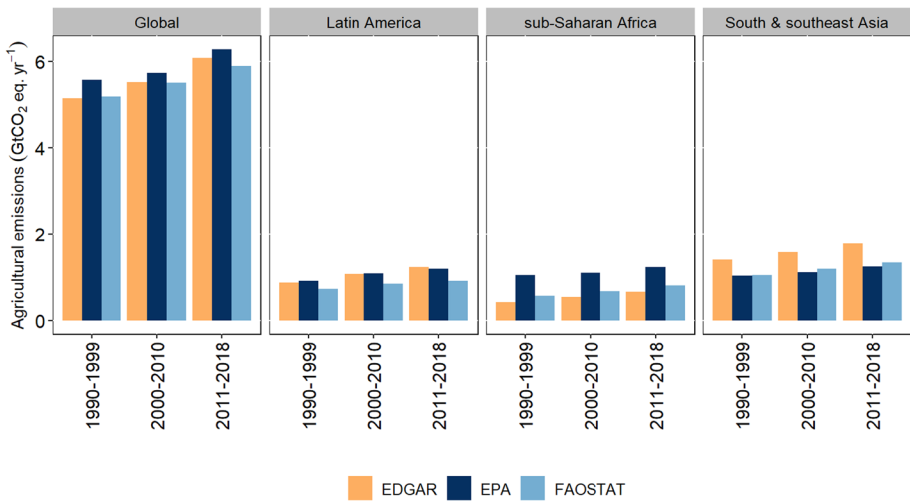


Fig. 5 Global and tropical regions net agricultural emissions (GtCO₂ eq. yr⁻¹) estimates from EDGAR, EPA and FAOSTAT

FOLU emissions, agricultural emissions were generally higher in Southeast Asia than in South Asia across the three data sources. The agricultural emissions from Latin America were mainly from South America. The total EPA emissions for the four sub-regions in sub-Saharan Africa were consistently higher than the estimates from EDGAR and FAOSTAT, with differences of up to 0.3 GtCO₂ eq. year⁻¹ over Central Africa (Fig. S5).

3.2.2 Disaggregated agricultural emissions.

Disaggregated values show a good agreement on the global and tropical region emissions from livestock, cropland, and rice cultivation, while there was a discrepancy in the emissions from agricultural fires (Fig. 6). All the data sources indicate that the livestock sector is the major contributor to agricultural emissions globally followed by croplands, rice cultivation and biomass burning from agricultural activities. Over the period 2011–2018, the global emissions from livestock were 2.52, 2.41, and 2.56 GtCO₂ eq. year⁻¹ for EDGAR, EPA, and FAOSTAT, respectively (Fig. 6), with the total emissions for the three tropical regions being 1.49, 1.32, and 1.43 GtCO₂ eq. year⁻¹. All the data sources show an increase in the global emissions from cropland cultivation and livestock, while there were no notable changes in the rice cultivation emissions. EDGAR and EPA had higher agricultural fire emissions compared to FAOSTAT globally and for the tropics (Fig 6).

Regional analyses showed that the largest livestock emissions were from Latin America followed by South and Southeast Asia, with lower values in sub-Saharan Africa (Fig. 7). The increase in the cropland emissions was evident across the three tropical regions, while an increase in the livestock emissions was more evident in sub-Saharan Africa and Latin America. Emissions from rice cultivation remained constant over time, with the South and Southeast Asia region being the major contributor. Although there was generally good agreement on the global emissions caused by agricultural fires among the EPA and EDGAR datasets, regional analyses show substantial differences in the emissions from sub-Saharan Africa with EPA estimates being much higher than EDGAR (Fig. 7). Further analyses show that this difference is mainly due to the emissions in Central Africa, with EPA estimating large emissions from agricultural fires compared to EDGAR and FAOSTAT. This also explains why the total agricultural emission estimates for EPA were larger than the other two data sources in Central Africa.

4 Discussion

4.1 Forest-related emissions

Causes of different FOLU estimates in the available global data sources have been assessed in detail in previous studies and can be broadly categorized into two: (1) differences in the system boundaries and (2) different estimates from similar contributing processes. For bookkeeping models and GHGIs, the differences in the system boundaries mainly result from varying spatial areas of managed lands with bookkeeping models having a broader definition of these lands (Grassi et al. 2018). In addition, there are conceptual differences in accounting for the direct and indirect human-induced effects of land-use change: NGH-GIs include the indirect effects of CO₂ fertilization, N deposition, and changes in climatic variables (e.g., temperature and precipitation), while bookkeeping models only account

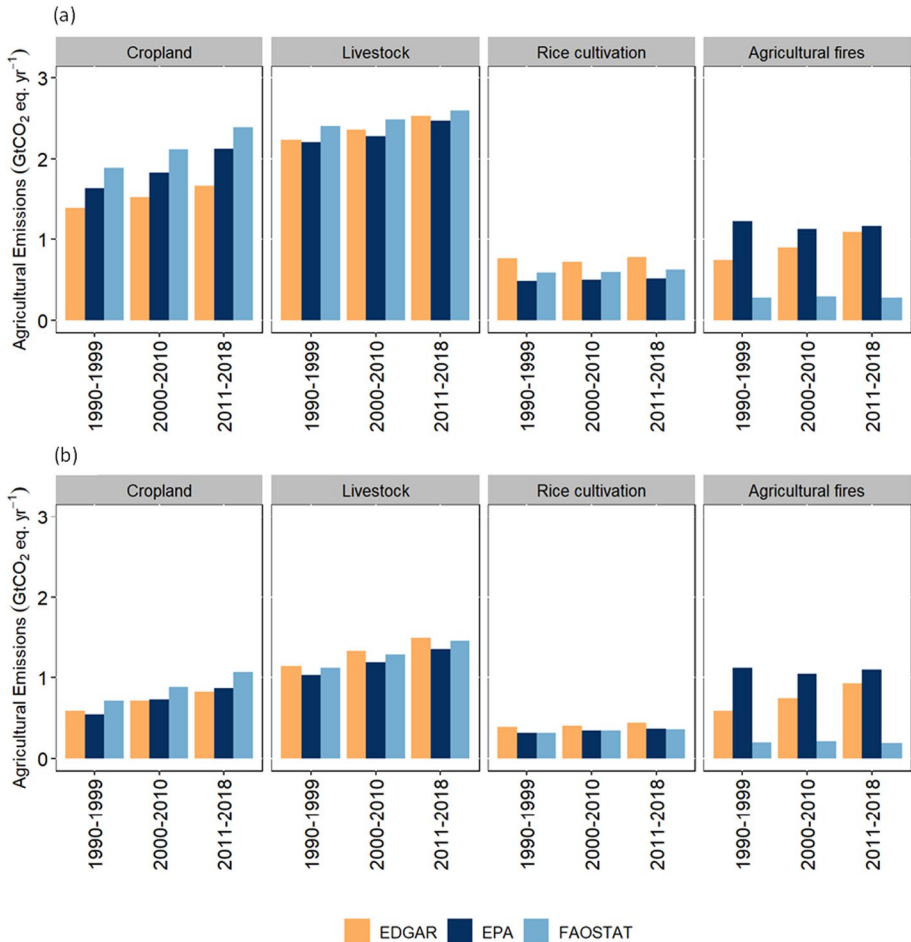


Fig. 6 (a) Global and (b) Tropical region disaggregated gross emissions from different agricultural activities

for the direct effects of land-use change, harvest, and management. Differences between FAOSTAT and NGHGI can be attributed to differences in estimates of the forest land area, incomplete accounting of all the carbon pools in FAOSTAT, and different methodologies in accounting for sink in some of the non-Annex 1 countries (Grassi et al. 2022b). Here, we assessed the differences in these three data sources through analysing both the net emissions and disaggregated emissions for the different FOLU activities.

The estimated difference in the net emissions for the tropics between the NGHGI and bookkeeping models is about 3.82 GtCO₂ year⁻¹ in the 2011–2018 period, assuming an average of 4.99 GtCO₂ year⁻¹ in the three booking models estimates (5.47, 5.22, and 4.28 GtCO₂ year⁻¹ in BLUE, OSCAR, and updated H&N2017, respectively - Table 2). The generally higher emissions in BLUE compared to the updated H&N2017 model are largely due to differences in carbon densities between natural or primary vegetation and secondary vegetation, and higher allocation of cleared and harvested material to fast turnover pools in BLUE compared to HN2017 (Bastos et al. 2021). The disaggregated emission data show

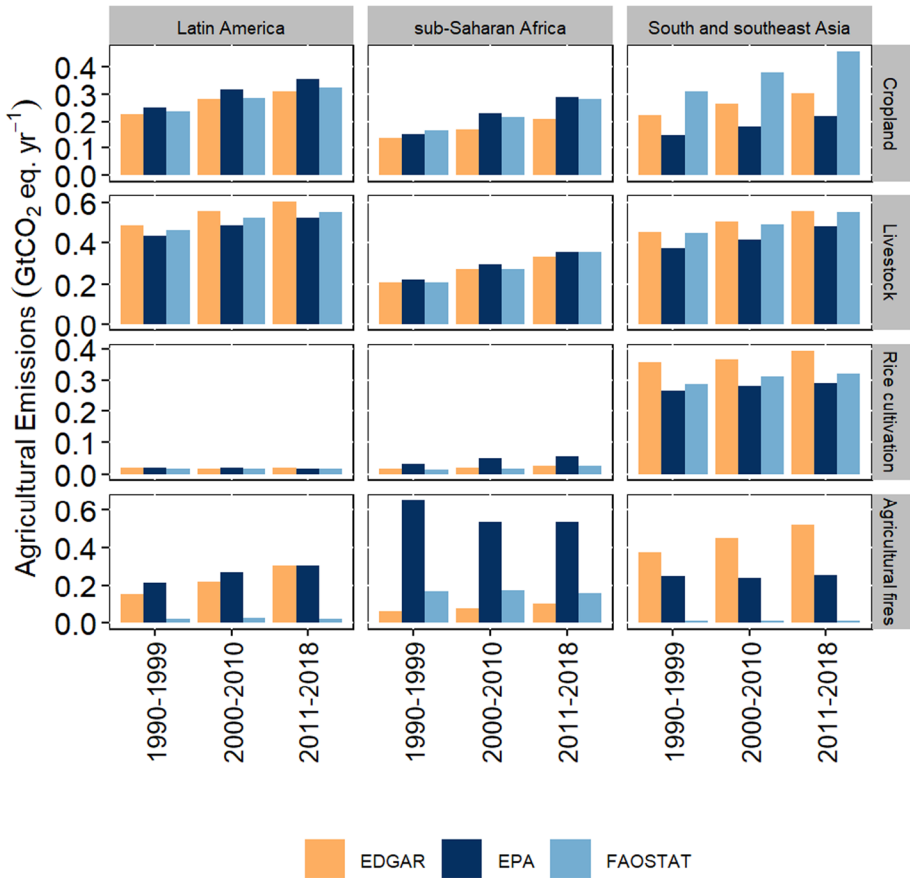


Fig. 7 Disaggregated gross emissions from different agricultural activities for the three tropical regions

that the differences in the emissions for the tropics between NGHGIs and the H&N2017 model are mainly due to the varying estimates of the forestland sink, which stems from the differences in the systems boundaries explained above. Although the results show a good agreement in the forest sink estimate between NGHGIs and FAOSTAT in Latin America, a difference of about 2 GtCO₂ year⁻¹ exists in sub-Saharan Africa and South and Southeast Asia. The differences in the sink between FAOSTAT and NGHGIs are mainly related to the different estimates of the forestland areas and carbon pools. In particular, Grassi et al. (2022a) found that five countries in the tropics (i.e., Malaysia, Philippines, Central African Republic, Mali, and Namibia) report an implausible forest sink due to the inaccurate implementation of the IPCC methodology. In addition, there is a large uncertainty in the carbon stock changes over time in the two data sources. Schwingshackl et al. (2022) investigated differences in NGHGIs and bookkeeping model estimates that remained even after the sink induced by environmental changes on managed forest land was accounted for in detail for several countries, including Brazil, Indonesia, and the DR Congo. Various shortcomings are discussed, such as the land-use data underlying the bookkeeping model estimates likely underestimating forest cover changes in Brazil or the NGHGIs capturing only parts of the substantial forest degradation in Indonesia and the DR Congo.

The disaggregated data show a difference of up to 2 GtCO₂ year⁻¹ the deforestation emissions, with the largest difference mainly stemming from the tropical regions of sub-Saharan Africa and South and Southeast Asia. This difference can be mainly attributed to the differences in the accounting in the considered data sources. FAOSTAT provides net forest conversion fluxes where the net loss emissions are discounted against the gains from forest area increase (Tubiello et al. 2021), while the NGHGs and bookkeeping models provide gross deforestation fluxes. This explains why the deforestation fluxes in FAOSTAT were lower than the bookkeeping model and NGHGs estimates. For the NGHGs, some countries (e.g., India) do not report gross deforestation emissions, but instead provide net fluxes (Grassi et al. 2023). Excluding the gains from forest recovery and regrowth would increase the estimated deforestation emissions and provide a better indication of the absolute mitigation potential in forests. Although the bookkeeping models estimate higher emissions than NGHGs, a recent study has shown that deforestation emission in the models are much lower when using high resolution data (Ganzenmüller et al. 2022). Overall the gross deforestation emission values of 2.96 to 5.43 GtCO₂ eq. year⁻¹ in the three data sources are within the range of the gross forest emission values of 5.3 ± 2.4 GtCO₂ eq. year⁻¹ estimated using spatially observed data combined with IPCC factors (Harris et al. 2021).

4.2 Other land use–related emissions

Emissions from other land use activities (e.g., shifting cultivation, non-forest related land use conversions, biomass burning, and peatland drainage) in the tropical regions are relatively small compared to those from deforestation. The net emissions for these activities were larger in the bookkeeping models compared to FAOSTAT and NGHGs. The higher deforestation emissions mainly stem from shifting cultivation, particularly for the tropical regions. Shifting cultivation has a relatively large importance, and a strong sensitivity has been shown towards the choice of underlying land-use dataset and spatial resolution (Ganzenmüller et al. 2022). Excluding emissions from organic soils in the other land use emission estimates in the NGHGs indicates that croplands, grasslands, and wetlands contribute to a sink of CO₂ in the tropical regions. However, most non-Annex 1 countries do not account for all emissions from other land use activities in their national reporting (Grassi et al. 2021; Grassi et al. 2018), which may explain why these are nearly negligible in sub-Saharan Africa and Latin America. A lack of reporting of these values may lead to uncertainties in the global stocktake especially when comparing NGHGs to other data sources. While emissions from these activities are currently small and do not exhibit a clear trend (Figs. 2 and 3), current national and global efforts to curb deforestation are likely to shift the trends in the land-use and land-use change activities. Increased activities in grassland areas and poor management of cropland areas are also likely to increase emissions from other land use; thus, making them equally relevant for the global stocktake.

Overall, our regional analyses provided insights on the trend of the three tropical regions. Kondo et al. (2022) found no clear trend in the net FOLU emissions for Southeast Asia with the two bookkeeping models indicating differing trends — the BLUE model indicated an increase while the HN2017 model a decrease. The additional analyses with FAOSTAT and NGHGs indicate no clear trend in the emissions for the same region. A slight decline in the emissions over Latin America and an increase over sub-Saharan Africa is evident in all the data sources. This is in line with a recent study which shows that the upward trend in emissions over Brazil has likely been overestimated due to artifacts in earlier land-use datasets (Rosan et al. 2021). A recent study covering the same period

in this study showed that there has been a global increase in the net AFOLU emissions (Lamb et al. 2021). The analyses presented here show that for the tropics, this increase is mainly from agricultural emissions and an increase in FOLU emissions particularly over sub-Saharan Africa. Although the analyses show a decline in the deforestation emissions over Latin America over the period 1990–2018, which is mainly because of government initiatives (Nepstad et al. 2014), this trend is likely to have reversed subsequently, as the 2019 and 2020 season had the highest deforestation rates in the Amazon region since 2008 (Silva Junior et al. 2021).

4.3 Agriculture-related emissions

Total global agricultural emissions for the considered period were more than the emissions from FOLU activities, with fewer discrepancies between the data sources for the emissions from livestock, cropland, and rice cultivation. The high level of agreement on the net emissions for the agricultural sector is because the considered data sources generally rely on the same activity data from FAO statistics. However, there are some small differences in the estimates between the data sources. Agricultural emission estimates from FAOSTAT solely rely on the IPCC Tier 1 methodology (FAO 2022). While most of the estimates in EDGAR are also based on Tier 1 methodology, CH₄ emission factors for enteric fermentation of dairy and non-dairy cattle have been updated including the IPCC 2006 Tier 2 methodology (Crippa et al. 2019). In addition, EDGAR uses data from both FAO statistics and International Fertilizer Association (IFA) in calculating N₂O and CO₂ emissions from fertilizer and urea use (Janssens-maenhout et al. 2019). This explains observed differences in the emission estimates between FAOSTAT and EDGAR. Quantifying agricultural emissions has clearly received less attention than forestry and other land use emissions, and the hidden assumption in estimates based largely on Tier 1 factors is that there is not a lot of spatial or temporal variability in these emissions. This is an argument for a greater diversity of approaches to better estimate the spatial and temporal variation of these emissions.

The results show that emissions from biomass burning in agricultural areas are highly uncertain, with FAOSTAT estimating small emissions compared to the other two data sources. The higher emissions in EPA compared to EDGAR, particularly for sub-Saharan Africa, is mainly because EPA estimates include emissions from savannah burning for agricultural expansions and these are not accounted for in EDGAR (Crippa et al. 2019). A lack of detailed and comprehensive reporting of national emissions from agricultural activities like that of FOLU limits a comparative analysis of these emissions. Future comparative analysis could benefit from improved agricultural reporting, and this would help in understanding the limitations of existing agricultural emissions databases.

Only FAOSTAT provides both agriculture and FOLU emissions. Summing the values in Table 2 and 4 results in 6.14 and 7.00 GtCO₂ eq. year⁻¹ AFOLU emissions globally and for the tropics over the period 2011–2018. The global value is much lower than the 12 GtCO₂ eq. year⁻¹ estimated by Lamb et al. (2021) for 2018. The latest IPCC AR6 report offers net global emission values of 6.49 GtCO₂ eq. year⁻¹ for LULUCF only (11% of the global 59 GtCO₂ eq. year⁻¹ GHG emissions) (Figure TS.6 in Pathak et al. (2022)); thus, the emissions presented here are much lower than the AR6 estimate. The main reason for these lower emissions is they do not account for CH₄ and N₂O emissions from savannah burning and peatland and forest fires. Of the three FOLU emission datasets in our analysis, only FAOSTAT explicitly includes emissions from forest fires, but these are relatively small (0.26 GtCO₂ eq. year⁻¹ for 2011–2018) and only account for CO₂ emissions only. In

addition, CH₄ and N₂O emissions from drained peatland soils and wetlands over managed lands are still not accounted for in the databases and in the recent AR6 estimates, although these emissions can be high (Hergoualc'h et al. 2020; Swails et al. 2021). Integrating emissions from fires, peatlands, and wetlands in the country reporting and global databases would also provide a more complete assessment of the AFOLU emissions.

5 Conclusion

This study provided a detailed comparative analysis of the emissions estimates from available global datasets for the AFOLU sector. The total net FOLU emissions for the tropical regions ranged between 1.17 and 5.47 GtCO₂ year⁻¹ compared to global values of -2.03 to 5.16 GtCO₂ year⁻¹ over the period 2011–2018 in the four analysed datasets. Disaggregated analyses show that these emissions are mainly from deforestation (2.96 to 7.16 GtCO₂ year⁻¹) and partly from other land-use activities (0.45 to 1.56 GtCO₂ year⁻¹), which exceed the net forestland sink (-0.53 to -3.08 GtCO₂ year⁻¹) and make the tropical region a net source of emissions for the FOLU sector. In terms of trend, three of the five data sources (updated H&N2017, FAOSTAT, and NGHGs) indicate a decline in the net emissions over the tropics, which is also present globally. The net agricultural pantropical emissions range between 3.08 and 3.70 GtCO₂ eq. year⁻¹, with all the data sources showing an increase. Emissions from deforestation and biomass burning are the most uncertain for the agricultural sector are highly uncertain for the tropical region.

Our analyses show that for global FOLU assessments, efforts have been made to provide more detailed datasets that allow for an assessment of not only net FOLU emissions, but also gross fluxes for the different contributing activities to this sector. Despite these advancements and the availability of more years of data, we find that there are still important gaps and that many emission sources are still not fully accounted for in the global databases. This is not new as Roman-Cuesta et al. (2016a) had already pointed out to the incomplete accounting of sources, such as from forest fires and peatland emissions, and not including non-CO₂ in the FOLU estimates, particularly N₂O and CH₄ emissions from forest fires. Given that most of the considered databases are likely to play a major role in the global stocktake, efforts should shift towards ensuring that all emission sources are fully accounted for, and more consistency is developed. Moreover, there is an urgent need to offer geographically appropriate AFOLU emissions factors, so that land managers, policy makers, and society can efficiently concentrate efforts and resources towards the existing hotspots of emissions. Aggregated country estimates for greenhouse gas emissions remain a barrier for targeted action and improving mitigation governance. In that line, spatial data such as those published by Roman-Cuesta et al. (2016b) and Harris et al. (2021) show a way forward. Nevertheless, our analysis shows that the existing databases can be an important resource in providing a benchmark for NGHGs in assessing the plausibility of their estimates, while investing in more detailed, complete, and accurate data is a key priority to underpin the current and future global stocktakes, considering both national to global level assessments.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s11027-023-10096-z>.

Acknowledgements We thank Clemens Schwingshackl for providing us with the net and disaggregated FOLU emissions for the three bookkeeping models.

Funding This work was funded by USAID through the CGIAR Trust Fund and by Norad through grant # QZA-21/0124 CIFOR under the CGIAR Mitigate+ initiative.

Data availability The national GHGs, FAOSTAT, EDGAR, and EPA used in the present study are openly available through the links (<https://doi.org/10.5281/zenodo.6390739>; <https://www.fao.org/faostat/en/#data/GT>; https://edgar.jrc.ec.europa.eu/dataset_ghg60; <https://www.epa.gov/global-mitigation-non-co2-green-house-gases/global-non-co2-ghg-emissions-1990-2030>). The country-level net emissions for the bookkeeping models are available at the Global Carbon Budget webpage (<https://www.globalcarbonproject.org/carbonbudget/>), while the disaggregated data are available upon author request.

Declarations

Conflict of interest The authors declare no competing interests.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.


References

- Bastos A, Hartung K, Nützel TB, Nabel JEMS, Houghton RA, Pongratz J (2021) Comparison of uncertainties in land-use change fluxes from bookkeeping model parameterisation. *Earth Syst Dynam* 12(2):745–762. <https://doi.org/10.5194/esd-12-745-2021>
- Crippa M, Oreggioni G, Guizzardi D, Muntean M, Schaaf E, Lo Vullo E, Solazzo E, Monforti-Ferrario F, Olivier JGJ, Vignati E (2019) Fossil CO₂ and GHG emissions of all world countries - 2019 report. <https://doi.org/10.2760/687800>
- Crippa M, Solazzo E, Huang G, Guizzardi D, Koffi E, Muntean M, Schieberle C, Friedrich R, Janssens-Maenhout G (2020) High resolution temporal profiles in the Emissions Database for Global Atmospheric Research. *Scientific Data* 7(1):1–17. <https://doi.org/10.1038/s41597-020-0462-2>
- Deb Richter D, Houghton RA (2011) Gross CO₂ fluxes from land-use change: Implications for reducing global emissions and increasing sinks. *Carbon Manag* 2(1):41–47. <https://doi.org/10.4155/cmt.10.43>
- FAO (2020a) Global Forest Resources Assessment 2020 — key findings. In: *Global Forest Resources Assessment 2020*. FAO. <https://doi.org/10.4060/ca8753en>
- FAO (2020b) Global Forest Resources Assessment 2020: main report. In: *Global Forest Resources Assessment 2020*. FAO, 10.4060/ca9825en
- FAO. (2022). FAOSTAT Climate Change, Emissions, Emissions Totals
- Federici S, Tubiello FN, Salvatore M, Jacobs H, Schmidhuber J (2015) New estimates of CO₂ forest emissions and removals: 1990–2015. *For Ecol Manage* 352:89–98. <https://doi.org/10.1016/j.foreco.2015.04.022>
- Friedlingstein P, Sullivan MO, Jones MW, Andrew RM, Gregor L, Hauck J, Le Quéré C, Luijkx IT, Olsen A, Peters GP, Peters W (2022) Global carbon budget 2022. *Earth Syst Sci Data* 14:4811–4900. <https://essd.copernicus.org/articles/14/4811/2022/>
- Ganzenmüller R, Bultan S, Winkler K, Fuchs R, Zabel F, Pongratz J (2022) Land-use change emissions based on high-resolution activity data substantially lower than previously estimated land-use change emissions based on high-resolution activity data substantially lower than previously estimated. *Environ Res Lett* 17(6):064050. <https://doi.org/10.1088/1748-9326/ac70d8>
- Gasser T, Crepin L, Quilcaille Y, Houghton RA, Ciais P, Obersteiner M (2020) Historical CO₂ emissions from land use and land cover change and their uncertainty. *Biogeosciences* 17(15):4075–4101. <https://doi.org/10.5194/bg-17-4075-2020>
- Grassi G, Conchedda G, Federici S, Abad Viñas R, Korosuo A, Melo J, Rossi S, Sandker M, Somogyi Z, Vizzarri M, Tubiello FN (2022a) Carbon fluxes from land 2000–2020: bringing clarity to countries' reporting. *Earth Syst Sci Data* 14(10):4643–4666. <https://doi.org/10.5194/essd-14-4643-2022>
- Grassi G, Federici S, Abad-Vinas R, Korosuo A, Rossi S (2022b) LULUCF data based on National GHG inventories (NGHGI DB). <https://doi.org/10.5281/ZENODO.7190601>

- Grassi G, House J, Kurz WA, Cescatti A, Houghton RA, Peters GP, Sanz MJ, Viñas RA, Alkama R, Arneth A, Bondeau A, Dentener F, Fader M, Federici S, Friedlingstein P, Jain AK, Kato E, Koven CD, Lee D et al (2018) Reconciling global-model estimates and country reporting of anthropogenic forest CO₂ sinks. *Nature Climate Change* 8(10):914–920. <https://doi.org/10.1038/s41558-018-0283-x>
- Grassi G, Schwingshackl C, Gasser T, Houghton RA, Sitch S, Canadell JG, Cescatti A, Ciais P, Federici S, Friedlingstein P (2023) Harmonising the land-use flux estimates of global models and national inventories for 2000–2020. *Earth Syst Sci Data* 15:1093–1114
- Grassi G, Stehfest E, Rogelj J, Van Vuuren D, Cescatti A, House J, Nabuurs G, Rossi S, Alkama R, Viñas RA, Calvin K, Ceccherini G, Federici S, Fujimori S, Gusti M (2021) Critical adjustment of land mitigation pathways for assessing countries' climate progress. *Nat Clim Change* 11:425–434. <https://doi.org/10.1038/s41558-021-01033-6>
- Hansis E, Davis SJ, Pongratz J (2015) Relevance of methodological choices for accounting of land use change carbon fluxes Special Section. *Global Biogeochem Cycles* 29:1230–1246. <https://doi.org/10.1002/2014GB004997>
- Harris NL, Gibbs DA, Baccini A, Birdsey RA, de Bruin S, Farina M, Fatoyinbo L, Hansen MC, Herold M, Houghton RA, Potapov PV, Suarez DR, Roman-Cuesta RM, Saatchi SS, Slay CM, Turubanova SA, Tyukavina A (2021) Global maps of twenty-first century forest carbon fluxes. *Nature Climate Change* 11(3):234–240. <https://doi.org/10.1038/s41558-020-00976-6>
- Hergoualc'h K, Dezeo N, Verchot LV, Martius C, Lent J, Aguila-Pasquel J, López Gonzales M (2020) Spatial and temporal variability of soil N₂O and CH₄ fluxes along a degradation gradient in a palm swamp peat forest in the Peruvian Amazon. *Glob Chang Biol* 26(12):7198–7216. <https://doi.org/10.1111/gcb.15354>
- Houghton RA (2003) Revised estimates of the annual net flux of carbon to the atmosphere from changes in land use and land management 1850–2000. *Tellus B Chem Phys Meteorol* 55(2):378–390. <https://doi.org/10.1034/j.1600-0889.2003.01450.x>
- Houghton RA, Nassikas AA (2017) Global and regional fluxes of carbon from land use and land cover change 1850–2015. *Global Planet Change* 31:456–472. <https://doi.org/10.1002/2016GB005546>
- Hurrut GC, Chini L, Sahajpal R, Frolking S, Bodirsky BL, Calvin K, Doelman JC, Fisk J, Fujimori S, Klein Goldewijk K, Hasegawa T, Havlik P, Heinemann A, Humpenöder F, JungCLAUS J, Kaplan JO, Kennedy J, Kristin T, Lawrence D, Lawrence P, Ma L, Mertz O, Pongratz J, Popp A, Poulter B, Riahi K, Shevliakova E, Stehfest E, Thornton P, Tubiello FN, van Vuuren DP, Zhang X (2020) Harmonization of global land use change and management for the period 850–2100 (LUH2) for CMIP6. *Geosci. Model Dev* 13:5425–5464. <https://doi.org/10.5194/gmd-13-5425-2020>
- IPCC (2022) Climate change 2022: mitigation of climate change. In: Shukla PR, Skea J, Slade R, Al Khourdajie A, van Diemen R, McCollum D, Pathak M, Some S, Vyas P, Fradera R, Belkacemi M, Hasija A, Lisboa G, Luz S, Malley J (eds) Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, USA
- Janssens-maenhout G, Crippa M, Guizzardi D, Muntean M, Schaaf E, Klimaschutz F, Emissionshandelsstelle D (2019) EDGAR v4 . 3 . 2 Global Atlas of the three major greenhouse gas emissions for the period 1970 – 2012. *Earth Syst Sci Data* 11:959–1002
- Kondo M, Sitch S, Ciais P, Achard F, Kato E, Pongratz J, Houghton RA, Canadell JG, Patra PK, Friedlingstein P, Li W, Anthoni P, Arneth A, Chevallier F, Ganzenmüller R, Harper A, Jain AK, Koven C, Lienert S et al (2022) Are land-use change emissions in Southeast Asia decreasing or increasing? *Global Biogeochem Cycles* 36(1). <https://doi.org/10.1029/2020GB006909>
- Lamb WF, Wiedmann T, Pongratz J, Andrew R, Crippa M, Olivier JGJ, Wiedenhofer D, Mattioli G, Al Khourdajie A, House J, Pachauri S, Figueroa M, Saheb Y, Slade R, Hubacek K, Sun L, Ribeiro SK, Khennas S, De La Rue D et al (2021) A review of trends and drivers of greenhouse gas emissions by sector from 1990 to 2018. *Environ Res Lett* 16(7). <https://doi.org/10.1088/1748-9326/abee4e>
- Maria A, Petrescu R, Peters GP, Janssens-maenhout G, Ciais P, Tubiello FN, Grassi G, Nabuurs G, Leip A, Carmona-garcia G, Winiwarter W, Höglund-isaksson L, Günther D, Solazzo E, Kiesow A (2020) European anthropogenic AFOLU greenhouse gas emissions : a review and benchmark data. *Earth Syst Sci Data* 3662371:961–1001. <https://doi.org/10.5194/essd-12-961-2020>
- Nepstad D, McGrath D, Stickler C, Alencar A, Azevedo A, Swette B, Bezerra T, DiGiano M, Shimada J, Da Motta RS, Armijo E, Castello L, Brando P, Hansen MC, McGrath-Horn M, Carvalho O, Hess L (2014) Slowing Amazon deforestation through public policy and interventions in beef and soy supply chains. *Science* 344(6188):1118–1123. <https://doi.org/10.1126/science.1248525>
- Pathak M, Slade R, Shukla PR, Skea J, Pichs-Madruga R, Ürge-Vorsatz D (2022) Technical Summary. In: Shukla PR, Skea J, Slade R, Al Khourdajie A, van Diemen R, McCollum D, Pathak M, Some S, Vyas P, Fradera R, Belkacemi M, Hasija A, Lisboa G, Luz S, Malley J (eds) Climate change 2022:

- mitigation of climate change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp 1–145. <https://doi.org/10.1017/9781009157926.002>
- Pongratz J, Reick CH, Houghton RA, House JI (2014) Terminology as a key uncertainty in net land use and land cover change carbon flux estimates. *Earth Syst Dynam* 5:177–195. <https://doi.org/10.5194/esd-5-177-2014>
- Roman-Cuesta RM, Herold M, Rufino MC, Rosenstock TS, Houghton RA, Rossi S, Butterbach-Bahl K, Ogle S, Poulter B, Verchot L, Martius C, De Bruin S (2016a) Multi-gas and multi-source comparisons of six land use emission datasets and AFOLU estimates in the Fifth Assessment Report, for the tropics for 2000–2005. *Biogeosciences* 13(20):5799–5819. <https://doi.org/10.5194/bg-13-5799-2016>
- Roman-Cuesta RM, Rufino M, Herold M, Butterbach-Bahl K, Rosenstock TS, Herrero M, Ogle S, Li C, Poulter B, Verchot L, Martius C, Stuver J, De Bruin S (2016b) Hotspots of gross emissions from the land use sector: patterns, uncertainties, and leading emission sources for the period 2000–2005 in the tropics. *Biogeosciences* 13(14):4253–4269. <https://doi.org/10.5194/bg-13-4253-2016>
- Romijn E, Herold M, Kooistra L, Murdiyarto D, Verchot L (2012) Assessing capacities of non-Annex I countries for national forest monitoring in the context of REDD+. *Environ Sci Policy* 19–20:33–48. <https://doi.org/10.1016/j.envsci.2012.01.005>
- Romijn E, Lantican CB, Herold M, Lindquist E, Ochieng R, Wijaya A, Murdiyarto D, Verchot L (2015) Assessing change in national forest monitoring capacities of 99 tropical countries. *For Ecol Manage* 352:109–123. <https://doi.org/10.1016/j.foreco.2015.06.003>
- Rosan TM, Goldewijk KK, Ganzenmüller R, Sullivan MO (2021) A multi-data assessment of land use and land cover emissions from Brazil during 2000–2019 OPEN ACCESS. *Environ Res Lett* 16:074004. <https://doi.org/10.1088/1748-9326/ac08c3/pdf>
- Schwingshackl C, Obermeier WA, Bultan S, Kurz WA, Sitch S, Pongratz J (2022) Differences in land-based mitigation estimates reconciled by separating natural and land-use CO₂ fluxes at the country level Graphical abstract Differences in land-based mitigation estimates reconciled by separating natural and land-use CO₂ flux. *One Earth* 5(12):1367–1376. <https://doi.org/10.1016/j.oneear.2022.11.009>
- Silva Junior CHL, Pessôa ACM, Carvalho NS, Reis JBC, Anderson LO, Aragão LEOC (2021) The Brazilian Amazon deforestation rate in 2020 is the greatest of the decade. *Nat Ecol Evol* 5(2):144–145. <https://doi.org/10.1038/s41559-020-01368-x>
- SmithP, Bustamante M, Ahammad H, Clark H, Dong H, Elsiddig E, Harberl H, Harper R, House J, Jafari M, Masera O, Mbow C, Ravindranath N, Rice C, Robledo Abad C, Romanisvskaya A, Sperling F, Tubiello F, Berndes G, ..., Suh S, van MJB (2014) Agriculture, forestry and other land use (AFOLU), in: *Climate change 2014: mitigation of climate change, Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_chapter11.pdf
- Swails E, Hergoualc’h K, Verchot L, Novita N, Lawrence D (2021) Spatio-temporal variability of peat CH₄ and N₂O fluxes and their contribution to peat GHG budgets in Indonesian forests and oil palm plantations. *Frontiers in Environmental. Science* 9. <https://doi.org/10.3389/fenvs.2021.617828>
- Tubiello F, Conchedda G, Wanner N, Federici S, Rossi S, Grassi G (2021) Carbon emissions and removals from forests: new estimates, 1990–2020. *Earth Syst Sci Data* 13(4):1681–1691. <https://doi.org/10.5194/essd-13-1681-2021>
- Tubiello F, Salvatore M, Córdor Golec R, Ferrara A, Rossi S, Biancalani R, Federici S, Jacobs H, Flammini A (2014) Agriculture, forestry and other land use emissions by sources and removals by sinks 1990–2011 analysis (Working Paper Series ESS/14-02. FAO Statistical Division
- Tubiello F, Salvatore M, Rossi S, Ferrara A, Fitton N, Smith P (2013) The FAOSTAT database of greenhouse gas emissions from agriculture. *Environ Res Lett* 8. <https://doi.org/10.1088/1748-9326/8/1/015009>
- UNFCCC (2016) The Paris Agreement. https://treaties.un.org/Pages/ViewDetails.aspx?src=TREATY&mtdsg_no=XXVII-7-
- UNFCCC Secretariat (2020) Reference manual for the enhanced transparency framework under the Paris Agreement. 1–88
- US EPA (2019) Global non-CO₂ greenhouse gas emission projections & marginal abatement cost analysis: Methodology Documentation. September, 287.

Authors and Affiliations

Sylvia S. Nyawira¹  · Martin Herold² · Kalkidan Ayele Mulatu³ · Rosa Maria Roman-Cuesta^{4,6} · Richard A. Houghton⁵ · Giacomo Grassi⁶ · Julia Pongratz^{7,8} · Thomas Gasser⁹ · Louis Verchot¹⁰

✉ Sylvia S. Nyawira
S.Nyawira@cgiar.org

¹ International Center for Tropical Agriculture (CIAT), Nairobi, Kenya

² Helmholtz GFZ German Research Centre for Geosciences, Potsdam, Germany

³ International Center for Tropical Agriculture (CIAT), Addis Ababa, Ethiopia

⁴ Technical University of Munich (TUM), Institute of Forest Management, Munich, Germany

⁵ Woodwell Climate Research Center, Falmouth, USA

⁶ Joint Research Centre (JRC), European Commission (EC), Ispra, Italy

⁷ Department für Geographie, Ludwig-Maximilians-Universität Munich, Luisenstr. 37, 80333 München, Germany

⁸ Max Planck Institute for Meteorology, 20146 Hamburg, Germany

⁹ International Institute for Applied Systems Analysis, Laxenburg, Austria

¹⁰ International Center for Tropical Agriculture (CIAT), Cali, Colombia