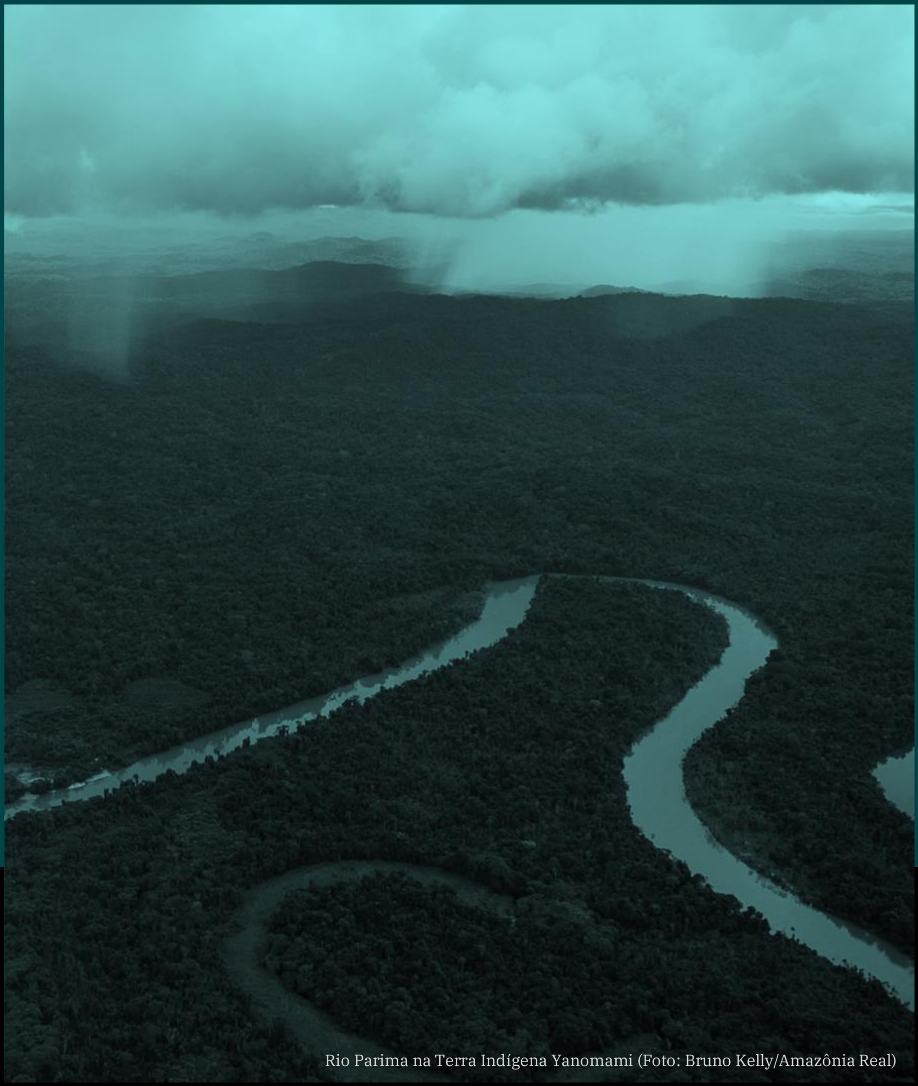
Amazon Assessment Report 2021

Cross Chapter 1
The Amazon Carbon Budget



Rio Parima na Terra Indígena Yanomami (Foto: Bruno Kelly/Amazônia Real)

THE AMAZON WE WANT

Science Panel for the Amazon

SUSTAINABLE DEVELOPMENT SOLUTIONS NETWORK
A GLOBAL INITIATIVE FOR THE UNITED NATIONS

About the Science Panel for the Amazon (SPA)

The Science Panel for the Amazon is an unprecedented initiative convened under the auspices of the United Nations Sustainable Development Solutions Network (SDSN). The SPA is composed of over 200 preeminent scientists and researchers from the eight Amazonian countries, French Guiana, and global partners. These experts came together to debate, analyze, and assemble the accumulated knowledge of the scientific community, Indigenous peoples, and other stakeholders that live and work in the Amazon.

The Panel is inspired by the Leticia Pact for the Amazon. This is a first-of-its-kind Report which provides a comprehensive, objective, open, transparent, systematic, and rigorous scientific assessment of the state of the Amazon's ecosystems, current trends, and their implications for the long-term well-being of the region, as well as opportunities and policy relevant options for conservation and sustainable development.

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Cross-Chapter: The Amazon Carbon Budget

Luciana V. Gatti[a,b], John Melack*[c], Luana S. Basso[a], Natalia Restrepo-Coupe[d], Ana Paula Aguiar[a], Sunitha Pangala[e], Scott R. Saleska[d], Luiz Aragão[a], Oliver L. Phillips[f], Dolors Armenteras[g]*

Abstract

The main objective of this cross-chapter is to summarize the status of the Amazon as a source or sink of carbon (C). The processes and studies involved are detailed in other SPA chapters. The major challenge of determining the Amazon's status as a net C source or sink at a continental scale is that many complex processes contribute to C fluxes. Unlike in other regions, emissions from the burning of fossil fuels are minor contributors to Amazonian fluxes. Instead, the major sinks and sources of C to the atmosphere are associated with the net accumulation or loss of biomass, with losses including deforestation, biomass burning, and tree mortality followed by decomposition. Biomass accumulates in areas where tree growth exceeds losses. The Amazon includes not only intact forests, also but degraded and logged forests, natural non-forests, agricultural and urban areas, and aquatic systems including wetlands that all contribute to regional carbon cycling.

Two methods are used to estimate land-atmosphere carbon balance at broad spatial scales. Bottom-up estimates use field measurements of biomass accumulation and loss (through mortality) in plots, and scale these based on remote sensing and modeling to characterize broad regions of similar vegetation type. Top-down approaches use measurements of CO_2 concentrations taken by satellites and aircraft together with atmospheric transport models to estimate net land-atmosphere fluxes. These fluxes represent all processes, including deforestation, degradation, forest mortality, imbalances between respiration and photosynthesis during dry season stress, biomass burning, agricultural activities, fossil fuel emissions, regrowth of secondary forests, and growth of intact (primary) forests. While forest plot measurements have been in place for several decades, only in the last decade or so have measurements of biomass change from satellites, aircraft, or airborne sensors been available. Thus, estimates of the net C balance at the scale of the whole Amazon have only been produced for the last decade, and there are high levels of uncertainty associated with the integration of different approaches, process, and regions.

Results from top-down and bottom-up studies for the period 2010 through 2019 indicate that the Amazon region as a whole, including all uptake and loss processes describe above, is a carbon source on the order of 0.30 ± 0.20 Pg C y^{-1} and 0.23 ± 0.20 Pg C y^{-1}, respectively. It is important to acknowledge and understand the assumptions behind these two approaches, and further research is needed to understand and reduce differences between them.

CB1. CO_2 Uptake and Emissions

During the last 40 to 50 years, the Amazon has experienced strong human impacts from deforestation and land use change. According to the Brazilian Annual Land Use and Land Cover Mapping Project (Mapbiomas Amazonia 2020), a cumulative total of 17% was deforested by 2019, of which

[a] Earth System Science Center (CCST), National Institute for Space Research (INPE), Av. dos Astronautas, 1.758, Jardim da Granja, São José dos Campos SP 12227-010, Brazil
[b] Nuclear and Energy Research Institute, IPEN-CNEN/SP, Av. Prof. Lineu Prestes, 2242, Butantã, São Paulo SP 05508-000, Brazil
[c] Bren School of Environmental Science and Management, University of California,, Santa Barbara CA 93117, USA
[d] Department of Ecology and Evolutionary Biology, University of Arizona, Tucson AZ 85721, USA
[e] Lancaster Environment Centre, Lancaster University, Library Avenue, Bailrigg, Lancaster LA1 4YQ, UK
[f] School of Geography, University of Leeds, Leeds, United Kingdom
[g] Ecología del Paisaje y Modelación de Ecosistemas ECOLMOD, Departamento de Biología, Facultad de Ciencias, Universidad Nacional de Colombia, Cra 45 #2685, Bogotá, Colombia

agriculture represents 14% (89% pasture and 11% crops) (MapBiomas Amazonia 2020). Inventories from long-term forest plot networks (e.g., RAINFOR), many beginning in the 1980s, provide data on carbon dynamics for intact, mature forests at nearly 300 sites. These individual plots, scaled to the total forested area, indicate that intact forests are a net sink for carbon, although the rate of carbon uptake has decreased over the past three decades, mainly due to increases in mortality (Brienen *et al.* 2015; Phillips and Brienen, 2017; Hubau *et al.* 2020) (see Chapter 6). The carbon sink or uptake (i.e., carbon removal from the atmosphere, reported here with a negative sign) estimated for mature upland forests, scaled to an area of 7.25 x 10^6 km^2, results in an estimate of mean net carbon uptake in intact forests for the 1990s of -0.59 ± 0.18 Pg C y^{-1}. In the first decade of the 2000s, carbon uptake decreased to -0.41 ± 0.20 Pg C y^{-1}, and in the decade of the 2010s was -0.22 ± 0.30 Pg C y^{-1} (see Table CC1; note all studies were scaled to the same area). Reported uncertainties are those reported in the publications and based on the variability among studies. According to these studies, the carbon sink has weakened by around 60% over the course of the last three decades; however, this decrease was not evenly distributed across the Amazon basin (Phillips and Brienen 2017). Historical deforestation and degradation affect the dry season, producing a dryer, hotter, and longer dry season; this is associated with climate trends that make forests more susceptible to fire and increased tree mortality, affecting carbon sinks, including in adjacent forests not directly impacted by fire. These fluxes also vary geographically (Gatti *et al.* 2021).

In the last decade, complementary bottom-up studies have focused on estimating carbon emissions and uptake from different land use and land cover changes (LUCC) (Aguiar *et al.* 2016; Assis *et al.* 2020; Aragão *et al.* 2018; Silva Junior *et al.* 2020; Crippa *et al.* 2019; Smith *et al.* 2020). These studies combined knowledge derived from fieldwork and remote sensing in models. The INPE-EM model (Aguiar *et al.* 2016; Assis *et al.* 2020) considered all LUCC components, and the results are similar to those of component-specific studies (Assis *et al.* 2020; Baccini *et al.* 2017), indicating positive net emissions related to LUCC processes of around 0.37 to 0.48 Pg C y^{-1}. However, there are many uncertainties in such measures, related to estimating actual C emissions during biomass burning, processes of loss, and uptake subsequent to disturbance. All studies in Table CC1 and CC2 are scaled to the area of the Amazon *sensu latissimo*, i.e., the entire Amazon Rainforest ecoregion without the Planalto (cerrado) (as delineated in Figure CC.2b) (Eva et al. 2005). Studies done in the Brazilian Amazon were scaled to the Amazon *sensu latissimo* without the Brazilian Planalto, based on the proportion of deforested area based on MapBioma analyses for both regions.

Based on eddy flux towers (Restrepo-Coupe *et al.* 2013; Saleska *et al.* 2013) and aircraft vertical profiles (Gatti *et al.* 2021), Figure CC.1 illustrates regional differences in carbon flux related to land use change and the occurrence of intact forests. In general, more carbon is absorbed in the western Amazon than the eastern (Malhi *et al.* 2015; Gatti *et al.* 2021) (see Chapters 4 and 6). Regional distributions of carbon emissions and uptake are shown in Figure CC.2 (adapted from Phillips and Brienen 2017), and are associated with geographical differences in climate (mainly the dry season), deforestation, and carbon sinks or sources (Gatti *et al.* 2021).

As noted in Chapter 6, rivers and associated floodplains move and distribute carbon laterally across the Amazon. High rates of gross and net primary production (GPP and NPP) by plants occur in Amazonian aquatic environments, and large amounts of carbon dioxide are emitted from rivers, lakes, and wetlands (Richey *et al.* 2002; Melack *et al.* 2009). Photosynthetic activity by emergent trees and herbaceous plants fixes atmospheric CO_2 and adds organic carbon or respired CO_2 to aquatic environments. Algal (phytoplankton and periphyton) NPP derived from dissolved inorganic carbon is smaller, mostly recycling carbon within the aquatic environment. Few measurements of flooded forest productivity are available, and photosynthesis by herbaceous plants is difficult to extrapolate spatially from specific sites. Hence, the estimates of water to atmosphere fluxes of 0.7 Pg C y^{-1} in Table CC1 have considerable uncertainty and large seasonal and interannual variability (Melack *et al.* 2009; Abril *et al.* 2014) (see Chapter 6). Annual inputs of carbon are estimated to be of similar order to estimates of CO_2 degassed from these habitats.

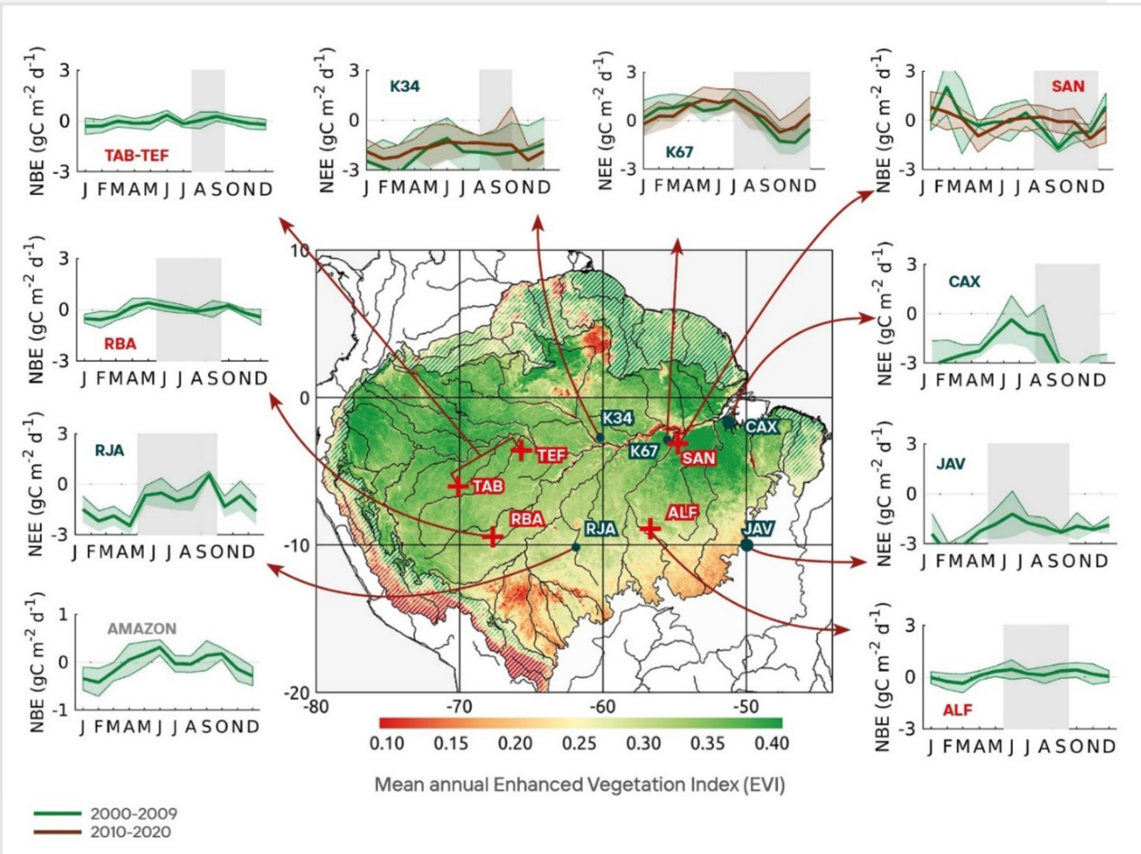

Figure CC.1 Map of mean annual Enhanced Vegetation Index (EVI) across the Amazon (scale at bottom, with greener colors indicating more photosynthesis; BRDF corrected MCD43C1 product for solar zenith angle of 15º and observed in nadir view (Schaaf and Wang 2015). Location of eddy covariance forest tower sites (Restrepo-Coupe *et al.* 2013, Saleska *et al*. 2013) (black dots) where measurements of annual average cycles of net ecosystem exchange (NEE) were included in this analysis (graphs in margin, gray shading indicates dry season months): Manaus forest (K34) 1999–2006, Santarém forest (K67) 2001–2005, 2008-2011 and 2015-2019, forest of Caxiuana (CAX) 1999-2003, Reserva Jarú southern forest (RJA) 2000-2002 and the seasonal inundated forest of Bananal (JAV) 2003-2006. Location of vertical profile sites (red crosses), and monthly mean net biome exchange (NBE) from the aircraft vertical profiles (2010-2018) at Santarem (SAN), Alta Floresta (ALF), Rio Branco, Acre (RBA), and Tabatinga (TAB; measures taken from 2010 to 2012) and Tefé (TEF; measures taken from 2013). Amazonian monthly mean NBE (2010-2018) was based on the weighted mean of fluxes for the 4 aircraft vertical profile sites (Gatti *et al.* 2021). The regions of influence for each vertical profile site are presented at Figure CC2b.

Hence, inputs and emissions of CO_2 in aquatic environments are approximately in balance, when integrated over the whole basin.

For the last decade (2010 through 2019), top-down studies based on vertical profiles, satellite data, and modelling provide estimates of the Amazon's carbon balance. These studies show large interannual variations. Top-down estimates indicate the Amazon as a whole is a carbon source (losses to the atmosphere) on the order of +0.30 ± 0.20 Pg C y^{-1} (Gatti *et al.* 2014; Feng *et al.* 2017; Baccini *et al.* 2017; Assis *et al.* 2020; Gatti *et al.* 2021), where mean fire emiss ions represent 0.44 ± 0.10 Pg C y^{-1} (Gatti *et al.* 2014, 2021; van der Laan-Luijkx *et al.* 2015; Baccini *et al.* 2017) (Table CC1) and mean forest uptake is -0.15 ± 0.20 Pg C y^{-1} (van der Laan-Luijkx *et al.* 2015; Alden *et al.* 2016; Baccini *et al.* 2017). These studies include all processes in the Amazon, including sinks in mature and secondary forests, recovery from disturbed forests, and carbon emissions from deforestation, degradation, logging, decomposi-

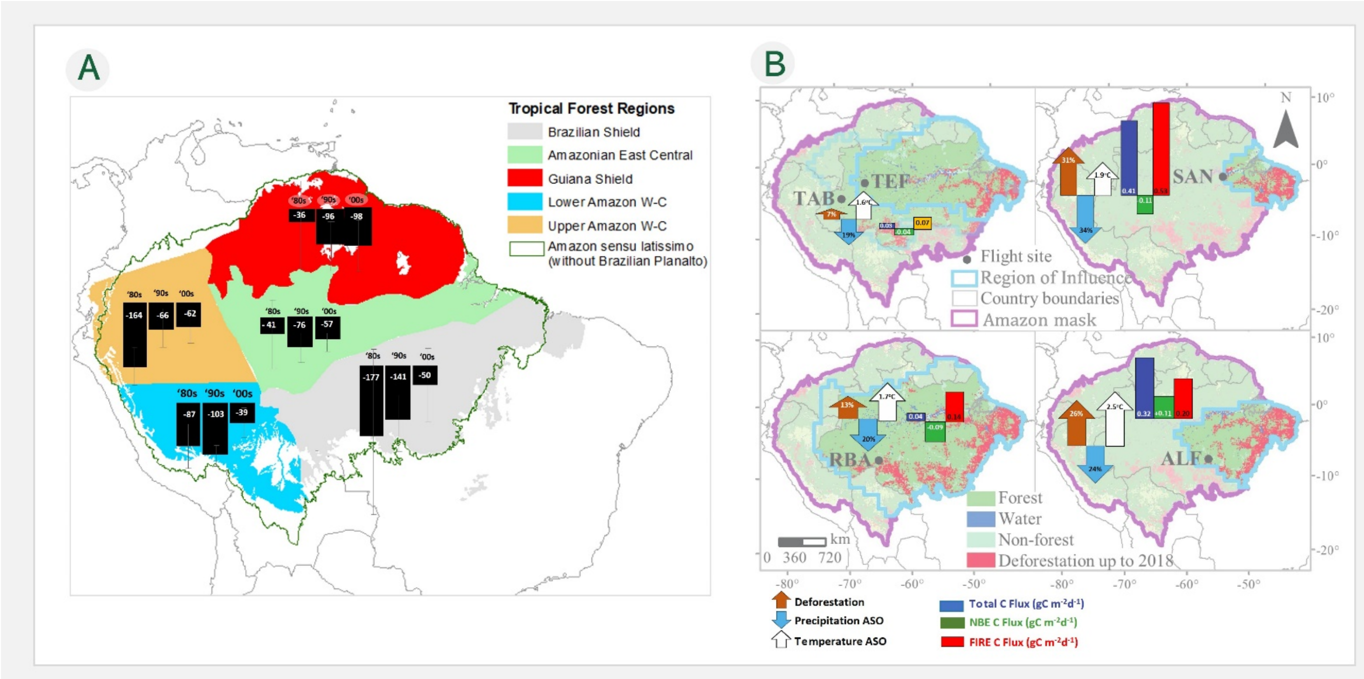

Figure CC.2 A) Amazon carbon fluxes in mature forests 1980s–2000s per region (black bars), measured in long-term plots of the RAINFOR network. Negative values represent uptake. Units are in Tg carbon per year (10^{12}g C y^{-1}). Adapted from Phillips and Brienen (2017) and Feldpausch *et al.* (2011). B) Accumulated deforestation per region of influence (limited by light blue lines) for vertical profiles sites (orange arrows), 40-year reduction in precipitation during the months of August, September and October (ASO) (light blue arrows), increase in temperature in ASO (white arrows) and 2010-18 carbon fluxes (Total: dark blue bars, net biome exchange (NBE): green bars, fire: red bars) (Gatti *et al.* 2021).

tion, fires, fossil fuels, and agriculture (pasture and crops).

For the last decade (2010 through 2019), bottom-up studies indicate that mature forests are carbon sinks of -0.22 ± 0.30 Pg C y^{-1} (Brienen *et al.* 2015; Phillips and Brienen, 2017; Hubau *et al.* 2020), and secondary forests -0.10 ± 0.02 Pg C y^{-1}. Carbon emissions include forest fires of 0.20 ± 0.20 Pg C y^{-1} (van der Werf *et al.* 2010; van der Laan-Luijkx *et al.* 2015; Baccini *et al.* 2017; Aragão *et al.* 2018; Silva *et al.* 2020), forest degradation, deforestation, and other carbon emissions of 0.32 ± 0.10 Pg C y^{-1} (Aguiar *et al.* 2016; Assis *et al.* 2020; Smith *et al.* 2020; Silva Junior *et al.* 2020), where fire emissions from deforestation are 0.05 ± 0.01 Pg C y^{-1} (Aguiar *et al.* 2016; Assis *et al.* 2020), representing 14% of total fires, included in the total fire emission estimate. Estimated energy sector emissions are 0.03 Pg C y^{-1} (Crippa *et al.* 2019). Combining mature forest growth, secondary regrowth, LUCC processes, and fire emissions (subtracting fires included in deforestation), the Amazon is currently a carbon source, representing 0.23 ± 0.20 Pg C y^{-1}, slightly less than the net emissions estimated from top-down studies. Large uncertainties, especially due to lack of knowledge about the emissions from degradation, decomposition, and fire emissions, (see Chapter 19) remain.

The results from top-down and bottom-up indicate that the Amazon as a whole is a carbon source, 0.30 ± 0.20 Pg C y^{-1} and 0.23 ± 0.20 Pg C y^{-1}, respectively.

Table CC.1 Amazon carbon balance, from bottom-up and top-down studies of various sources (C losses) and sinks (C uptake) for the area of 7.25 x 10^6 km^2.

	Period	C uptake (PgC y^{-1})	C losses (PgC y^{-1})	Total C Balance (PgC y^{-1})
Bottom-up studies				
Phillips and Brienen 2017 (Mature forest growth: uptake; LUCC: losses)	1990-99	- 0.54 ± 0.18	0.27 (LUCC)[1]	-0.27
	2000-09	- 0.38 ± 0.20	0.28 (LUCC)[1]	-0.10
	2010-19	- 0.20[2]		
Brienen *et al.* 2015 (Mature forest growth: uptake; LUCC: losses)	1990-99	- 0.62 ± 0.09		
	2000-09	- 0.44 ± 0.10		
	2010-19	- 0.23[2]		
Hubau *et al* 2020 (Mature forest growth: uptake; LUCC: losses)	1990-99	-0.68 ± 0.15		
	2000-09	-0.45 ± 0.13		
	2010-19	-0.25 ± 0.30		
INPE-EM System[3,4] (Deg+Def+SF, not PF)	2010-19	-0.16 ± 0.01	0.34 ± 0.09	0.18 ± 0.09
Assis *et al.* 2020[3] (Deg+Def+SF, not PF)	2007-16	-0.15 ± 0.02	0.37 ±0.08	0.23 ± 0.13
Aguiar et al. 2016[3] (Deg+Def, not PF/SF)	2007-13	-0.06 ±0.003	0.26 ±0.06	0.20 ± 0.11
Silva Jr. *et al.* 2020 (Deg+Def)	2001-15		0.26 ± 0.05	
Smith et al, 2020[3] (Secondary forests)	1985-17	- 0.10 ± 0.02		
GFED (Global fire data)	2010-18		0.18	
Aragao *et al.* 2018 (Fire emissions)	2003-15		0.21 ± 0.23	
Crippa *et al.* 2019 (EDGAR data base)[5]	2015		0.03	
Bottom-up Total balance 2010-2020		**- 0.32 ± 0.20[6]**	**0.55 ± 0.20[7]**	**+ 0.23 ± 0.20**
Aquatic systems				
Rivers			0.14 ± 0.04	
Lakes and floating plants			0.03 ± 0.01	
Streams			0.10 ± 0.03	
Forested floodplains			0.26 ± 0.8	
Other wetlands			0.16 ± 0.5	
Hydroelectric reservoirs			0.01 ± 0.003	
Total aquatic C balance		**-0.7 ± 0.3**	**0.7 ± 0.2**	**~0**
Top-down Studies				
Gatti *et al.* 2021 (Aircraft/ Inv. modeling)	2010-18	- 0.12 ± 0.40 (NBE)[8]	0.41 ± 0.05 (Fire)	0.29 ± 0.40
Gatti *et al.* 2014 (Aircraft/ Inv. modeling)	2010-11	- 0.15 ± 0.18 (NBE)[8]	0.43 ± 0.10 (Fire)	0.28 ± 0.14
Alden e*t al.* 2016 (Regional Bayesian Inversion modelling)	2010-12	-0.14 ± 0.32		
Van der Laan-Luijkx *et al.* 2015 (models: IASI, GFED4, GFAS, FINN, SiBCASA-GFED4)	2010-11	-0.27 ± 0.42[9]	0.24 ± 0.42 (Fire)[9]	
Feng *et al.* 2017 (Satelite/aircraft/modeling)	2010-14			0.32 ± 0.14
Baccini *et al.* 2017(MODIS pantropical satellite and modeling)	2003-14	-0.18 ± 0.02	0.48 ± 0.07	0.30 ± 0.07
Top-down Total balance 2010-20		**- 0.15 ± 0.20**	**0.44 ± 0.10**	**+ 0.30 ± 0.20**

1- LUCC land-use changes—including fragmentation and edge effects, logging, fire, secondary re-growth and subsequent disturbance
2- Extrapolated using the trend
3- Scaled to Amazon *sensu latissimo*, without Planalto using MapBiomas deforestation
4- INPE-EM Operational System: http://inpe-em.ccst.inpe.br/en/
5- Energy sector, Industrial Processes and Product Use, and Agricultural waste burning
6- Uptake PF + SF (-0.22 + (-10)). Primary Forest (PF), Secondary Forest (SF);
7- Losses Assis (2020) losses from Deforestation (Def) + Degradation (Deg): 0.37 + Fire: 0.15 (0.20 - 0.05 (computed by Assis)) + energy: 0.03
8- NBE (Net Biome Exchange: Total C flux less Fire);
9- Qualitative results for comparison between 2010 and 2011, not used quantitatively.

Table CC.2 Methane Emissions

	Period	CH_4 uptake	CH_4 Fire emission	Total CH_4 emission
Area normalized 7.25 x 10^6 km^2		**($TgCH_4$ y^{-1})**	**($TgCH_4$ y^{-1})**	**($TgCH_4$ y^{-1})**
Bottom-up studies				
Natural emissions				
Rivers				0.7 ± 0.2
Lakes				0.7 ± 0.2
Streams				0.4 ± 0.2
Forested floodplains				
Flux from water surface				16.4 ± 5
Flux from trees				18.2 ± 5.5
Flux from exposed soil				1.1 ± 0.2
Other wetlands				7 ± 2
Upland soils*		1.0 - 3.0		
Anthropogenic				
Hydroelectric reservoirs				2.0 ± 0.6
Energy sector**	2015			0.8
Waste**	2015			0.5
Agriculture**	2015			4.7
Top-down Studies				
Aircraft/Modelling Studies				
Basso *et al.* 2021	2010-18		7.7 ± 1.6	46.2 ± 10.3
Wilson *et al.* 2021	2010-13			40.1 ± 5.6
	2014-17			47.9 ± 5.5
Pangala *et al.* 2017 (Column Budget Technique)	2010-13		4.2 ± 0.7	46.2 ± 6.1
Wilson *et al.* 2016 (3-D atmospheric chemical transport model)	2010-11		2.2 ± 1.5	37.5 - 50.8
Satelite/modelling Studies				
Bergamaschi *et al.* 2009 (inverse modeling + revised SCIAMACHY retrievals)	2004			40.0 – 44.7
Fraser *et al.* 2014 (inverse modeling and GOSAT)	2010			44.6 ± 2.4

* Estimated by Davidson and Artaxo 2004

** Emissions based on EDGAR database for the year 2015

CB2. Methane Emissions

Descriptions of terrestrial and aquatic methane fluxes, processes, and the CH_4 budget are provided in Chapter 6. For comparison to the CO_2 budget, we scaled CH_4 estimates to the same area (7.25x10^6 km^2); a proportional adjustment based on the two areas and assuming sufficiently similar habitats are represented. Top-down and bottom-up estimates for this region have reasonable agreement given the considerable uncertainties in these fluxes (Table CC2). Fluxes of CH_4 from natural aquatic environments in the Amazon Basin are estimated to be approximately 44.5 Tg CH_4 y^{-1}. Interannual variations in the area of inundated habitats and highly variable fluxes associated with ebullition outgassing by trees, and temporal and spatial differences in dissolved CH_4 concentrations and gas exchange velocities (Melack *et al.* 2004; Pangala *et al.* 2017; Barbosa *et al.* 2020) make uncertainty estimates only approximate. Estimates of anthropogenic CH_4 emissions based on the EDGAR v.5.0 model include energy production, agriculture, industrial processes, product uses, and waste management. These sources contribute 6 Tg CH_4 y^{-1}, with emissions from agriculture responsible for 78% and enteric fermentation the main source from this sector (93%), highlighting the importance of cattle in anthropogenic Amazonian methane emissions. Fluxes from the 159 medium to large hydroelectric reservoirs currently in the Amazon Basin, excluding those in the lower Tocantins Basin and including major ones in Venezuela, Suriname, and French Guiana, total 2 Tg CH_4 y^{-1}.

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CONTACT INFORMATION

SPA Technical-Scientific Secretariat New York
475 Riverside Drive, Suite 530
New York NY 10115
USA
+1 (212) 870-3920
spa@unsdsn.org

SPA Technical-Scientific Secretariat South America
Av. Ironman Victor Garrido, 623
São José dos Campos – São Paulo
Brazil
spasouthamerica@unsdsn.org

WEBSITE theamazonwewant.org
INSTAGRAM @theamazonwewant
TWITTER @theamazonwewant