Science Panel for the Amazon (SPA)

CROSS- CHAPTER – THE AMAZON CARBON BUDGET

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The main objective of this cross-chapter is to summarize sinks and sources of carbon in Amazon, answering the important question: Is the Amazon a carbon sink or carbon source to the atmosphere? Several key studies discussed in other SPA chapters are included, both bottom-up (e.g., when changes in biomass are measured in the field, then extrapolated to the region via model parametrization) and top-down (e.g., when gas concentration or biomass changes are measured from satellite, aircraft or airborne sensors) studies are included. The results from top-down and bottom-up for the last decade (2010-2020) indicate that the Amazon is a carbon source, 0.30 ± 0.20 Pg C y^{-1} and 0.16 ± 0.15 Pg C y^{-1}, respectively. It is important to acknowledge and understand discrepancies between these two approaches.

CO_2 UPTAKE AND EMISSIONS

In 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

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Mapping Project (Mapbiomas Amazonia 2.0), a cumulative total of 17% was deforested by 2019, of which agriculture represents 14% (89% pasture and 11% crops) (MapBiomas Amazonia 2020) (**Chapter 19**). Long-term inventories (e.g., RAINFOR), based on carbon stock estimates (bottom-up studies), started in the 1980s, providing data on carbon dynamics of intact mature forest at around 300 sites. Here we present mean values from the three important publications on mature forest carbon balance spanning three decades, that report decreases in carbon uptake capacity, mainly due to increases in mortality over three decades (Brienen *et al.* 2015; Phillips and Brienen 2017; Hubau *et al.* 2020) (**Chapter 6**). The Amazonian carbon sink or uptake (i.e., carbon removal from the atmosphere, reported here as negative signal) estimated for mature upland forests was scaled to the area of 7.25 x 10^6 km^2. The mean net carbon uptake for the 1990s was -0.59 ± 0.18 Pg C y^{-1}; in the first decade of 2000s the carbon uptake decreased to -0.41 ± 0.20 Pg C y^{-1}, and the decade of 2010s had a carbon uptake of -0.22 ± 0.30 Pg C y^{-1} (see **Table 1** where all studies were scaled to the same area). The uncertainty is related from the original uncertainties and the variability between all studies. According to these studies the carbon sink has weakened by around 60% in these three decades, however this decrease was not evenly distributed across the Amazon basin (Phillips and Brienen 2017). Deforestation (MapBiomas Amazonia 2020) and climate changes affect carbon sinks (**Chapter 23**) and both vary geographically (Gatti *et al.* 2021).

For the last decade, complementary bottom-up studies, have focused on estimating the carbon emissions and uptake from different land use and land cover changes (LUCC) (Melack *et al.* 2009; Gatti *et al.* 2014; Aguiar *et al.* 2016; Feng *et al.* 2017; Baccini *et al.* 2017; Assis *et al.* 2020). These studies combined knowledge derived from fieldwork and remote sensing in models. The INPE-EM model (Gatti *et al.* 2014) considered all the LUCC components, and the results are similar to the component-specific studies (Feng *et al.* 2017; Baccini *et al.* 2017), indicating a positive net emission related to LUCC processes of around 0.16 to 0.30 Pg C yr^{-1}. However, there are many uncertainties in such measures, in particular related to biomass burning and processes leading to uptake after disturbance. All studies in **Table 1** and **2** are normalized to the Pan-Amazon; deforestation values for the Brazilian Amazon were scaled to the Pan-Amazon.

Based on eddy flux towers and aircraft vertical profiles (Gatti *et al.* 2021), **Figure 1** illustrates regional differences in carbon flux. In general, more carbon is absorbed in western regions than on the eastern side (Malhi *et al.* 2015, Gatti *et al.* 2021) (see **Chapter 4**, **Chapter 6**). Regional distributions of carbon emissions and uptake are shown in **Figure 2** (adapted from Phillips and Brienen, 2017), and associated geographical differences in climate, mainly in dry season, deforestation and carbon sink/source (Gatti *et al.* 2014; Phillips and Brienen, 2017).

High rates of net primary production (NPP) by plants occur in Amazonian aquatic environments, and large amounts of carbon dioxide are emitted from rivers, lakes and wetlands (Melack *et al.* 2009). Aquatic NPP is considered to be carbon inputs to aquatic systems derived from photosynthetic activity by emergent trees and herbaceous plants using atmospheric CO_2 and adding organic carbon or respired CO_2 to the water. Algal (phytoplankton and periphyton) NPP derived from dissolved inorganic carbon is not included. Few measurements of flooded forest NPP are available, and NPP by herbaceous plants is difficult to extrapolate from specific sites. Hence, the estimate of 0.7 Pg C y^{-1} is only approximate with considerable uncertainty (Melack *et al.* 2009; Abril *et al.* 2014). Water to atmosphere fluxes of carbon dioxide from all aquatic environments in the Amazon are estimated to be approximately 0.7 Pg C y^{-1} with large uncertainties associated with seasonal and inter-annual variations in inundated habitats and highly variable fluxes caused by variations in dissolved CO_2 concentrations and gas exchange velocities (see **Chapter 6**). Annual inputs of carbon are of similar order to estimates of CO_2 degassed from these habitats. Hence, inputs and emissions of CO_2 in aquatic environments are approximately in balance.

For the last decade, top-down studies, based on vertical profiles, satellite data and modelling, provide estimates of the Amazon's carbon balance. Overall, The Amazon is a carbon source (losses to the atmosphere) 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 a mean fire emissions represent 0.39 ± 0.20 Pg C y^{-1} (Gatti *et al.* 2014, 2021; van der Laan-Luijkx *et al.* 2015; Baccini *et al.* 2017) (**Table 1**) and a mean forest uptake represents -0.20 ± 0.15 Pg C y^{-1} (van der Laan-Luijkx *et al.* 2015; Alden *et al.* 2016; Baccini *et al.* 2017), others sources like degradation and decomposition can be included in the studies or not, but the agreement in the Amazon balance is supported from four studies (Gatti *et al.* 2014, 2021; Feng *et al.* 2017; Baccini *et al.* 2017). These studies show the results of all processes in The Amazon, including sinks in mature and secondary forests, the recovery from disturbed forest and also the carbon emissions from deforestation, degradation, logging, decomposition, fires, fossil fuel and agriculture (pasture and crops).

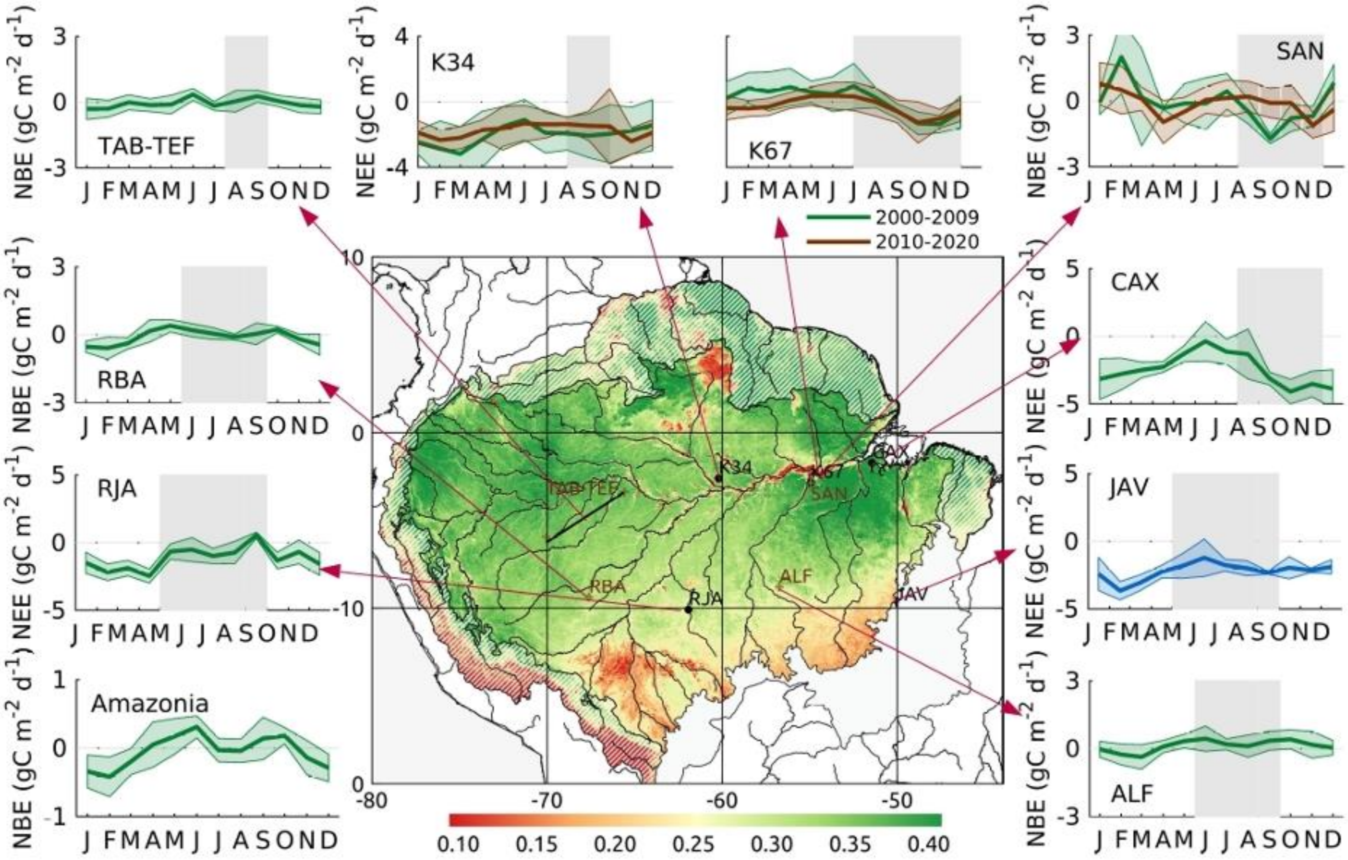

Figure 1- - Mean annual EVI across the Amazon basin (BRDF corrected MCD43C1 product for solar zenith angle of 15deg and observer at nadir view (Schaaf and Wang 2015). Location of eddy covariance tower sites (Restrepo-Coupe et al. 2013; Saleska et al. 2013) (black dots) where measurements of net ecosystem exchange (NEE) were included in this analysis: Manaus forest (K34) 1999–2006, Santarém forest (K67) 2001–2005, 2008-2011 and 2015-2019 and pasture (K77) 2000-2005, forest of Caxiuana (CAX) 1999-2003, Reserva Jarú southern forest (RJA) 2000-2002 and Fazenda Nossa Senhora (FNS) 1999-2002, and the seasonal inundated forest of Bananal (JAV) 2003-2006. Location of flask measurements (brown crosses), and monthly net biome exchange (NBE) mean aircraft vertical profiles (2010-2018) Santarem (SAN), Alta Floresta (ALF), Rio Branco, Acre (RBA), and Tabatinga_Tefé (TAB_TEF). Amazonian monthly NBE

mean (2010-2018) was based on the weighted mean of fluxes for the 4 aircraft vertical profiles sites (Gatti et al. 2021).

From bottom-up, considering the components for the last decade (2010-2020), 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). Carbon emissions (see **Chapter 19**) include forest fires of 0.20 ± 0.20 Pg C y^{-1} (van der Werf *et al.* 2010; Gatti *et al.* 2014, 2021; van der Laan-Luijkx *et al.* 2015; Baccini *et al.* 2017; Aragão *et al.* 2018; Silva *et al.* 2020); degradation, deforestation, recovering (Aguiar *et al.* 2016; Assis *et al.* 2020; Smith *et al.* 2020) and other carbon emissions of 0.23 ± 0.10 Pg C y^{-1} (Aguiar *et al.* 2016; Crippa 2019; Assis *et al.* 2020; Silva Junior *et al.* 2020), where fire emission from deforestation is 0.05 ± 0.01 Pg C y^{-1} (Aguiar *et al.* 2016; Assis *et al.* 2020) representing 14% of total fires. Combining mature forests growth, secondary regrowth, LUCC processes and fire emissions (subtracting fires included in deforestation), the Amazon is currently a carbon source, representing 0.16 ± 0.15 Pg C y^{-1}, slightly less than that estimated from top-down studies. Many uncertainties and 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 is a carbon source, 0.30 ± 0.20 Pg C y^{-1} and 0.16 ± 0.15 Pg C y^{-1}, respectively.

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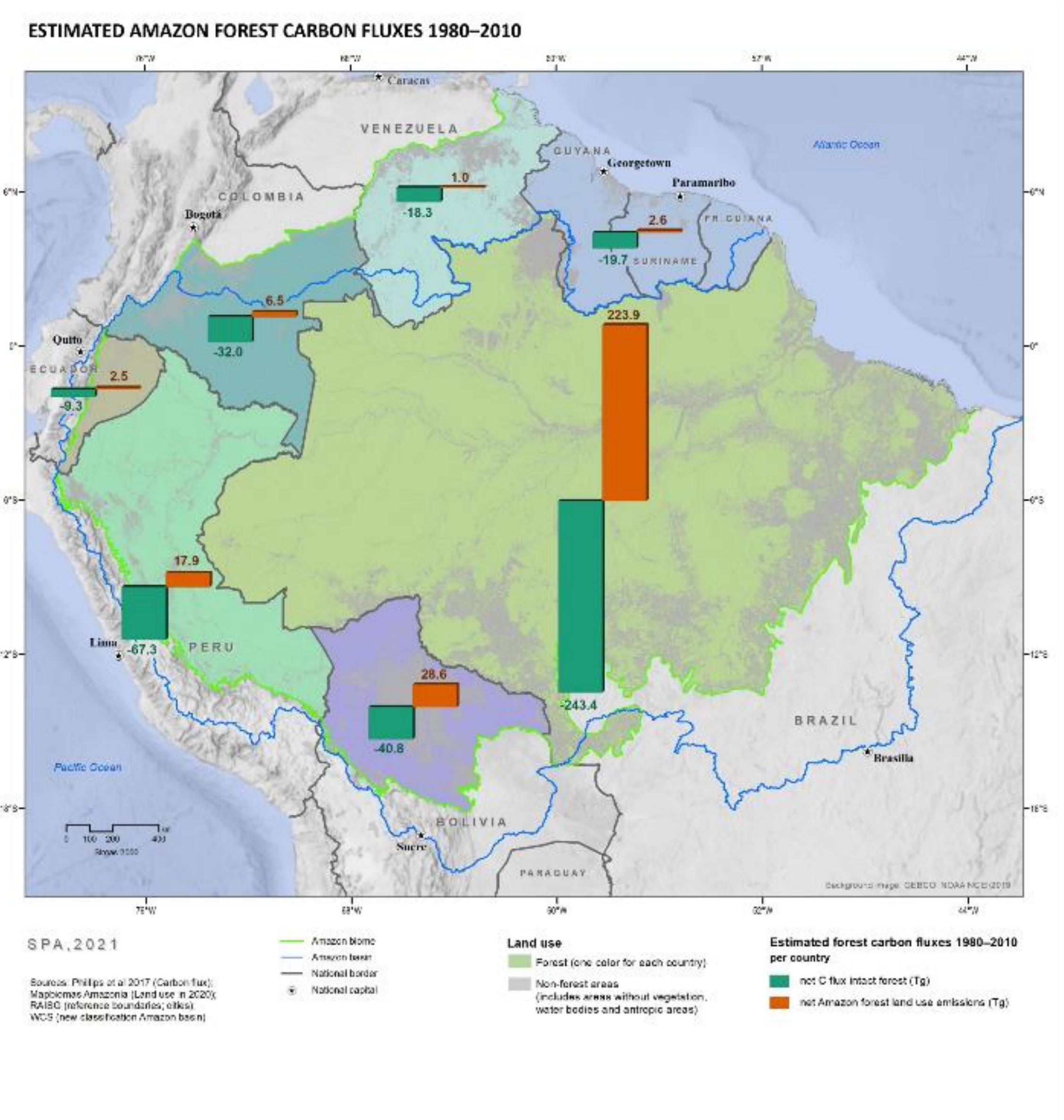

Figure 2 – Estimated Amazon carbon fluxes 1980–2010 per country. Net carbon flux in mature forests (green bars) (negative values represent uptake), the net fluxes from deforestation, i.e., losses from deforestation and degradation minus gains from regrowth (red and positive). Units are in Tg carbon per year (10^{12} g C y^{-1}). Adapted from Phillips and Brienen (2017).

Table 1 - Amazon carbon balance, from bottom-up and the top-down studies of various sources (C losses) and sinks (C uptake) for the Amazon 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; LUC: losses)	1990-00	- 0.54 ± 0.18	0.27 (LUC)[1]	-0.27
	2000-10	- 0.38 ± 0.20	0.28 (LUC)[1]	-0.10
	2010-20	- 0.20[2]		
Brienen et al, 2015 (Mature Forest Growth: uptake; LUC: losses)	1990-00	- 0.62 ± 0.09		
	2000-10	- 0.44 ± 0.10		
	2010-20	- 0.23[2]		
Hubau et al, 2020 (Mature Forest Growth: uptake; LUC: losses)	1990-00	-0.68 ± 0.15		
	2000-10	-0.45 ± 0.13		
	2010-20	-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	
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		-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)[6]	0.41 ± 0.05 (Fire)	0.29 ± 0.40
Gatti et al., 2014 (Aircraft/ Inv. modeling)	2010-11	- 0.15 ± 0.18 (NBE)[6]	0.43 ± 0.10 (Fire)	0.28 ± 0.14
Alden at al., 2016 (Regional Bayesian Inversion modelling)	2010-12	-0.14 ± 0.32		
Van der Laan-Luijkx, I. T. et al., 2015 (models: IASI, GFED4, GFAS, FIN, SiBCASA-GFED4)	2010-11	-0.27 ± 0.42	0.24 ± 0.42 (Fire)	
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

1- LUC land-use changes—including fragmentation and edge effects, logging, fire, secondary re-growth and subsequent disturbance
2- extrapolated using the trend
3- scaled to Pan Amazonia 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- NBE (Net Biome Exchange: Total C flux less Fire)

CH_4 EMISSIONS

Detailed descriptions of natural terrestrial and aquatic methane fluxes and the CH_4 budget are provided in Chapter 6. For comparison to the CO_2 budget, we scaled the CH_4 estimates for the same area of 7.25×10^6 km^2. Top-down, and bottom-up estimates for this region have reasonable agreement given the considerable uncertainties in these fluxes (**Table 2**). Water to atmosphere fluxes of CH_4 from all aquatic environments (including hydroelectric reservoirs) in the Amazon basin is estimated to be approximately 46 Tg CH_4 y^{-1}. Inter-annual 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. Fluxes and areas for the 159 medium to large hydroelectric reservoirs currently in the Amazon basin are summarized in **Chapter 6.** Here we excluded the reservoirs in the lower Tocantins basin and added major ones in Venezuela, Suriname and French Guiana.

Estimates of Amazonian CH_4 emissions based on the EDGAR v.5.0 model includes energy power, agriculture, industrial processes, product uses and waste management. All anthropogenic 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. Anthropogenic sources of methane are discussed in detail by WG8.

Table 2 - Amazon methane balance, based on bottom-up and top-down studies of various sources and sinks for the Amazon area of 7.25 x 10^6 km^2

Area normalized 7.25 x 10^6 km^2	Period	CH4 uptake (TgCH4 $\bar{y}^1$)	CH4 Fire emission (TgCH4 $\bar{y}^1$)	Total CH4 emission (TgCH4 $\bar{y}^1$)
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				
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 + GOSAT)	2010			44.6 ± 2.4

Wilson et al., 2021 (in

* Estimated by Davidson and Artaxo, 2004

** Emissions based on EDGAR database for the year 2015

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