nature portfolio

https://doi.org/10.1038/s41586-021-03629-6

Supplementary information

Amazonia as a carbon source linked to deforestation and climate change

In the format provided by the authors and unedited

SI Guide

The Supplementary Information is composed by 10 pages:

Supplementary Information Figure 1 - Supplementary Methods related to the background analysis and uncertainties, showing the comparison between the background and the top of vertical profiles.

Supplementary Information Figure 2 - Supplementary Methods related to the continuity analysis of northwest-central site, where TAB site is related to the period 2010-2012 and TEF 2013-2018.

Supplementary Information Table 3 - Supplementary Table presenting a review of Amazon balance studies with bottom-up and top-down approaches

Supplementary Information Fig. 4 - Supplementary Methods related to the definition of Amazon mask, based on the forest biome limits.

Supplementary Information Fig. 5 - Supplementary Methods showing sample system installation on aircraft.

Supplementary Information Fig. 6 - Supplementary Methods presenting background methodology details

Supplementary Information Fig. 7 - Supplementary Methods presenting the comparison between biogenic carbon monoxide (CO), adopted as natural CO emissions, and CO fluxes calculated from the vertical profiles.

Supplementary Information Fig. 8 - Supplementary Methods related to the validation for precipitation and temperature used in this study

Supplementary Information Fig. 9 - Supplementary Methods related to the filling gaps method used to fill the monthly fluxes gaps in the time series.

Supplementary Information Table 10 - Supplementary Methods related to the uncertainty input data for travel times, CO_2 and CO background, and fluxes.

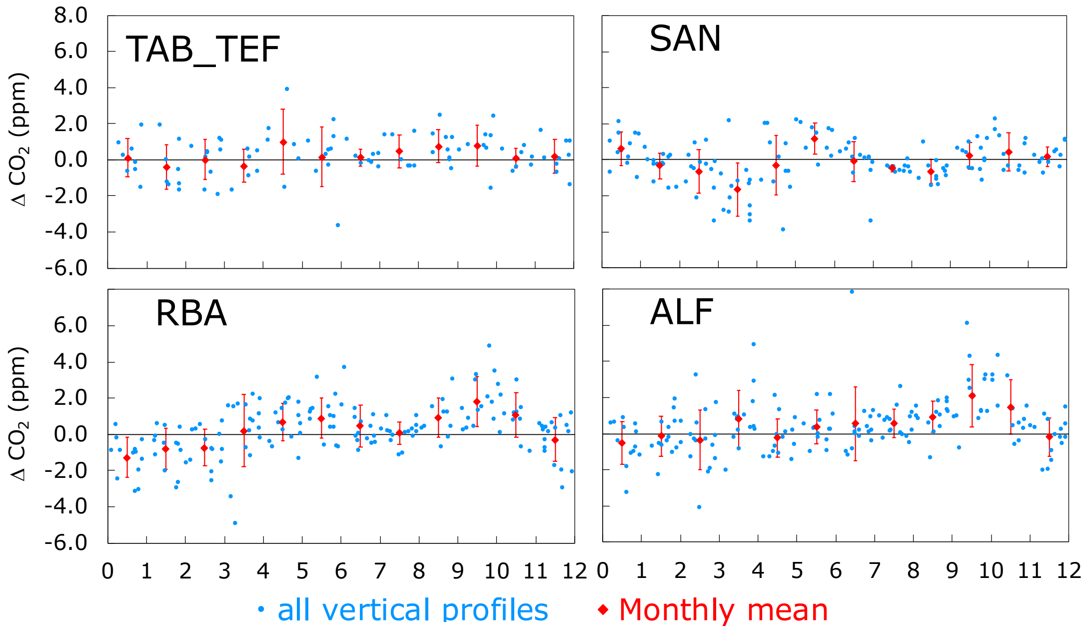
a)

annual mean CO_2 (ppm)	ALF	SAN	RBA	TAB_TEF
2010	0.64	0.32	0.79	0.23
2011	0.14	-0.42	0.22	-0.23
2012	0.52	-0.13	0.49	0.01
2013	0.66	-0.12	0.26	0.63
2014	0.84	0.00	-0.05	0.85
2016	1.04		0.35	
2017	-0.18	-0.39	-0.14	0.56
2018	0.15	-0.64	-0.38	-0.17
MEAN	**0.48**	**-0.20**	**0.19**	**0.27**

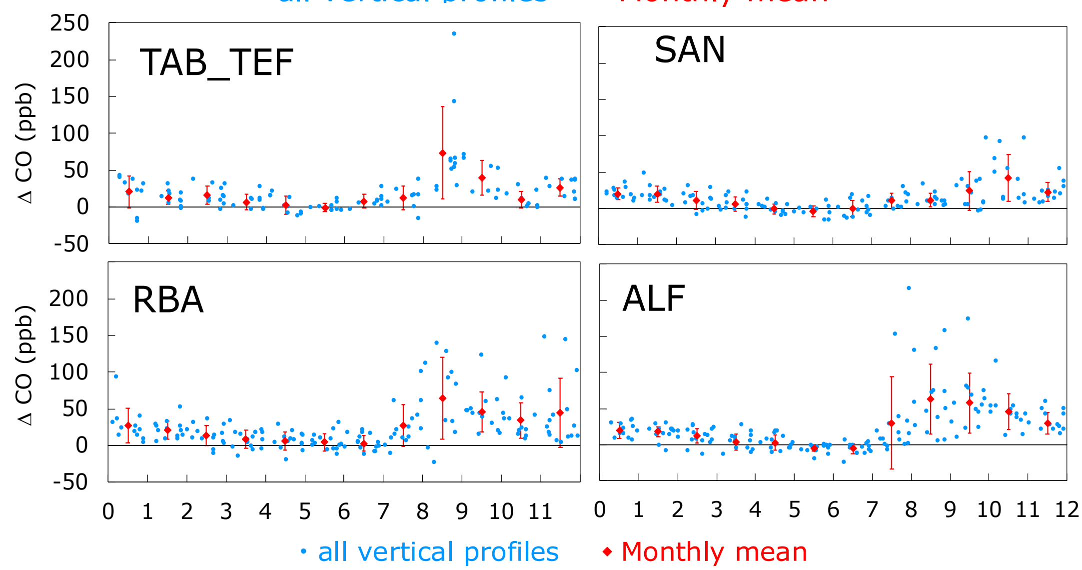
b)

annual mean CO (ppb)	ALF	SAN	RBA	TAB_TEF
2010	31.4	15.5	25.7	30.0
2011	15.0	7.2	15.4	16.9
2012	19.4	18.7	29.3	12.2
2013	10.2	8.7	11.4	9.5
2014	17.2	15.4	12.3	21.6
2016	22.6		33.5	
2017	33.9	17.6	30.6	24.5
2018	21.3	10.6	16.7	16.0
MEAN	**21.4**	**13.4**	**21.9**	**18.7**
ASO mean (dry season)	50.3	15.6	45.9	33.3

c)

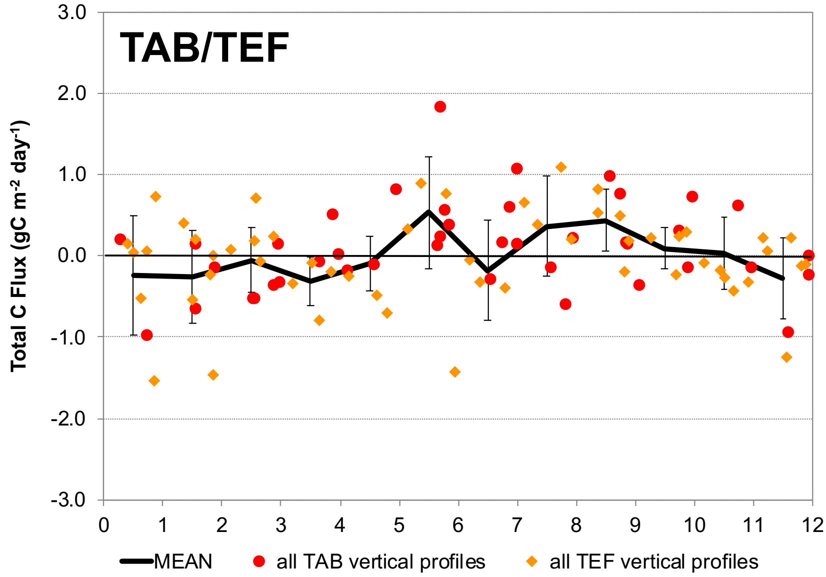


d)

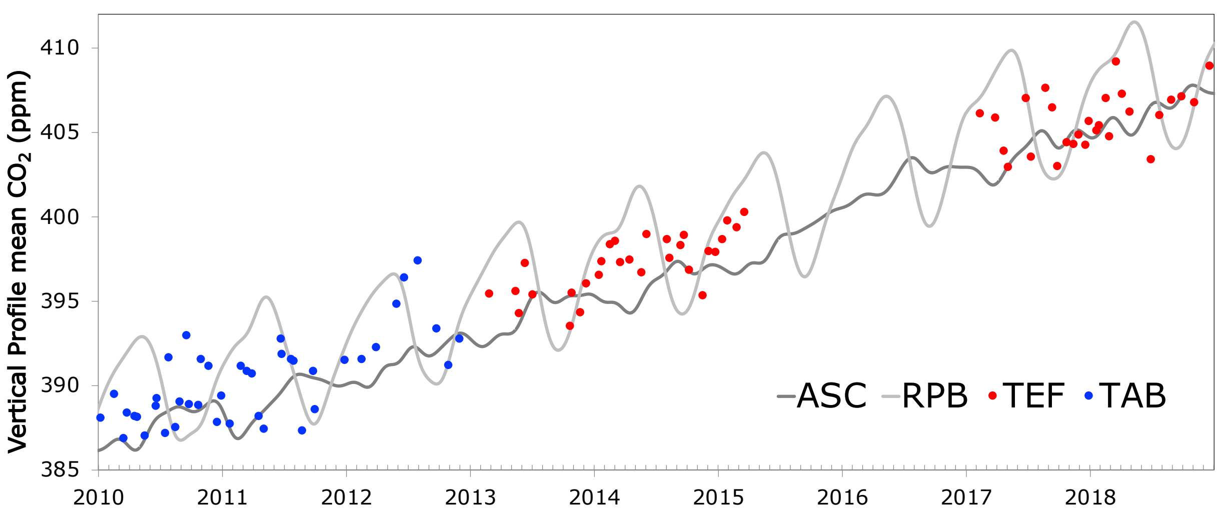


Supplementary Information Fig. 1 | Comparison between the top of VP and BKG. a) Differences from mean concentration above 3.8 km height at vertical profiles (VP) and the background concentrations for the correspondents heights. b) Dispersion per month along the year for the CO_2 differences from mean concentration above 3.8 km height and the background concentrations for these same heights and c) Dispersion per month along the year for the CO differences from mean concentration above 3.8 km height and the background concentrations for these same heights.

a)



b)



c)

Years	Tabatinga (TAB) Area total km^2	% of CARBAM Area	Year deforestation km^2	% of the site	% of CARBAM mask	Previous deforestation km^2	% of the site	% of CARBAM mask	Total deforestation km^2	% of the site	% of CARBAM mask
2010	3,059,333	73	4,447	0.1	0.105	352,190	12	8.35	356,637	12	8.46
2011	2,625,241	62	1,892	0.1	0.045	199,033	8	4.72	200,925	8	4.77
2012	3,547,392	84	3,376	0.1	0.080	508,604	14	12.06	511,980	14	12.14
	Tefé (TEF)										
2013	2,279,111	54	1,750.2	0.0	0.042	343,542	15	8.15	345,292	15	8.19
2014	2,089,728	50	1,598.9	0.0	0.038	286,708	14	6.80	288,307	14	6.84
2015	2,043,123	48	2,780.9	0.0	0.066	327,895	16	7.78	330,676	16	7.84
2016	2,320,823	55	3,170.9	0.0	0.075	361,416	16	8.57	364,587	16	8.65
2017	2,313,878	55	3,258.8	0.0	0.077	403,592	17	9.57	406,851	18	9.65
2018	2,397,517	57	3,148.3	0.0	0.075	409,295	17	9.71	412,443	17	9.78

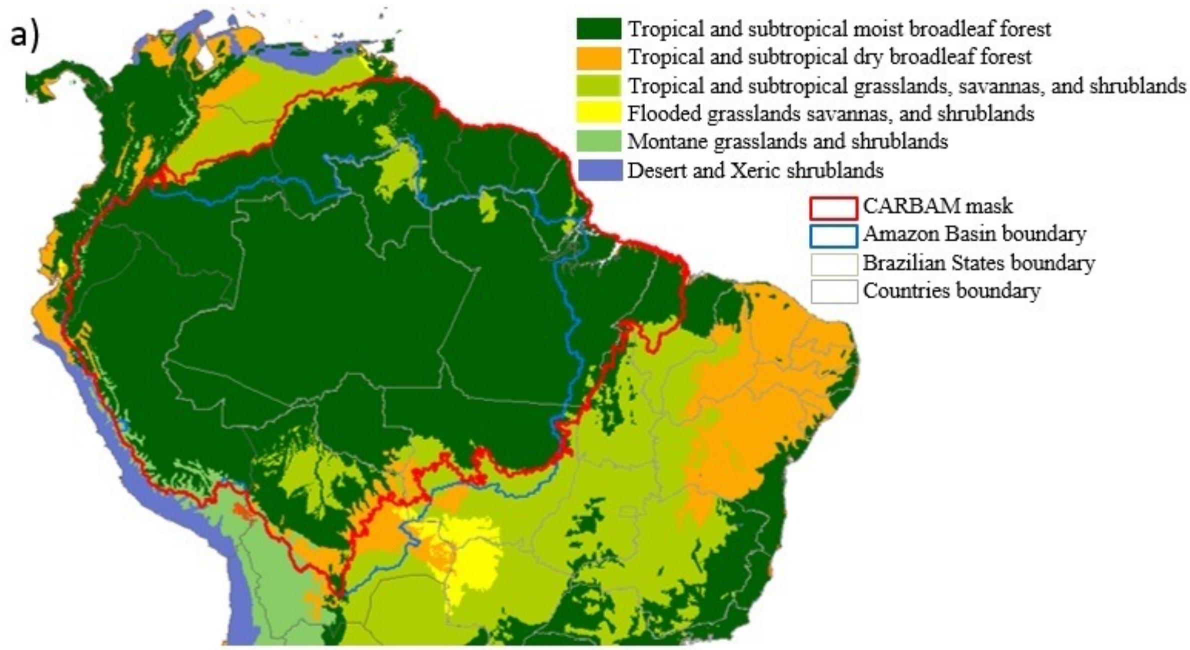
Supplementary Information Fig. 2 | TAB_TEF time series and deforestation. a) TAB and TEF total fluxes organized by month (from individual profiles). Red circles are TAB total C fluxes (2010 to 2012) and orange diamonds are for TEF (2013 to 2018). b) Time series presenting TAB mean vertical profiles in blue circles and TEF in red circles, light grey RPB (Barbados Island) and dark grey ASC (Ascension Island). c) present the deforestation at both regions, show the amount of annual deforestation and accumulated deforestation, and the Amazon representation area.

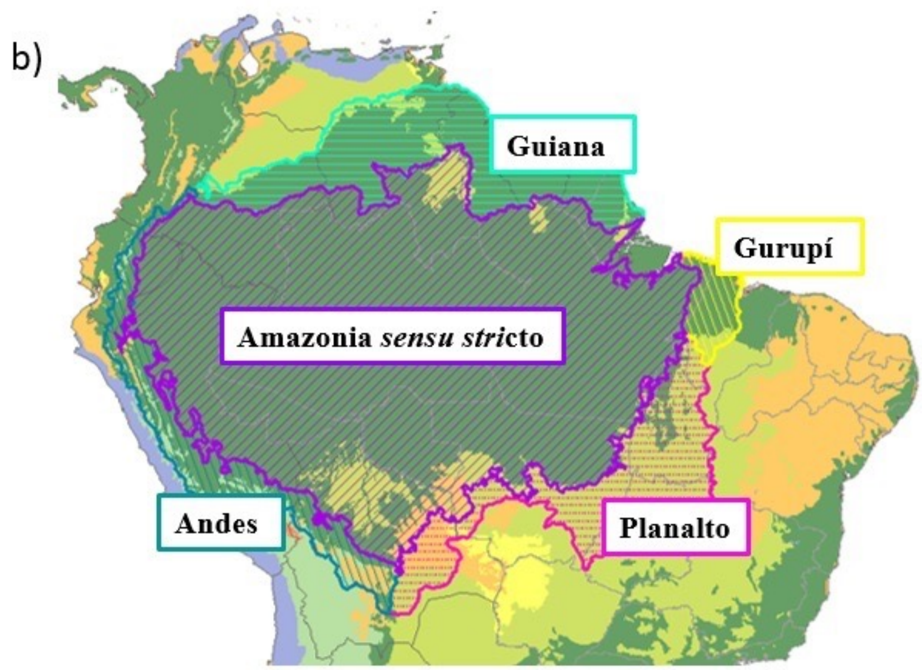
Supplementary Information Table 3 | Amazon Carbon Balance. Review of Amazon balance studies with bottom-up and top-down approaches, such as forest census inventories[1-3], inverse modelling[4,65,66], vertical profiles[4], remote sensing[13,67–76] and others modelling[66] approaches. The results from all studies were normalized to the Amazon area of 7.25 x 10^6 km^2

Area normalized 7.25 x 10^6 km^2	Period	C up take ($PgC\ y^{-1}$)	C losses ($PgC\ y^{-1}$)	Total C Balance ($PgC\ y^{-1}$)
Bottom-up studies				
Amazon Forest Inventory Network				
	1990-00	- 0.54 ± 0.18	0.27 (LUC)[1]	-0.27
Phillips and Brienen, 2017	2000-10	- 0.38 ± 0.20	0.28 (LUC)[1]	-0.10
	2010-20	- 0.20[2]		
	1990-00	- 0.62 ± 0.09		
Brienen et al, 2015	2000-10	- 0.44 ± 0.10		
	2010-20	- 0.23[2]		
	1990-00	-0.68 ± 0.15		
Hubau et al, 2020	2000-10	-0.45 ± 0.13		
	2010-20	-0.25 ± 0.30		
Assis et al., 2020[3] (recovery)	2007-16	-0.15 ± 0.02		
Smith et al, 2020[3] (recovery)	1985-17	- 0.10 ± 0.02		
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
Deforestation				
Silva Jr. et al., 2020	2001-15		0.19 ± 0.05	
INPE-EM[3]	2010-19		0.18 ± 0.03	
INPE-EM (Deforest: as decomposition)[3]	2010-19		0.13 ± 0.03	
Assis et al., 2020[3]	2007-16		0.26 ± 0.07	0.23 ± 0.13
Degradation				
Silva Jr. et al., 2020 (edge effects)	2001-15		0.07 ± 0.01	
Assis et al., 2020[3]	2007-16		0.11 ± 0.08	0.23 ± 0.13
Fire Emissions				
GFED (www.globalfiredata.org)	2010-18		0.18	
Aragao et al., 2018 (Fire emissions)	2003-15		0.21 ± 0.23	
Fossil Fuel and others antropogenic emissions				
Crippa et al., 2019 (EDGAR data Base)[4]	2015		0.03	
Top-down Studies				
Aircraft/Modelling Studies				
Gatti et al., 2021 (in revision) (Column Budget Technique)	2010-18	- 0.12 ± 0.40 (NBE)[5]	0.41 ± 0.05 (Fire)	0.29 ± 0.40
Gatti et al., 2014 (Column Budget Technique)	2010-11	- 0.15 ± 0.18 (NBE)[5]	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)	
Satelite/Aircraft /modelling Studies				
Feng et al, 2017	2010-14			0.32 ± 0.14
Satelite/modelling Studies				
Baccini et al, 2017 (MODIS pantropical satellite)	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- Energy sector, Industrial Processes and Product Use, and Agricultural waste burning
5- NBE (Net Biome Exchange: Total C flux less Fire)

65. Alden, C. B. *et al.* Regional atmospheric CO 2 inversion reveals seasonal and geographic differences in Amazon net biome exchange. *Glob. Chang. Biol.* **22**, 3427–3443 (2016).
66. van der Laan-Luijkx, I. T. *et al.* Response of the Amazon carbon balance to the 2010 drought derived with CarbonTracker South America. *Global Biogeochem. Cycles* **29**, 1092–1108 (2015).
67. Silva Junior, C. H. L. *et al.* Persistent collapse of biomass in Amazonian forest edges following deforestation leads to unaccounted carbon losses. *Sci. Adv.* **6**, eaaz8360 (2020).
68. Baccini, A. *et al.* Tropical forests are a net carbon source based on aboveground measurements of gain and loss. *Science (80-.).* **358**, 230–234 (2017).
69. Giglio, L., Randerson, J. T. & Van Der Werf, G. R. Analysis of daily, monthly, and annual burned area using the fourth-generation global fire emissions database (GFED4). *J. Geophys. Res. Biogeosciences* **118**, 317–328 (2013).
70. Crippa, M. *et al.* EDGAR v5.0 Greenhouse Gas Emissions. European Commission, Joint Research Centre. (2019). Available at: https://data.jrc.ec.europa.eu/dataset/488dc3de-f072-4810-ab83-47185158ce2a.
71. Feng, L. *et al.* Consistent regional fluxes of CH4 and CO2 inferred from GOSAT proxy XCH4:XCO2 retrievals, 2010–20. *Atmos. Chem. Phys.* **17**, 4781–4797 (2017).
72. Assis, T. O. *et al.* CO2 emissions from forest degradation in Brazilian Amazon. *Environ. Res. Lett.* **15**, 104035 (2020).
73. Aguiar, A. P. D. *et al.* Land use change emission scenarios: anticipating a forest transition process in the Brazilian Amazon. *Glob. Chang. Biol.* **22**, 1821–1840 (2016).
74. Smith, C. C. *et al.* Secondary forests offset less than 10% of deforestation-mediated carbon emissions in the Brazilian Amazon. *Glob. Chang. Biol.* **26**, 7006–7020 (2020).
75. European Comission. EDGAR-Emissions Database for Global Atmospheric Research. doi:https://data.europa.eu/doi/10.2904/JRC_DATASET_EDGAR
76. INPE-EM. Available at: http://inpe-em.ccst.inpe.br/en/deforestation-driven-gross-emissions-old-growth-forests-amz/. (Accessed: 3rd February 2021)

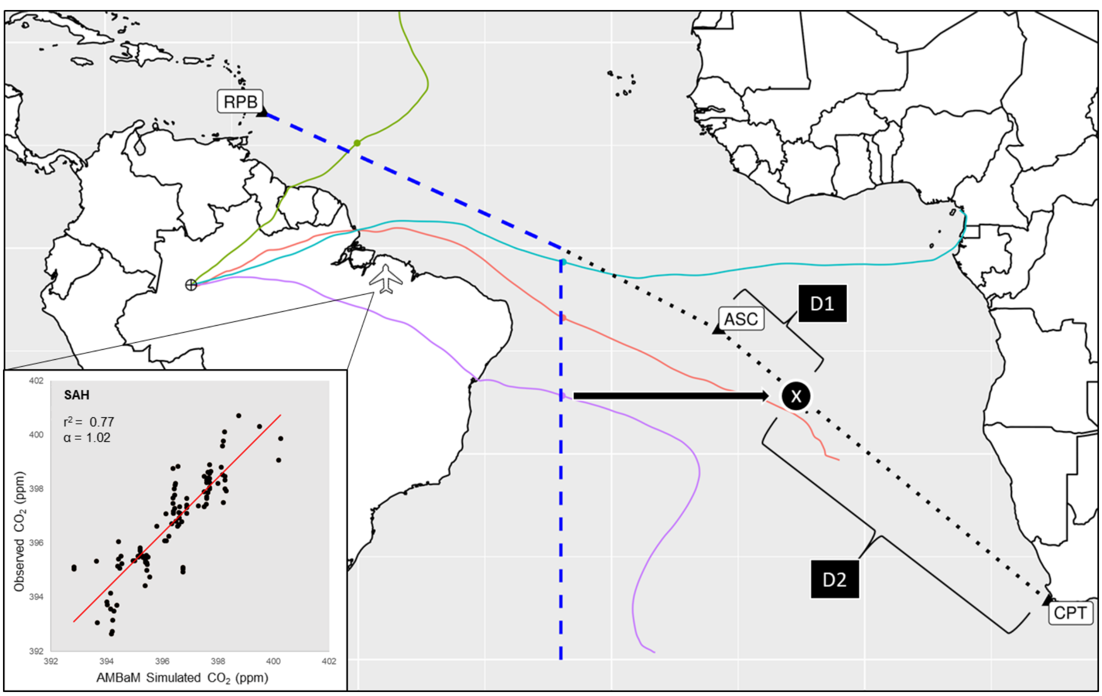




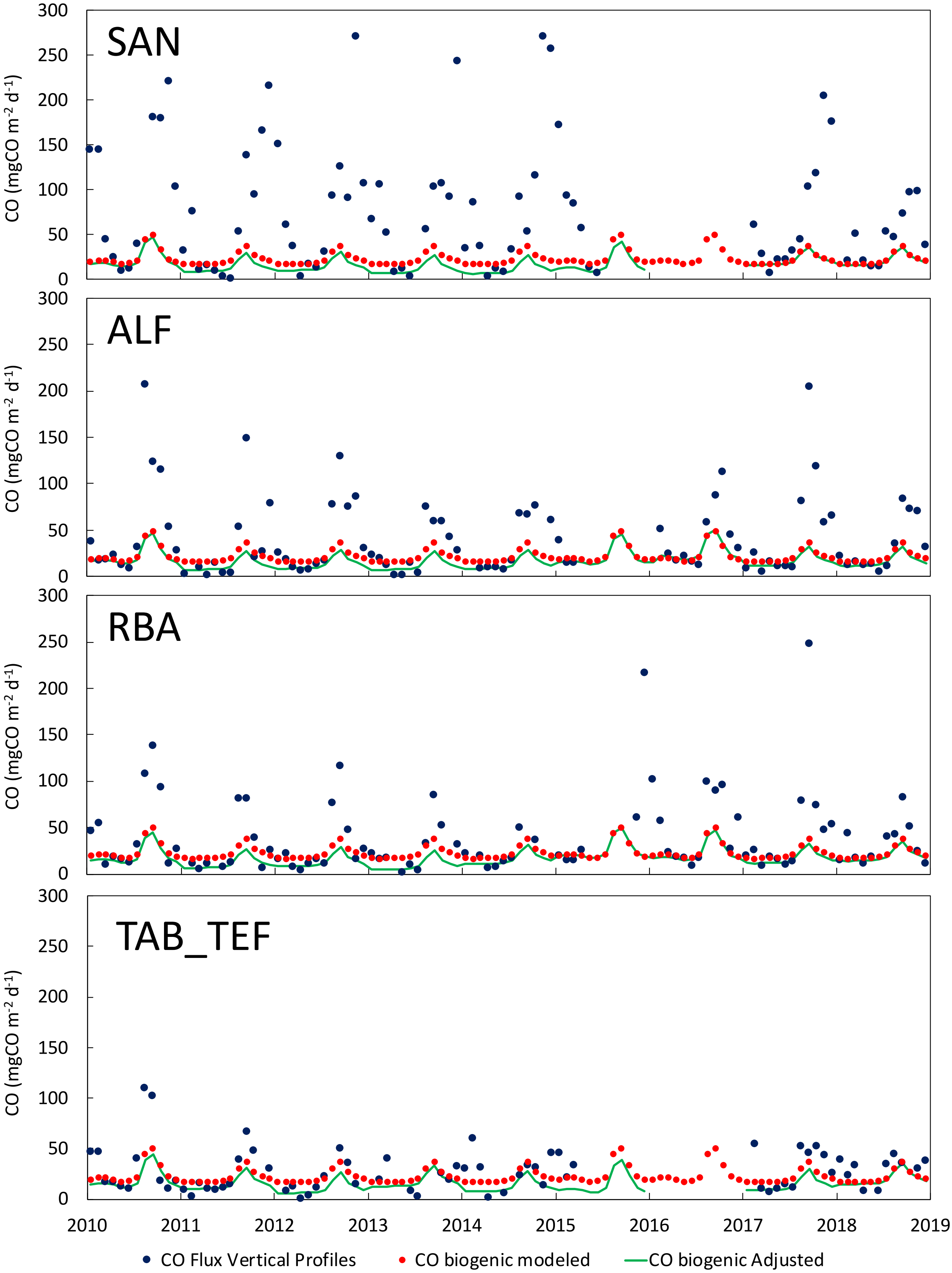
Supplementary Information Fig. 4 | Amazon ecosystem regions. a) Amazon mask 7,256,362 km^2 (study area) biomes defined from Olson et al.[33]; b) Amazon subregions used to define the Amazon mask (Amazon *sensu stricto*: 5,569,174 km^2, Andes: 555,564 km^2, Guiana: 970.161 km^2 and Gurupi; 161,463 km^2, we excluded the Planalto: 864,951 km^2) of Eva et al.[32]

Supplementary Information Fig. 5 | Sampling details installation. a) Twin-engine aircraft used at RBA, showing in detail the inlet in the inspection window (curved stainless steel tube) and temperature and relative humidity (T & H) sensor and the PCP (Portable Compressor Package) and PFP (Portable Flask Package) installed in the aircraft. b) Single-engine aircraft used at ALF, where the inlet and T & H sensor is installed in the wing and the PCP and PFP are behind the pilot's seat)

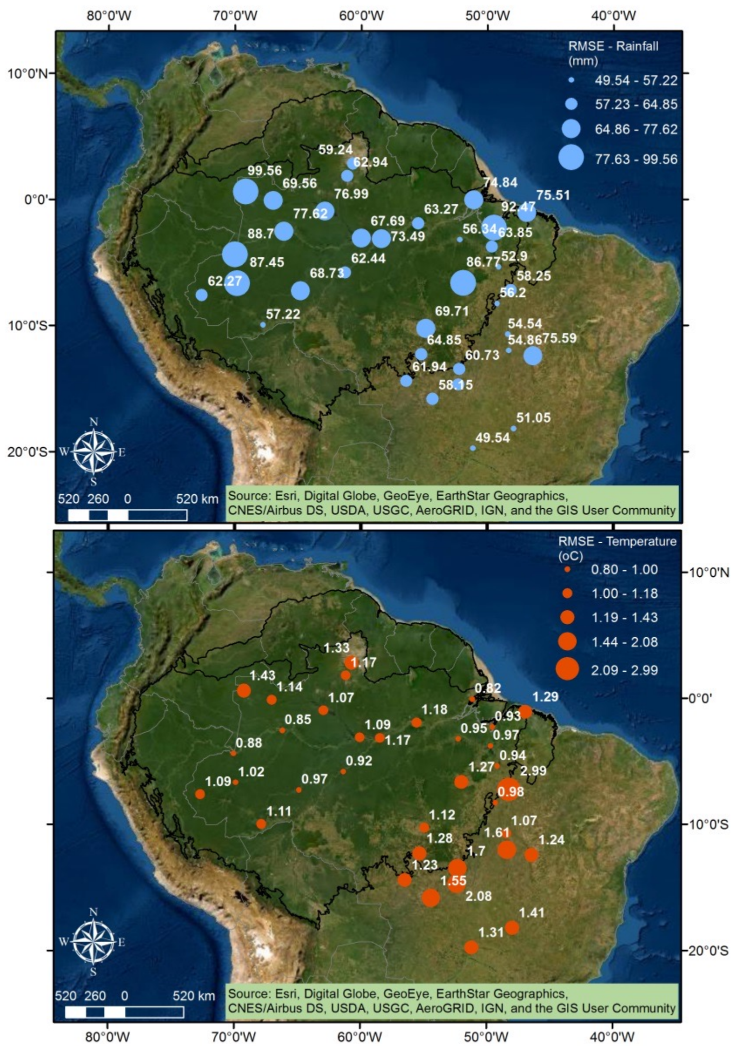
The Air-Mass Back-Trajectories Method (AMBaM)[41] was designed as an independent method of a direct GHG measurement air-mass tracer. It is an open source method, employing the Hybrid Single-particle Lagrangian Integrated Trajectory (Hysplit) transport and dispersion model air-mass back-trajectories, and GHG mixing ratios from the Global Monitoring Laboratory (GML) Observational Sites, Barbados (RPB), Ascension (ASC) and Cape Point (CPT). By the geographical position from each specific air-mass back-trajectory at the crossing point on the virtual limit (dashed blue line), a projection is made until the section ("X") between the GML observational sites pairs (RPB – ASC or ASC – CPT). The distance between the projected point and the global stations (D1 and D2) determines the weighting of the GHG concentrations at each global, therefore determining the background mixing ratio. To validate the method, AMBaM was used to simulated vertical profiles performed on the coastal site Salinópolis (SAH; 0.76° S, 47.8° W) using the same sampling date, time and height, showing robust agreement when compared with the samples results.



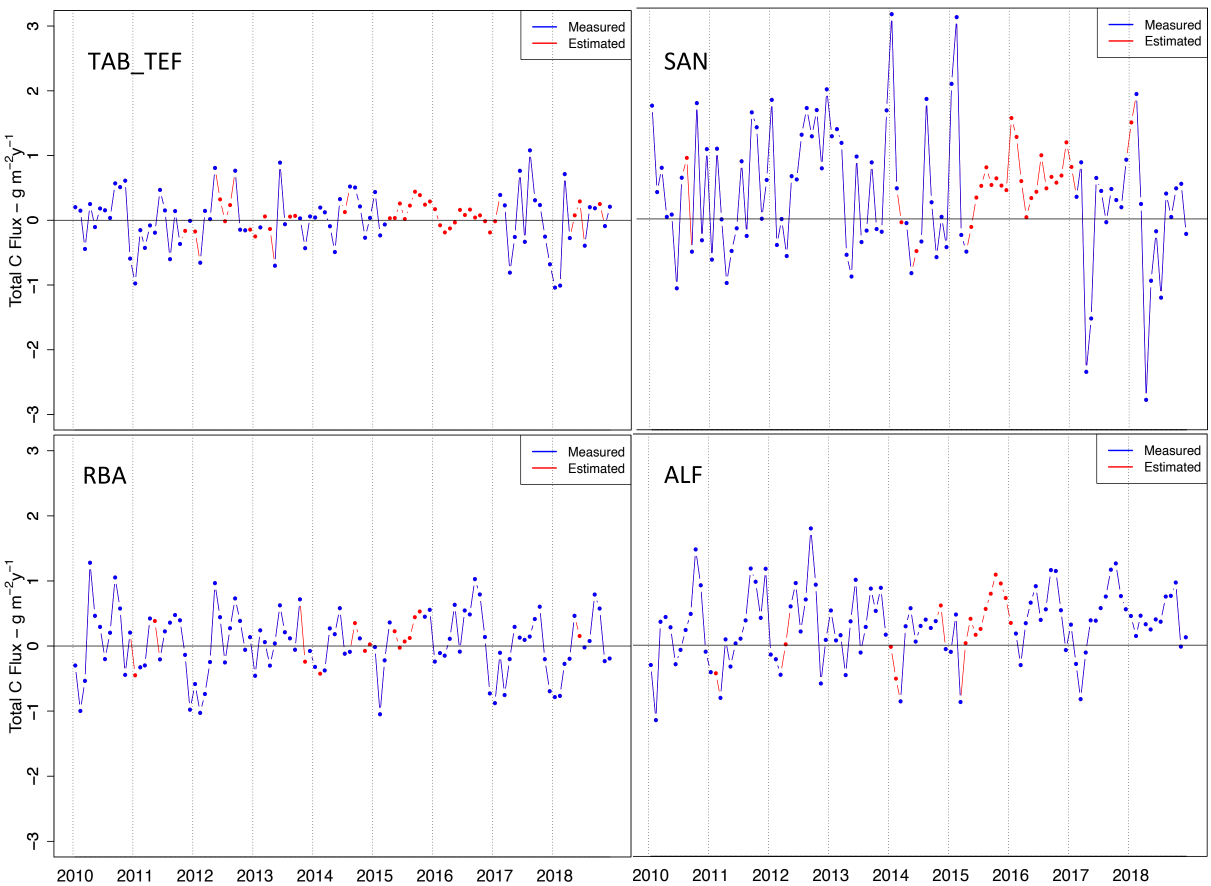
Supplementary Information Fig. 6 | Background Method. Air-mass back-trajectories method scheme. Blue dashed line is the Virtual Limit. Green, red, cyan and purple are examples of air-mass back-trajectories. D1 and D2 are the distances between the projected (black arrow) position "X" and the NOAA global stations, using the purple air-mass back-trajectory as an illustration of the AMBaM BKG calculation. Airplane symbol indicates the approximated SAH costal site location and AMBaM results comparison with vertical profiles samples mixing ratios.



Supplementary Information Fig. 7 | Biogenic Carbon monoxide. Dark blue filled circles: monthly mean total CO flux calculated according to eq. M1; Red filled circles: biogenic CO monthly mean modeled for 2010 (repeated in 2015 and 2016) and 2011 (repeated in 2012, 2013, 2014, 2017, 2018); Green line: monthly biogenic CO adjusted from modeled values (see Methods).



Supplementary Information Fig. 8 | Validation for precipitation and temperature. Validation sites of the (a) Global Precipitation Climatology Project (GPCP) and (b) ERA Interim products, showing the root-mean-square error (RMSE) for each gauge station from the INMET (National Institute of Meteorology, Brazil). The symbol's size in the maps represents the magnitude of the RMSE for each gauge station.



Supplementary Information Fig. 9 | Time series with filled gaps. Time series of carbon total flux (FC_{Total}) calculated according to eq. M1 for the sites SAN, ALF, RBA and TAB_TEF (blue filled circles) and the filled gaps using "Miss Forest" methodology (red filled circles).

Supplementary Information Table 10 | Uncertainty input data. a) Mean time back-trajectory (days) calculated for the methods HYSPLIT, FLEXPART Lagrangian particle dispersion model and back trajectories derived from the meso-scale model BRAMS, for all vertical profiles in 2010. b) Uncertainty calculated and used for each parameter in Monte Carlo error propagation

a)

	ALF	SAN	RBA	TAB
	mean time trajectories (days)			
HYSPLIT	4.8±1.0	2.6±1.3	6.3±1.1	6.0±1.3
BRAMS	5.1±1.2	2.7±1.5	6.6±1.2	6.1±1.1
FLEXPART	4.7±1.0	2.3±0.7	7.4±2.3	6.2±1.6
	difference between trajectory methods (RMSE)			
Hysplit-Brams*	1.2	0.6	1.1	1.5
Hysplit-Flexpart*	0.7	0.4	2.1	0.8

b)

Uncertainties parameters	**ALF**	**RBA**	**SAN**	**TAB_TEF**
CO BKG concentration (mgCO m^{-2} d^{-1})	27.4	29.8	19.0	25.6
CO total flux (mgCO m^{-2} d^{-1})	6.3	7.0	15.6	5.7
natural CO flux (mgCO m^{-2} d^{-1})	4.3	4.3	4.1	3.9
ratio CO:CO_2 (ppb CO (ppm CO_2)$^{-1}$)	9.9	15.1	14.5	17.2
CO_2 BKG concentration (ppm)	1.6	1.9	1.5	1.1
time trajectory (days)	1.2	2.1	0.6	1.5