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1 **Decrease in Amazonia carbon uptake linked to trends in deforestation and climate**

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32 **Summary**

33 Amazonia hosts Earth's largest tropical forests and has represented a globally important sink for
34 atmospheric CO₂ over recent decades, although the sink appears to be declining due increasing in
35 mortality¹⁻³. To improve diagnosis of Amazonia's carbon cycle, starting in 2010, we initiated regular
36 observation of lower troposphere CO₂ and CO concentrations at four aircraft vertical profiling sites
37 spread over the Brazilian Amazonia⁴. Using an air column budgeting technique, which integrate
38 vertical profiles CO₂ subtracting the correspondent background for each flask/height and considering
39 the air parcels travel time from coast to site, we calculate total and biomass burning C fluxes in the
40 regions upwind of each site, from 2010 to 2018. Over our study period, total C emissions are larger
41 in the east than in the west, which mainly results from spatial differences in CO-derived fire
42 emissions. For the southeast Amazonia, in particular, net C flux (total flux minus fire) represent a
43 source to the atmosphere. Over the past 40 years, the eastern Amazonia has been subject to more
44 deforestation, rapid warming, and moisture stress⁵, than the less human impacted west, especially
45 during the dry season, with the southeast experiencing the strongest trends. The higher eastern C
46 fluxes could be explained by climate and disturbance trends promoting both higher fire emissions and
47 greater stress on ecosystems, increasing mortality and reducing photosynthesis^{1,6}.

48

49 **Introduction**

50 Amazonia forests contain on the order of 123 ± 23 Pg C of biomass above and belowground⁷, which
51 can be released rapidly and may thus result in sizeable positive feedbacks on global climate⁸.
52 Additionally, deforestation and forest degradation reduce Amazonia's capacity to act as carbon sink.
53 Hydrologically, Amazonia is one of the three major air upwelling regions in the tropics, resulting in
54 the rainforest receiving rainfall on average across the whole Amazon around 2200 mm y⁻¹. Amazonia
55 exhibits complex relationships between ecosystem carbon and water fluxes and climate^{9,10}. For
56 example, evapotranspiration has been estimated from several studies to be responsible for 25 to 35%

57 of total rainfall¹⁰⁻¹². Large-scale human disturbance of these ecosystems can reasonably be expected
58 to alter these ecosystem-climate interactions. Over the last 40 to 50 years human impact has
59 increasingly affected Amazon, resulting in forest loss of around 17%, of which 14% has been
60 converted mostly to agriculture (89% pasture and 10% crops)¹³. Removal of forests causes increases
61 in temperatures^{9,14-16} and reduces evapotranspiration, and has been shown to reduce precipitation
62 downwind of deforested areas^{10,17,18}. Regional deforestation and selective logging furthermore lead
63 to degradation of adjacent forests, which increases their vulnerability to fires promoting further
64 degradation^{4,9,19}. These effects are further enhanced by temperature increases caused by a decrease in
65 forest cover^{17,20} and are superimposed on the backdrop of global warming.

66

67 **Atmospheric carbon vertical profiles**

68 A large-scale integrating indicator of the state of an ecosystem is its greenhouse gases balance, mainly
69 the carbon balance. Here, we report CO₂ fluxes between 2010 and 2018 based on almost 600 CO₂
70 (Extended Data Fig. 1a) and CO aircraft vertical profiles that tell us about responses of Amazonian
71 ecosystems to direct human impact and regional climate change. Fig. 1 shows the regions of influence
72 and the location for four vertical profiling sites. Profiles extend from near the surface to
73 approximately 4.5 km above sea level and are collectively sensitive to surface fluxes from a large
74 fraction of Amazonia. The air arriving at our sampling sites comes predominantly from the east with
75 the north-south component of the flow dependent on the seasonally varying position of the ITCZ (Fig.
76 1, Extended Data Fig. 2a). As a result, air samples collected at the four sites are influenced by regions
77 with differing levels of human disturbance (Fig. 1). Site-specific regions of influence were determined
78 using air-mass back-trajectory calculations (Extended Data Fig. 2, see Methods). We use quarterly-
79 resolved regions of influence to determine the average spatially-weighted magnitudes of potential
80 carbon flux drivers such as historical deforestation extent, temperature, and precipitation, upwind of

81 each site. Additionally, the regions of influence for each site are used to calculate spatially-weighted
82 mean fluxes for all of Amazonia (see Methods).

83 Annual mean vertical profile (VP) (Extended Data Fig. 1b) enhancements or depletions (ΔVP) are a
84 function of the cumulative effect of all C sources and sinks between the Atlantic coast and each site.
85 We examine ΔVP as a direct data analysis approach to gain a first-order understanding of C source
86 and sink patterns. Annual mean ΔVP is calculated by subtracting background (BKG) concentrations
87 determined from Atlantic Ocean remote sites from CO_2 concentrations at each VP sampling height
88 (Fig. 2) and the annual mean concentration integrated from the surface to the top of the profile
89 (Extended Data Fig. 1c) (see Methods). Figure 2 shows the annual and nine-years mean ΔVP for each
90 site. The eastern sites SAN (at northeast Amazon, hereafter referred to as SAN-NE) and ALF (at
91 southeast Amazon, hereafter ALF-SE) exhibit higher CO_2 relative to background, when integrated
92 from the surface to the top of the profile (see Methods), than the western sites RBA (southwest-central
93 Amazon, hereafter RBA-SWC) and TAB_TEF (northwest-central Amazonia, hereafter TAB_TEF-
94 NWC). Vertically integrated ΔVP (Extended Data Fig. 1c), which are proportional to surface flux,
95 suggest that ALF-SE has the largest CO_2 emission to the atmosphere, followed by SAN-NE. In
96 contrast VPs after BKG subtraction for the western sites RBA-SWC and TAB_TEF-NWC indicate
97 near neutral or C sinks.

98 An alternative way of examining the VPs is to not subtract BKG, but just consider the vertical
99 differences between the top of the profiles ($> 3.8km$) and that portion below the planetary boundary
100 layer ($\sim >1.5km$) (Extended Data Fig. 1d). As with the BKG subtraction approach, positive
101 enhancements suggest a land source, while negative depletions suggest a sink. This vertical
102 difference approach shows similar behavior to the BKG subtraction approach, with positive CO_2
103 surface emission to the atmosphere from eastern sites (SAN-NE and ALF-SE) and almost neutral or
104 removal of CO_2 from surface for the western sites (RBA-SWC and TAB_TEF-NWC). At ALF-SE
105 annual mean ΔVP (Fig. 2) is observed after the last strong El Nino 2015/16 higher CO_2 concentrations

106 near surface, representing increasing in emissions. Only RBA-SWC exhibits significantly different
107 behavior from the two approaches with near neutral C balance with BKG subtraction and apparent C
108 uptake when examining vertical differences (Extended Data Fig. 1c&d). The annual mean RBA-
109 SWC VP shows clearly the strongest carbon sink compared to the other regions, and when we just
110 consider the vertical differences between >3.8km and <1.5km the uptake from surface is more
111 evident. Long travel times of air masses from the coast to vertical profile sites allows for a more
112 convective process promoting vertical mixing between the atmosphere's layers we measure and those
113 above it. The result of such mixing is that some surface flux signal can be lost through the top of our
114 measurement domain. In the case of CO, during the dry season, we observe larger enhancements in
115 the difference >3.8km and BKG indicating loss of signal, although CO plumes, in particular are
116 associated with pyro-convection and not the same degree of signal loss for CO₂ (Supplementary
117 Information Fig. 1). Vertical loss of signal is one source of uncertainty in our approach that we
118 account for (see Methods).

119 **Regional Amazonia Carbon Fluxes**

120 Partial columns of CO₂ are used to determine total carbon fluxes (FC_{Total}) that represents the result of
121 all surface sources and sinks (natural and anthropogenic) between the coast and the sample site. CO
122 is used to determine the fraction of FC_{total} derived from biomass burning emissions (FC_{Fire}).
123 Removing FC_{Fire} from FC_{Total} we obtain Net Biome Exchange (FC_{NBE}) for the region upwind of given
124 vertical profile (a negative NBE represents C sink). Total, fire and NBE carbon fluxes were combined
125 into monthly, annual and long-term averages, and into east, west and basin-wide totals (Extended
126 Data Table 2; see Methods).

127 For SAN-NE, the nine-year mean fluxes for FC_{Total}, FC_{Fire} and FC_{NBE} are 0.41 ± 0.25 , 0.53 ± 0.03 and
128 -0.11 ± 0.26 gC m⁻² d⁻¹, respectively (Fig. 3; Extended Data Table 2). This region presented the highest
129 carbon fluxes among our sites. The seasonality of carbon fluxes (Extended Data Fig. 3 & 4) is the
130 second largest for SAN-NE as is true for the seasonalities of precipitation, temperature, and Enhanced

131 Vegetation Index (EVI, a measure of vegetation of greenness, see Methods). ALF-SE shows the
132 second highest FC_{Total} over nine years ($0.32 \pm 0.09 \text{ gC m}^{-2} \text{ d}^{-1}$; Fig. 3) and exhibits the strongest
133 seasonality for carbon fluxes, precipitation, temperature, and EVI. At dry season low EVI value
134 reflects a susceptible period of drier biomass for ignition, which this region presented the highest
135 burned area (Extended Data Table 2). Over nine-years, FC_{NBE} for this region is a possible carbon
136 source to the atmosphere ($+0.11 \pm 0.13 \text{ gC m}^{-2} \text{ d}^{-1}$) representing one third of FC_{Total} . Seasonally, the
137 region is a weak sink only during part of the wet season with most positive FC_{Total} in the dry season
138 resulting from fire emissions and net respiration (Extended Data Fig. 3). Note, however, that part of
139 the seasonality in fluxes observed for ALF-SE may result from the region of influence shifting
140 southward to areas of greater historical disturbance in the 2nd and 3rd quarters regions of influence
141 (see Climate Trends and Human Impact below), which corresponds to the end of wet season (April-
142 May) and dry season (June-September) (Extended Data Fig. 2a,b). The Cerrado (savanna) biome to
143 the south and east of the rainforest may represent about 40% in the 2nd and 3rd quarters of the region
144 of influence (Extended data Fig 2a). Over the 9 years studied (2010 - 18), NBE for ALF-SE indicates
145 that it is a source each year greater, presenting an increase rate (slope) per year of $0.036 \pm 0.015 \text{ gC m}^{-2} \text{ d}^{-1}$
146 (Pearson's correlation, $r = 0.68$, $p = 0.045$) (Extended Data Fig. 5a). Between 2010 and 2018,
147 annual FC_{Fire} averages $0.20 \pm 0.01 \text{ g C m}^{-2} \text{ d}^{-1}$. RBA-SWC, which has experienced less disturbance
148 than the east, averaged a weak source over nine years (FC_{Total} : 0.05 ± 0.02), with FC_{NBE} an annual
149 mean sink (-0.10 ± 0.02), compensating about two thirds of FC_{Fire} ($0.14 \pm 0.01 \text{ gC m}^{-2} \text{ d}^{-1}$). The mean
150 seasonal cycle of NBE exhibits a wet season sink from November through March (Extended Data
151 Fig. 3). RBA FC_{Fire} is high due in large part to the fact that the "Arc of Deforestation" is in the
152 southern portion of the region upwind of the site (Extended Data Fig. 2).

153 Air samples from TAB_TEF-NWC are sensitive to the northwest and central Amazonia, one of the
154 regions least impacted by human activities. Vertical profiles of CO_2 and CO were measured at TAB
155 from 2010 to 2012, and at TEF from 2013 to 2018, but their regions of influence and flux seasonal

156 cycles are very similar, so we have analysed them as a single time series (Supplementary Information
157 2 and Extended Data Fig. 4). Combining TAB and TEF, the nine-year mean FC_{Total} is near neutral
158 (0.03 ± 0.08), with FC_{NBE} (-0.06 ± 0.08) nearly compensating for fire emissions ($0.08 \pm 0.01 \text{ gC m}^{-2} \text{ d}^{-1}$)
159 (Extended Data Table 2). Seasonality in both FC_{Total} and FC_{NBE} is absent for TAB_TEF, with both
160 FC_{Total} and FC_{NBE} near neutral all year. This lack of seasonality may result from the near absence of
161 dry months (less than 100 mm of precipitation) in the upwind region, which is also expressed as low
162 seasonal fire fluxes and burned area; EVI seasonality is also the smallest of all sites. Lack of EVI
163 seasonality is related to a relatively high constant fraction of photosynthetically active radiation
164 (fPAR) absorbed by plants, and thus a lower fraction of dry biomass throughout the year, reducing
165 fire risk (Extended Data Fig. 3 & 4).

166 CO_2 gradients from the annual mean vertical profiles and the estimated carbon fluxes for these sites
167 indicated a link between areas more impacted by land use and cover change and higher carbon
168 emissions to the atmosphere.

169 Considering the upwind areas of each site, we combine fluxes from all sites to calculate a total
170 Amazonia carbon balance for our nine-year study period (see Methods) of $0.29 \pm 0.40 \text{ PgC y}^{-1}$ (FC_{Total}
171 $0.11 \pm 0.15 \text{ gC m}^{-2} \text{ d}^{-1}$), where fire emissions represent $0.41 \pm 0.05 \text{ PgC y}^{-1}$ (FC_{Fire} $0.15 \pm 0.02 \text{ gC m}^{-2} \text{ d}^{-1}$)
172 with NBE removing only 31% of fire emissions from the atmosphere, $-0.12 \pm 0.40 \text{ PgC y}^{-1}$ (FC_{NBE}
173 $-0.05 \pm 0.15 \text{ gC m}^{-2} \text{ d}^{-1}$). The east (region 1 at Extended Data Fig 6) represents 24% of the whole
174 Amazonia, 27% deforested, is responsible for 72% of total Amazon carbon emission, where 62% is
175 from fires. Forest fires contribute with cumulative gross emissions of carbon of. $\sim 126.1 \text{ Mg CO}_2 \text{ ha}^{-1}$
176 for 30 y after a fire event and a mean annual flux value of $4.2 \text{ Mg CO}_2 \text{ ha}^{-1} \text{ y}^{-1}$ (0.48 PgC y^{-1} using
177 the same area from our study). Cumulative CO_2 uptake only offsets 35% of these²¹. Another recent
178 study pointed out fire emissions from Amazonia $\sim 0.21 \pm 0.23 \text{ PgC y}^{-1}$ ⁹. Recently, Van der Werf et
179 al.²² estimated for the period between 1997-2009 that globally, fires were responsible for an annual
180 mean carbon emission of 2.0 Pg C yr^{-1} , where about 8% appears to have been associated with forest

181 fires, based on estimates from the Global Fire Emission Dataset (GFED) product for South America.
182 The RAINFOR project showed for mature forest a decline in sink ability due increase in mortality¹⁻
183 ³. Considering a mean value for these three studies, the 90's ~ -0.56 , 00's ~ -0.38 and 10's -0.20 Pg C
184 y^{-1} . The NBE from this study represents (decade 10's) the uptake from forest, but also all non-fire
185 emissions (more comparisons can be found at Supplementary Information Table 2).

186

187 **Climate trends and human impact**

188 The regions of influence for the four sites differ substantially with regard to human impact, in
189 particular deforestation. Using site-specific regions of influence averaged over our nine-year study
190 period (Extended Data Figure 2c), we determine cumulative historical deforestation fractions of the
191 areas upwind of SAN-NE, ALF-SE, RBA-SWC and TAB_TEF-NWC to be 31%, 26%, 13% and 7%,
192 respectively (see Methods). SAN-NE and ALF-SE vertical profiles sample air affected by yet higher
193 levels of deforestation during the 2nd and 3rd quarters of the year (Extended Data Fig. 2a,b). For SAN-
194 NE, deforestation increases to 39 and 42%; for ALF-SE increases are 32 and 39%, respectively.

195 Regions of influence of eastern and western Amazonia sites also differ with regard to long-term
196 climate trends. We found similar annual mean warming trends for the whole Amazonia
197 ($1.02 \pm 0.12^\circ\text{C}$) as for the global average (0.98°C)²³ between 1979 and 2018 (see Methods). However,
198 warming trends differ between months, and the largest increases were observed for three dry season
199 months of August, September and October (ASO; $1.37 \pm 0.15^\circ\text{C}$). Annual mean precipitation has not
200 significantly changed, but similar to temperature trends, ASO precipitation has decreased by 17%,
201 enhancing the dry-season/wet-season contrast (Extended Data Fig. 7 and Table 1).

202 Between 1979 and 2018 there are also considerable regional contrasts in temperature and
203 precipitation trends, mainly in the dry season. Those for the eastern regions SAN-NE and ALF-SE,
204 which have the largest fractions of historically deforested land, stand out, highly impacted mainly by
205 livestock and, to a lesser extent, by crops¹³. For the SAN-NE, deforested 37%, it was the unique

206 region where the annual mean precipitation has decreased 9% in the past 40 years ($208\pm 167\text{mm}$),
207 where the largest reduction was during ASO (34%) (Fig. 4 & 5 and Extended Data Table 1). Although
208 annual mean precipitation upwind of ALF-SE has not changed significantly, ASO precipitation
209 decreased by 24%, as noted previously for a similar region of Amazonia^{17,20,24}. Although the
210 fractional and absolute reduction rate in ASO precipitation for SAN-NE and ALF-SE is similar to the
211 western sites (Extended Data Table 1), the impact of this drying on the ecosystems is probably greater,
212 because dry season moisture in the east is lower than the west during the last 4 decades (Fig. 4 and
213 Extended Data Figure 8). Temperature trends for the eastern regions are also larger than for
214 Amazonia as a whole: $1.38\pm 0.15^\circ\text{C}$ at SAN-NE and $1.46\pm 0.11^\circ\text{C}$ at ALF-SE annually, with changes
215 of $1.86\pm 0.16^\circ\text{C}$ and $2.54\pm 0.29^\circ\text{C}$, respectively, during ASO (Extended Data Fig. 8 & Table 1).
216 Moreover, these trends appear to be accelerating over the last 40, 30, and 20 years (Extended Data
217 Table 1). For ALF-SE, temperature has also increased by $3.07\pm 0.29^\circ\text{C}$ for the two hottest months
218 August and September (AS) (Extended Data Fig. 8). These temperature and precipitation changes
219 are also associated with a large positive trend in Vapor Pressure Deficit in the southeast Amazonia⁵,
220 which suggests increasing plant stress. For ALF-SW, two phenomena are acting to increase the
221 temperature: global climate change^{5,18,25-27} and large-scale deforestation and forest degradation
222 amplifying these trends in this region.

223 The two western sites, RBA-SWC and TAB_TEF-NWC, also exhibit their strongest trends during
224 the dry season. There has been no significant annual mean change in precipitation for RBA-SWC,
225 but ASO precipitation has dropped by 20% (Fig. 4). Its annual mean temperature increases similarly
226 to global rates, although it is also largest during ASO ($1.72\pm 0.15^\circ\text{C}$). The relatively pristine region
227 upwind of TAB_TEF-NWC (7% historical deforestation), also shows a decreasing trend in ASO
228 precipitation of 20%, but no significant annual mean trend (Fig. 4). A possible reason for this 20%
229 decrease in precipitation in both western regions, less deforested, is the cascade effect¹⁰. That is,
230 deforestation in the eastern Amazonia may be reducing evapotranspiration, which in turn may be

231 reducing the recycling of water vapor that is transported to the western Amazonia. Annual mean
232 temperature trends of TAB and TEF have been similar to global trends, and although ASO
233 temperature trends are larger than for the annual mean, they are smaller than for the other regions
234 (Extended Data Table 1). The analysis of 40 years of temperature and precipitation data over
235 Amazonia shows the relationship between deforestation extent and decreases in precipitation and
236 increases in temperature, mainly during the dry season, with different trends observed for the eastern,
237 western and whole Amazonia.

238

239 **East versus West Amazonia contrasts**

240 Dividing Amazonia into regions (Extended Data Fig. 6a) influencing eastern (SAN and ALF: region
241 1) and western (RBA and TAB_TEF: region 2) sites reveals notable differences. The east side (region
242 1) represents approximately $1.6 \times 10^6 \text{ km}^2$, with cumulative historical deforestation of approximately
243 27%. The west (region 2), on the other hand, has a much larger region of influence (approximately
244 $4.1 \times 10^6 \text{ km}^2$) and a much smaller fraction of deforested land (11%). The historical deforestation
245 and climate changes in the east could be reflected in eastern average annual mean FC_{Total} of 0.35 ± 0.11 ,
246 FC_{Fire} of 0.31 ± 0.01 and FC_{NBE} of $+0.04 \pm 0.11 \text{ gC m}^{-2} \text{ d}^{-1}$ (see Methods). The eastern averages are
247 strongly influenced by the southeast Amazonia, represented by observations from ALF-SE, which is
248 characterized by a positive NBE (carbon emission), very strong changes in dry season with increase
249 of temperature, decrease of precipitation and large historical deforestation (Extended Data Table 1 &
250 2).

251 At ALF-SE, for the 2010 - 2018 period of our CO_2 and CO observations, we can directly observe
252 the relationship between moisture and temperature and FC_{NBE} and FC_{Fire} . The positive trend in NBE
253 at ALF-SE correlates with the annual mean temperature and GRACE (equivalent water thickness)
254 satellite soil water storage anomalies (see methods) (multivariate linear correlation, $r = 0.88$, $p =$
255 0.011), suggesting that temperature and water availability in the soil have a significant impact on the

256 vegetation carbon balance at least in the southeast (Extended Data Fig. 3, 4 & 5b). Interannual
257 variations of FC_{Fire} at ALF-SE are strongly correlated with ASO (peak of dry season) temperature and
258 precipitation ($r = 0.81$ and $r = -0.73$, respectively), showing that temperature and moisture impact
259 both components of FC_{Total} . This region also exhibits almost twice the burned area of any other region
260 (Extended Data Fig. 3 & 4), and interannual burned area is highly correlated with FC_{Fire} ($r = 0.97$).
261 Historically, the eastern Amazonia has experienced strong increase in dry season temperature,
262 reduced precipitation and increased duration^{5,17,20,25,28-31}, which together are creating an increasingly
263 severe environment for vegetation, not only during extreme drought years, but every year, especially
264 for the southeast³².

265 In contrast, the regions influencing the western sites have experienced relatively lower levels of
266 human disturbance and dry season climate trends. For the regions upwind of TAB_TEF-NWC and
267 RBA-SWC, we observed a near neutral FC_{Total} of $0.04 \pm 0.07 \text{ gC m}^{-2} \text{ d}^{-1}$, minimal fire emissions
268 (0.11 ± 0.01) and a carbon sink (FC_{NBE}) of $-0.08 \pm 0.07 \text{ gC m}^{-2} \text{ d}^{-1}$ (Extended Data Table 2). In a
269 scenario where the whole Amazonia had the same NBE as western sites, the whole area would act as
270 a sink of 0.20 PgC y^{-1} .

271 The east-west difference in total flux can be explained mainly on the basis of CO₂-based fire
272 emissions and burned area (Fig. 5 and Extended Data Table 2). However, the dry season climate
273 trends and the stronger historical deforestation and degradation in the east could make the area more
274 susceptible to fire⁹. Historical land use change and climate trends could also explain higher (positive)
275 NBE, especially in the southeast. Recent study pointed out that after 30 years burned area still is a
276 CO₂ source to the atmosphere, which 73% resulted from subsequent tree mortality and
277 decomposition²¹. This decomposition emission could not be compensated by CO₂ uptake by
278 photosynthesis. For undisturbed forests, increasing temperatures and moisture stress may increase
279 in tree mortality^{1-3,6}, as well as, negatively impact photosynthetic C uptake by trees via a decline in
280 photosynthetic capacity³¹. Moreover, higher air temperatures generally lead to higher rates of soil

281 carbon decomposition in both intact forests and disturbed land. Historical trends of regional climate
282 and land disturbance in Amazonia may be connected; our results suggest that such interactions may
283 have long-term impacts on the C balance of Amazonia.

284

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438

439 **Fig. 1 | Regions of influence.** Average Regions of Influence (2010-2018), delimited by light blue
440 line based on the density of HYSPLIT back trajectories (see Methods and Extended Data Fig. 2c for
441 detailed regions of influence) inside Amazon Mask, (purple line, 7.25×10^6 km²) for each vertical
442 profile site: TAB_TEF (northwest; TAB, 2010-2012 and TEF 2013-2018), SAN (northeast), ALF
443 (southeast) and RBA (southwest). The aircraft vertical profiles sites (Flight sites) are shown as black
444 circles. Deforestation data is from PRODES only for the Brazilian Amazon up to 2018 (see Methods).

445

446 **Fig. 2 | Annual Mean Vertical Profiles.** From vertical profile monthly mean (for each height was
447 subtracted the background) was produced the Annual Mean Vertical Profile for each year (2010-
448 2018), where the concentrations were corrected by the correspondent air density for each level. The
449 black line represents the 9 years mean vertical profiles for each site. The mean for annual vertical
450 profiles for each site in ppm and the site mean are presented at Extended Data Fig 1c.

451

452 **Fig. 3 | Annual carbon fluxes.** Annual carbon fluxes for the regions upwind of SAN, ALF, RBA
453 and TAB_TEF (TAB 2010-2012 and TEF 2013-2018). Blue bars are total C Flux, red bars are fire
454 C Flux and green bars NBE (total less fire flux). Error bars are uncertainties of annual means (see
455 Methods).

456

457 **Fig. 4 | 40-years precipitation and temperatures trends.** Precipitation trends using GPCP V2.3
458 (upper panels) and temperature trends using ERA-Interim, from 1979 to 2018 (lower panels), for 4
459 sites. Annual (black), ASO (red; August, September and October) and JFM (blue; January, February
460 and March) totals (for precipitation) and means (for temperature) between 1979 and 2018 (see
461 Methods). TAB_TEF ASO and JFM is shown only for TEF, since there is no dry season at TAB;
462 annual values are shown for the combination of both sites

463

464 **Fig. 5 | Spatial results overview.** Summary of deforestation per site (orange arrows), reduction in
465 precipitation during the months August, September and October (ASO) (light blue arrows), increase
466 in temperature in ASO (white arrows) and carbon fluxes (Total: dark blue bars, NBE: green bars, fire:
467 red bars).

468

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478

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483 data weighted studies; LGD, CC, SC and RL contributed with GHG concentration analysis; GT
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485

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489

490 **Additional Information** Extended Data and Supplementary Information is available for this paper.
491 Correspondence and requests for materials should be addressed to luciana.gatti@inpe.br.

492

493 **Methods**

494 **Sites, Air sampling and analysis** The Amazon study area was defined according to Eva et al.³³
495 subregions and Olson et al.³⁴ biomes. For the Amazon mask we considered the subregions of Amazon
496 *sensu stricto*, Andes, Guiana and Gurupi given a total study area of 7,256,362 km²; we excluded the
497 Planalto sub-region as it is outside the Tropical and subtropical moist broadleaf forest biome
498 (Supplementary Information Fig. 3).

499 The four aircraft vertical profiles sites from the CARBAM project at Amazon were started in 2010:
500 SAN (2.86S 54.95W); ALF (8.80S 56.75W); RBA (9.38S 67.62W); TAB (5.96S 70.06W) from
501 2010-2012, and TEF (3.39S 65.6W), starting in 2013. The sampling period was typically twice per
502 month. Over nine years, 590 vertical profiles were performed (Extended Data Fig. 1a,b) in a
503 descending spiral profile from 4420 m to 300 m a.s.l. A mean of 75 vertical profiles was performed
504 per year from 2010 to 2018 at the 4 sites, except for 2015 and 2016. In 2015 the flight collection was
505 stopped in April at all sites, returning only in November at RBA. In 2016 only RBA and ALF were

506 measured. The vertical profiles were usually taken between 12:00 and 13:00 local time. Air is
507 sampled by semi-automatic filling of 0.7 L boro-silicate flasks inside purpose-built suitcases³⁵; there
508 are two versions, one with 17 flasks at SAN, and another with 12 flasks at TAB_TEF, ALF and RBA.
509 This suitcase is connected to a compressor package, containing batteries, which is connected to an air
510 inlet on the outside of the aircraft at wing or window, depending on the aircraft model (Supplementary
511 Information Fig. 4a,b). Air samples were analyzed with a non-dispersive infrared (NDIR) analyzer
512 for CO₂ and by gas chromatography HgO reduction detection (GC-RGD) for CO. Detailed methods
513 have been presented earlier³. To ensure accuracy and precision, we analyzed CO₂ mole fraction from
514 “target tanks” (calibrated CO₂ in air in high pressure cylinders treated as unknowns) and demonstrated
515 long-term repeatability of 0.02 ppm and a difference between measured and calibrated values of 0.03
516 ppm³⁶.

517
518 **Annual Mean Vertical Profiles** We calculated annual mean partial column averages from our
519 vertical profiles as a simple way to assess the robustness of our annual fluxes. For each site annual
520 mean profiles were calculated starting with individual profiles and then averaging to monthly and
521 annual values (Extended Data Fig. 1b). We also constructed the annual mean vertical profiles
522 subtracting the background values at each altitude of each vertical profiles (Δ VP) to produce the
523 annual mean enhancement or depletion at each altitude (Fig. 2). The air density-weighted column
524 mean was then calculated and compared to the annual mean flux calculated from the same profiles
525 (Extended Data Fig. 1c). For all sites, we observed a high positive correlation between the column
526 means and fluxes suggesting that at least at the annual mean level our fluxes, which incorporate more
527 detail, such as travel time, are consistent with a simpler interpretation of the data.

528
529 **Carbon Flux estimation** Fluxes for each vertical profile were calculated using a column budget
530 technique, that consist in the difference between trace gas concentration at the sites and corresponding

531 background values for each flask (ΔX) and the travel time of air parcels along the trajectory from the
 532 coast to the site t (eq. M1). Detailed information can be found at Gatti et al.⁴, and was also used by
 533 Miller et al.³⁷, Gatti et al.³⁸, Basso et al.³⁹ and D'Amelio et al.⁴⁰.

$$534 \quad F_X = \int_{z=0(\text{agl})}^{4.4\text{km}(\text{asl})} \frac{\Delta X}{t(z)} dz \quad (\text{M1})$$

535 To apply eq. M1 we convert mole fractions $\{\mu\text{mol CO}_2 (\text{mol dry air})^{-1}$, i.e. ppm $\}$ to concentrations
 536 $(\text{mol CO}_2 \text{ m}^{-3})$ using the density of air, where temperature (T) and pressure (P) were measured during
 537 the vertical profiles and for situations where weren't, it were calculated T, P using the equation
 538 derived for temperature and pressure based in all measured T and P relating to height for each site.
 539 The used equations are presented M2 to M9, where x: height (m), T ($^{\circ}\text{C}$), P (mbar).

$$\text{SAN_Temperature} \quad y = 1.9586x^2 - 249.49x + 5815 \quad r^2 = 0.97 \quad (\text{M2})$$

$$\text{SAN_Pressure} \quad y = 0.0024x^2 - 12.46x + 11069 \quad r^2 = 0.87 \quad (\text{M3})$$

$$\text{ALF_Temperature} \quad y = 0.4202x^2 - 170.62x + 5201 \quad r^2 = 0.89 \quad (\text{M4})$$

$$\text{ALF_Pressure} \quad y = 0.0059x^2 - 20.21x + 14402 \quad r^2 = 0.87 \quad (\text{M5})$$

$$\text{RBA_Temperature} \quad y = 0.1985x^2 - 167.77x + 4953 \quad r^2 = 0.97 \quad (\text{M6})$$

$$\text{RBA_Pressure} \quad y = 0.0079x^2 - 21.10x + 13872 \quad r^2 = 0.89 \quad (\text{M7})$$

$$\text{TAB_Temperature} \quad y = 2.415x^2 - 253.98x + 5542 \quad r^2 = 0.95 \quad (\text{M8})$$

$$\text{TAB_Pressure} \quad y = 0.0051x^2 - 18.87x + 13828 \quad r^2 = 0.87 \quad (\text{M9})$$

540 For assigning background concentrations, we use the geographical position of each air-mass back-
 541 trajectory when it intersects two virtual limits. The first one is a latitude limit, from the Equator
 542 southwards at 30° W, and the second segment is a line from the Equator to the NOAA/GML
 543 observation site at Ragged Point, Barbados (RPB). The atmospheric air circulation over Amazonia is
 544 characterized by trade-wind easterlies coming from the tropical Atlantic Ocean³⁷ and moving towards
 545 the Andes (west). This behaviour allows us to relate the position that air mass crosses the virtual line
 546 with the concentrations measured at the remote sites in the Atlantic: RPB, ASC and CPT from the
 547 NOAA Global Monitoring Laboratory (NOAA/GML) to determine background. This method is
 548 published in Domingues et al.⁴¹ (supplementary Information Fig. 5).

549 To estimate travel times (t , equation M1) we calculate back trajectories for each air sampling level
550 for each flight. 13 days backwards trajectories are derived from the online version of the HYSPLIT
551 model⁴². Then, with a resolution of 1 hour, the time when the back trajectory crosses the coast is
552 calculated. Mean travel times (2010-2018) from the coast to SAN 2.4 ± 1.5 days, ALF 5.0 ± 2.0 days,
553 RBA 6.6 ± 2.1 days, TAB (2010-2012) 5.9 ± 1.9 days and TEF 4.9 ± 2.0 days. For each height interval,
554 we calculate the associated flux and then sum them to obtain the flux estimate for the specific
555 measured vertical profile. For calculating annual means, we first calculate monthly mean fluxes
556 (typically with two fluxes per site per month) and then average them.

557

558 **Fire Flux estimation** To estimate fluxes due to biomass burning, we used measured CO
559 concentrations as a biomass burning tracer. We estimate CO:CO₂ fire emission ratios from clearly
560 identifiable plumes in the vertical profiles during the dry season, typically from August to December⁴.
561 Average CO:CO₂ ratios were calculated by site: ALF CO:CO₂= 53.4 ± 9.9 , based on 16 vertical
562 profiles; SAN CO:CO₂= 55.5 ± 14.7 , based on 19 vertical profiles; RBA CO:CO₂= 73.2 ± 15.1 , based
563 on 12 vertical profiles; and TAB_TEF CO:CO₂= 71.6 ± 17.2 , based on 5 vertical profiles, where the
564 units are [ppb CO (ppm CO₂)⁻¹]. The two eastern sites showed lower ratios and western sites higher
565 ratios. The eastern sites are sensitive to more deforested and degraded land, and also receive influence
566 from Cerrado and Caatinga. The western sites are sensitive to more preserved areas and have a higher
567 representativity of Amazonia⁴³. TAB_TEF represents a pristine area with many fewer biomass
568 burning events.

569 Equation M10 was used to estimate CO₂ emission from biomass burning. F_{CO} is calculated identically
570 to CO₂ fluxes according to eq. M1. To isolate the biomass burning flux from total CO flux we subtract
571 the “natural” CO flux, $F_{CO}^{Natural}$, arising from direct soil CO emissions and mainly CO from oxidation
572 of VOCs like isoprene that are emitted from the forest. Basin wide average $F_{CO}^{Natural}$ between the
573 surface and 600 mbar (the approximate maximum altitude of the vertical profiles) was calculated for

574 2010 and 2011 starting with output from the Belgian Institute for Space Aeronomy (BIRA)
575 IMAGESv2 chemical transport model (CTM). The VOC production in the model was tuned to
576 HCHO (formaldehyde) observations from the GOME-2 and OMI satellites⁴⁴, resulting in improved
577 estimates of atmospheric CO production from VOCs. These modeled fluxes were then adjusted on a
578 site by site basis with a constant offset each year to match the mean late wet season, early dry season
579 observed total CO flux, which in past studies^{4,36} we have taken to be equal to the year-round biogenic
580 CO flux (late wet season, early dry season is March – June, except for SAN, in which March is
581 excluded, because high CO fluxes are sometimes observed). 2010 fluxes were applied to all the dry
582 years (2010, 2015, 2016) and 2011 fluxes were applied to all wet years (2011-2014, 2017-2018).
583 Observed, natural (modeled), and natural (adjusted), CO fluxes for 2010-2018 are shown in
584 Supplementary Information Fig. 6. This biomass burning CO flux ($F_{CO} - F_{CO}^{Natural}$) was then
585 converted to biomass burning CO₂ flux (F_{Fire}) using the observed CO₂:CO emission ratios discussed
586 above, on a site by site basis. NBE represents the result of emissions and uptake from all process
587 from the influenced area for a specific vertical profile, monthly and annual mean, excepted Fire C
588 emissions (NBE = total – fire).

$$589 F_{Fire} = R_{CO_2:CO} (F_{CO} - F_{CO}^{Natural}) \quad (M10)$$

590

591 **Regions of Influence** *Regions of Influence* are, by definition, those areas covered by the set of back-
592 trajectories by each vertical profile and altitude integrated on an annual and a quarterly basis per site.
593 *Annual Regions of Influence* are the average areas throughout the series upwind of the vertical profile
594 per site (Fig 1 and Extended Data Fig 2c). We developed a method⁴³ that used individual back-
595 trajectories for each sample in each vertical profile, calculated by the Hysplit trajectory model^{42,45}, at
596 a resolution of 1 hour using 1°x1° GDAS meteorology. For each site, all the back-trajectories in a
597 quarter (JFM, AMJ, JAS, OND) or annually were binned, and the number of instances (at hourly
598 resolution) that the back trajectories passed over a 1°x1° grid cell was counted to determine the

599 trajectory density, d_i , in each grid cell. The density of trajectories from a single location and height
600 passed over a grid cell ($1^\circ \times 1^\circ$) from 300 to 3,500 m above sea level. We consider the cutoff 3,500 m
601 due to three observations: first, plume rise associated with biomass burning rarely exceed 3,500 m
602 asl; second, mole fractions of CO_2 and other gases observed above 3,500 m asl are very similar to gas
603 mole fractions from measurements in the Tropical Atlantic marine boundary layer, which indicates
604 minimal Amazonian surface influence; and third, changing the upper altitude limit from 3,500 to
605 1,300 m (typical Planetary Boundary Layer) has a minimal impact on our results. A back-trajectory
606 may intersect a grid cell once or multiple times. The annual region of influence is defined by those
607 grid cells with trajectories passing through them falling within the Amazon mask and further
608 excluding grid cells associated with the lowest 2.5% of distribution of d_i (blue lines in Extended Data
609 Fig. 2b.) Note that back-trajectories for “missing” vertical profiles (i.e. gaps in the data record) are
610 calculated so that there are always trajectories for two vertical profiles per month, six per quarter, and
611 24 per year. The mean annual regions of influence (Fig. 1, limited to just the Amazon mask, and
612 Extended Data Fig. 2c) were determined by averaging the nine annual regions of influence for each
613 site, by the sum of the number of points (frequency) within each grid cell integrating all vertical
614 profiles in the year (24 vertical profiles per site), and then averaging all nine years⁴³.

615

616 **Quarterly Region of Influence** are maps of “weighted trajectory density”, w_i , which are simply
617 maps of trajectory density, d_i , divided by the sum of all densities over South American land, where k
618 is the number of all land grid cells (Extended Data Fig 2a,b, limited to the Amazonia mask). There
619 are seasonal differences in circulation patterns, where the first and fourth quarters receive
620 contributions from Northern Hemisphere, when the ICTZ (Intertropical Convergence Zone) lies
621 below equator, and in the second and third quarters when air masses always have origins south of the
622 Equator, producing important differences in the regions of influence throughout the year⁴³.

$$w_i = \frac{d_i}{\sum_{i=1}^k d_i} \quad (M11)$$

623

624

625 **Weighted Mean** We used maps of w_i as spatial weighting functions for all studied parameters
626 (temperature, precipitation, EVI, burned area and GRACE) to determine how each parameter
627 influenced the carbon flux.

628

629 **Temperature** We used 2 meter temperature from ERA Interim, monthly means of daily means,
630 obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF), available at
631 (<https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era-interim>), accessed on:
632 January 25, 2019)⁴⁶. Monthly data are available since 1979 and were used with a resolution of 1°x1°
633 latitude-longitude. For the 40-year study we used maps of quarterly mean weights, w_i , averaged from
634 2010-2018, to determine the mean temperature upwind of each site (Fig. 4 and Extended Data Fig. 7
635 & 8 & Table 1). For comparison with the vertical profiles from January 2010 to December 2018
636 (Extended Data Fig. 3 & 4), we used trajectory-based weights corresponding to the specific quarter
637 (2010 JFM, 2010, AMJ etc.).

638

639 **Precipitation** We used the data-based Global Precipitation Climatology Project (GPCP)
640 (http://eagle1.umd.edu/GPCP_ICDR/GPCP_Monthly.html), accessed on: 25 January 2019). We
641 used version 2.3 (described by Adler *et al.*)⁴⁷ and version 1.3 (described by Huffman *et al.*)⁴⁸. Version
642 2.3 represents monthly mean global precipitation with resolution of 2.5° x 2.5° lat-long, since 1979
643 and was used for the 40-year analysis (Fig. 4, Extended Data Fig. 7 & 8 & Table 1). Version 1.3 is
644 daily data with resolution of 1° x 1° lat-long, since 1996 and was used for comparison with calculated
645 carbon fluxes (Extended Data Fig. 3 & 4).

646

647 **Temperature and Precipitation data Validation** The GPCP and ERA Interim dataset were
648 validated using thirty-five automatic meteorological field stations for rainfall and temperature data
649 from the INMET (National Institute of Meteorology, Brazil), covering the period between 1996 to
650 2018, and 1979 to 2018, respectively. Precipitation from GPCP was also validated by Santos et al.⁴⁹.
651 In our study, the least-squares regression analysis was carried out by using the GPCP and ERA
652 Interim data as the dependent variable and the automatic meteorological field stations as the
653 independent variable. The GPCP and ERA Interim dataset explained 62% to 94% and 16 to 93% of
654 the rainfall and temperature variability captured by the automatic meteorological field stations,
655 respectively (Supplementary Information Fig. 7). The RMSE for the entire region was estimated to
656 be ± 68.22 mm and ± 1.19 °C, but it is not homogeneous in the study area, varying from ± 49.5 mm to
657 ± 99.5 mm and ± 0.82 °C to ± 2.99 °C for the rainfall and temperature, respectively.

658

659 **GRACE** For equivalent water thickness we used the JPL (Jet Propulsion Laboratory) monthly land
660 mass grids which contain land water mass anomaly given as equivalent water thickness derived from
661 GRACE (Gravity Recovery & Climate Experiment) time-variable gravity observations at $1.0^\circ \times 1.0^\circ$
662 resolution⁵⁰. For more details see Landerer and Swenson⁵¹.

663

664 **Burned Area** The evaluation of the burned area (BA) was carried out with the Moderate Resolution
665 Imaging Spectroradiometer (MODIS) Collection 6 MCD64A1 burned area product⁵². Collection 6
666 provides monthly tiles of burned area with 500 m spatial resolution over the globe with an overall
667 accuracy of 97%⁵². The algorithm uses several parameters for detecting BA from the Terra and Aqua
668 satellite products, such as a daily active fire (MOD14A1 and Aqua MYD14A1), daily surface
669 reflectance (MOD09GHK and MYD09GHK), and annual land cover (MCD12Q1)⁵³⁻⁵⁵. The updated
670 algorithm has the advantages of better detection of small fires (26% increase) and also reducing the
671 temporal reporting accuracy from 68% in 2 days after the active fire⁵². The BA product was resampled

672 to 1x1° spatial resolution using the fraction of area burned in that grid cell and summed for each
673 quarter in the IDL/ENVI®.

674

675 **EVI** The Enhanced Vegetation Index (EVI) is a vegetation index that aims to highlight the fraction
676 of absorbed photosynthetically active radiation (fPAR) from terrestrial vegetation targets, similar to
677 NDVI - Normalized Difference Vegetation Index. In general, high positive values show a higher
678 proportion of fPAR, and therefore, greater vegetation greenness (vegetation vigor). EVI can also
679 reveal the seasonality of different vegetation types, where tree-individuals partly lose leaves during
680 the dry season, become drier, thus reducing the index value. Unlike NDVI, EVI includes a blue band
681 that minimizes the influence of aerosols and other adjustments to improve signal/noise ratio.
682 Moreover, in high leaf area index environments such as the Amazon, NDVI can saturate, whereas
683 EVI will not. EVI is computed as Eq M11⁵⁶:

$$684 \quad \boxed{EVI = G \times \frac{(NIR - Red)}{(NIR + C1 * Red - C2 * Blue + L)}} \quad M11$$

685 where Near-infrared (NIR) (0.841-0.876 μm), Red (0.62-0.67 μm), and Blue (0.459-0.479 μm) are
686 the atmospherically-corrected surface reflectance bands from MODIS; L is the correction of radiative
687 transfer gain between NIR and Red in the canopy $L = 1$; C1 and C2 are the aerosol correction terms
688 for NIR and Red, respectively $C1 = 6$, $C2 = 7.5$; G is the gain factor $G = 2.5$. The EVI product used
689 was the MANVI: MODIS multiangle implementation of atmospheric correction (MAIAC) nadir-
690 solar adjusted vegetation indices for South America, generated by spatial resolution of 1 km and
691 temporal resolution of 16 days⁵⁷.

692

693 **Deforestation** Deforestation was calculated inside the Amazon mask for the whole Amazon and for
694 each region of influence using the annual mean region of influence (Fig. 1) and quarterly mean region
695 of influence (Extended Data Fig. 2) from 2010 to 2018. The deforestation data was from the
696 Deforestation Monitoring Program known as PRODES produced by INPE⁵⁸ (2015) that measures the

697 annual and official deforestation (larger than 6.25 ha) rate in the Brazilian Legal Amazon since
698 1988⁵⁹. We normalized the trajectories density of the different influence areas, and also calculated
699 the weighted deforestation (see weighted mean section).

700

701 **Missing Data Imputation** Total, fire, and NBE fluxes were missing for months in red in
702 Supplementary Information Fig 8 at ALF, SAN, RBA, TAB_TEF due to sampling and laboratory
703 logistical issues. To fill these gaps, we applied “Miss Forest”, a nonparametric missing value
704 imputation using Random Forest methodology⁶⁰. It is used to impute continuous and/or categorical
705 data, mainly when involved phenomena show complex interactions and nonlinear relations⁶¹. After
706 each iteration of the method, the difference between the previous and the new imputed data matrix is
707 assessed for all variables. To adjust the set parameters, such as number of iterations, number of trees,
708 number of variables randomly sampled at each split and others, all monthly known data of each site
709 were used. We did the imputation of total C Flux (FC_{Total}) and fire C Flux (FC_{Fire}) one at a time⁶² and
710 to train the method we used 85% of the following monthly variables with the remaining 15% withheld
711 for cross-validation: temperature, precipitation, EVI, burned area and GRACE. FC_{Fire} , FC_{Total} , and
712 cross-validation calculations were computed 1000 times and the results are the mean values,
713 presented in Fig. 3 and Extended Data Fig. 3 & 4 for missing months. Cross-validation was conducted
714 with 15% of random known data for each site for both fire and total fluxes at each site. The NRMSE
715 (Normalized root mean squared error) was below 0.0043 for all sites and fluxes. The root mean
716 squared errors (RMSE) for the cross-validation statistics were 0.0064, 0.0253, 0.0047, and 0.0054 gC
717 $m^{-2} d^{-1}$ for total fluxes and 0.0013, 0.0029, 0.0011, and 0.0003 gC $m^{-2} d^{-1}$ for fire fluxes at ALF, SAN,
718 RBA, and TAB_TEF, respectively. These values were used in our uncertainty calculations for
719 months with missing fluxes. We used the MissForest implementation from the R Language⁶³.

720

721 **Uncertainty analysis - Monte Carlo error propagation** For Monte Carlo error propagation we take
722 into account the uncertainty in the background concentration and the uncertainty in air parcel travel
723 time. For separation of total fluxes in fire and land vegetation fluxes unrelated to fire, we account for
724 the uncertainty in emission ratios, CO total fluxes and natural CO flux. The uncertainty due to CO₂
725 measurement uncertainty (< 0.1 ppm) is negligibly small. In the calculation of the background values,
726 we account for the difference between the top of profile mean concentration above 3.8 km and the
727 background mean concentration for the same levels (Supplementary Information Fig. 1), using the
728 root-mean-square error (RMSE). Using this difference, we addressed to the background uncertainties
729 the possible losses of surface flux through the top of our measurement domain (4.4 km of altitude)
730 due vertical mixing. We estimate back-trajectory uncertainties based on the comparison between
731 HYSPLIT and two additional models, FLEXPART Lagrangian particle dispersion model⁶⁴ and back-
732 trajectories derived from the meso-scale model BRAMS⁶⁵, for all profiles of 2010 (Supplementary
733 Information Table 1a). We consider the largest difference in mean profile travel time from HYSPLIT
734 and the other two models using the RMSE values. For fluxes from fire we use the standard deviation
735 of emissions ratios of each site and account the CO flux uncertainties (estimated as for CO₂ fluxes)
736 and consider uncertainty in natural CO flux. All parameters used in the Monte Carlo error propagation
737 are listed at Supplementary Information Table 1b. The theoretical uncertainty for the nine-year mean
738 fluxes is [$\sigma = \sqrt{\sum(\sigma_i^2)/9}$], but this assumes that annual fluxes are uncorrelated. To
739 be conservative, allowing for significant year to year correlation, we calculate the nine-year
740 uncertainties as [$\sigma = \sum(\sigma_i)/9$].

741
742 **Scaling to the Amazon mask** Since the aircraft sites influenced areas flux are very different
743 comparing east and west sites, we decided to separate Region of Influence (SAN + ALF) region 1 in
744 the Extended Data Fig 6a, since it was observed interannual variability, the area was calculated by
745 year. Region 2 is RBA influenced area integrated with TAB (2010 to 2012) and TEF (2013 to 2018),

746 with the subtraction of region 1. And region 3 is the remaining region not covered by regions 1 and
747 2. The Carbon flux for region 1 was calculated using the weighted mean flux SAN and ALF for total,
748 Fire and NBE C flux. For region 2 also was calculated weighted mean flux of RBA and TAB (2010-
749 2012) and RBA and TEF (2013+2018). Extended Data Fig. 6b show the results for the 9 years for the
750 3 regions. The Balance is related to the Amazonia mask (7,256,362 km²).

751

752 **DATA AVAILABILITY STATEMENT** Data is available at PANGAEA Data Archiving &
753 Publication PDI-25578 (Data submission 2020-09-18T17:00:40Z (Luciana V. Gatti, Instituto
754 Nacional de Pesquisas Espaciais) (This data will receive a DOI)

755

756 **Extended Data Figure 1 | Vertical profiles, time series and annual mean CO₂ concentrations.**

757 a) Time series of mean vertical Profiles (VP) CO₂ mole fractions of the flasks below 1.5 km height
758 (red circles) and above 3.8 km height (blue circles) for SAN, ALF, RBA and TAB_TEF sites (590
759 VP) and background sites RPB (Ragged Point Barbados), ASC (Ascension Island, UK) and CPT
760 (Cape Point, South Africa). b) Annual mean vertical profiles for 4 sites (annual mean per height, see
761 Methods), c) Annual mean Δ VP is calculated by subtracting background (BKG) concentrations
762 determined from Atlantic Ocean remote sites from CO₂ concentrations at each height and nine-years
763 mean, d) Annual mean differences from below 1.5 km height and the top of vertical profile (higher
764 than 3.8 km height) (see Methods)

765

766 **Extended Data Figure 2 | Regions of Influence.** a) Mean quarterly region of influence for ALF,
767 SAN, RBA, TEF and TAB sites, averaged between 2010 and 2018, calculated by density of back
768 trajectories (see Methods), b) Deforestation inside quarterly regions of influence and the Amazon
769 mask (purple line) using data from PRODES (see Methods), c) Annual mean regions of influence
770 (trajectory densities) averaged between 2010 and 2018.

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