Amazon methane budget derived from multi-year airborne observations highlights regional variations in emissions

Luana S. Basso, Luciano Marani, Luciana V. Gatti, John B. Miller, Manuel Gloor, John Melack, Henrique L. G. Cassol, Graciela Tejada, Lucas G. Domingues, Egidio Arai, Alber H. Sanchez, Sergio M. Corrêa, Liana Anderson, Luiz E. O. C. Aragão, Caio S. C. Correia, Stephane P. Crispim, & Raiane A. L. Neves

Atmospheric methane concentrations were nearly constant between 1999 and 2006, but have been rising since by an average of ~8 ppb per year. Increases in wetland emissions, the largest natural global methane source, may be partly responsible for this rise. The scarcity of in situ atmospheric methane observations in tropical regions may be one source of large disparities between top-down and bottom-up estimates. Here we present 590 lower-troposphere vertical profiles of methane concentration from four sites across Amazonia between 2010 and 2018. We find that Amazonia emits 46.2 ± 10.3 Tg of methane per year (~8% of global emissions) with no temporal trend. Based on carbon monoxide, 17% of the sources are from biomass burning with the remainder (83%) attributable mainly to wetlands. Northwest-central Amazon emissions are nearly aseasonal, consistent with weak precipitation seasonality, while southern emissions are strongly seasonal linked to soil water seasonality. We also find a distinct east-west contrast with large fluxes in the northeast, the cause of which is currently unclear.
Methane (CH₄) is the second most important greenhouse gas (GHG) causing anthropogenic radiative forcing contributing to climate change⁴, and it is essential to understand the CH₄ budget and possible changes in future emissions to achieve the main goals of the Paris Agreement⁷. The relative contribution of different sources to the global CH₄ budget remains uncertain despite on-going efforts to improve the estimates from the varied sources and sinks³⁻⁵. Furthermore, the causes of the recent atmospheric CH₄ increases and the preceding period of stalled growth are not fully understood. Global mean atmospheric CH₄ was nearly constant at 1774 ppb from 1999 to 2006, but rose to 1834 ppb by 2015 and to 2020 its average was 1879 ppb⁶. With limited measurements, it is not possible to confirm the reasons for this recent increase⁷. One possible cause of resumed growth since 2007 is tropical South American positive precipitation anomalies during La Niña events, which could increase wetland emissions⁷⁻⁸. Alternatively, increased emissions have been attributed to anthropogenic sources in tropical and temperate regions⁹. Analysis of 1³CH₄ suggests substantial biogenic emissions from either agricultural or wetland sources⁴ may have been an important factor.

Global CH₄ emissions estimated by top-down inversions (2008–2017), averaged 576 (range of 550–594, corresponding to the minimum and maximum estimates) TgCH₄ y⁻¹⁵, with 62% from anthropogenic emissions, 31% from wetlands and 7% from other natural sources (including inland waters)¹¹, although aquatic sources have large uncertainty¹¹. Globally, bottom-up emissions are almost 30% larger (average of 737 TgCH₄ y⁻¹, with a range of 594–881 TgCH₄ y⁻¹) than top-down inversion methods, suggesting that at least some of the bottom-up emissions are overestimated⁴, highlighting the global uncertainties in methane sources and sinks.

Tropical regions host some of the largest wetlands on Earth, but the paucity of in situ observations, which would allow for accurate regional-scale flux estimation¹²⁻¹⁶, leads to large emissions uncertainty⁵. About 20% of Amazonia is permanently or seasonally inundated¹⁶, and these aquatic habitats are a major CH₄ source¹⁷. Significant contributions to Amazonian CH₄ emissions include CH₄ formed in the anoxic zone of floodplains and released to the atmosphere via the stems of flooded trees¹⁸, diffusive and ebullitive fluxes¹⁷⁻¹⁹ from inland waters, and lesser emissions from termites²⁰ and upland forests²¹. Thus, understanding the Amazonian CH₄ budget and its regional and temporal variations are essential to determine Amazonia’s contribution to the dramatic increase in global CH₄ emissions responsible for the ~100 ppb rise in global atmospheric CH₄ in the last 15 years.

Here, we quantify seasonal and annual Amazonian CH₄ fluxes, and their changes over time, based on measurements of 590 atmospheric CH₄ lower-troposphere (from ~300 m a.s.l. to 4.4 km a.s.l.) vertical profiles using an air column-budgeting technique¹²⁻²⁴ (Methods). The profiles have been collected from 2010 to 2018 at four sites (Fig. 1) using small aircraft. The four sites are ALF (southeast), SAN (northeast), RBA (southwest-central region) and TEF which superseded TAB in 2013 (northwest-central region; hereafter TAB_TEF) (Fig. 1 and Supplementary Fig. 1). Fluxes estimated using the column-budgeting technique (F TOTAL_CH4) result from all sources and sinks within the area traversed by air masses flowing from the Atlantic coast to the site (representative of regional scales, ~10⁵⁻¹⁰⁶ km²). We refer to the area upwind of each site as the region of influence⁵ (Fig. 1 and Supplementary Fig. 1).

To estimate surface fluxes we first integrate the difference of vertical profile CH₄ mole fraction and a so-called background mole fraction to obtain ΔCH₄. By dividing ΔCH₄ by the travel time of air parcels from the Atlantic, the background sites, to the vertical profiling site we obtain an average CH₄ flux estimate (see “Methods”) according to Eq. 1. Where CH₄ is methane concentration in units of (mol m⁻³), z is the height above sea level (m), and t(z) is air mass travel time (s) from the coast to the site at level z. We estimate background mole fractions based on interpolation of CH₄ mole fractions from remote Atlantic Ocean sites (RPB, ASC and CPT; see “Methods”), thus assume that oceanic sources and sinks along air-mass trajectory paths across the Atlantic are negligible compared to fluxes from Amazonia.

Biomass burning is responsible for about 5% of total anthropogenic emissions and results from incomplete combustion⁴. Biomass burning emissions are mainly concentrated in the tropics and subtropics, where forests may be burned to clear land for agricultural purposes or to maintain pastures⁵. We use carbon monoxide (CO) measured concomitantly with CH₄ to estimate CH₄ emissions from biomass burning (F FIRE_CH4) according to Eq. 2. Here F CO is the total CO flux and F CO_Natural is the biogenic CO flux, both in mgCO m⁻² d⁻¹ for each vertical profile and r CH₄:CO is the ratio of the emission related to each site (see “Methods”). Non-fire fluxes (F NON–FIRE_CH4) were determined as the difference of total CH₄ flux (F TOTAL_CH4) and F FIRE_CH4, and are the sum of both natural and non-fire related anthropogenic sources and sinks (Eq. 3).

\[
F_{\text{TOTAL-CH}_4} = \int_{\text{surface}}^{4 \text{km}} \frac{\text{CH}_4(z) - \text{CH}_4(\text{BS})}{t(z)} \, dz \\
F_{\text{FIRE-CH}_4} = r_{\text{CH}_4: \text{CO}} \times (F_{\text{CO}} - F_{\text{CO-Natural}}) \\
F_{\text{NON–FIRE-CH}_4} = (F_{\text{TOTAL-CH}_4} - F_{\text{FIRE-CH}_4})
\]

To help analyse the results we determined, for each of the sites’ quarter-yearly resolved air-mass trajectory density-weighted regions of influence²⁵ (Supplementary Fig. 1b, see “Methods”), the factors possibly influencing CH₄ fluxes including air temperature, precipitation, equivalent water thickness (EWT), vapour pressure deficit (VPD), burned area, land use and cover, and anthropogenic emissions from EDGAR (Emissions Database for Global Atmospheric Research) v5.0²⁶,²⁷.

**Results and discussion**

Our data reveal that the annual mean difference (ΔCH₄) between CH₄ at each site and the background mole fraction is enhanced in the planetary boundary layer (PBL; below 1.5 km) in comparison with the free troposphere (above 3.8 km), indicating significant Amazonian emissions (nine-year mean difference of ΔCH₄ between the PBL and free troposphere for SAN: 48.4 ± 7.5 ppb, TAB_TEF: 30.4 ± 8.4 ppb, RBA: 28.6 ± 5.4 ppb and ALF: 12.4 ± 3.2 ppb; Fig. 2). Free troposphere mole fractions are similar to the global mean mole fractions (Fig. 2b). There are clear regional differences in annual mean ΔCH₄; PBL CH₄ enhancements were largest for the SAN region, suggesting the highest emissions from the northeast of Amazonia. Webb et al.²⁸ reported CH₄ vertical profiles data measured at a northeastern Brazilian coastal site (São Pedro dos Carajás, 0°55’S, 48°20’W), with lower concentrations than those at SAN, indicating that SAN PBL CH₄ enhancements are due to sources between the Brazilian coast and SAN (Supplementary Fig. 2a and b). These high SAN mole fractions are consistent with previous vertical profile concentration observations at this site measured from 2000 to 2013¹²,²⁴. In contrast, PBL CH₄ enhancements were the smallest for the southeastern region (ALF), indicating lower fluxes (Fig. 2b). The difference between Amazonian mean mole fractions in the PBL and free troposphere does not have a significant upward trend between 2010 and 2018, indicating no change in net emissions over this period (Fig. 2b and Supplementary Fig. 3). The annual CH₄ atmospheric growth rates observed between 2010 and 2018...
Amazonian CH$_4$ fluxes. Our data reveal distinct spatial and seasonal CH$_4$ flux patterns (Fig. 3). Northeast Amazonia (SAN) had the largest F$_{TOTAL,CH_4}$ and F$_{NON-FIRE,CH_4}$ fluxes (Tukey test: $p < 0.05$), with nine-year means of 53.4 ± 6.9 and 41.3 ± 7.2 mgCH$_4$ m$^{-2}$ d$^{-1}$, respectively, and a F$_{NON-FIRE,CH_4}$ seasonal pattern with higher fluxes during the beginning of the wet season (February–March) and beginning of the dry season (August–September; Fig. 3 and Supplementary Figs. 5 and 6). Although fluxes upwind of SAN were highest among all sites, their contribution to the Amazonian mean is modest, because of SAN’s relatively small region of influence (~11% of total Amazon area$^{29}$). Northwest-central Amazonia (TAB_TEF) had the second-highest flux, with nine-year mean F$_{TOTAL,CH_4}$ and F$_{NON-FIRE,CH_4}$ of 16.2 ± 2.8 and 15.0 ± 2.3 mgCH$_4$ m$^{-2}$ d$^{-1}$, respectively, and the smallest seasonal amplitude of all sites (Fig. 3 and Supplementary Fig. 6). ALF and RBA (southern regions) had statistically similar (Tukey test: $p < 0.05$) nine-year means of F$_{TOTAL,CH_4}$ of 13.1 ± 2.1 and 14.0 ± 2.5 mgCH$_4$ m$^{-2}$ d$^{-1}$, and F$_{NON-FIRE,CH_4}$ of 10.3 ± 2.2 and 11.2 ± 2.6 mgCH$_4$ m$^{-2}$ d$^{-1}$, respectively, and their seasonal amplitudes were similar. Both F$_{TOTAL,CH_4}$ and F$_{NON-FIRE,CH_4}$ for ALF, RBA, and TAB_TEF were just 24 to 36% of those for SAN (Table 1). To estimate wetland fluxes (F$_{WTL,CH_4}$) for the regions upwind of each site we subtracted F$_{NON-FIRE,CH_4}$ anthropogenic (Table 1) and termite fluxes (~0.5 mgCH$_4$ m$^{-2}$ d$^{-1}$)$^{20}$, and added CH$_4$ uptake by upland soils (~1 mgCH$_4$ m$^{-2}$ d$^{-1}$)$^{30}$. Oxidation of CH$_4$ by OH radical over land should impact both observed vertical profile concentrations and background similarly and was ignored.

In principle, ignoring CH$_4$ oxidation between remote Atlantic sites and the Brazilian coasts should lead to an underestimate of fluxes (by overestimating background). Comparisons between coastal and inland vertical profiles above 2 km height (Supplementary Fig. 2a), reveal a difference of only 4.8 ± 9.2 ppb suggesting that the magnitude of this under-estimate is small. We estimated the magnitude of methane loss from oxidation by OH and Cl reactions while air is travelling from the background location to the Atlantic coast before entering Amazonia (see “Methods”). We find a decrease in air column CH$_4$ of ~1.5 ppb and ~0.03 ppb, respectively, which are small compared to the observed Amazon vertical profile CH$_4$ enhancements (around 30–40 ppb). Finally, the background estimated for the Amazon sites agreed well with the CH$_4$ observations measured at Brazilian coast sites (Supplementary Fig. 2c).

In addition to the potential bias introduced by assuming negligible ocean sources and sinks other biases related to our background estimate based on oceanic observation sites could affect our result that eastern Amazon fluxes upwind of SAN are larger than fluxes from the rest of Amazonia. Therefore, we estimated air-mass CH$_4$ at the Atlantic coast, the background used in our method, with two alternative background methods: using SAN data above 3.8 km a.s.l., and using means of each SAH (Salinópolis) vertical profile interpolated to the time of the SAN profiles. SAH is located at the Atlantic coast a bit to the north of Santarem (Supplementary Fig. 2b). While CH$_4$ fluxes estimates based on these two backgrounds are smaller than the estimate based on the ocean site background estimate, they are still much larger than the fluxes estimated for the upwind regions of the other three sites, confirming high emissions at SAN (Supplementary Fig. 7).

Nine-year mean F$_{WTL,CH_4}$ for ALF, RBA, TAB_TEF and SAN represent 67%, 83%, 94%, and 94%, respectively of F$_{NON-FIRE,CH_4}$
(total CH₄ emissions less fire emissions; Table 1), indicating that northern Amazonian regions have a larger relative contribution of wetland emissions than southern regions, which have larger relative contribution from anthropogenic sources in comparison to northern regions.

ALF, SAN and RBA, had the largest biomass burning relative contributions to the total fluxes ($F_{\text{TOTAL}_CH4}$), 22%, 23 and 20% (Tukey test: $p < 0.05$), respectively, with only 8% at TAB_TEF (Table 1). There is a clear seasonality in $F_{\text{FIRE}_CH4}$ for all regions, with an increase during dry periods (August–December, in general) in each region of influence, when there is less EWT, higher temperatures (0.5–1.5 °C) favouring increased fire occurrence (Fig. 3 and Supplementary Figs. 5, 6 and 8a).

We investigated the possible effects of climate conditions on the inter-annual variability observed in $F_{\text{FIRE}_CH4}$ and $F_{\text{WTTL}_CH4}$ emissions. An increase in $F_{\text{FIRE}_CH4}$ was observed during hotter and drier years (Fig. 4 and Supplementary Fig. 9a), mainly during El Niño events (2010 and 2015–16), which had the largest burned areas. In the southern regions (ALF and RBA), annual burned area (ALF: $r = 0.97$, $p = 2.2 \times 10^{-5}$; RBA: $r = 0.66$, $p = 5.4 \times 10^{-2}$) and temperature (ALF: $r = 0.62$, $p = 7.6 \times 10^{-2}$; RBA: $r = 0.82$, $p = 6.4 \times 10^{-3}$) correlated strongly with $F_{\text{FIRE}_CH4}$ inter-annual variability. For the northern regions (SAN and TAB_TEF) $F_{\text{FIRE}_CH4}$ inter-annual variability also correlates with EWT (SAN: $r = 0.67$, $p = 4.8 \times 10^{-2}$; TAB_TEF: $r = 0.58$, $p = 1.0 \times 10^{-4}$; Supplementary Fig. 9a). While, for most sites and variables we did not find a clear relationship between $F_{\text{WTTL}_CH4}$ inter-annual variability and climate conditions. Only for the northeast (SAN) was $F_{\text{WTTL}_CH4}$ positively correlated with temperature ($r = 0.67$ and $p = 4.6 \times 10^{-2}$; Fig. 4 and Supplementary Fig. 9b).

We estimated regional mean CH₄ fluxes based on each site’s annual regions of influence, and combined them (Methods) to yield a nine-year mean $F_{\text{TOTAL}_CH4}$ of $17.4 \pm 3.9$ mgCH₄ m⁻² d⁻¹ for Amazonia, of which $17 \pm 3\%$ is from fire emissions (Table 1) and $83 \pm 23\%$ from non-fire net emissions. Total CH₄ emission of $46.2 \pm 10.3$ TgCH₄ y⁻¹ (Methods) was obtained by extrapolating the mean flux to the entire Amazonian (~7.25 x 10⁶ km²; Amazon
Fig. 3 Climatological (2010-2018) monthly mean CH₄ fluxes estimated using vertical profiles. CH₄ flux monthly means for total (grey bars), non-fire (total less fire emissions; dark blue bars), wetlands (non-fire less anthropogenic and termite emissions, plus the CH₄ uptake from upland soils; light blue bars) and fire (brown bars), air temperature (green lines), equivalent water thickness (EWT; blue lines) and burned area (black lines) for all regions. Error bars represent the standard deviation of monthly means over the nine years. Note the expanded flux axis for SAN.
respectively. In addition, atmospheric CH$_4$ increases at ALF, SAN, and RBA were in the Amazon region with the most deforestation 31. Although, human disturbances in each region of influence differ regarding human disturbance patterns (Fig. 1, Supplementary Fig. 10 and Supplementary Table 1) and climatic conditions (Fig. 1). To understand possible drivers of these spatio-temporal patterns, we investigated climatic conditions and human disturbances in each region of influence on a quarterly basis. Our regions of influence differ regarding human disturbance patterns (Fig. 1, Supplementary Fig. 10 and Supplementary Table 1) and climatic conditions (Fig. 1). Part of the CH$_4$ flux seasonality for SAN and ALF may result from the region of influence shifting southward to areas with more agriculture (23–26% and 24–25% of the total area, respectively), during the second and third quarters of the year. The western sites, RBA and TAB_TEF, were less affected by these activities, with agriculture influencing 16–18% and 9–11% of the total upward area, respectively. In addition, atmospheric CH$_4$ increases at ALF, SAN and RBA were influenced by the “Arc of Deforestation”, the Amazon region with the most deforestation 31. Although, FIRE_CH4 intra-annual seasonality correlates strongly with burned area seasonality, annual mean FIRE_CH4 across sites does not entirely correspond with the mean burned area in each site’s region of influence. For example, FIRE_CH4 from SAN is highest while it has only the third highest mean burned area (Table 1); although variable or incorrectly specified CO:CH$_4$ emissions ratios could contribute, the reasons for this discrepancy are unclear at this time. Even using the mean CO:CH$_4$ emissions ratios from ALF, RBA and TAB_TEF to estimate SAN FIRE_CH4 the discrepancy cannot be explained.

The contribution of (non-fire) anthropogenic CH$_4$ fluxes in Amazonia, especially relative to NON-FIRE_CH4, can be significant. These fluxes are primarily from livestock via enteric fermentation (EF) and are more significant in the south and east (Table 1). França et al.33 reported an increase of 680% in the Brazilian Amazonian cattle herd between 1985 and 2019, with 41.81 million animals in 2019. CH$_4$ emissions from full exploitation of coal, gas and oil, in addition to oil refineries and transformation industry account for 12% of total anthropogenic emissions in the whole Amazon region (based on EDGAR v5.0 26,27, emissions for 2015), but totals only 0.7 TgCH$_4$ y$^{-1}$. Based on 2010–2015 emissions from EDGAR v5.0 26,27, we estimate the anthropogenic emissions in our regions of influence, where EF is the mainly anthropogenic source, to contribute 90, 84, 71 and 69% of total (non-fire) anthropogenic emissions at ALF, RBA, TAB_TEF and SAN, respectively. This indicates that the region upwind of ALF is most strongly impacted by agricultural activity, and while EF represents 35% of NON_FIRE_CH4 total EF upwind of ALF is only 3.5 ± 0.4 mgCH$_4$ m$^{-2}$ d$^{-1}$ (Table 1, Supplementary Figs. 10 and 11). At RBA, TAB_TEF, and SAN, EF represents 18%, 6% and 5% of our NON_FIRE_CH4 estimates, respectively.

The eastern regions (ALF and SAN) had the largest seasonal variations in temperature and precipitation (Fig. 3, Supplementary Figs. 5a and 6), and the highest monthly mean temperatures during the dry season. ALF had the largest reduction in precipitation during the dry season (<30 mm/month during July and August 9–year monthly mean in comparison with >300 mm/month, considering the mean during the wet season, January to March), and the highest VPD. Lower precipitation and higher temperatures during this period result in lower water availability (Fig. 3, Supplementary Tables 2 and 3).
**Fig. 4** Annual mean CH₄ fluxes estimated using vertical profiles. Colours and fluxes are defined as in Fig. 3. Annual mean error bars represent the uncertainty estimated by Monte Carlo error propagation (Methods); temperature, burned area and EWT error bars represent the standard deviation of monthly means over 9 years.
Supplementary Figs. 5 and 6). In contrast, the TAB_TEF had a shorter dry season (just two months with mean precipitation below 100 mm between 2010 and 2018), when total precipitation was higher than 80 mm/month, resulting in a smaller reduction in water availability (Supplementary Figs. 5 and 6).

The southern regions (ALF and RBA) had larger F_WTL.CH4 during the period of the year with larger EWT and lower temperature, suggesting that wetland fluxes were sensitive to water availability (Fig. 3 and Supplementary Figs. 5, 6 and 8b). However, flux seasonality is different in the northern Amazonian regions. For instance, the northwest-central region (TAB_TEF) had the least F_WTL.CH4 seasonal variability, which may have resulted from lower seasonal amplitudes in precipitation, temperature and VPD (Fig. 3 and Supplementary Figs. 5 and 6).

The causes of the F_WTL.CH4 seasonality and larger signals in the northeast (SAN) are not fully understood, highlighting the need for more studies to understand the nature of the methane sources in this region. Wetlands CH4 fluxes peaked during the early ascending phase of water level rise (February–March) and again during the beginning of dry season (August–September). Other studies do report higher emissions during low water levels18,19,34. According to Barbosa et al.19, the higher river emissions during low water season in comparison with the high water season may be explained by the greater dilution of incoming CH4 from sediments and ground waters and greater time for CH4 oxidation in deeper water columns during high water. Also, the increase in hydrostatic pressure during high water season resulted in significantly lower ebullition34. Nonetheless, the mechanisms behind the increase in wetland emissions during the beginning of the dry season remain unclear. A previous study of the SAN region24 reported similar seasonality (higher fluxes during the early ascending phase of water level rise and again during the beginning of the dry season) and emissions, with a mean F_WNL.FIRE.CH4 of 47.7 ± 4.8 mgCH4 m⁻² d⁻¹ (between 2000 and 2013). Based on a global inverse model using satellite data, Wilson et al.15 also found large emissions from eastern Amazonia. Their simulations using satellite data improved the agreement with SAN atmospheric CH4 observations in comparison with simulations of SAN atmospheric CH4 vertical profiles using the Joint UK Land Environment Simulator (JULES) model wetlands flux estimates35,36. One possibility could be that aquatic environments such as flooded forests represent larger areas of influence for the SAN region than for other regions and are not adequately represented in process models. Such aquatic habitats are known to be important biogenic methane sources17-19,34. Floodplain fluxes via aerenchyma in trees, in particular, can be considerable18, and regional differences in these fluxes could contribute to the relatively high emissions at SAN. The largest CH4 emission rates from Amazonian floodplains emitted via tree stems (between 2 and 6 times higher than other) were observed in the Tapajos River region, which is directly below the SAN sampling location18. Also, the small VPD seasonal amplitude suggests that the SAN region may be less water-stressed (Supplementary Fig. 5b) compared to the southeast region (ALF). Both the large annual magnitude and double-peak seasonality of the SAN fluxes suggest that the processes influencing these CH4 emissions are not well understood, highlighting the need for further studies to elucidate the processes responsible for Amazonian emissions.

**Trends and inter-annual variability of CH4 emissions.** F_FIRE.CH4 inter-annual variability correlates with climatic variations and human disturbances. Forest fires are associated with a combination of human activities to provide the ignition source and climatic factors to create drier conditions39. In contrast, agricultural and deforestation fires are more associated with human actions than with climate38. Fluxes are elevated during hotter and drier years, and correlated with the largest burned areas (Supplementary Fig. 9a), with temperature being a stronger predictor of F_FIRE.CH4 than EWT for all regions. With more frequent and severe droughts, the increase in climate variability impacts both the Amazonian forest19 and savannah biomes, increase tree mortality40 and ecosystem vulnerability to fire41-42. Therefore, without fire-use regulations, more and larger fires are likely11, increasing Amazonian CH4 fire emissions.

Wetland emissions are expected to be larger with warmer and wetter conditions2. However, the impacts of temperature and precipitation may be somewhat cancelling: hotter years may promote methanogenesis, but these years are typically drier; likewise, cooler years may suppress methanogenesis, but these years are typically wetter. Northeast F_WTL.CH4 was sensitive to temperature, even with the drier condition during these years. The inter-annual variability observed in F_WTL.CH4 flux can be partially explained based both annual mean temperature and precipitation (r = 0.80 and p = 0.05 for multiple linear regression, but appears to be mainly driven by temperature (r = 0.67 and p = 0.05; Supplementary Fig. 12). The temperature effect on microbial activity estimated using a Q10 of 243 is too small to explain the inter-annual variability observed in our F_WTL.CH4. An increase in wet season CH4 emissions was reported in the northeast Amazon, suggesting that the emissions were more sensitive to the increase in temperature than to the decrease in wetland fraction15. Meanwhile, the absence of the relationship with the temperature at the other sites could be related to higher water sensitivity of CH4 emissions in southern regions and with the lower climate variability in the northwest, in addition to the potential cancelling effects of precipitation and temperature. Also, Amazonian temperatures have increased, most strongly in the east, over the last 40 years44. Continued positive temperature trends may contribute to CH4 emissions increases in northeastern Amazonia and could represent a positive carbon-climate feedback.

**Amazonian CH4 budget.** For comparison, we summarize results from previous studies of Amazonian CH4 emissions (Table 2). Melack et al.17 estimated wetland emissions from Amazon lowland area (29 TgCH4 y⁻¹) based on a combination of field measurements of methane fluxes from aquatic environments, and remote sensing of inundated areas and aquatic habitats; however, their study area did not include part of the region upwind of SAN near the mouth of the Amazon, where we found higher CH4 fluxes. The fact of their study is not representative of part of this region could make the results of this study and theirs more similar. Tunnicliffe et al.45 used GOSAT (Greenhouse gases Observing SATellite) data in an inverse model and estimated wetland emissions of 9.2 ± 1.8 TgCH4 y⁻¹ for a portion of the Brazilian Amazon, a value much smaller than ours or other estimates (Table 2). Using a combination of CH4 mole fraction data from the surface in situ sites and satellite-based atmospheric column CH4 data from the Scanning Imaging Absorption Spectrometer for Atmospheric Chartography (SCIA-MACHY), Bergamaschi et al.46 reported total Amazonian emissions of 47.3-53.0 Tg CH4 y⁻¹ for 2004, with the inversions showing reasonable agreement with vertical profile mole fractions from SAN, although with higher CH4 estimates than ours for the western Amazon. Inverse modelling of the atmospheric CH4 data from the same sites described here14, yielded total Amazonian emissions of 31.0-42.0 Tg CH4 y⁻¹ for 2010–2011, with 0.6-3.1 TgCH4 y⁻¹ from biomass burning. Recently, Wilson et al.15 using GOSAT data in an inverse model estimated an increase in Amazon Basin emissions (natural, agricultural and biomass burning emissions),
Table 2 Estimates of CH4 emissions (Tg CH4 yr\(^{-1}\)) and details of previous studies from the Amazon region and estimates from this study.

| Method                      | Area (km\(^2\)) | Emissions (Tg CH4 yr\(^{-1}\)) |
|-----------------------------|-----------------|-------------------------------|
| Melack et al.\(^{17}\)     | -5.0 \times 10^6 | 29                            |
| Bergamaschi et al.\(^{46}\) | -8.6 \times 10^6 | 47.3-53.0                      |
| Wilson et al.\(^{14}\)      | -6.0 \times 10^6 | 31.0-42.0                      |
| Wilson et al.\(^{15}\)      | -6.0 \times 10^6 | 38.2 \pm 5.3-45.6 \pm 5.2      |
| Pangala et al.\(^{16}\)    | -6.7 \times 10^6 | 38.5 \pm 6.1-45.1 \pm 6.4      |
| Tunnicliffe et al.\(^{45}\) | -3.7 \times 10^6 | 43.7 \pm 5.6                   |
| WetCharts                   | -7.2 \times 10^6 | 9.2 \pm 1.8                    |
| This study                  | -7.2 \times 10^6 | 39.4 \pm 10.3                  |

from 38.2 \pm 5.3 (between 2010 and 2013) to 45.6 \pm 5.2 TgCH4 (between 2014 and 2017). Based on extensive field measurements, Pangala et al.\(^{18}\) estimated Amazonian CH4 emissions from tree stems and aquatic surfaces between 38.5 \pm 6.1 and 45.1 \pm 6.4 TgCH4 y\(^{-1}\) (2013–2014) and found good agreement with top-down estimates (2010–2013) of 43.7 \pm 5.6 TgCH4 y\(^{-1}\).

WFTL\(_{CH4}\) upwind of each site compared to analogous fluxes from the WetCharts wetland model ensemble\(^{47}\) (Fig. 5; see "Methods") are similar except for the SAN region, where WFTL\(_{CH4}\) is much higher. WetCharts does show substantial emissions upwind of SAN, but still just 40% of our estimates. The basin-wide annual WetCharts wetland emissions are 39.4 \pm 10.3 TgCH4 y\(^{-1}\) (Table 2), while our data-based approach yields a similar value of 33.8 \pm 10.9 TgCH4 y\(^{-1}\). This similarity may be an artefact of our column-budgeting approach sensing higher eastern fluxes, while not being sensitive to large emissions in the far west of the Basin simulated by many WetCharts ensemble members (Supplementary Fig. 13a). Basin-wide emissions calculated using fluxes upwind of each site derived from gridded WetCharts fields and each site’s regions of influence (Fig. 5) are \sim 6 TgCH4 y\(^{-1}\) less than their basin-wide total (33.0 \pm 11.4 TgCH4 y\(^{-1}\)), suggesting that our network configuration leads to a low bias, although across-model variation for far-western fluxes in WetCharts is considerable (Supplementary Fig. 13b). Considering the wide variety of approaches: bottom-up (field measurement, remote sensing and process model) and top-down (both in situ and remote sensing), as well as the different areas considered, we find broadly similar emissions between our top-down estimates and the range of previous Amazonian estimates, with the exception of the high fluxes we calculate for the region upwind of SAN. This highlights regional differences in Amazonian emissions, also observed in CH4 flux seasonality and its drivers.

Nine-year mean CH4 emissions constitute \sim 8% of global emissions (576 TgCH4 y\(^{-1}\)), demonstrating that Amazonia is an important CH4 source to the atmosphere, and our Amazonian CH4 fire emission estimate represents \sim 45% of the global fire emissions (17 TgCH4 y\(^{-1}\)). Our Amazonian CH4 wetland emissions also represent \sim 23% of the global wetland emissions (149 TgCH4 y\(^{-1}\)). We observed strong regional variability in non-fire CH4 emissions, with northeastern fluxes 175–300% higher than fluxes from other regions. The reason for these large fluxes and their seasonality is not understood and contrasts strongly with wetland flux patterns from WetCharts model ensemble. The southern regions’ flux seasonality appears to be related to EWT; seasonality in the northwest-central region is nearly absent, and while the northeast exhibits seasonality, it correlates with neither temperature nor EWT. While Amazonia is an important global CH4 source, we observed no significant change in emissions between 2010 and 2018, indicating that Amazonia is not significantly contributing to the strong global CH4 enhancement observed over the same period.

Methods

Air sampling and vertical profile regions of influence. We collected a total of 590 vertical air profiles from January 2010 to December 2018 biweekly at four Brazilian Amazonia sites (Fig. 1). The sites were ALF (8.8°S, 56.7°W) in the southeast, SAN (2.8°S, 54.9°W) in the northeast, RBA (9.3°S, 67.6°W) in the southwest-central region and TAB (5.9°S, 70.0°W) in the northwest-central region. A sampling gap started in April 2015 at all sites and ended in November 2015 at RBA, February 2016 at ALF, and January 2017 at SAN and TAB. Vertical profiles measured at TAB and TEF were analysed as a single time series (TAB_TEF) due to their similar regions of influence and seasonal patterns.

Air samples were collected in a descending vertical profile from 4420 m a.s.l. to around 300 m a.s.l., using a two-component portable semi-automatic collection system. The first unit of this system consisted of two compressors and rechargeable batteries, and the second unit contained 17 or 12 borosilicate glass flasks (700 mL), installed on board of small aircraft with one or two engines. Vertical profiles were made between 12:00 and 13:00, local time, a period when the planetary boundary layer tends to be well mixed, such that the profiles integrate gas fluxes from large regions under its region of influence (detailed information in Gatti et al.\(^{22}\); Gatti et al.\(^{23}\); Basso et al.\(^{24}\)).

We define regions of influence as those areas covered by the density of back-trajectories integrated over all vertical profiles and altitudes (up to 3500 m) integrated on an annual and a quarterly basis per site\(^{36,38}\) (Supplementary Fig. 1). Individual back-trajectories for each sample for each vertical profile and all flights between 2010 and 2018 were calculated by the Hysplit trajectory model\(^{48,49}\), at a resolution of 1 h using 1° \times 1° Global Data Assimilation System (GDAS) meteorological data. Back-trajectories started from the day, time, and sampling altitude (in metres above sea level) from the central horizontal point of each vertical profile going back 13 days prior to sampling. For each site, all the back-trajectories in a quarter (January–March, April–June, July–September, October–December) or annually were binned, and the number of instances (at hourly resolution) that the back-trajectories passed over a 1° \times 1° grid cell
was counted to determine the trajectory density in each grid cell up to an altitude of 3500 m a.s.l.

The annual region of influence is defined by those grid cells with trajectories passing through them within the Amazonia mask and excluding grid cells with the lowest 2.5% trajectory density distribution. The mean annual regions of influence (Fig. 1, limited to Amazonia mask, and Supplementary Fig. 1a) were determined by averaging the nine annual regions of influence for each site, by the sum of the number of points (frequency) within each grid cell integrating all vertical profiles in the year and then averaging all nine years. The region of influence integrates the back-trajectories quarterly in order to understand the patterns of atmospheric circulations at each location and their seasonality (Supplementary Fig. 1b). In order to obtain the frequency of factors related to CH4 fluxes, we used maps of region of influence based on trajectory density to calculate spatial weighting functions for these factors, which means that grids with higher density of trajectories have a larger influence than the grids with lower density of trajectories.

Our study area (Amazonia mask, about ~7.25 x 106 km2) is the Amazonia limit of Eva and Hubei and includes the Amazonian subregions of Amazonia sensu stricto, Andes, Guiana, Gurupí (tropical and subtropical moist broadleaf forest) excluding the Planalto region (predominantly tropical and subtropical grasslands, savannas, and shrublands). A higher grid density is included to avoid species loss in poorly sampled regions. No significant loss was noticed in the resulting maps.

Measurements. Air samples collected at each site (ALF, SAN, RBA, TAB, TEF) were analysed at the National Institute for Space Research (INPE), Brazil, where a replica of the National Oceanic and Atmospheric Administration (NOAA) GHG analytical system was installed for measuring GHG mole fraction in air. The CH4 analysis system is a gas chromatograph (HP 6890 Plus) with flame ionisation detection, a 198 cm pre-column of silica gel 80/100 mesh, a 106 cm column of molecular sieves 5 Å 80/100 mesh, and a 12 mL volume sample loop. In order to assess the accuracy and long-term repeatability of the CH4 measurements, a previously calibrated sample is measured as an unknown in the system regularly. These results indicate long-term repeatability (one sigma) of 1.0 ppb. Also, INPE and NOAA weekly measurements at NAT were compared between 2010–2016 (a surface Brazilian northeast coast site, Supplementary Fig. 4a), where the samples were taken simultaneously (with 2 pairs of flask, each pair analysed by one of the laboratories). Analyses by INPE and NOAA had a mean difference of 0.2 ± 2.67 ppb (r = 0.98).

Annual mean ΔCH4 vertical profiles. To calculate the annual mean ΔCH4 vertical profiles for each site and each sample/height, background mole fractions were subtracted from the observed vertical profile concentrations at each sample/height. The means were calculated for individual profiles and then averaged to monthly and annual values (Fig. 2).

CH4 fluxes. We used a column budget technique, which consists of the difference between CH4 concentration measured in the vertical profile and the estimated background concentration (ΔCH4) based on the travel time of air parcels along the trajectory back to the site (following the methodology in Gatti et al., 2012, Gatti et al , 2015, D’Amelio et al., 2021, Gatti et al., 2023, Basso et al., 2024 and Gatti et al., 2024). Thus, the net methane flux (ΔCH4) along the air mass path is calculated according to Eq. 1.

\[ \text{SAN, Temperature} y = 19.586x^2 - 249.49x + 5815y - 97 = 0.97 \]

\[ \text{SAN, Pressure} y = 0.0024x^2 - 12.46x + 11069y^2 - 0.87 \]

\[ \text{ALF, Temperature} y = 0.4202x^2 - 170.62x + 5201y - 0.89 \]

\[ \text{ALF, Pressure} y = 0.0598x^2 + 20.21x + 14402y^2 - 0.87 \]

\[ \text{RBA, Temperature} y = 0.1985x^2 + 167.77x + 4953y^2 - 0.99 \]

\[ \text{RBA, Pressure} y = 0.0797x^2 - 21.10x + 13872y^2 = 0.89 \]

\[ \text{TAB, TEF, Temperature} y = 2.415x + 253.98x + 5542y^2 = 0.95 \]

\[ \text{TAB, TEF, Pressure} y = 0.0051x + 18.87x + 13828y^2 - 0.87 \]

We estimated the background concentrations following the Air-Mass Back-Trajectories Method (AMBM). The incoming air has larger or smaller contributions from Northern Hemisphere or Southern Hemisphere depending on the Intertropical Convergence Zone (ITCZ) position. Mixing fractions / between NOAA global stations (RBP, ASC and CPT) were estimated based on the latitude and longitude (geographical position) of back-trajectories calculated for each flask/ site. For assigning trajectories in the vertical profile, we use the geographical position of each air-mass back-trajectory where it intersects two virtual limits. One is a line from the equator to the NOAA/GML observation site at RBP, the second is a latitude limit, from the equator southwards at 30° W. The background concentration is related to the position the back-trajectory crosses the virtual lines and this position is based on the positions (latitude and longitude) and concentrations at the corresponding day at the regional stations (RBP, ASC and CPT).

CH4 emissions from biomass burning. CH4 emissions from biomass burning were obtained by using the ratio (CH4/CO) in ppbCH4/ppbCO (or mole/mole). Carbon monoxide (CO) is a product of incomplete combustion and could be used as biomass burning tracer. To estimate the CH4/CO ratio, we selected profiles only during the dry season, in which a biomass burning plume was identifiable in the profile after subtraction of CO and CH4 background (Supplementary Fig. 14). The CH4/CO depends on the nature of fire, enabling an estimation of CH4 fraction from biomass burning as CH4/CO = (CH4/CO) - (CH4/CO)natural, where (CH4/CO) is the total CH4 flux in CO m−2 d−1 estimated analogously to CH4 flux from each points trajectory and (CH4/CO)natural is the ratio of the emission related to each site: TAB TEF (4.9 ± 2 ppbCO/ppbCH4, mean of 7 profiles and 2.6 is one sigma), ALF (5.0 ± 1.8 ppbCO/ppbCH4, 20 profiles mean), RBA (4.7 ± 2.2 ppbCO/ppbCH4, 24 profiles mean) and SAN (3.2 ± 1.3 ppbCO/ppbCH4, 9 profiles mean). To isolate the biomass burning flux from F CO it was necessary to consider the effect of a F CO_Natural as a by-product of isoprene emissions by trees and from soil, which was subtracted from the F CO.

To apply in Eq. 1 we converted mole fractions [nmol CH4 (mol dry air)]−1 to CH4 fluxes (F CO) expressed as monthly and annual means. To estimate wetland fluxes (F WT CH4) for the regions upwind of each site we apply corrections to F NON-FIRE CH4. The correction comes from anthropogenic fluxes (Table 1) and from termites (0.5 mgCH4 m−2 d−1)23, 24, both negative, and a positive flux correction from CH4 uptake from upland soil.25 Emissions observed at night in the forest canopy (~5 mgCH4 m−2 d−1) reported by do Carmo et al.26 are not accounted for, because of their unknown origin. Oxidation of CH4 by OH over land should impact both vertical profiles observed concentrations and background similarly and is also ignored. Possible methane loss between our back-ground sites and the Brazilian coast from oxidation by OH and Cl reactions was estimated to be of order only 1.5 ppb and 0.03 ppb, respectively, assuming a travel time of 2 days and using the loss rates based on model simulations reported by Hossaini et al.27. Considering the difference between profiles mean concentrations and the background of around 30 and 40 ppb, OH and Cl sinks will not have a significant influence on the fluxes estimated. In addition, Gromov et al.28 using observations of δ13C of CO and Wang et al.29 based on modelling study of global Cl suggested a very limited role for the CH4 sink due to marine boundary layer Cl.

Precipitation. We compared our CH4 fluxes to the data from the Global Precipitation Climatology Project (GPCP) (http://eagle1.umd.edu/GPCP_ICDR/GPCP_Monthly.html, accessed on 25 January 2019) version 1.35. The GPCP data is a daily data with resolution of 1° x 1° from 2010 to 2018 (Supplementary Figs. 5 and 6).

Temperature. Air temperatures at a height of 2 m from the ERA Interim, monthly means of daily means, obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF), available at (https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era-interim), accessed on January 25, 2019 with a resolution of 1° x 1° were used.

Equivalent water thickness (EWT). The Jet Propulsion Laboratory (JPL) monthly land mass grids that contain land water mass anomaly as EWT derived from the Gravity Recovery & Climate Experiment (GRACE) time-variable gravity observations at 1° x 1° resolution31 were used. For more details see Landerer and Swenson32.
Vapour pressure deficit (VPD). The VPD product is a measure of the indirect VPD in kPa (resolution of 2.5 arc-minute) of monthly means of temperature and humidity, provided by Climatic Research Unit (CRU) CRU Tisc.0.1. VPD is the difference near-surface vapour pressure and saturation vapour pressure and reflects the water demand in the surface available for evapotranspiration and soil moisture, water use efficiency by plants, and seasonal large-scale atmospheric fluxes64. The dataset was resampled to a 1° × 1° spatial resolution using the monthly mean.

Burned area. Evaluation of burned area was obtained from with the Moderate Resolution Imaging Spectroradiometer (MODIS) Collection 6 MCD64A1 burned area product65. Collection 6 provides monthly tiles of burned area with 500 m spatial resolution over the globe with an overall accuracy of 97%65. The algorithm uses several parameters for detecting burned area from the Terra and Aqua satellite products, including daily active fire (MOD14A1 and Aqua MYD14A1), daily surface reflectance (MOD09HGK and MYD09HGK), and annual land cover (MCD12Q1)66–68. The burned area product was resampled to 1° × 1° spatial resolution.

CH4 anthropogenic emissions. Anthropogenic emissions (from energy sector, industrial processes and product use, agriculture and waste) were obtained from the European Commission, Joint Research Centre (EC-JRC)/Netherlands Environmental Assessment Agency (PBL), Emissions Database for Global Atmospheric Research (EDGAR) v5.0 (1970–2015)69, open access database available at (https://edgar.jrc.ec.europa.eu/open.php?v=50_GHG).

Land use and cover change data. We used the land use and cover change (LUCC) dataset (classes included: forest, savanna, mangrove, flooded forest, wetland, grassland, mosaic of agriculture and grass, other non-forest natural formations, non-vegetated area, and river, lake and ocean) covering the Pan-Amazon, Mapbiomas Amazonia collection 2.3 to estimate the relative contribution of different classes of land use and cover change to each region of influence (Fig. 1, Supplementary Table 1 and Fig. 10). In this study natural forest-non class includes data of three different classes from Mapbiomas2.3: savannah formation, grass and other non-forest natural formation, and the class others include data of non-vegetated area. Mapbiomas Amazonia is an open access database of annual LUCC product derived from Landsat images classified for 1985 to 2018 at 30 m resolution70. Wetlands and other aquatic environments are not well represented and their temporal variability is not included in this dataset.

Missing data. The F TOTAL_CH4 and F FIRE_CH4 fluxes were missing for months in red in Supplementary Fig. 15 at ALF, SAN, RBA and TAB_TEF due to logistical, laboratory/instrumental and funding issues. We applied “Miss Forest,” a non-parametric missing value approach using Random Forest methodology69 to fill these gaps. Nonparametric methods are used when the population is not large and when the data do not follow a defined distribution. For the imputation of missing data several methods were tested, such as Amelia, MICE, Supporting Vector Machine (SVM), KNN, MNLR (multiple non-linear regression) and MissForest. We used as a metric cross-validation with 15% of the known data, evaluating the data several methods were tested, such as Amelia, MICE, Supporting Vector Machine (SVM), KNN, MNLR (multiple non-linear regression) and MissForest. We used as a metric cross-validation with 15% of the known data, evaluating the

Data availability

The CH4 vertical profile data that support the findings of this study are available from PANGAEA Data Archiving, at https://doi.pangaea.de/10.1594/PANGAEA.934596.

Received: 2 June 2021; Accepted: 27 October 2021; Published online: 29 November 2021

References

1. Myhre, G. et al. Anthropogenic and Natural Radiative Forcing. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (2013) doi:10.1073/pnas.0750991107.

2. Nisbet, E. G. et al. Very strong atmospheric methane growth in the 4 years 2014–2017: implications for the Paris agreement. Global Biogeochem. Cycles 33, 318–342 (2019).
Saunois, M., Jackson, R. B., Bousquet, P., Poulter, B. & Canadell, J. G. The growing role of methane in anthropogenic climate change. Environ. Res. Lett. 11, 020701 (2016).

Kirschke, S. et al. Three decades of global methane sources and sinks. Nat. Geosci. 6, 813–823 (2013).

Saunois, M. et al. The Global Methane Budget 2000–2017. Earth Syst. Sci. Data 12, 1561–1623 (2020).

Dlugokencky, E. J. et al. Trends in atmospheric methane. NOAA/ESRL www.esrl.noaa.gov/gmd/ccgg/trends (2017).

Cassol, H. L. G. et al. Determination of region of influence for methane emissions from the eastern Amazon basin. Geophys. Res. Lett. 36, L18803 (2009).

Nisbet, E. G., Dlugokencky, E. J. & Bousquet, P. Methane on the rise-again. Science 343, 493–495 (2014).

Jackson, R. B. et al. Increasing anthropogenic methane emissions arise equally from agricultural and fossil fuel sources. Environ. Res. Lett. 15, 071002 (2020).

Schaefer, H. et al. A 21st-century shift from fossil-fuel to biogenic methane emissions indicated by 13C/CH4. Science 352, 80–84 (2016).

Roestenreiter, J. A. et al. Aquatic ecosystems are highly variable sources contributing half of the global methane emissions. Nat. Geosci. 14, 225–230 (2021).

Miller, J. B. et al. Airborne measurements indicate large methane emissions from the eastern Amazon basin. Geophys. Res. Lett. 34, L10809 (2007).

Bloom, A. A., Palmer, P. L., Fraser, A. & Ray, D. S. Seasonal variability of tropical wetland CH4 emissions: the role of the methanogen-available carbon pool. Biogeosciences 8, 2821–2830 (2011).

Wilson, C. et al. Contribution of regional sources to atmospheric methane over the Amazon Basin in 2010 and 2011. Biogeosciences 13, 400–420 (2016).

Wilson, C. et al. Large and increasing methane emissions from eastern Amazonia derived from satellite data, 2010–2018. Atmos. Chem. Phys. 21, 10643–10669 (2021).

Hess, L. L. et al. Wetlands of the lowland Amazon Basin: extent, vegetative cover, and dual-season inundated area as mapped with JERS-1 synthetic aperture Radar. Wetlands 35, 745–756 (2015).

Melack, J. M. et al. Regionalization of methane emissions in the Amazon Basin with microwave remote sensing. Glob. Chang. Biol. 10, 530–544 (2004).

Pangala, S. K. et al. Large emissions from floodplain trees close the Amazon methane budget. Nature 525, 230–234 (2017).

Barbosa, P. M. et al. Dissolved methane concentrations and fluxes to the atmosphere from a tropical floodplain lake. Biogeochemistry 148, 129–151 (2020).

Martius, C. et al. Methane emission from wood-feeding termites in Amazonia. Science 268, 623–632 (1993).

Carmo, J. B do et al. A source of methane from upland forests in the Brazilian Amazon. Geophys. Res. Lett. 33, L04809 (2006).

Gatti, L. V. et al. Vertical profiles of CO2 above eastern Amazonia suggest a net carbon flux to the atmosphere and balanced biosphere between 2000 and 2009. Tellus, Ser. B Chem. Phys. Meteorol. 62, 581–594 (2010).

Gatti, L. V. et al. Desertification is a major source of Amazonian carbon balance revealed by atmospheric measurements. Nature 506, 76–80 (2014).

Basso, L. S. et al. Seasonality and interannual variability of CH4 fluxes from the eastern Amazon Basin inferred from atmospheric mole fraction profiles. J. Geophys. Res. Atmos. 11, 168–186 (2014).

Cassola, H. L. G. et al. Determination of region of influence obtained by aircraft vertical profiles using the density of trajectories from the HYPSPLIT model. Atmosphere 11, 1073 (2020).

European Commission. EDGAR Emissions Database for Global Atmospheric Research. https://data.europa.eu/yer2019/IRC_DATASET_EDGAR.

Crippa, M. et al. Fossil CO2 and GHG emissions of all world countries – 2019. European Commission, 2020. Report. https://doi.org/10.2760/655913 (2019).

Webb, A. J. et al. CH4 concentrations over the Amazon from GOSAT consistent with in situ vertical profile data. J. Geophys. Res. Atmos. 121, 11,006–11,020 (2016).

Dlugokencky, E. J., Lang, P. M., Crotwell, A. M., Thoning, K. W. & Crotwell, M. J. Atmospheric Methane Dry Air Mole Fractions from the NOAA ESRL Carbon Cycle Cooperative Global Air Sampling Network. ftp://aftp.cmdl.noaa.gov/data/trace_gases/ch4/flask/surface/ (2017).

Keller, M. et al. Soil-atmosphere exchange of nitrous oxide, nitric oxide, methane, and carbon dioxide in logged and undisturbed Forest in the Tapajos National Forest, Brazil. Earth Interact. 9, 1–28 (2005).

Diniz, F. H., Kok, K., Hott, M. C., Hoogstra-Klein, M. A. & Arts, B. From space and from the ground: Determining forest dynamics in settlement projects in the Brazilian Amazon. Int. For. Rev. 15, 442–455 (2013).

Mapbox. Proyecto MapBiomas Amazonia - Colección [2.0] de los mapas anuales de cobertura y uso del suelo. http://amazonia.mapbox.org/mapas-de-la-coleccion (2020).

Perera, J. P. et al. Examining the role of cattle and pasture in Brazil’s deforestation: a response to “fire, deforestation, and livestock when the smoke clears”. Land Use Policy 108, 105195 (2021).
Acknowledgments

This work was funded by many projects supporting the long term measurements and analyses: State of Sao Paulo Science Foundation - FAPESP (2016/02018-2, 2011/51841-0, 2008/58120-3, 2011/17914-0, 2018/14006-4, 2018/14243-4, 2018/18493-7, 2019/21789-8, 2019/23654-2, 2020/02656-4), UK Environmental Research Council (NERC) AMAZONICA project (NE/F005806/1), NASA grants (11-CMS11-0025, NRM1000-17-00431, NNXi7AK49), European Research Council (ERC) under Horizon 2020 (649087), 7FP EU (283080), MCTI/CNPq (2013), CNPq (134878/2009-4). We thank numerous people at NOAA/GML who provided advice and technical support for air sampling and measurements in Brazil and for observations from ASC, RPB, and CPT, and the pilots and technical team at aircraft sites who collected the air samples. We also thank J. F. Mueller for modelled biogenic CO fluxes.

Author contributions

L.S.B. wrote the first version of the manuscript. L.S.B., L.M., L.V.G., J.B.M., M.G., J.M., H.L.G.C., G.T., A.H.S., S.M.C., L.A. and L.E.O.C.A. participated in commenting and reviewing the manuscript; L.V.G., M.G. and J.B.M. conceived the basin-wide measurement program and approach; L.G.D., A.H.S., L.S.B., H.L.G.C., G.T., L.M. and L.V.G. contributed to the region of influence analysis; L.S.B., H.L.G.C., E.A., L.V.G., S.M.C., G.T., J.B.M., L.A. and L.E.O.C.A. contributed to inclusion of climate and human disturbance data; L.G.D., C.S.C.G., S.P.C. and R.A.L.N. participated in analysis of G.H.G. concentrations; J.B.M. provided WetCharts model ensemble estimates and analysis; J.B.M. and L.V.G. provided estimates of the biogenic CO; and L.S.B., J.B.M., S.M.C., L.M., L.V.G. and M.G. performed uncertainty estimates.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information

The online version contains supplementary material available at https://doi.org/10.1038/s43247-021-00314-4.

Correspondence and requests for materials should be addressed to Luana S. Basso.

Peer review information

Communications Earth & Environment thanks the anonymous reviewers for their contribution to the peer review of this work. Primary Handling Editors: Joshua Dean and Clare Davis. Peer reviewer reports are available.

Reprints and permission information

is available at http://www.nature.com/reprints

Publisher’s note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Open Access

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

© The Author(s) 2021