



Explaining the rapid 2019-2024 increase in methane emissions from Colombia seen in satellite observations: a high-resolution inverse analysis

Sarah E. Hancock¹, Daniel J. Jacob¹, Nicholas Balasus¹, Carlos Andres Garzon², Ciniro Costa Junior², Matthew R. Johnson³, Nikolai Calderón-Cangrejo³, Scott Winton⁴, Megan He¹, Lauren Potyk¹, Lucas A. Estrada¹, Rodrigo Jimenez⁵, Andrés Ardila⁵, Luis Morales-Rincon⁵, James L. France^{6,7}

¹: Harvard University, School of Engineering and Applied Sciences, Cambridge, MA, USA

²: International Center for Tropical Agriculture (CIAT), Cali, Colombia

³: Carleton University, Department of Mechanical and Aerospace Engineering, Ottawa, Canada

⁴: University of California Santa Cruz, Department of Environmental Studies, Santa Cruz, CA, USA

⁵: Universidad Nacional de Colombia–Bogotá, Department of Chemical and Environmental Engineering, Bogotá, Colombia

⁶: Environmental Defense Fund Europe, Avenue des Arts 47-49, Brussels, Belgium

⁷: Royal Holloway University of London, Earth Sciences Department, Egham, Surrey, UK

Correspondence to: Sarah E. Hancock (sarahhancock@g.harvard.edu)

Abstract. Colombia has been identified as a hotspot of increasing methane emissions over the 2019-2024 period by coarse-resolution global inversion of TROPOMI satellite observations. Here we reproduce this result with a high-resolution ($25 \times 25 \text{ km}^2$) monthly analytical inversion of TROPOMI observations for the same period conducted within the Integrated Methane Inversion (IMI) framework and evaluated independently with GOSAT and GHGSat satellite observations. Prior estimates for the inversion include spatially-resolved national inventory reports and a measurement-based oil and gas sector inventory for anthropogenic emissions and high-resolution monthly CYGNSS satellite inundation data. We exploit the seasonality in the monthly inversion results to separate wetlands from anthropogenic sources. Total emissions from Colombia optimized by the inversion increase at a best estimated rate (and uncertainty) of 0.23 ($0.025\text{--}0.46$) Tg a^{-2} ($2\% \text{ a}^{-1}$) during 2019–2024. Most of this increase is attributed to wetland emissions, peaking in 2021-2022 due to high precipitation driven by La Niña but reflecting interannual variability rather than a sustained trend. Anthropogenic sources account for 34% of the increase driven by cattle population growth, concentrated waste sources near Bogotá, increasing depth of surface coal mines, and fugitive emissions in oil and gas fields. The large seasonal and interannual variability of wetland emissions closely aligns with total water storage anomalies measured by the GRACE satellite instrument, consistent with the importance of water table dynamics in controlling emissions. This work demonstrates that high-resolution satellite inversions can resolve sectoral drivers of national methane trends and monitor changes in emissions at policy-relevant scales.



1. Introduction

Atmospheric methane (CH_4) has contributed approximately 30% of observed global warming since pre-industrial time, and its concentration has been rising rapidly in recent years. Identifying the countries and source sectors driving the observed increase is essential for charting a path to methane mitigation under the Paris Agreement and the Global Methane Pledge. Most individual countries report annual bottom-up emission inventories for individual sectors, constructed by applying emission factors to activity data (IPCC, 2019) to the United Nations Framework Convention on Climate Change (UNFCCC). Satellite observations of atmospheric methane concentrations from GOSAT (2009–present) and TROPOMI (2018–present), combined with inverse modeling frameworks using the bottom-up inventories as prior estimates, offer an opportunity to evaluate and improve these inventories (Jacob et al., 2022).

Recent satellite observations have identified Colombia as a hotspot of increasing methane emissions. Total methane emissions in Colombia have been estimated from a 2023 inversion of TROPOMI observations to be 8.9 Tg a^{-1} , with 5.7 Tg a^{-1} from wetlands and 3.2 Tg a^{-1} from anthropogenic sources including livestock (2.0 Tg a^{-1}), waste (0.76 Tg a^{-1}), and fossil fuel exploitation (0.25 Tg a^{-1}) (Hancock et al., 2026). In a global TROPOMI inversion for 2019–2024, He et al. (2026) found a growth rate in Colombian emissions of 0.2 Tg a^{-2} or $2\% \text{ a}^{-1}$, some of the highest in the world. Global GOSAT inversions previously identified large increases in total (L. Feng et al., 2023) and wetland (Lin et al., 2024) emissions in Colombia during 2019–2021. This rapid rise in emissions from Colombia was not seen in GOSAT inversions for the 2010s (Maasakkers et al., 2019; Zhang et al., 2021; Feng et al., 2022). Given Colombia's stated commitment to decrease its emissions (Colombia, 2025), there is a compelling reason to understand the drivers of the increase.

A new opportunity to understand anthropogenic emission trends is provided by countries' Biennial Transparency Reports (BTRs), submitted under the Paris Agreement as part of the Enhanced Transparency Framework, with first submissions completed by the end of 2024. BTRs replace the Biennial Update Reports (BURs) previously submitted by non-Annex I countries and expand reporting to include annually resolved greenhouse gas inventory time series using consistent methodologies. Colombia's BTR reports an increase of methane emissions from 1990 to 2021 of 0.037 Tg a^{-2} or $1.8\% \text{ a}^{-1}$ (Figure S1), driven primarily by livestock emissions ($1.1\% \text{ a}^{-1}$) due to cattle population growth (Colombia, 2024). The fastest growth occurs in the waste sector ($3.6\% \text{ a}^{-1}$), reflecting increased waste generation and a transition to managed landfills, while fuel emissions increased at $3.5\% \text{ a}^{-1}$ but declined in recent years due to lower oil/gas and coal production during COVID-19 and regulatory efforts. However, the BTR currently extends only through 2021 and relies on bottom-up emission factors that may not fully capture real-world variability.

Global inversions using TROPOMI data can identify more recent emission trends, but their coarse resolution ($>100 \text{ km}$) limits quantification of national emissions and attribution to specific sources. A number of studies have used regional inversions at 10–50 km resolution to quantify and attribute emissions for individual countries (Nathan et al., 2024; S. Feng et al., 2025; Maliehe et al., 2026). Such inversions need high-quality, spatially resolved bottom-up inventories both as prior estimates and to attribute inversion results. Hancock et al. (2025) conducted a 2021 TROPOMI inversion over South America at up to 25-km resolution using UNFCCC totals as prior estimates and found higher Colombian emissions than reported by the BUR, but were limited in relating emissions to sector-level processes due to their use of global inventories for sectoral allocation including the separation of wetlands from anthropogenic



sources. Hancock et al. (2026) improved on this work by conducting a 12-km resolution TROPOMI inversion over Colombia for 2023 using a spatially allocated national bottom-up inventory from Colombia's most recent BUR (Colombia, 2022), together with high-resolution wetland information from the Global Lakes and Wetlands Database (GLWDv2) (Lehner et al., 2025). The inversion showed upward adjustments to the BUR emissions, but it did not address emission trends or optimize the seasonality of emissions, which can provide a lever for separating wetland and anthropogenic contributions (Dowd et al., 2023).

Here we use the Integrated Methane Inversion (IMI 2.0) to quantify and attribute changes in Colombian methane emissions from 2019 to 2024 by analytical inversion of TROPOMI observations with $0.25^\circ \times 0.3125^\circ$ ($\approx 25 \times 25$ km²) resolution and monthly temporal resolution (Figure 1). The IMI is a versatile open-source software tool for analytical inversion of satellite data using the GEOS-Chem chemical transport model to relate emissions to the satellite observations (Varon et al., 2022; Estrada et al., 2025). The analytical inversion framework provides closed-form characterization of error statistics and enables generation of an inversion ensemble exploring uncertainty in inversion parameters. We start from an improved version of the BUR bottom-up inventory and a new wetlands emission inventory as prior estimates. The inversion then proceeds as a suboptimal Kalman filter where the optimal posterior solution for a month is used as prior estimate for the next month (Varon et al., 2023). The monthly resolution enables improved separation of wetlands and anthropogenic sources that are spatially overlapping but seasonally distinct. We resolve in this manner the sectoral contributions to the emission trend, and develop new understanding of the hydrological drivers of wetland emissions. Our system provides a blueprint for continuous tracking of emission changes in a country over time.

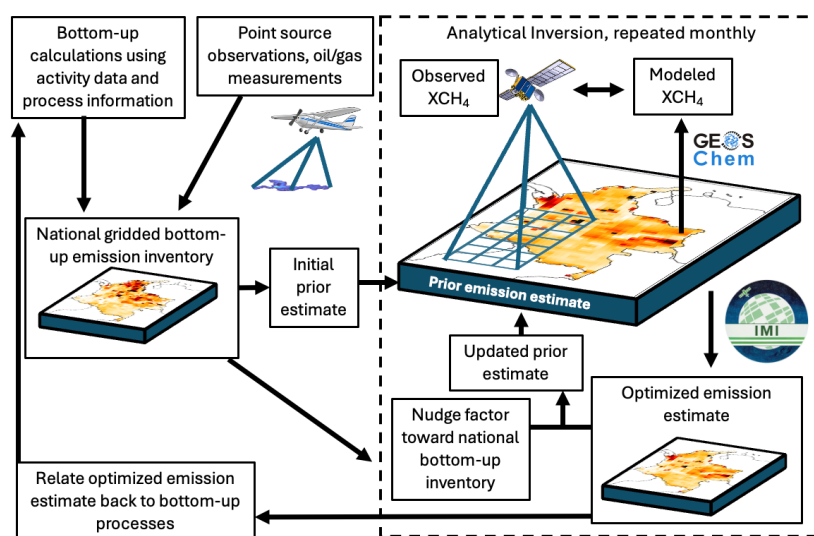


Figure 1: Inversion framework used to quantify and interpret 2019-2024 monthly methane emissions over Colombia through the integration of bottom-up and top-down methods. The national bottom-up inventory is used as the prior estimate in an initial 1-month GEOS-Chem simulation of atmospheric methane dry column mixing ratios (XCH₄), which are compared to satellite observations from TROPOMI to optimize emissions for that month through an analytical inversion. The optimized (posterior) monthly emission estimate is then used as prior estimate for the next month, with some nudging back to the original prior estimate, and the process is repeated every month over the 2019-2024 period.



2. Bottom-up Emission Estimates

We start from the bottom-up anthropogenic emission inventory of Hancock et al. (2026) for Colombia, which spatially allocates the national BUR submitted to the UNFCCC (Colombia, 2022) with updates for coal, waste, and livestock (Ardila et al., 2025). We further update emissions from the oil/gas production and rice agriculture sectors as described below. We use the new WetCHARTs-CYGNSS monthly bottom-up wetlands emission inventory (Balasus et al., 2026), monthly termite emissions from Ito (2023), daily fire emissions from the Global Fire Emissions Database version 4s (GFED4s) (van der Werf et al., 2017), and seep emissions from Etiope et al. (2019) with global scaling to 2 Tg a^{-1} from Hmiel et al. (2020). Bottom-up emissions for neighboring countries are as described by Hancock et al. (2026). All emissions are regridded to the $0.25^\circ \times 0.3125^\circ$ ($\approx 25 \times 25 \text{ km}^2$) GEOS-Chem resolution used here.

Table 1 lists our bottom-up emission estimates and Figure 2 shows their spatial distribution. The WetCHARTs-CYGNSS wetlands inventory of Balasus et al. (2026) combines observed monthly $0.01^\circ \times 0.01^\circ$ inundation from the CYGNSS satellite constellation using GPS signals (Pu et al., 2024) with emission intensity per unit inundated area from the WetCHARTs model system (Bloom et al., 2017). WetCHARTs uses heterotrophic respiration from the CARDAMOM biogeochemical model together with CH_4/CO_2 respiration ratios. WetCHARTs-CYGNSS reproduces high wetland emissions in the La Mojana region of northern Colombia that align with seasonal TROPOMI enhancements reported by Hancock et al. (2026). The GLWDv2 inundation dataset previously used by Hancock et al. (2026) has a similar spatial distribution to CYGNSS but lacks seasonal information. Emissions from upstream oil/gas production are from a measurement-based inventory at $0.1^\circ \times 0.1^\circ$ resolution developed using aerial and ground-based remote sensing (Calderón-Cangrejo et al., 2025). In grid cells without upstream emissions in Calderón-Cangrejo et al. (2025), we retain oil/gas emissions from Hancock et al. (2026) to represent downstream sources, but these are negligibly small compared to upstream emissions. We use the rice inventory of Garzon Leniz and Costa Junior (2025), who estimate annual emissions for individual municipalities in Colombia with IPCC Tier 2 methodology and BTR emission factors (Unidad de Planificación Rural Agropecuaria, 2024). Within each municipality, we use the CORINE national land cover map (LCM) (Instituto de Hidrología, Meteorología y Estudios Ambientales (IDEAM), 2021) to spatially allocate the emissions to cropland.

The overall seasonality in the bottom-up estimates is driven by Northern wetlands, peaking in May-September and with interannual variability over the 2019-2024 period. Open fire emissions have opposite seasonality to wetlands but are relatively small. Emissions from the dominant anthropogenic sectors (livestock, waste, oil/gas) are taken to be aseasonal with no 2019-2024 trend. Livestock emissions are primarily from cattle enteric fermentation (93%), and while there could be some seasonality in livestock counts and migration, we have no information to specify this seasonality and assume it to be relatively small.



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Table 1: Methane emissions from Colombia^a

Sector	Bottom-up (Tg a ⁻¹) ^b	Posterior (Tg a ⁻¹) ^c
Total	8.6	10.7 (9.5–11.2)
Anthropogenic	2.8	3.2 (3.1–3.3)
Livestock	1.7	2.0 (1.9–2.0)
Waste ^d	0.62	0.71 (0.66–0.75)
Oil/Gas	0.20	0.24 (0.22–0.24)
Reservoirs	0.12	0.13 (0.099–0.14)
Coal	0.046	0.096 (0.092–0.10)
Other Anthropogenic ^e	0.051	0.058 (0.052–0.061)
Rice	0.03	0.032 (0.031–0.033)
Natural	5.8	7.5 (6.4–7.9)
Wetlands	5.4	7.1 (6.0–7.4)
Termites	0.30	0.35 (0.33–0.36)
Open Fires ^f	0.061	0.065 (0.061–0.065)
Seeps	0.017	0.02 (0.019–0.021)

^a Mean values for 2019–2024.

^b Bottom-up prior emission estimates used in the inversion. Anthropogenic emissions are from Colombia's Biennial Update Report (BUR) to the UNFCCC with improvements described in Section 2. Wetland emissions are from the WetCHARTs-CYGNSS inventory (Balasus et al., 2026).

160 ^c Best posterior emission estimates from the monthly analytical inversion of TROPOMI observations using IMI 2.0 (Sect. 3). Ranges from the 24-member inversion ensemble are in parentheses.

^d Waste includes landfills and wastewater treatment.

^e Including industry, stationary and mobile combustion, aircraft, composting, and agricultural residue burning.

165 ^f Open fires in Colombia have a substantial anthropogenic component associated with deforestation, pasture maintenance, and agricultural burning (Armenteras, 2022; Armenteras & Retana, 2012) but are treated as natural here for consistency with previous top-down studies and because GFED does not resolve anthropogenic from natural burning. The BTR-reported anthropogenic fire emission of 0.014 Tg a⁻¹ is 23% of our prior open-fire estimate.

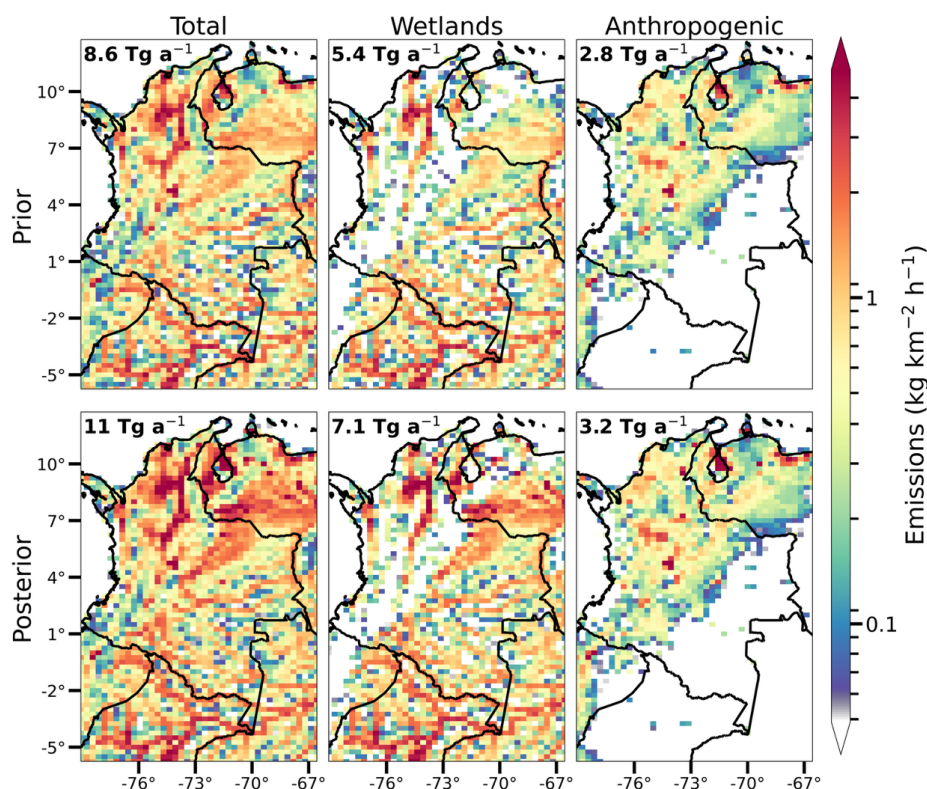


Figure 2. Prior (top) and posterior (bottom) methane emission estimates on the $0.25^\circ \times 0.3125^\circ$ grid of the inversion. Values are means for 2019–2024. Total emissions for Colombia are inset. The contributions from different sectors are described in the text and listed in Table 1.

3 Top-down information and inversion methods

We optimize a state vector of methane emissions over a rectilinear inversion domain covering Colombia and neighboring regions (-5.75° to 12.75° latitude, -79.0625° to -66.5625° longitude, domain of Figure 2) at $0.25^\circ \times 0.3125^\circ$ resolution ($\approx 25 \times 25 \text{ km}^2$) for each month from 2019 through 2024 using methane observations from TROPOMI (Sect. 3.1) with the GEOS-Chem chemical transport model as forward model for the inversion. Starting from the bottom-up inventories of Sect. 2 as the prior estimate for January 2019, the inversion derives a posterior estimate for each month that then serves as prior estimate for the following month (Sect. 3.2). We also conduct an ensemble of sensitivity inversions varying inversion parameters to characterize errors in the posterior estimate.

3.1 TROPOMI satellite observations

TROPOMI was launched in October 2017 on a sun-synchronous polar orbit with a 13:30 local overpass time and provides full global daily coverage with a spatial resolution of $7 \times 5.5 \text{ km}^2$ in the nadir. It retrieves XCH_4 from solar backscatter in the $2.3 \text{ }\mu\text{m}$ absorption band with a success rate of 3% limited by clouds and dark or heterogeneous surfaces (Veefkind et al., 2012).

We use the blended TROPOMI product from Balasus et al. (2023) (available at



<https://registry.opendata.aws/blended-tropomi-gosat-methane>), which applies machine learning to correct the TROPOMI operational product of Lorente et al. (2023) using co-located GOSAT observations, henceforth referred to as TROPOMI. We include glint observations over the ocean to inform emissions from onshore coastal sources. We have 752099 successful TROPOMI retrievals over the inversion domain during 2019-2024, which we average over the GEOS-Chem 0.25°×0.3125° grid cells ($\approx 25 \times 25$ km²) for individual orbits to produce $m_{\text{TROPOMI}} = 185694$ super-observations (Rijsdijk et al., 2025). Figure 3 shows the mean TROPOMI XCH₄ data for 2019-2024, and differences with GEOS-Chem driven by either prior or posterior emissions. Observations are densest in the principal dry season (January-March) and sparse over the Amazon in southern Colombia (Hancock et al., 2026). Major populated areas near the Andes lack observations because TROPOMI excludes scenes with high sub-pixel topographic variability, but the inversion still gains information about their emissions through atmospheric transport, which carries their methane enhancements downwind to observed areas.

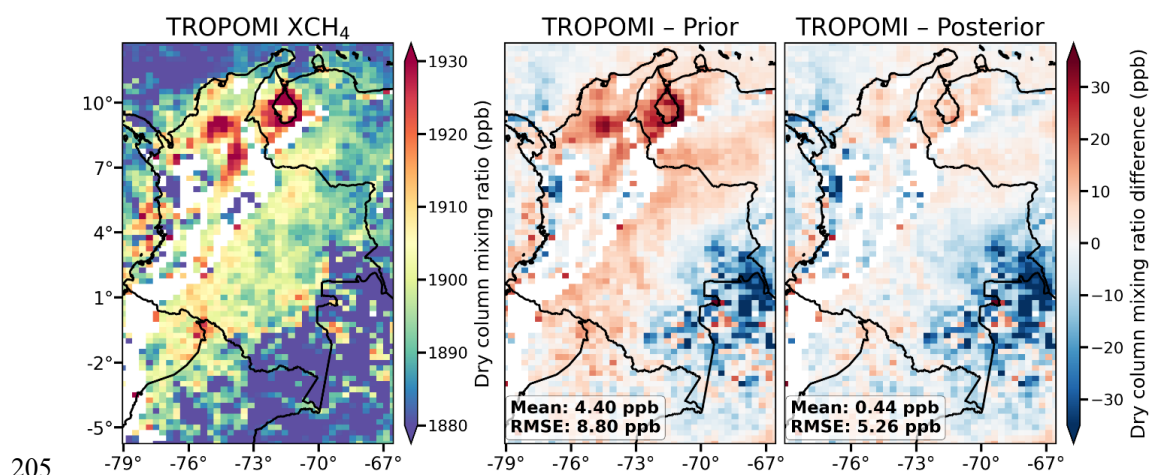


Figure 3: TROPOMI observations of methane dry column mixing ratios (XCH₄) over Colombia, and comparison to GEOS-Chem simulations using either prior or posterior emission estimates. Values are 2019-2024 means and are shown on the 0.25°×0.3125° GEOS-Chem grid used to optimize emissions. Areas in white have no observations. Legends give the means and spatial root-mean-square errors (RMSEs) for the differences between TROPOMI and GEOS-Chem XCH₄ over the domain of the Figure.

3.2 Analytical Inversion

We apply the Integrated Methane Inversion (IMI 2.0) (Estrada et al., 2025) to optimize methane emissions over Colombia using TROPOMI XCH₄ observations. The inversion uses the nested GEOS-Chem 14.4.1 chemical transport model at 0.25°×0.3125° resolution with dynamic boundary conditions updated every three hours from smoothed TROPOMI-corrected GEOS-Chem fields (Estrada et al., 2025). The inversion minimizes the Bayesian cost function for a state vector with normal error statistics and solves analytically for the best estimate of the posterior state vector together with posterior error covariances (Brasseur and Jacob, 2017). The state vector consists of monthly emissions in each 0.25°×0.3125° GEOS-Chem land grid cell of the domain of Figure 3, plus boundary conditions for the four quadrants (north, south, west, east) for a total of $n = 2864$ state vector elements. We perform sequential monthly analytical inversions from January 2019 to December 2024 using the IMI's sub-optimal Kalman filter framework



(Varon et al., 2023; Estrada et al., 2025), in which the posterior solution from month $i - 1$ updates the prior estimate for month i with partial nudging toward the original prior estimates (Varon et al., 2023). Inversion specifications and parameters are given in Table 2. To ensure that posterior emission trends over 2019–2024 are driven by the observations rather than by initialization, we perform an initial 12-month burn-in for 2019, starting from prior estimates, and use the resulting December 2019 posterior as the initial condition for our January 2019 inversion. We confirmed that the 12-month burn-in is sufficient by verifying December 2019 posterior estimates were not substantially different for the burn-in and inversion months.

To estimate observational error variances, we use the residual error method (Heald et al., 2004). The observational error includes contributions from the TROPOMI instrument, the retrieval, and the forward model. The residual error method uses the residual error between the observations and the forward model simulation with prior estimates as a measure of the total observational error on the model grid. Following Chen et al., (2023), we derive the observational error variance of the super-observations (σ_{super}^2) on the GEOS-Chem $0.25^\circ \times 0.3125^\circ$ grid (P individual retrievals averaged into one super-observation) by separating the contributions from the transport error variance $\sigma_{\text{transport}}^2$ (perfectly correlated for the individual observations within a GEOS-Chem grid cell) and the instrument and single-retrieval error variance ($\sigma_{\text{retrieval}}^2$):

$$\sigma_{\text{super}}^2 = \sigma_{\text{retrieval}}^2 \left(\frac{1-r}{P} + r \right) + \sigma_{\text{transport}}^2, \quad (2)$$

where r is the retrieval error correlation coefficient for the individual observations averaged into a super-observation. Our fit of residual errors to Eq. (2) for Colombia for 2019–2024 yields $\sigma_{\text{transport}} = 7.3$ ppb, $\sigma_{\text{retrieval}} = 18.1$ ppb, and $r = 0.22$. The average observational error standard deviation for the TROPOMI super-observations in the inversion domain is 12.9 ppb.

To account for uncertainties in the choice of inversion parameters including the prior error standard deviation on emissions σ_e , an error standard deviation σ_b for boundary conditions, and a nudging factor α , we generate a 27-member ensemble of sensitivity inversions varying σ_e (50%, 100%, or 200%), σ_b (5, 10, or 20 ppb), and α (0.1, 0.2, or 0.4). We remove three ensemble members (members with both $\sigma_e = 200\%$ and $\alpha = 0.1$) that show poor minimization of the Bayesian cost function, and report the best posterior estimate of emissions as the inversion that best minimizes the Bayesian cost function ($\sigma_e = 100\%$, $\sigma_b = 10$ ppb, $\alpha = 0.4$). The range of solutions given by the remaining members gives an estimate of the posterior uncertainty. This is a more conservative error estimate than the posterior error covariance matrix $\hat{\mathbf{S}}$, which does not account for uncertainty in inversion parameters (Chen et al., 2022).



Table 2: Specifications of the inversion ensemble

Specification	Value ¹
Inversion framework ²	Sequential monthly analytical inversion using sub-optimal Kalman filter
Inversion period	2019–2024
Forward model	Nested GEOS-Chem 14.4.1
Model resolution	0.25°×0.3125°
State vector	Native-resolution grid cell emissions and boundary conditions (north, south, east, west); total $n = 2864$
Methane sinks	Not optimized ³
Error probability density functions	Normal
Regularization parameter γ ⁴	1
Prior error standard deviation on emissions	50%, 100% , 200%
Boundary condition error standard deviation (ppb)	5, 10 , 20
Nudging factor α ⁵	0.1, 0.2, 0.4
Observational error standard deviation (ppb)	Derived from residual error method; mean 12.9 ppb

¹ Best inversion values are shown in bold.

² We use the Integrated Methane Inversion (IMI 2.0) framework (Estrada et al., 2025) in sub-optimal Kalman filter mode.

260 ³ Methane sinks included in GEOS-Chem (oxidation by tropospheric OH and Cl, stratospheric oxidation, and soil uptake) are prescribed and not optimized because they have relatively uniform spatial distributions over the domain and are effectively corrected through optimization of boundary conditions.

265 ⁴ The regularization parameter $\gamma \in [0, 1]$ applied to the observational terms of the cost function balances the prior and observational terms in the cost function to avoid overfit (Lu et al., 2021). Overfit is not an issue here because of the high model resolution and relatively sparse observations, so we use $\gamma = 1$.

⁵ The nudging factor α determines the weight assigned to the original prior emissions relative to the previous month's posterior emissions in the Kalman update. The best inversion uses $\alpha = 0.4$ (40% original prior emissions, 60% previous posterior emissions).

4 Monthly Colombia emissions and 2019–2024 trends

270 Figure 2 and Table 1 show the best posterior emission estimates from the inversion averaged over the 2019–2024 period. Total methane emissions from Colombia are adjusted from 8.6 Tg a⁻¹ in the bottom-up inventory to 10.7 Tg a⁻¹ (9.5–11.2 Tg a⁻¹) in the posterior estimate. Previous regional TROPOMI inversions for 2023 estimated total emissions for Colombia of 11.5 (9.0, 12.2) Tg a⁻¹ (East et al., 2025) and 8.9 (8.7 - 9.1) Tg a⁻¹ (Hancock et al., 2026), compared to
 275 11.0 (9.8–11.9) Tg a⁻¹ here. The lower value in Hancock et al. (2026) reflects their use of a prior wetland emission inventory with lower emissions in northern Colombia. Our posterior emissions are enhanced relative to the prior estimate across much of northern Colombia, with the largest increases in the Orinoquía and Magdalena wetland regions. Figure 3 shows that the inversion substantially improves agreement between GEOS-Chem modeled XCH₄ and TROPOMI
 280 observations, reducing the mean bias from 4.4 to 0.4 ppb and the root-mean-square error from 8.8 to 5.3 ppb relative to the prior estimate. The corrections are mainly for northern Colombia, as



TROPOMI observations over southern Colombia are sparse due to persistent cloud cover (Hancock et al., 2026).

We conducted independent evaluation of the inversion results with observations from the Greenhouse Gases Observing Satellite (GOSAT) (Parker & Boesch, 2020), which provides a much sparser dataset than TROPOMI but performs better over dark and heterogeneous surfaces (Jacob et al., 2022). Comparison of GOSAT to GEOS-Chem simulations driven by bottom-up or posterior emissions (Figure 4) shows a decrease in the linear regression slope from 1.30 to 1.16, indicating a better fit to posterior emissions. There is an offset of 9.1 ppb between GOSAT and TROPOMI observations (Figure 4) which explains the corresponding offset between GOSAT and the GEOS-Chem simulations using posterior emissions. This is of no consequence for our results because our boundary conditions are calibrated to the TROPOMI observations.

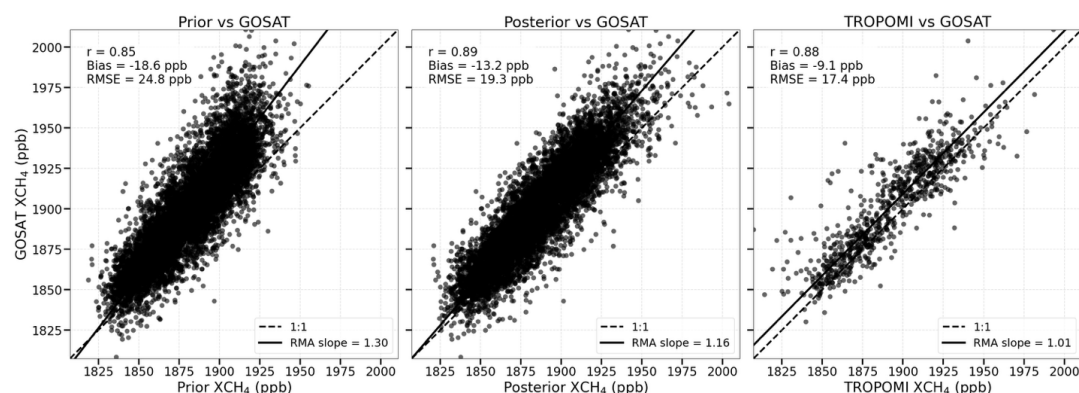
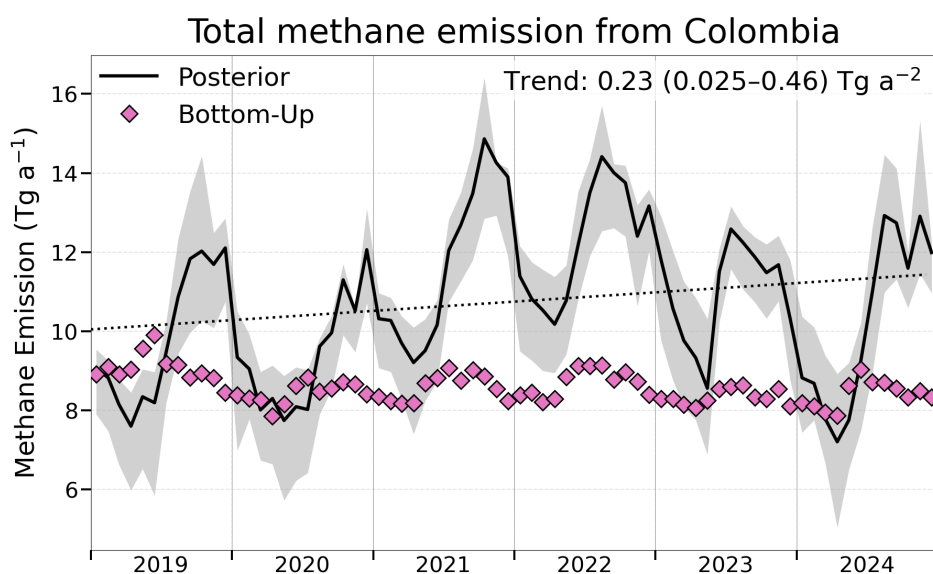
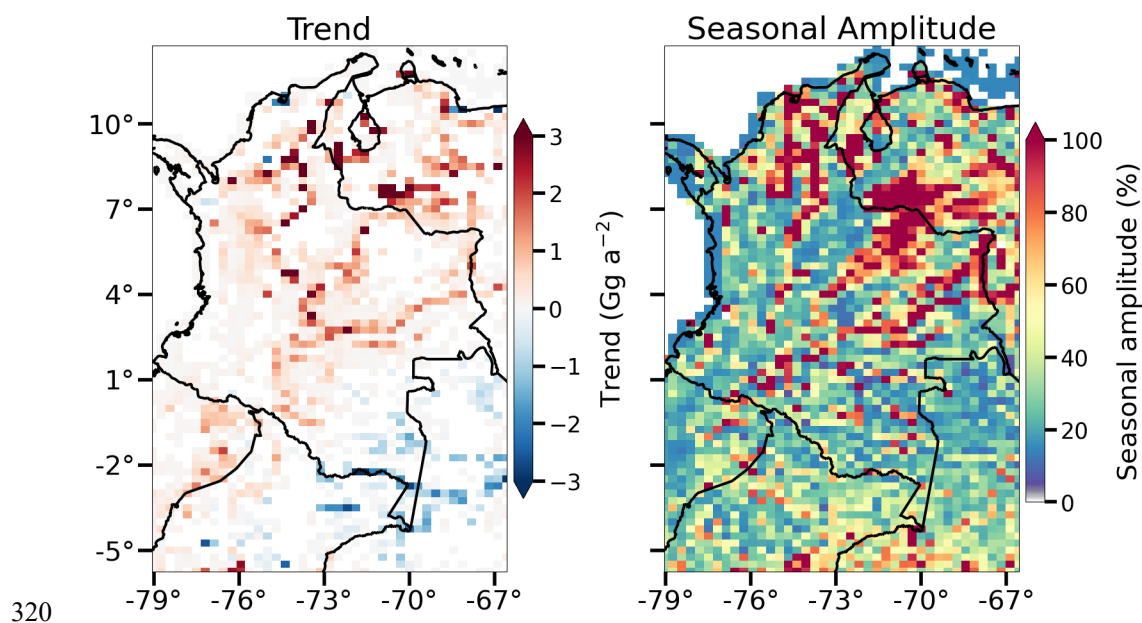


Figure 4: Evaluation of inversion results with independent GOSAT satellite observations of XCH_4 . The Figure compares individual GOSAT observations sampled over the domain of Figure 2 for the 2019–2024 period to the GEOS-Chem simulation using either prior or posterior emission estimates, and to the TROPOMI observations. Also shown are the 1:1 and reduced-major-axis (RMA) regression lines. Reported statistics include the Pearson correlation coefficient (r), mean bias, root-mean-square error (RMSE), and slope of the RMA regression line.

Figure 5 shows the trends in monthly total methane emission from Colombia over the 2019–2024 period inferred from the TROPOMI inversion and compared to the bottom-up estimates from Section 2. Posterior emissions have much larger seasonality than the bottom-up estimate. They also show a positive long-term trend over 2019–2024, whereas the bottom-up inventory exhibits a decreasing tendency over the same period due to a decline in CYGNSS inundation. We calculate trends using the Theil-Sen estimator applied to deseasonalized posterior monthly estimates and find an increase of 0.23 (0.02–0.46) Tg a^{-2} (2.2% a^{-1}). The uncertainty provided is from the Theil-Sen 95% confidence interval because this is larger than the spread across the ensemble. This trend is consistent in magnitude with the 2019–2024 increase of 0.2 Tg a^{-2} found by He et al. (2026) but the increase is in fact not linear, with maxima in 2021 and 2022. The hydrological drivers of the seasonality and interannual variability of posterior emissions will be discussed in Sect. 6.



315 **Figure 5: Monthly methane emissions from Colombia over the January 2019 - December 2024 period. Black lines show the best posterior emissions from the TROPOMI inversion, with shading indicating the range across the inversion ensemble. Magenta diamonds denote the bottom-up inventory estimates. The dotted line shows the Theil-Sen trend fit to the deseasonalized posterior emissions, with the corresponding trend magnitude and 95% confidence intervals reported inset.**



320 **Figure 6: Trends and seasonal amplitudes of optimized (posterior) methane emissions, 2019-2024. The trends are from pixel-wise Theil-Sen estimates fit to the deseasonalized posterior emissions on the 0.25°x0.3125° grid. Seasonal amplitudes are calculated as the relative difference between the maximum and minimum of the detrended monthly climatology,**



325 normalized by the mean, using monthly emissions averaged across all years. Trends that are not significant (same sign across the ensemble) are not shown.

330 Spatial patterns of 2019-2024 emission trends and mean 2019-2024 seasonal amplitudes are shown in Figure 6 on the $0.25^\circ \times 0.3125^\circ$ grid. We find the largest positive emission trends and the largest seasonal amplitudes in wetland-dominated areas of northern Colombia (Figure 2), while smaller positive trends are observed over regions associated with livestock production, fossil fuel activity, and waste. The much larger seasonal variability of posterior emissions over known wetland regions, amplifying the variability in the bottom-up estimate (Figure 5), supports our use of seasonal variability as a means to separate wetland and anthropogenic contributions to emissions and their trends as described below.

5 Sectoral contributions to emissions and 2019-2024 trends

335 The inversion returns posterior/prior emission ratios on the $0.25^\circ \times 0.3125^\circ$ grid but does not by itself attribute the correction to individual sectors. We follow standard practice for sectoral attribution by applying the posterior/prior ratios in a grid cell to the prior emissions from all sectors in that cell (Wecht et al., 2014). However, this makes it difficult to separate corrections to wetlands and livestock, which are often spatially adjacent or overlap (Pendergrass et al., 2025).

340 For those grid cells dominated by wetlands and livestock, we take advantage of the monthly resolution of the inversion by assigning the full posterior correction to wetlands if the seasonal amplitude in the posterior emissions exceeds 30% (Figure 6). This threshold is defined from the median seasonal amplitude of wetland-dominated grid cells in the bottom-up estimate and is thus a conservative indicator of wetland-driven signal.

345 The resulting mean Colombian posterior emissions by sector are listed in Table 1. Wetlands increase from 5.4 in the prior estimate to 7.1 (6.0–7.4) Tg a^{-1} in the posterior estimate, while anthropogenic emissions increase from 2.8 to 3.2 (3.1–3.3) Tg a^{-1} . Livestock emissions increase from 1.7 to 2.0 (1.9–2.0) Tg a^{-1} , and coal has a large relative adjustment from 0.046 to 0.096 (0.092–0.10) Tg a^{-1} . Smaller adjustments are inferred for waste, oil/gas, and rice. These estimates are consistent with the 3.2 Tg a^{-1} anthropogenic total (2.0 Tg a^{-1} from livestock, 0.1 Tg a^{-1} from coal) found by Hancock et al. (2026) (Table S1). In global GOSAT inversions, Janardanan et al. (2020) and Janardanan et al. (2024) find similar anthropogenic totals for 2011–2017 and 2009–2020 (2.9 and 3.4 Tg a^{-1} , respectively). East et al. (2025) find a much larger anthropogenic total of 5.8 (3.8–6.4) Tg a^{-1} for 2023. Our lower estimate is due to our Colombia-specific prior emission inventory and improved sectoral attribution methodology that cause more emissions to be attributed to wetlands instead of livestock and waste.

355 Posterior emission trends for major sectors are shown in Figure 7. Wetlands account for 60% of the 2019-2024 increase and for the bulk of the interannual variability with a 2021-2022 maximum. Total anthropogenic emissions rise more steadily by 0.079 (0.054–0.11) Tg a^{-2} (2.5% a^{-1}). This anthropogenic trend exceeds Colombia's BTR increase of 1.8% a^{-1} for 1990–2021 (Figure S1).

365 Livestock exhibits the largest anthropogenic trend in our inversion results, increasing by 0.033 (0.021–0.048) Tg a^{-2} , or 1.7 (1.1–2.4)% a^{-1} over the 2019-2024 period. This rate is comparable to the long-term trend in livestock emissions reported in the BTR (1.1% a^{-1}). It can be simply explained by growth in cattle population, estimated to be 0.78% a^{-1} by the Federación Colombiana de Ganaderos (FEDEGAN, 2026) from vaccination records, and 1.9% a^{-1} by the Food and Agriculture Organization (FAO, 2026) (Figure S2). Both emissions and cattle



population data show an increase from 2019 to 2022 followed by a decrease in 2023. However, while cattle populations increase again in 2024 and reach a peak, our emissions do not show a corresponding rebound. This could be due to lower emissions per head driven by drier conditions in 2023–2024 that reduce forage availability and quality (Díaz-Almanza et al., 2025), leading to lower feed intake and smaller cattle. Methane emission factors are sensitive to diet quality (Caicedo et al., 2023; Vargas et al., 2018), and even minor changes in emission factors would explain the divergence between cattle population and emissions trends seen here.

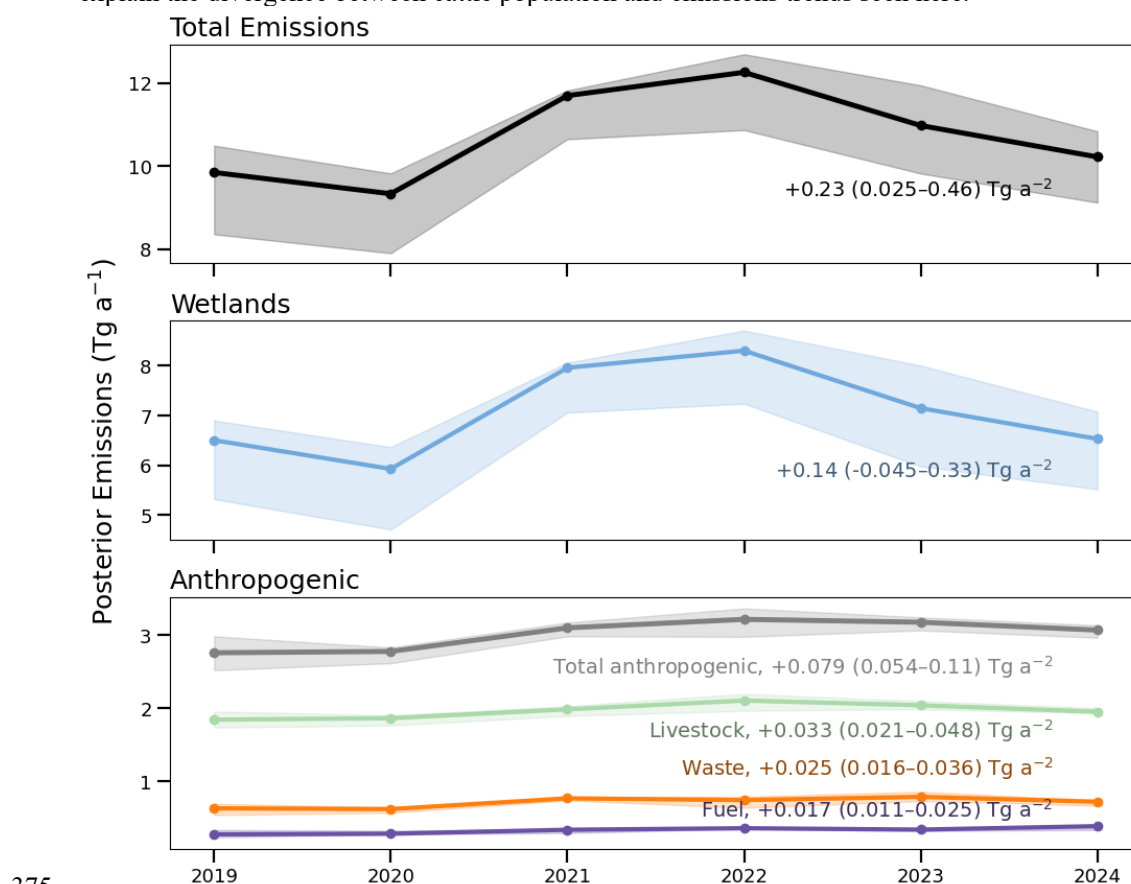


Figure 7: Trends in annual posterior methane emissions from Colombia over the 2019–2024 period. The top panel shows total posterior emissions as in Figure 5 but annually averaged. The middle panel shows wetland emissions, and the bottom panel shows anthropogenic emissions and the dominant components (livestock, waste, and fuel). Shading represents the ranges across the inversion ensemble. Legends report emission trends over the study period from Theil-Sen regression applied to deseasonalized monthly data, with ranges from the 95% confidence interval in parentheses.

Waste shows a positive emission trend of 0.025 (0.016–0.036) Tg a^{–2} or 3.5 (2.2–5.1)% a^{–1} concentrated around Bogotá. While this upward trend is larger than Colombia’s population growth for the same period (1.2% a^{–1}) (Departamento Administrativo Nacional de Estadística, 2024), it aligns with the long-term trend in waste emissions in Colombia’s BTR (3.6% a^{–1}, Fig. S1). Methane emissions from waste have outpaced population growth because of economic growth leading to higher per-capita waste production, urbanization and regulatory shifts leading



to more waste in managed landfills (>96%) rather than open dumps, and the growth of industrial activities increasing emissions from industrial wastewater (Jimenez et al., 2026; Government of Colombia, 2024).

Fuel shows a positive emission trend of 0.017 (0.011 - 0.025) Tg a^{-2} . Half (0.008 Tg a^{-2}) of this trend is attributed to coal and occurs despite declining coal production (Agencia Nacional de Minería, 2025), consistent with the hypothesis that emission factors at Colombia's large surface mines have increased over time due to increasing mine depths (Hancock et al., 2026). Colombia's BTR uses a Tier 2 methodology in which emission factors depend on both depth and methane content derived from basin-specific drilling data, but does not account for trends in depth. Most of the trend in oil/gas is concentrated near the Puerto Boyacá region where recent aerial surveys have identified significant venting from steam-assisted oil production (Calderón-Cangrejo et al., 2025). This area has also been highlighted in previous satellite surveys (Hancock et al., 2026).

Independent observations from GHGSat satellite instruments (Jervis et al., 2025) provide additional information on large methane point sources in northern Colombia. 79 GHGSat observations are available in 2022-2024 from eight landfills and three open-pit coal mines (Figure 8). We convert the instantaneous emission rates reported by GHGSat to monthly mean emissions following Jervis et al. (2026), using persistence factors of either 1 or 0.6 for waste (Cusworth et al., 2024) and 1 or 0.47 for coal (Jervis et al., 2026), to compare with our bottom-up and posterior emissions. The bottom-up estimate distributes evenly the national landfill emissions across all landfills unless facility-level bottom-up estimates are available from Ardila et al. (2025) (Hancock et al., 2026). The posterior estimate improves on this distribution in a manner consistent with GHGSat ($r = 0.73$). Assuming a persistence of unity improves the agreement between GHGSat and the model, and the resulting posterior emissions are 40% higher than the GHGSat values on the basis of linear regression. We find that the correlation mainly reflects the spatial distribution of landfills, rather than any significant seasonal or interannual variability. Our posterior coal mine emissions for the three $0.25^\circ \times 0.3125^\circ$ grid cells observed by GHGSat are much higher than GHGSat but this is to be expected because each of these grid cells includes emissions from more than 10 mines, whereas each GHGSat observation is for a single mine.

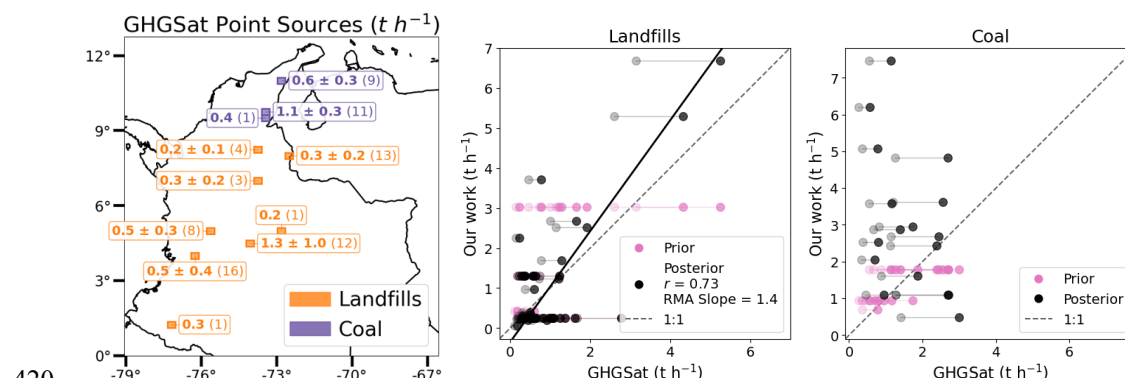


Figure 8: 2022-2024 GHGSat observations of landfill and coal point sources, and comparison with our bottom-up and posterior emission estimates for waste and coal. (Left) Point source locations of GHGSat detections colored by sector. Emissions in units of tons h^{-1} as reported by GHGSat are averaged over all observations for each point source with standard deviations (numbers of observations are in parentheses). (Middle and right) Monthly GHGSat observations for individual facilities (converted to monthly mean emissions using persistence factors of 1 and 0.6 for waste and 1 and 0.47



for coal) versus bottom-up and posterior emission estimates for the corresponding $0.25^{\circ} \times 0.3125^{\circ}$ grid cells. Bottom-up emission estimates do not include monthly or interannual variability. Correlation coefficient and reduced-major-axis (RMA) regression line and slope are shown for the comparison of GHGSat landfill observations to the posterior emission estimates.

430 6 Hydrological drivers of wetland emissions

Understanding the variability of wetland emissions from a bottom-up perspective is important for separating wetland from anthropogenic contributions. WetCHARTs-CYGNSS does better than other models in capturing the spatial distribution of wetlands in northern Colombia (Hancock et al., 2026) but it still fails to reproduce the magnitude, seasonal variability, and interannual
435 variability of emissions (Figure 5). An inversion of TROPOMI observations over Africa by Balasus et al. (2026) using WetCHARTs-CYGNSS as a prior estimate found that CYGNSS produced the correct spatial and seasonal patterns of inundation, but that CARDAMOM used in WetCHARTs produced large errors in methane intensity per unit of inundated area. Here we examine if the same applies for Colombia and if other hydrological variables can explain our
440 posterior results.

To identify hydrological drivers, we examine correlations between posterior wetland methane emissions and predictor variables including total water storage anomalies from the GRACE satellites measured as liquid water equivalent (LWE) thickness (cm) (Landerer et al., 2020), SMAP soil moisture (Entekhabi et al., 2010), CYGNSS inundation extent (Ruf et al.,
445 2016), GEOS-FP precipitation and near-surface temperature (NASA Global Modeling and Assimilation Office, 2023), and CARDAMOM heterotrophic respiration (Bloom et al., 2016). The GRACE LWE gravity measurement includes changes in surface water, soil moisture, and groundwater, and thus captures basin-scale water accumulation and depletion. SMAP provides surface soil moisture and root-zone soil moisture, distinguishing between short-lived wetting in
450 the upper soil layer and deeper, more persistent saturation.

For each predictor variable, we evaluated temporal lags of up to ± 12 months and report the lag yielding the maximum correlation (Table S2). Lags between hydrological variables and emissions reflect the delayed onset of methanogenesis following inundation, as microbial communities first consume alternative electron acceptors (e.g., nitrate and ferric iron), a process
455 that is particularly important in iron-rich tropical soils and not represented in WetCHARTs-CYGNSS (Mohanty et al., 2014; Gadol et al., 2022). We find that posterior emissions correlate most strongly with total water storage anomalies with a 2-month lag, with root-zone soil moisture showing comparable correlations but also strong correlations with total water storage. Correlations with surface soil moisture and CYGNSS inundation are not as strong (Table S2).

Figure 9 shows the alignment between wetland emissions, total water storage anomalies, inundation, and precipitation, along with CARDAMOM intensities. CARDAMOM is out of phase with inundation and emissions and dampens the WetCHARTs-CYGNSS seasonal cycle, just as Balasus et al. (2026) found in Africa. This is why the seasonality of WetCHARTs-CYGNSS emissions in Figure 5 is so weak. We see from Figure 9 that wetland emissions align
465 best with LWE with a 2-month time lag, and that LWE captures the interannual variability of emissions (including the 2021-2022 maximum) much better than CYGNSS inundation. The high LWE in 2021-2022 can be related to anomalously high 2020-2022 precipitation associated with a rare, prolonged La Niña event (Hasan et al., 2022). Wetland emissions are expected to follow total water storage measured by LWE because methane production depends on how long and
470 how deeply soils remain saturated, and sustained precipitation and inundation drive changes in



the water table height (Corona et al., 2023; Cui et al., 2024; J. Zhang et al., 2024). Very high water levels can suppress ebullition by increasing hydrostatic pressure and can also limit plant-mediated transport, but subsequent water table drops allow accumulated methane to be rapidly released through ebullition (Calabrese et al., 2021; Harrison et al., 2017). GRACE LWE reflects these water table dynamics by integrating subsurface and surface hydrological changes over time. Our results for Colombia suggest that water storage anomalies should be an important predictor of wetland emissions in bottom-up models.

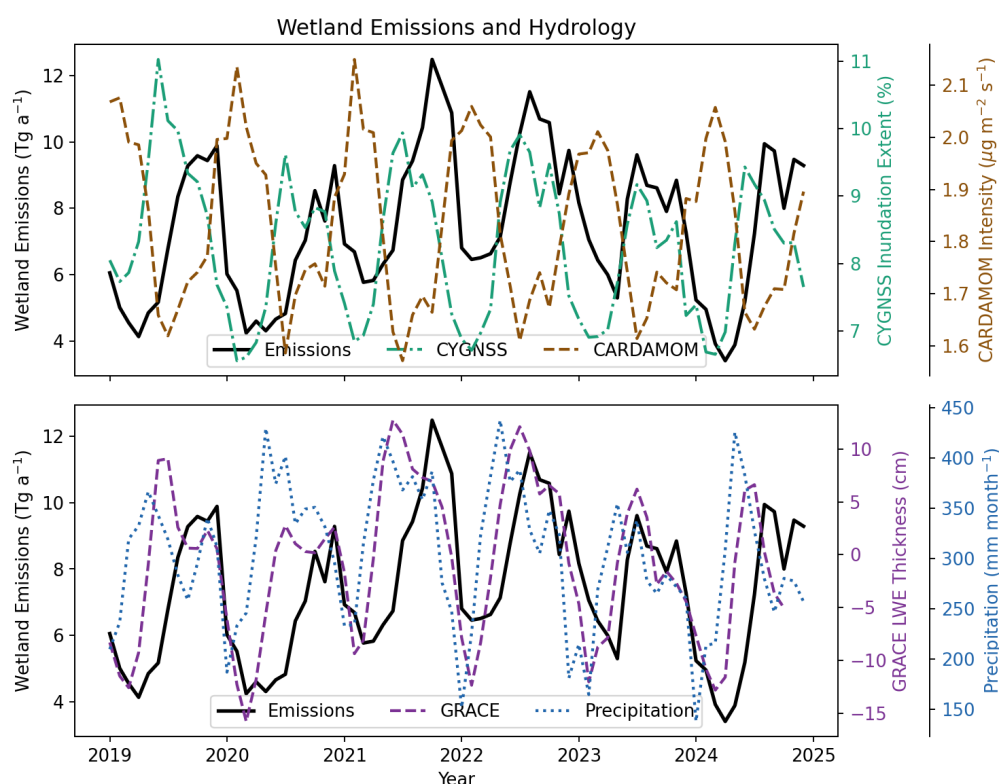


Figure 9: Relationships between wetland methane emissions and hydrological variables in Colombia. Posterior emissions (black) are compared with GRACE-FO total water storage anomalies measured as liquid water equivalent (LWE) thickness (purple dashed); CYGNSS inundation extent (green dashed); GEOS-FP precipitation (blue dotted); and CARDAMOM intensity (brown dashed). Values are monthly totals or averages for Colombia.

7 Limitations and Outlook

Our sectoral attribution method (Sect. 5) provides the best separation we can achieve with currently available information, but it has limitations. Livestock enteric fermentation emissions may themselves follow the wetland seasonality, because cattle concentrate near water and forage improves in the wet season (Díaz-Almanza et al., 2025), but we do not have enough information to prescribe this seasonality in our inversion. Where wetland emissions overlap spatially with other sources such as fossil fuels, we likewise cannot separate them without better information on the seasonality of those sources (Hu et al., 2025; Varon et al., 2026), most notably for the



open-pit coal mines of the wetland-rich Magdalena region, where the strong wetland signal makes coal emissions difficult to constrain.

These limitations reflect that the inversion constrains total emissions in each grid cell and does not by itself apportion the correction among the sectors present; we currently do so only with a seasonal heuristic for wetlands and livestock (Sect. 5). Characterizing the prior error separately for each sector, with its magnitude and spatial correlation structure derived from inventories and process-model ensembles rather than assumed, would allow for apportioning each correction according to sector uncertainty.

The broader goal of this work is to improve Colombia's national methane inventory, and our satellite inversion is one part of a wider effort that also includes new bottom-up measurements across sectors (Ardila et al., 2025; Jimenez et al., 2026). Better characterization of wetlands, which dominate Colombian emissions, would most improve the satellite component. Continued satellite monitoring of Colombia, together with its improving bottom-up inventory, could track emissions over time and quantify how much the improved prior estimates sharpen the attribution of emissions and trends.

8 Conclusions

We used a high-resolution ($\approx 25 \times 25 \text{ km}^2$), monthly analytical inversion of TROPOMI satellite methane observations to quantify and attribute changes in Colombian methane emissions from 2019 to 2024. Our work was motivated by Colombia being identified as a hotspot of rising emissions in a coarse-resolution global inversion of 2019–2024 TROPOMI satellite data (He et al., 2026). Understanding the cause of national emission trends is critical for meeting Nationally Determined Contributions (NDCs) under the Paris Agreement and the collective Global Methane Pledge. Colombia has large emissions from wetlands as well as anthropogenic sources. The monthly resolution of our inversion provides information on seasonality of emissions that can be used to isolate the contributions from wetlands.

Our optimized posterior estimate of mean 2019–2024 Colombian emissions is 10.7 (9.5 – 11.2) Tg a^{-1} including 7.1 (6.0 – 7.4) from wetlands, 2.0 (1.9 – 2.0) from livestock, 0.71 (0.66 – 0.75) from waste, 0.24 (0.22 – 0.24) from oil/gas, and 0.096 (0.092 – 0.1) from coal, where parentheses represent the range in the inversion ensemble used to quantify uncertainty. This estimate is consistent with previous inversions for 2023 (East et al., 2025; Hancock et al., 2026) and independently evaluated here with GOSAT satellite data.

We find from the inversion that total methane emissions in Colombia increased by 0.23 Tg a^{-2} (0.025 – 0.46 Tg a^{-2}) or 2% a^{-1} over the 2019–2024 period, where parentheses represent the Theil-Sen regression 95% confidence interval. This trend confirms the results from the He et al. (2026) global inversion. However, the trend is not linear and features instead a 2021–2022 maximum superimposed on a large seasonality. Using the seasonality of the results together with prior information for sectoral attribution, we find that wetlands account for 60% of the trend and are responsible for the 2021–2022 maximum. Anthropogenic sources account for 34% of the 2019–2024 trend and show a steadier increase. Livestock accounts for 42% of the growth in anthropogenic emissions and this can be explained by cattle population growth. Waste accounts for 32% and is concentrated around Bogotá, consistent with increasing municipal and concentrated waste sources described in Colombia's BTR. Fuel accounts for 22% of the growth of emissions and half of that is from coal, despite declining coal production, suggesting an increase in emissions as surface mines dig deeper for coal. Oil and gas trends are concentrated



near Puerto Boyacá, a region distinguished by its use of steam-assisted oil production and characterized by high levels of vented emissions identified through aerial surveys.

We find that wetland emissions exhibit stronger interannual variability, larger seasonal amplitude, and delayed seasonal maxima than the WetCHARTs–CYGNSS inventory used as prior estimate. This is partly because heterotrophic respiration as represented by the CARDAMOM model built into WetCHARTs has opposite seasonality to that observed for wetland emission intensity. In addition, we find that inundation alone as measured by CYGNSS is insufficient to describe wetland emission dynamics. Wetland emissions correlate more strongly with total land water storage anomalies measured by the GRACE satellite instrument. Total water storage is a measure of water table depth and hydrological persistence that are key drivers of methane emission. Better accounting for this factor in bottom-up wetland models would improve the separation of anthropogenic sources and attribution of trends in inversions of satellite data to support climate policy.

9 Data Availability

The IMI source code and documentation is available at <https://carboninversion.com/>. The blended TROPOMI+GOSAT satellite observations are available at <https://registry.opendata.aws/blended-tropomi-gosat-methane> (Balasus et al., 2023). The GOSAT methane retrievals version 9.0 are available at <https://doi.org/10.5285/18ef8247f52a4cb6a14013f8235cc1eb> (Parker & Boesch, 2020).

10 Author contributions

SH and DJJ contributed to the study conceptualization. RJ, AA, LMR, CAG, and CCJ provided bottom-up emission estimates and activity data. SH conducted the data and modelling analysis with contributions from DJJ, RJ, AA, LMR, CAG, CCJ, MJ, SW, MH, LP, LAE, and NB. SH and DJJ wrote the paper with input from all authors.

11 Competing Interests

The authors declare that they have no conflict of interest.

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