

Environmental Science Atmospheres

Accepted Manuscript

This article can be cited before page numbers have been issued, to do this please use: S. Ibarra-Espinosa, L. Hu, C. Harkins, B. McDonald, S. Miller, Y. Oh, L. Bruhwiler, C. Sweeney and A. Andrews, *Environ. Sci.: Atmos.*, 2026, DOI: 10.1039/D6EA00004E.



This is an Accepted Manuscript, which has been through the Royal Society of Chemistry peer review process and has been accepted for publication.

Accepted Manuscripts are published online shortly after acceptance, before technical editing, formatting and proof reading. Using this free service, authors can make their results available to the community, in citable form, before we publish the edited article. We will replace this Accepted Manuscript with the edited and formatted Advance Article as soon as it is available.

You can find more information about Accepted Manuscripts in the [Information for Authors](#).

Please note that technical editing may introduce minor changes to the text and/or graphics, which may alter content. The journal's standard [Terms & Conditions](#) and the [Ethical guidelines](#) still apply. In no event shall the Royal Society of Chemistry be held responsible for any errors or omissions in this Accepted Manuscript or any consequences arising from the use of any information it contains.

Environmental Significance Statement

This study leverages the COVID-19 pandemic as a unique "natural experiment" to assess the sensitivity of atmospheric monitoring systems to abrupt changes in anthropogenic activity. By applying high-resolution inverse modeling to atmospheric methane (CH₄) observations across the U.S., we detected and quantified subtle emission reductions in 2020 and 2021 that process-based inventories partly underestimated. Specifically, our results reveal that while fossil fuel reductions were consistent with drilling activity declines, agricultural emission reductions—likely driven by disruptions in the livestock sector—were more pronounced than reported in the EPA Greenhouse Gas Inventory. Furthermore, the analysis captures the opposing signal of record-breaking wildfire emissions in the Western U.S. These findings demonstrate the critical role of top-down atmospheric inversions in verifying bottom-up inventories and refining our understanding of how specific sectors drive regional methane budgets, a key step for designing effective climate mitigation policies.



ARTICLE

Cooperative Institute for Research in Environmental Sciences, University of Colorado-Boulder, Boulder, CO, United States.
NOAA Global Monitoring Laboratory, Boulder, CO, United States.
+Now at Cooperative Institute for Satellite Earth System Studies (CISESS)/Earth System Science Interdisciplinary Center (ESSIC), University of Maryland
NOAA Chemical Sciences Laboratory, Boulder, CO, United States.
Department of Environmental Health and Engineering, Whiting School of Engineering, Johns Hopkins University, Baltimore, MD 21218.

Received 00th January 20xx,
Accepted 00th January 20xx

Supplementary Information available: [details of any supplementary information available should be included here]. See DOI: 10.1039/x0xx00000x

DOI: 10.1039/x0xx00000x

Introduction

The Coronavirus disease 2019 (COVID-19) pandemic profoundly disrupted global socioeconomic activities and human behavior [1,2]. Between the first cases of infection in China in December 2019 and October 2023, there were more than 676 million registered cases and almost 7 million deaths [3]. Many governments implemented lockdowns and quarantines to limit spread of the virus [4]. Consequently, human mobility was reduced, corroborated by daily anonymized reports from internet companies using smartphones and other devices [5,6]. During that period, air quality improved in many cities worldwide [7].

In this study, we investigated the impact of COVID-19 on U.S. emissions of CH₄, a potent greenhouse gas with a ~11.8 year atmospheric lifetime and a Global Warming Potential of 27 to 30 over 100 years [8]. Its current atmospheric abundance contributes a total radiative forcing of 0.54 (0.43 to 0.65) W m⁻² relative to 1750 [8]. On average, between 2008 and 2017, global CH₄ emissions have been 577 (550-594) Tg y⁻¹, with the primary sources being agriculture, fossil fuel production and use, and wetlands [9]. The main sink of atmospheric CH₄ is the reaction with hydroxyl radicals (or OH) [10]. Atmospheric mole fractions of CH₄ increased in the decades before 2000, were relatively stable between 1999 and 2006, and have since increased rapidly [11, 12, 13]. Some studies have proposed that the recent increases in global atmospheric CH₄ abundance are due to intensified emissions from microbial sources such as wetlands and agriculture, in combination with reduced atmospheric mole fractions of OH [14, 15; 16; 17; 18].

Reduced U.S. Methane Emissions during the COVID-19 Pandemic

Sergio Ibarra-Espinosa^{a,b*+}, Lei Hu^b, Colin Harkins^{a,c}, Brian C. McDonald^c, Scot M. Miller^d, Youmi Oh^{a,b}, Lori Bruhwiler^b, Colm Sweeney^b, Arlyn Andrews^b

The coronavirus disease 2019 (COVID-19) pandemic disrupted normal human activities worldwide, and mobility reductions resulted in reduced levels of air pollutants and greenhouse gases emissions. Here, we examine the impact of these disruptions on a potent greenhouse gas, methane (CH₄), over the U.S. In this study, we quantified CH₄ emissions from the contiguous U.S. between 2019 and 2021 by analyzing inverse modeling results derived from atmospheric measurements made at 35 sites across the country. Our estimates indicate emission reductions of -2.5 (±0.43) Tg y⁻¹ CH₄ in 2020 and -2.9 (±1.63) Tg y⁻¹ in 2021, relative to 2019. The respective percentage change was a -4.3 (-5.1 to -3.5) % reduction in 2020 and -4.8 (-8.3 to -0.7) % in 2021, relative to 2019. Combining with process-based inventory emission datasets, we found that this reduction was primarily due to decreased fossil fuel and agricultural emissions; however, record-breaking forest fires resulted in an increase of 0.4 (0.1 to 0.8) Tg y⁻¹ in 2020-2019, equal to a 20 (3 to 46) % increase in CH₄ emissions from the western U.S.

CH₄ emission estimates for the U.S. show discrepancies across studies and inventories. For example, the U.S. Environmental Protection Agency Greenhouse Gas Inventory (USEPA-GHGI), a bottom-up inventory based on activity data and emission factors from various source categories, shows a small negative trend in total anthropogenic CH₄ emissions, with 33 Tg y⁻¹ in 1990 and 29 Tg y⁻¹ in 2019 [19]. In 2021, the energy and agriculture sectors were reported to emit 11 Tg y⁻¹ and 10 Tg y⁻¹, or 38% and 36% of total U.S. anthropogenic CH₄ emissions, respectively. Other studies using different approaches provide varying estimates. NOAA's CarbonTracker-CH₄, an atmosphere-based inversion model that uses CH₄ and CH₄ isotope observations to constrain sectors, estimated 29 Tg y⁻¹ fossil emissions in 2021 for the contiguous United States (CONUS) [20]. A fuel-based inventory focusing on direct measurements and modeling specific to the oil and gas sector reported 15 Tg y⁻¹ for oil and gas emissions in the CONUS in 2015 [21]. For natural sources in the U.S., estimates also differ, ranging from 9.5 Tg y⁻¹, average 2010 to 2017, [22], 14.3 Tg y⁻¹, average 2008 to 2017, [9], to 12.5 Tg y⁻¹, average 2010 to 2019, [23]. These variations underscore inconsistencies in the current understanding of U.S. CH₄ emissions, arising from uncertainties inherent in the different estimation methods.

The marked reduction in anthropogenic activity during the COVID-19 pandemic provided a unique opportunity to investigate its impact on emissions of key pollutants and greenhouse gases, such as CH₄. However, this area of research remains a complex area of study, evidenced by discrepancies in quantitative estimates across different analyses and scales. The EPA's GHGI reported that U.S. anthropogenic CH₄ emissions decreased by 0.6 Tg y⁻¹ (2.1%) from 2019 to 2020 and by 1.3 Tg y⁻¹ (4.3%) from 2019 to 2021 [19]. In



CarbonTracker-CH₄, a near-zero change was found for the U.S. between 2019 and 2020 and a reduction of 2.2 Tg y⁻¹ (-3.5%) was found by comparing 2019 and 2021 [20]. Nevertheless, both estimates agree with the fact that there was a more substantial reduction in 2021 than in 2020. [24], using the satellite-based TROPospheric Monitoring Instrument (TROPOMI) observations and a 4D-Var Integrated Forecasting System (4D-Var IFS), compared the first six months of 2020 with 2019 and found a global increase of 1.6%, and a 2.2% increase in the U.S. In California, aircraft measurements in 2020 revealed a 35% reduction relative to 2017 in CH₄ emissions from the oil and gas sector [25]. Here, we analyze U.S. CH₄ emissions from 2019 to 2021 derived from a high-resolution regional inverse modeling study [26]. We used the notation 2020-2019 and 2021-2019 to represent the anomaly period of the pandemic years, 2020 and 2021, versus the pre-pandemic year 2019. Using these atmospheric observation-based emission estimates, we investigate changes in U.S. national and regional CH₄ emissions during and after the COVID-19 pandemic relative to the pre-pandemic year of 2019. Then, we compare these changes with process-based inventories to improve the characterization of changes in CH₄ emissions during and after the COVID-19 pandemic.

Methods

U.S. CH₄ emissions derived from atmospheric observations

The observations used in this study are shown in supplementary figures S1 and S2 showing atmospheric CH₄ observations between 2019 and 2021 over the U.S., assimilated by [26]. Different from many national-scale CH₄ inversions over the U.S. (e.g., 22, 27, 28), [26] simulated atmospheric transport at high resolution (10 - 12 km horizontally with 40 - 60 vertical levels), determined the error covariance matrices with an objective approach, and conducted an ensemble of analytical inversions with different considerations of background values and prior emissions. In this study, we analyzed the six inversion results from [26] that included three background and two prior emission estimates, incorporating OH loss by considering monthly climatological 3D OH concentrations. We aggregated the 1 degree x 1 degree x weekly posterior emissions from the inversions into national and regional emissions each year, as posterior national and regional emission estimates have much smaller uncertainties than grid-scale estimates. Posterior uncertainties of national and regional emissions from each inversion were calculated from the full posterior error covariance matrix that included cross correlations among grid cells.

The presented uncertainties for the annual emissions below include two measures of uncertainty (Eq. 1) as described in [29]. One is the analytical (internal) uncertainty that quantifies the random errors within a single inversion resulted from prior error covariance and model-data mismatch errors. This quantity reflects how well the atmospheric observations constrain emissions given a specific set of prior assumptions and background estimate. Hence, observational constraints should result in a decrease in uncertainty relative to the prior uncertainty. To characterize the features of our inversion, we define the external uncertainty as one standard deviation across the results of the six ensemble members. This metric captures the sensitivity of the methane flux estimates to variations in prior assumptions, background and transport model configurations. A narrow ensemble spread, therefore, increases confidence that our findings are robust and not an artifact of a single set of modeling choices.

The pandemic anomalies were calculated from the difference in annual CH₄ emissions between the pre-pandemic year 2019 and the pandemic years 2020 and 2021 for each of the six ensemble members. Our best estimate of the pandemic CH₄ anomalies discussed below were the mean anomaly among the six members and their one standard deviation as its uncertainty. To determine if the emission changes between the pre-pandemic (2019) and pandemic (2020, 2021) periods were statistically significant, we used z-scores for each ensemble member and its associated uncertainty, as shown in Figure S5. The z-score quantifies the difference between the groups in units of standard deviation, where a larger absolute z-score and a corresponding p-value < 0.05 indicate a statistically significant difference [30]. In addition, we used the non-parametric Mann-Whitney U Test, appropriate for comparing two independent groups, in this case the ensemble group for each year and region, as shown in Table S1.

Estimates of U.S. natural and anthropogenic CH₄ emissions

To isolate the anthropogenic CH₄ signal from the atmospheric observation-based total net CH₄ emissions discussed above, we subtracted estimates of natural emissions from the atmosphere-based top-down estimates. Natural emission estimates exhibit discrepancies among different products due to different data sources and methodologies. To account for this variability, we considered multiple datasets. Table 1 summarizes the 2019-2021 average values and standard deviations (representing interannual variability) of these natural emission components over the U.S., as used in this study. The natural emission estimates inputs for CarbonTracker-CH₄ [31], derived from a combination of inventory data and process-based modeling, include: wetlands (16.3 ± 0.4 Tg y⁻¹), soil sink (-6.3 ± <0.1 Tg y⁻¹), termites (0.4 ± <0.1 Tg y⁻¹), wild animals (0.2 ± <0.1 Tg y⁻¹), and geological seeps (6.6 ± <0.1 Tg y⁻¹) [32-35]. Although estimates of CH₄ emissions from geological seeps may contain a high bias [36], this bias does not affect the estimates of interannual variabilities in natural or anthropogenic CH₄ emissions. Besides estimates from CarbonTracker-CH₄, we also included wetland estimates calculated by [26] using the Kaplan model [37] (6.6 ± <0.1 Tg y⁻¹ for 2006-2021, 1x1 degree resolution), and reported by [18] (Climate Research Units (CRU): 9.9 ± 0.1 Tg y⁻¹ ; Modern-Era Retrospective analysis for Research and Applications Version 2 (MERRA): 10.8 ± 0.2 Tg y⁻¹ for 2001-2021, 0.5x0.5 degree resolution). Although there was a substantial difference in the magnitudes of wetland emissions among different products, their interannual variability between 2019 - 2021 is consistently small. The differences among these products were considered as the uncertainty in the U.S. natural CH₄ emissions and included in the overall uncertainty of our derived anthropogenic CH₄ emission estimates.

View Article Online
DOI: 10.1039/C6EM00041A



Table 1. Natural emissions products used in this study.

Product	Sources	Timespan	Mean 2019-2021 (Tgy ⁻¹)	Reference
Carbon Tracker - CH ₄ priors	Wetlands	1984-2021	16.3 (± 0.4)	[33]
	Soil sink		-6.3 (± < 0.1)	
	Termites		0.4 (± < 0.1)	[34]
	Wild Animals		0.2 (± < 0.1)	[32]
	Geological Seep		6.6 (± < 0.1)	[35]
Kaplan	Wetlands	2006-2021	6.6 (± < 0.1)	[26]
Zhang	Wetlands CRU	2001-2021	9.9 (± 0.1)	[18]
	Wetlands MERRA	2001-2021	10.8 (± 0.2)	

Auxiliary datasets

The estimated anthropogenic emissions from atmospheric inversions provide spatial information on the differences of U.S. CH₄ emissions during the COVID pandemic (2020 - 2021) relative to the pre-pandemic period (2019), but do not contain process information on the causes of differences. To investigate the processes that may have caused the differences in CH₄ emissions in 2020 - 2021 relative to 2019, we analyzed anthropogenic CH₄ emission inventories: the U.S. Environmental Protection Agency (EPA) Greenhouse Gas Inventory [19] and the NOAA CSL Fuel-based Oil and Gas (FOG) inventory [21]. For the U.S. EPA inventory, EPA collects inputs from federal and state agencies, as well as from industry and academic researchers. The FOG inventory was calculated following a bottom-up approach, with activity data at the facility level for sources such as drilling rigs, compressor stations, dehydrators and other equipment. The inventory was designed to estimate nitrogen oxides (NO_x) emissions [38] and expanded to CH₄ and non-methane volatile organic compounds (VOCs) [21]. CH₄ and VOC emissions in FOG are estimated using the tracer-tracer ratios (CH₄/NO_x and VOC/CH₄) from measurements by the NOAA P3 aircraft during the Southeast Nexus (SENEX) 2013 and Shale Oil & Natural Gas Nexus (SONGNEX) 2015 field campaigns. For this study, the FOG inventory has been updated to separate drilling emissions from other production sources as well as to make monthly CH₄ emissions for the oil and gas production sector throughout the study time period. These updated emissions assume the same tracer-tracer ratios are applicable to

both drilling and other production sources and also assume that these tracer-tracer ratios do not vary with time between 2015 (the year the ratios were developed for) and the COVID-19 study time period here (2019-2021). Both of these assumptions provide a basis for analysis in this study, as further airborne field campaigns to redetermine these values have not occurred. Satellite-derived estimates suggest that the CH₄ intensity from US oil and gas production has decreased with time [39], while NO_x emissions have increased with production [40], which future versions of FOG will incorporate. Therefore, the 2015 CH₄/NO_x ratio used to infer oil and gas CH₄ emissions during the COVID-19 period is likely an upper bound estimate. As cattle are a key contributor to agricultural CH₄ emissions, we also used the total cattle census data [41]. This report is a bi-annual publication by the National Agricultural Statistics Service (USDA/NASS) and distributed by Cornell University. This report provides a detailed inventory of all cattle and calves across the United States, by state, class (including beef and milk cows, and heifers held for breeding herd replacement), and number of operations. Lastly, we used emissions estimates from the Global Fire Emissions Database (GFED) [43] to understand CH₄ emissions from wildfires during our study period.

Results

U.S. annual total net CH₄ emissions in 2019, 2020, and 2021 were estimated to be 59.2 (±3.7, 1-sigma uncertainty), 56.7 (±3.7), and 56.3 (±3.3) Tgy⁻¹, respectively (Figure S3). Considering 2019 as our reference year for the pre-pandemic period, there were reductions in the U.S. CH₄ emissions in 2020 and 2021 (figure 1a). In 2020, there was a decrease of -2.5 (±0.43) Tgy⁻¹ or -4.3 (-5.1 to -3.5) %. In 2021, emissions were comparable to 2020 and below those in 2019 by -2.9 (±1.63) Tgy⁻¹ or -4.8 (-8.3 to -0.7) %. The values in parentheses represent our best estimates of uncertainties, 1-sigma standard deviation of the differences in the changes among the six inversion members. Hence, uncertainties largely cancel out when calculating the interannual delta. Furthermore, average anomalies of priors (Figure 1a) shows slight increases in CH₄ emissions in 2020 - 2021 relative to 2019, suggesting that the reduction in CH₄ emissions in the posterior estimates were derived from atmospheric observations. Additionally, Figure S4 provides spatial maps comparing priors and optimized estimates. However, these changes represent the changes in the U.S. total net CH₄ emissions. In order to understand changes of CH₄ emissions related to anthropogenic activities, we need to separate natural emissions from the total net CH₄ emissions. The differences between 2019 and 2020 or 2021 in the estimated natural CH₄ emissions (Figure 1b), show little changes with the spread centered near zero, suggesting that the change in natural emissions during COVID-19 was insignificant in the U.S. The anthropogenic emissions calculated as optimized emissions from atmospheric observations minus natural emissions (Figure 1c) follow a similar pattern. The estimated anthropogenic CH₄ emissions in 2020 was 2.6 (4.0 to 1.7) Tgy⁻¹ or 5.6 (9.2 to 3.7) % lower than 2019. In 2021, anthropogenic CH₄ emissions were 2.9 (5.2 to 0.4) Tgy⁻¹ or 6.1 (12.5 to 0.3) % lower than 2019.

Figure 1. Differences in 2020-2019 and 2021-2019 CH₄ emissions over the U.S. from the inversion for a) net emissions, b) the natural component, c) the anthropogenic component, d) from the U.S. EPA inventory [19], e) from the FOG oil and gas inventory [21], and f) Global





To investigate the processes that may have caused the differences in CH₄ emissions in 2020 - 2021 relative to 2019, we analyzed process-based information from anthropogenic emission inventories. The U.S. EPA inventory-based emissions (Figure 1d) are also lower in 2020 and 2021 compared to 2019, consistent with our finding, although smaller in magnitude. The 2020 reduction in the EPA inventory was -0.4 Tgy⁻¹, and, for 2021, it was -1.1 Tgy⁻¹, or -1.5% and -3.8%, respectively, relative to 2019. The EPA data suggest that this reduction was mainly caused by the energy sector, whose anomalies were -0.8 Tgy⁻¹ and -1.1 Tgy⁻¹, or -6.7% and -9.7% for 2020 and 2021. The EPA-reported reductions of CH₄ emissions in the energy sector in 2020 - 2021 are also consistent with the change reported by the FOG inventory, but with lower magnitudes. The net decrease of CH₄ emissions in the oil and gas sector, estimated by the FOG inventory, is -1.1 Tgy⁻¹ in 2020 and -1.6 Tgy⁻¹ in 2021 relative to 2019 (Figure 1e), representing -6.1% and -9.0% reductions. The reductions in FOG were dominated by reduced emissions from drilling, while emissions from other production activities were increased in 2020 - 2021. The CH₄ emissions reduction associated with drilling was -2.8 Tgy⁻¹ in 2020 and -1.9 Tgy⁻¹ in 2021, similar to our optimized posterior anomalies. Besides reduction of CH₄ emissions in the energy sector, there were also likely reductions of CH₄ emissions from agriculture (Figure 1g). Comparing U.S. Department of Agriculture (USDA) cattle inventory anomalies to EPA agriculture emission anomalies for 2020 and 2021, both relative to a 2019 baseline, reveals a consistent decreasing trend. USDA data show cattle inventory anomalies of -1.0% in 2020 and -1.2% in 2021 compared to 2019. The EPA's 2023 report indicates U.S. agriculture emission anomalies of 0.02 Tgy⁻¹ (0.23%) in 2020 and -0.07 Tgy⁻¹ (-0.76%) in 2021 relative to 2019. While the EPA's reported emission changes are smaller, particularly the slight increase in 2020, the decrease in both cattle inventory and overall agriculture emissions in 2021 relative to 2019 is consistent with the expected relationship between livestock numbers and a component of agricultural emissions, acknowledging that total agricultural emissions encompass various sources beyond just cattle. Wildfire CH₄ emissions shown in Figure 1f) increased during this period, similarly to Land Use and Land Use Forestry (LULUF) in Figure 1d), discussed in more detail in next section.

The inversion system and spatial and temporal density of the measurements allow emissions to be derived on regional scales, which provide a spatial understanding of the changes during the COVID period. Hence, Figure 2 shows the six regions considered in this study and Figure 3 shows annual changes in total posterior emission changes by region. Consistent negative CH₄ emission anomalies observed across multiple datasets in the oil and gas-dominated Central South (CS) region point strongly to reduced drilling activity as the primary driver during the COVID period. We found negative anomalies in the optimized posterior fluxes, and given that the natural emissions in this region are insignificant, the anthropogenic component is very similar to the posterior values. The negative anomalies in the U.S. EPA [19] are similar to our estimates and primarily arise from changes in the energy sector. The net anomaly in the FOG inventory also agrees with our results and those of the U.S. EPA [19]. Specifically, in the region CS, for the periods 2020-2019 and 2021-2019, we found reductions of -0.7 (±0.31) Tgy⁻¹ and -1.6 (±0.51) Tgy⁻¹, in our posterior results. These changes are statistically significant after applying z-score test between the estimates of ensemble members, and Mann-Whitney U test, as shown in figure S5 and table S1. In case of US EPA [19], we found -0.6 Tgy⁻¹ and -0.9 Tgy⁻¹ for 2020-2019 and 2021-2019; and for FOG [21] -1.1 Tgy⁻¹. There are some reductions in cattle in the CS during these years. In this region, we also see a significant reduction in drilling and increment of methane emissions associated with oil and gas production. Indeed, a study found that during the pandemic, lower demand for oil and gas resulted in turned-off wells, reducing CH₄ emissions [43]. Other studies also found substantial CH₄ reductions in oil-dominated regions [23; 44]. There are similarities between negative FOG emissions in the drilling sector and negative optimized estimates. Figure S6 shows correlations with interval confidence between posterior emissions and FOG emissions by production and drilling. Here, we see that the region CS has significant correlations between posterior and drilling CH₄ emissions in 2020, corroborating that the main driver in reduced CH₄ emissions in 2020 was likely due to reduced drilling activities. The percentage change in the FOG-drilling inventory in 2020 and 2021, about 2019, was -46.6% and -31.4%, respectively, while the same change for the FOG-production sector was 15.1% and 2.7%. This is because the



Journal Name ARTICLE

COVID lockdown resulted in fewer drilling activities and associated emissions, but the cause of production emissions increase is unclear. The total change was -6.1% from 2019 to 2020 and -9.0% from 2019 to 2021.

The Central North (CN) region exhibited substantial negative anomalies in the U.S. CH₄ emissions during the COVID period, representing one of the largest regional changes (Figure 3). Specifically, for the periods 2020-2019 and 2021-2019, we found reductions of -3.4 (±0.62) Tgy⁻¹ and -3.3 (±0.69) Tgy⁻¹, in our posterior results (see figure S5 and table S1). The FOG shows negative anomalies for both periods, and production showed a slight increase in 2020-2019 and a reduction in 2021-2019. Even though these anomalies agree with the emission decrease in our results, they do not explain the higher magnitude of the changes found in our study. The EPA shows slight negative anomalies, which also are not consistent with the values we found. According to the U.S. EPA Greenhouse Gas Inventory report [19], 70% of the CH₄ agricultural emissions come from enteric fermentation. Furthermore, among the agricultural categories (field burning of agricultural residues, enteric fermentation, manure management, and rice cultivation) only enteric fermentation exhibited strong and negative anomalies (Figure S7), with a stronger anomaly in 2021 than 2020, similar to our results. Also, from the enteric fermentation sub-sector in the inventory [19], beef cattle are responsible for 71% of the totals for 2021 and show a more significant negative anomaly than other animals, as shown in Figure S8 supplementary material, which is consistent with the anomalies presented by the U.S. EPA, but our findings suggest a potential under-representation. The methodology for the agriculture sector is Tier 2 of IPCC [8]. For the enteric fermentation, they use the Cattle Enteric Fermentation Model (CEFM), as shown in the Common Reporting Format (CRF) Source Category 3A [45]. This methodology uses estimates of cattle populations by animal type and state, as shown in table A-126, Annex 3, greenhouse gases report in the US [45]. Research has shown that 3-nitrooxypropanol (3-NOP), included in ruminants' diets, reduces methane emissions by about 30% [46, 47]. However, 3-NOP (BovaerTM) was approved by the Food and Drug Administration just in 2024 [48], well after the period discussed here. Therefore, changes in the diet is not the cause to the reduction we observed at CN. During COVID-19 and the associated lockdowns, the livestock sector was particularly impacted because of a shortage of animal feed and health resources, workers, and a decrease in purchasing power [49]. Also, sharp decreases in meat, milk, and egg production have been documented during this period, which is explained by mobility restrictions of workers, including veterinary services, among others [50]. A map of the anomalies in livestock can be seen in Figure S9. Furthermore, posterior emissions derived by multiple independent atmospheric inversions, i.e., from [26], CarbonTracker-CH₄, Copernicus Atmosphere Monitoring Service, and [51] (Figure S9 in [26]) in the CN region are higher than EPA inventory estimates, suggesting likely underestimation of agricultural emissions, and therefore reductions in agricultural emissions, by the EPA inventory. In the other regions, the anomalies had smaller magnitudes. In the North East (NE) region, there is only a significant increment of emissions for 2020-2019 (see also figure S5 and table S1) and not 2021-2019, which agrees with production in FOG and US EPA showing small negative anomalies. The posterior anomalies in the South East (SE) region were only significant for 2021-2019 and not 2020-2019. Coincidentally, the cattle also showed a small increase of around 20 thousand heads. Since the SE region is a primarily subtropical region with high precipitation and humidity levels, natural

emissions may play a more pivotal role here. The natural anomaly for 2020-2019 is significant for this region. Wetlands are an important source of natural CH₄ emissions [16; 9], and over the US, the southeast has a high density of this source. Our model captures the natural variability since the optimized posterior values agree with the natural anomalies derived independently, as shown in Figure 2, panel b) for the difference 2021 - 2019 in the region NE.

In the Mountain (M) region, our posterior total emission anomalies were +0.3 (±0.33) Tgy⁻¹ for 2020 relative to 2019 and +0.1 (±0.28) Tgy⁻¹ for 2021 relative to 2019. Nevertheless, the anomaly was not significant after checking scores and Mann-Whitney U test (p.value >0.05) in figure S5 and table S1, respectively. For comparison, US EPA inventory anomalies for the same periods were +0.11 Tgy⁻¹ and +0.02 Tgy⁻¹, primarily attributed to the LULUF sector. The GFED fire emissions dataset also indicated positive anomalies of +0.14 Tgy⁻¹ and +0.09 Tgy⁻¹ for 2020-2019 and 2021-2019, respectively. A slight negative anomaly in cattle was also observed in figure 3 g).

In the West (W) region, our analysis reveals positive posterior anomalies of +0.4 (±0.29) Tgy⁻¹ (2020-2019) and +0.3 (±0.37) Tgy⁻¹ (2021-2019). These results align well with [19] inventory anomalies derived from the LULUF sector, reported as +0.4 Tgy⁻¹ for both periods. Furthermore, the change was significant only for the period 2020-2019, also corroborated by the z-scores and Mann-Whitney U test figure S5 and table S1. While the baseline LULUF sector emissions (per EPA definitions) are dominated by sources like flooded land remaining flooded (FLRF, 58.4%), which exhibit relatively stable emissions, our results indicate the observed positive anomaly in this region is driven primarily by Forest Fires (Figure S10). This aligns with Forest Fires constituting 31.4% of baseline LULUF. California displayed the most significant state-level positive anomaly (Figure S11), consistent with the record number of large fires in 2020 propagated by severe drought [52]. Therefore, our optimized fluxes effectively capture the influence of wildfire activity on CH₄ emissions, corroborating inventory trends [19]. Further, GFED biomass burning anomalies for the W region were substantial at 0.49 Tgy⁻¹ (2020-2019) and 0.37 Tgy⁻¹ (2021-2019). Indeed, the annual time series from GFED confirms that 2020 saw record-breaking wildfire emissions, particularly impacting the M and W regions in Figures S12 and S13.





To investigate the influence of natural emissions further, we calculated the anthropogenic anomalies at 1-degree resolution by subtracting the natural emissions from our posterior emissions. As shown in figure S14, we then compared these anthropogenic anomalies with the posterior anomalies. The strong correlation observed suggests that the posterior emissions are primarily driven by the anthropogenic component, allowing us to focus on the posterior results for further analysis. No statistical differences and high correlations were inferred after applying Mann-Whitney U and correlation tests between total optimized and anthropogenic components, as shown in panels c) and f).

Even though [19] considered CH₄ losses related to its reactions with OH, the OH field considered were monthly climatological values that do not contain interannual variability. Studies found that atmospheric OH concentration was reduced globally and over regions like the US during the 2020 pandemic period, largely due to decreased NO_x emissions [17]. Globally, tropospheric OH concentrations decreased by $1.6 \pm 0.2\%$ relative to 2019, a reduction that could explain $53 \pm 10\%$ of the coincident increase in global atmospheric methane abundance in 2020 [17]. Regional methane emission estimates are sensitive to interannually varying OH fields

[56]. Over the U.S., the tropospheric OH reduction was approximately 5% at maximum due to pandemic-related NO_x emission decrease [57]. This reduction in OH has implications for methane budget calculations. For example, if less OH is present in the atmosphere, the atmospheric lifetime of CH₄ becomes longer. This increased lifetime enhances the contribution of background CH₄ arriving from remote regions to the concentrations observed at a measurement site and smaller concentration enhancements would be attributable to emissions. For instance, assuming a linear sensitivity to the pandemic-related 5% reduction in tropospheric OH to our 2020 posterior estimate of 56.7 Tgy^{-1} could increase the reported reduction of -2.5 Tgy^{-1} to $-2.8 (2.6 \text{ to } 3.0) \text{ Tgy}^{-1}$. This further supports our results as a conservative estimate of the pandemic's impact. Therefore, if reduction in OH was considered in [26], a slightly larger reduction of CH₄ emission would be expected to be derived.

While our regional inversion [26] used a monthly climatological OH field, we now explicitly acknowledge that a global drop in OH during 2020–2021, driven by reduced NO_x and CO emissions, likely explained a dominant portion of the global methane surge [11; 12]. Our finding of reduced U.S. fossil fuel emissions (particularly in the Central South) aligns with latest isotopic evidence showing that the record global surge in 2020–2022 was driven almost entirely by microbial sources, while fossil fuel emissions remained stable or declined in many regions [14; 15].

Figure 3. Difference 2020-2019 and 2021-2019 in CH₄ emissions over the US Tgy⁻¹, by regions in the US North East (NE), South East (SE), Central North (CN), Central South (CS), Mountain (M), West (W), as defined by [53] by a) year, b) natural component, c) anthropogenic component, d) from U.S. EPA inventory [19], e) by the FOG oil and gas inventory [21], and f) Global Fire Emissions Database [42], and g)





Discussion and Conclusion

This study demonstrates that through a high resolution inversion approach that subtle changes (decreases) in emissions can be detected and provide valuable perspective relative to inventory estimates. Our results suggest percentage changes from 2019 to 2020 of -4.3 (-5.1 to -0.4) % and 2021 of -4.8 (-8.3 to -0.7) %, indicating reductions of methane emissions during the COVID pandemic in 2020 - 2021 relative to the prepandemic period in 2019. The reduction in CH_4 emissions was primarily driven by reduced anthropogenic activities during the COVID-19 pandemic. Natural

anomalies, based on independent data sources used in this study, were insignificant in the U.S. and most regions. The energy sector, which significantly decreased drilling in the oil and gas industry in the Central South region, was a key contributor to the reduction of U.S CH_4 emissions in 2020 and 2021. While agricultural inventory-based estimates suggest a decrease in emissions, particularly from livestock, our study suggests the impact in this sector may be underestimated in the EPA's greenhouse gas emission inventory. We found that our model captured the impact of wildfire with the agreement between our results and positive anomalies in the EPA inventory in the West. The COVID-19 pandemic served as a natural experiment, allowing our study to document the impact of changes in key anthropogenic activities, particularly in oil and gas drilling and



ARTICLE

Journal Name

agriculture, on U.S. CH₄ emissions. These insights improve our understanding of drivers of variability of CH₄ emission during and after the COVID-19 pandemic.

Author contributions SIE: Formal analysis, Visualization, Writing - original draft, Methodology, Software. LH: Conceptualization, Funding acquisition, Project administration, Supervision, Methodology, Formal analysis, Writing - review & editing. SIE, LH, CH, BM, YO, LB, SM, AA, CS: Formal analysis, Data curation, Investigation, Writing - review & editing.

Conflicts of interest

“There are no conflicts to declare”.

Data availability

Posterior CH₄ emissions estimated from this analysis are available at <https://doi.org/10.15138/zmd2-cy30> as published by [26]. NOAA's CH₄ data is publicly available and can be downloaded from <https://gml.noaa.gov/dv/data/>. For other questions related to data used or produced from this paper, please contact the corresponding author: Dr. Sergio Ibarra-Espinosa (Sergio.ibarra-espinosa@colorado.edu or zergioibarra@gmail.com).

Funding Sources

This project is funded by the NOAA Climate Program Office AC4 and COM programs (NA21OAR4310233 / NA21OAR4310234). This research was supported by the NOAA cooperative agreement NA22OAR4320151.

Acknowledgements

We thank Stephen Montzka, John Miller, and Kathryn McKain for their scientific input on this analysis and paper. We also thank Kenneth Schuldt and Kirk Thoning for programming support. We thank the numerous technical and scientific staff at NOAA GML and CIRES and site partners for providing the atmospheric measurement data.

References

- 1 Ciotti M, Ciccozzi M, Terrinoni A, Jiang WC, Wang CB, Bernardini S. The COVID-19 pandemic. Critical reviews in clinical laboratory sciences. 2020 Aug 17;57(6):365-88. <https://doi.org/10.1080/10408363.2020.1783198>
- 2 Schuchat A. Public health response to the initiation and spread of pandemic COVID-19 in the United States, February 24–April 21, 2020. MMWR. Morbidity and mortality weekly report. 2020;69. <https://doi.org/10.15585/mmwr.mm6918e2>
- 3 Dong E, Du H, Gardner L. An interactive web-based dashboard to track COVID-19 in real time. The Lancet infectious diseases. 2020 May 1;20(5):533-4. [https://doi.org/10.1016/S1473-3099\(20\)30120-1](https://doi.org/10.1016/S1473-3099(20)30120-1)

- 4 Cohen J, Kupferschmidt K. Countries test tactics in 'war' against COVID-19. <https://doi.org/10.1126/science.367.6484.1287>
- 5 Alessandretti L. What human mobility data tell us about COVID-19 spread. Nature Reviews Physics. 2022 Jan;4(1):12-3. <https://doi.org/10.1038/s42254-021-00407-1>
- 6 Ibarra-Espinosa S, de Freitas ED, Ropkins K, Dominici F, Rehbein A. Negative-Binomial and quasi-poisson regressions between COVID-19, mobility and environment in São Paulo, Brazil. Environmental research. 2022 Mar 1;204:112369. <https://doi.org/10.1016/j.envres.2021.112369>
- 7 Sokhi RS, Singh V, Querol X, Finardi S, Targino AC, de Fatima Andrade M, Pavlovic R, Garland RM, Massagué J, Kong S, Baklanov A. A global observational analysis to understand changes in air quality during exceptionally low anthropogenic emission conditions. Environment international. 2021 Dec 1;157:106818. <https://doi.org/10.1016/j.envint.2021.106818>
- 8 Intergovernmental Panel on Climate Change (IPCC). Climate Change 2021 - The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press; 2023.
- 9 Sauniois M, Stavert AR, Poulter B, Bousquet P, Canadell JG, Jackson RB, Raymond PA, Dlugokencky EJ, Houweling S, Patra PK, Ciais P. The global methane budget 2000–2017. Earth System Science Data Discussions. 2019 Aug 19;2019:1-36. <https://doi.org/10.5194/essd-12-1561-2020>
- 10 Qu Z, Jacob DJ, Shen L, Lu X, Zhang Y, Scarpelli TR, Nesser H, Sulprizio MP, Maasakkers JD, Bloom AA, Worden JR. Global distribution of methane emissions: a comparative inverse analysis of observations from the TROPOMI and GOSAT satellite instruments. Atmospheric Chemistry and Physics. 2021 Sep 24;21(18):14159-75. <https://doi.org/10.5194/acp-21-14159-2021>
- 11 Ciais P, Zhu Y, Cai Y, Lan X, Michel SE, Zheng B, Zhao Y, Hauglustaine DA, Lin X, Zhang Y, Sun S. Why methane surged in the atmosphere during the early 2020s. Science. 2026 Feb 5;391(6785):eadx8262.
- 12 Nisbet EG, Manning MR. What is causing the methane surge?. Science. 2026 Feb 5;391(6785):556-7.
- 13 Lan X, Nisbet EG, Dlugokencky EJ, Michel SE. What do we know about the global methane budget? Results from four decades of atmospheric CH₄ observations and the way forward. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences. 2021 Nov 15;379(2210).
- 14 Riddell-Young B, Michel SE, Lan X, Tans P, Röckmann T, Dasgupta B, Oh Y, Bruhwiler LM, Fujita R, Umezawa T, Morimoto S. Microbial driver of 2006–2023 CH₄ growth indicated by trends in atmospheric δD–CH₄ and δ13C–CH₄. Proceedings of the National Academy of Sciences. 2025 Dec 16;122(50):e2516543122.
- 15 Michel SE, Lan X, Miller J, Tans P, Clark JR, Schaefer H, Sperlich P, Brailsford G, Morimoto S, Moossen H, Li J. Rapid shift in methane carbon isotopes suggests microbial emissions drove record high atmospheric methane growth in 2020–2022. Proceedings of the National Academy of Sciences. 2024 Oct 29;121(44):e2411212121.
- 16 Oh Y, Zhuang Q, Welp LR, Liu L, Lan X, Basu S, Dlugokencky EJ, Bruhwiler L, Miller JB, Michel SE, Schwietzke S. Improved global wetland carbon isotopic signatures support post-2006 microbial methane emission increase. Communications Earth & Environment. 2022 Jul 12;3(1):159. <https://doi.org/10.1038/s43247-022-00488-5>
- 17 Peng S, Lin X, Thompson RL, Xi Y, Liu G, Hauglustaine D, Lan X, Poulter B, Ramonet M, Sauniois M, Yin Y. Wetland emission and atmospheric sink changes explain methane growth in 2020. Nature. 2022 Dec 15;612(7940):477-82. <https://doi.org/10.1038/s41586-022-05447-w>
- 18 Zhang Z, Poulter B, Feldman AF, Ying Q, Ciais P, Peng S, Li X. Recent intensification of wetland methane feedback.



- Nature Climate Change. 2023 May;13(5):430-3. <https://doi.org/10.1038/s41558-023-01629-0>
- 19 US Environmental Protection Agency (US EPA). Greenhouse gas inventory data explorer; 2023. <https://cfpub.epa.gov/ghgdata/inventoryexplorer/>
- 20 Oh Y, Bruhwiler L, Lan X, Schuldt K, et al. CarbonTracker CH4 2025. 2025. <https://doi.org/10.25925/hxks-v755>
- 21 Francoeur CB, McDonald BC, Gilman JB, Zarzana KJ, Dix B, Brown SS, de Gouw JA, Frost GJ, Li M, McKeen SA, Peischl J. Quantifying methane and ozone precursor emissions from oil and gas production regions across the contiguous US. *Environmental Science & Technology*. 2021 Jun 23;55(13):9129-39. <https://doi.org/10.1021/acs.est.0c07352>
- 22 Lu X, Jacob DJ, Wang H, Maasackers JD, Zhang Y, Scarpelli TR, Shen L, Qu Z, Sulprizio MP, Nesser H, Bloom AA. Methane emissions in the United States, Canada, and Mexico: evaluation of national methane emission inventories and 2010–2017 sectoral trends by inverse analysis of in situ (GLOBALVIEWplus CH 4 ObsPack) and satellite (GOSAT) atmospheric observations. *Atmospheric Chemistry and Physics*. 2022 Jan 12;22(1):395-418. <https://doi.org/10.5194/acp-22-395-2022>
- 23 Saunio M, Martinez A, Poulter B, Zhang Z, Raymond PA, Regnier P, Canadell JG, Jackson RB, Patra PK, Bousquet P, Ciais P. Global methane budget 2000–2020. *Earth System Science Data*. 2025 May 9;17(5):1873-958. <https://doi.org/10.5194/essd-17-1873-2025>
- 24 McNorton J, Boussez N, Agustí-Panareda A, Balsamo G, Cantarello L, Engelen R, Huijnen V, Inness A, Kipling Z, Parrington M, Ribas R. Quantification of methane emissions from hotspots and during COVID-19 using a global atmospheric inversion. *Atmospheric Chemistry and Physics*. 2022 May 6;22(9):5961-81. <https://doi.org/10.5194/acp-22-5961-2022>
- 25 Thorpe AK, Kort EA, Cusworth DH, Ayasse AK, Bue BD, Yadav V, Thompson DR, Frankenberg C, Herner J, Falk M, Green RO. Methane emissions decline from reduced oil, natural gas, and refinery production during COVID-19. *Environmental Research Communications*. 2023 Feb 1;5(2):021006. <https://doi.org/10.1088/2515-7620/acb945>
- 26 Hu L, Andrews AE, Montzka SA, Miller SM, Bruhwiler L, Oh Y, Sweeney C, Miller JB, McKain K, Ibarra Espinosa S, Davis K. An unexpected seasonal cycle in US oil and gas methane emissions. *Environmental science & technology*. 2025 May 14;59(20):9968-79. <https://doi.org/10.1021/acs.est.4c14090>
- 27 Turner AJ, Jacob DJ, Wecht KJ, Maasackers JD, Lundgren E, Andrews AE, Biraud SC, Boesch B, Bowman KW, Deutscher NM, Dubey MK. Estimating global and North American methane emissions with high spatial resolution using GOSAT satellite data. *Atmospheric Chemistry and Physics*. 2015 Jun 30;15(12):7049-69. <https://doi.org/10.5194/acp-15-7049-2015>
- 28 Nesser H, Jacob DJ, Maasackers JD, Lorente A, Chen Z, Lu X, Shen L, Qu Z, Sulprizio MP, Winter M, Ma S. High-resolution US methane emissions inferred from an inversion of 2019 TROPOMI satellite data: contributions from individual states, urban areas, and landfills. *Atmospheric Chemistry and Physics*. 2024 Apr 30;24(8):5069-91. <https://doi.org/10.5194/acp-24-5069-2024>
- 29 Hu L, Ottinger D, Bogle S, Montzka SA, DeCola PL, Dlugokencky E, Andrews A, Thoning K, Sweeney C, Dutton G, Aepli L. Declining, seasonal-varying emissions of sulfur hexafluoride from the United States. *Atmospheric Chemistry and Physics*. 2023 Jan 26;23(2):1437-48. <https://doi.org/10.5194/acp-23-1437-2023>
- 30 R Core Team. R: A language and environment for statistical computing. Vienna, Austria; 2024. <https://www.R-project.org/>
- 31 Oh Y, Bruhwiler L, Lan X, Basu S, Schuldt K, Thoning K, et al. CarbonTracker CH4 2023. NOAA Global Monitoring Laboratory; 2023. <https://doi.org/10.25925/40JT-QD67>
- 32 Houweling S, Kaminski T, Dentener F, Lelieveld J, Heimann M. Inverse modeling of methane sources and sinks using the adjoint of a global transport model. *Journal of Geophysical Research: Atmospheres*. 1999 Nov 20;104(D21):26137-60. <https://doi.org/10.1029/1999JD900428>
- 33 Liu L, Zhuang Q, Oh Y, Shurpali NJ, Kim S, Poulter B. Uncertainty quantification of global net methane emissions from terrestrial ecosystems using a mechanistically based biogeochemistry model. *Journal of Geophysical Research: Biogeosciences*. 2020 Jun;125(6):e2019JG005428. <https://doi.org/10.1029/2019JG005428>
- 34 Sanderson MG. Biomass of termites and their emissions of methane and carbon dioxide: A global database. *Global Biogeochemical Cycles*. 1996 Dec;10(4):543-57. <https://doi.org/10.1029/96GB01893>
- 35 Etiopie G, Ciotoli G, Schwietzke S, Schoell M. Gridded maps of geological methane emissions and their isotopic signature. *Earth System Science Data*. 2019 Jan 7;11(1):1-22. <https://doi.org/10.5194/essd-11-1-2019>
- 36 Hall KR, Weber TS, Stock MP, Buursink ML, Piao H, Zhu M, Walter Anthony KM, Petrenko VV. New measurements indicate that natural geologic methane emissions from microseepage in the Michigan Basin are likely negligible. *Elem Sci Anth*. 2026 Jan 8;14(1):00058.
- 37 Pickett-Heaps CA, Jacob DJ, Wecht KJ, Kort EA, Wofsy SC, Diskin GS, Worthy DE, Kaplan JO, Bey I, Drevet J. Magnitude and seasonality of wetland methane emissions from the Hudson Bay Lowlands (Canada). *Atmospheric Chemistry and Physics*. 2011 Apr 27;11(8):3773-9.
- 38 Gorshov Negron AM, McDonald BC, McKeen SA, Peischl J, Ahmadvor R, de Gouw JA, Frost GJ, Hastings MG, Pollack IB, Ryerson TB, Thompson C. Development of a fuel-based oil and gas inventory of nitrogen oxides emissions. *Environmental Science & Technology*. 2018 Aug 3;52(17):10175-85. <https://doi.org/10.1021/acs.est.8b01799>
- 39 Lu X, Jacob DJ, Zhang Y, Shen L, Sulprizio MP, Maasackers JD, Varon DJ, Qu Z, Chen Z, Hmiel B, Parker RJ. Observation-derived 2010-2019 trends in methane emissions and intensities from US oil and gas fields tied to activity metrics. *Proceedings of the National Academy of Sciences*. 2023 Apr 25;120(17):e2217900120. <https://doi.org/10.1073/pnas.2217900120>
- 40 Dix B, de Bruin J, Roosenbrand E, Vlemmix T, Francoeur C, Gorshov-Negron A, McDonald B, Zhizhin M, Elvidge C, Veeffkind P, Levelt P. Nitrogen oxide emissions from US oil and gas production: recent trends and source attribution. *Geophysical Research Letters*. 2020 Jan 16;47(1):e2019GL085866. <https://doi.org/10.1029/2019GL085866>
- 41 US Department of Agriculture (USDA). National Agricultural Statistics Service (NASS), Agricultural Statistics Board; 2024. <https://usda.library.cornell.edu/concern/publications/h702q636h>
- 42 van Wees D, van der Werf GR, Randerson JT, Rogers BM, Chen Y, Veraverbeke S, Giglio L, Morton DC. Global biomass burning fuel consumption and emissions at 500 m spatial resolution based on the Global Fire Emissions Database (GFED). *Geoscientific Model Development*. 2022 Nov 21;15(22):8411-37. <https://doi.org/10.5194/gmd-15-8411-2022>
- 43 Townsend-Small A, Hoschouer J. Direct measurements from shut-in and other abandoned wells in the Permian Basin of Texas indicate some wells are a major source of methane emissions and produced water. *Environmental Research Letters*. 2021 May 1;16(5):054081. <https://doi.org/10.1088/1748-9326/abf1a6>
- 44 Lyon DR, Hmiel B, Gautam R, Omara M, Roberts K, Barkley ZR, David KJ, Miles NL, Monteiro VC, Richardson SJ, Conley S. Concurrent variation in oil and gas methane emissions and oil price during the COVID-19 pandemic. *Atmospheric*



- Chemistry and Physics Discussions. 2020 Dec 11;2020:1-43. <https://doi.org/10.5194/acp-21-6605-2021>
- 45 US Environmental Protection Agency (US EPA). Inventory of U.S. greenhouse gas emissions and sinks: 1990-2021; 3.10. Methodology for estimating CH₄ emissions from enteric fermentation; 2023. <https://www.epa.gov/system/files/documents/2023-04/US-GHG-Inventory-2023-Annex-3-Additional-Source-or-Sink-Categories-Part-B.pdf>
- 46 Hristov AN, Melgar A, Wasson D, Arndt C. Symposium review: Effective nutritional strategies to mitigate enteric methane in dairy cattle. *Journal of dairy science*. 2022 Oct 1;105(10):8543-57. <https://doi.org/10.3168/jds.2022-21861>
- 47 Kebreab E, Bannink A, Pressman EM, Walker N, Karagiannis A, van Gastelen S, Dijkstra J. A meta-analysis of effects of 3-nitrooxypropanol on methane production, yield, and intensity in dairy cattle. *Journal of dairy science*. 2023 Feb 1;106(2):927-36. <https://doi.org/10.3168/jds.2022-22162>
- 48 Ohio Dairy Industry Resources Center (ODIRC). 3-NOP (Bovaer™) receives FDA approval. Ohio State University Extension; 2025. <https://dairy.osu.edu/newsletter/buckeye-dairy-news/volume-26-issue-3/3-nop-bovaer%E2%84%A2-receives-fda-approval>
- 49 Hashem NM, González-Bulnes A, Rodríguez-Morales AJ. Animal welfare and livestock supply chain sustainability under the COVID-19 outbreak: An overview. *Frontiers in veterinary science*. 2020 Oct 15;7:582528. <https://doi.org/10.3389/fvets.2020.582528>
- 50 Rahman MT, Islam MS, Shehata AA, Basiouni S, Hafez HM, Azhar EI, Khafaga AF, Bovera F, Attia YA. Influence of COVID-19 on the sustainability of livestock performance and welfare on a global scale. *Tropical Animal Health and Production*. 2022 Oct;54(5):309. <https://doi.org/10.1007/s11250-022-03307-4>
- 51 Miller SM, Wofsy SC, Michalak AM, Kort EA, Andrews AE, Biraud SC, Dlugokencky EJ, Eluszkiewicz J, Fischer ML, Janssens-Maenhout G, Miller BR. Anthropogenic emissions of methane in the United States. *Proceedings of the National Academy of Sciences*. 2013 Dec 10;110(50):20018-22. <https://doi.org/10.1073/pnas.1314392110>
- 52 Li S, Banerjee T. Spatial and temporal pattern of wildfires in California from 2000 to 2019. *Scientific reports*. 2021 Apr 22;11(1):8779. <https://doi.org/10.1038/s41598-021-88342-w>
- 53 Hu L, Montzka SA, Miller JB, Andrews AE, Lehman SJ, Miller BR, Thoning K, Sweeney C, Chen H, Godwin DS, Masarie K. US emissions of HFC-134a derived for 2008–2012 from an extensive flask-air sampling network. *Journal of Geophysical Research: Atmospheres*. 2015 Jan 27;120(2):801-25. <https://doi.org/10.1002/2014JD022619>
- 54 Kahle D, Wickham H. ggmap: Spatial Visualization with ggplot2. <http://journal.r-project.org/archive/2013-1/kahle-wickham.pdf>
- 55 Wickham H. Data analysis. ggplot2: elegant graphics for data analysis 2016 Jun 9 (pp. 189-201). Cham: Springer international publishing.
- 56 Belikov DA, Patra PK, Saitoh N. Hydroxyl interannual variability impacts estimation of regional methane emissions. *Journal of Geophysical Research: Atmospheres*. 2026 Feb 28;131(4):e2025JD044457.
- 57 He J, Harkins C, O'Dell K, Li M, Francoeur C, Aikin KC, Anenberg S, Baker B, Brown SS, Coggon MM, Frost GJ. COVID-19 perturbation on US air quality and human health impact assessment. *PNAS nexus*. 2023 Dec 21;3(1):pgad483. <https://doi.org/10.1093/pnasnexus/pgad483>

View Article Online
DOI: 10.1039/D6EA00004E



Data Availability Statement

The posterior CH₄ emission estimates derived from this analysis are available at <https://doi.org/10.15138/zmd2-cy30> (Hu et al., 2025). The atmospheric methane observation data used in this study are publicly available from the NOAA Global Monitoring Laboratory at <https://gml.noaa.gov/dv/data/>. Data related to the FOG inventory and other auxiliary datasets can be accessed through their respective citations in the main text. For any additional questions regarding the data or code used in this study, please contact the corresponding author, Dr. Sergio Ibarra-Espinosa.

