QUANTIFYING URBAN AND LANDFILL METHANE EMISSIONS IN THE UNITED STATES USING *TROPOMI* SATELLITE DATA

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Summary

Urban areas are a major source of population-driven methane emissions but quantifying these emissions and estimating the contribution from different source sectors remains a challenge. This study uses satellite observations of atmospheric methane concentrations and a high-resolution (12 kilometer by 12 kilometer) inversion framework to estimate methane emissions from 12 major U.S. urban areas and from 53 large individual landfills. The authors find substantial discrepancies between their results and the emissions previously reported for urban areas using bottom-up estimation methods. Overall, their analysis points to substantial underestimation of urban methane emissions in bottom-up inventories, with an estimate of total emissions for the 12 areas studied that is 80% higher than currently reflected in the U.S. Environmental Protection Agency's national Greenhouse Gas Inventory. Undercounting of landfill emissions appears to be a principal cause of this discrepancy, likely because current reporting methods overstate the real-world performance of landfill gas collection and control systems. An exception is Los Angeles, where the inversion analysis indicates that landfill gas collection efficiencies are far higher than in other areas. This finding suggests large potential to mitigate urban methane emissions through improved landfill management.

Background and context

Methane (CH_4), a short-lived but potent greenhouse gas, is estimated to account for 30% of the climate warming observed since pre-industrial times (Szopa *et al*. 2021). Several important sources of methane emissions, including natural gas distribution systems, landfills, wastewater treatment plants, and residential combustion, are concentrated in urban areas. Accurately quantifying these emissions and attributing the contribution from different source sectors is essential for national, state, and municipal efforts to reduce greenhouse gas emissions and track progress toward climate goals.

Recent studies that use inverse methods to estimate emissions from satellite or aircraft observations of atmospheric methane concentrations consistently find that existing emission inventories understate methane emissions over urban areas, in many cases by large margins (Nesser *et al*. 2024; Plant *et al*. 2022; Sargent *et al*. 2021). This is likely because prior methods for estimating emissions have generally relied on bottom-up calculations — for example, multiplying measures of activity

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(e.g., counts of gas distribution services) by average emissions factors (e.g., methane emitted per service) — that are susceptible to large uncertainties. This study examines methane emissions from the 10 most populous urban areas in the United States (New York, Los Angeles, Chicago, Philadelphia, Dallas, Miami, Houston, Washington, Atlanta, and Boston) plus Cincinnati and Detroit, which were included because they were found to have high levels of emissions in previous research using satellite observations. These 12 urban areas are densely populated, accounting for nearly a third (27%) of the population of the contiguous United States but only 1.5% of its land area. The second part of the analysis focuses specifically on emissions from large landfills, comparing emissions calculated using satellite observations to the emissions reported by landfill operators to the U.S. Environmental Protection Agency (EPA) under its Greenhouse Gas Reporting Program (GHGRP).

Data and methods

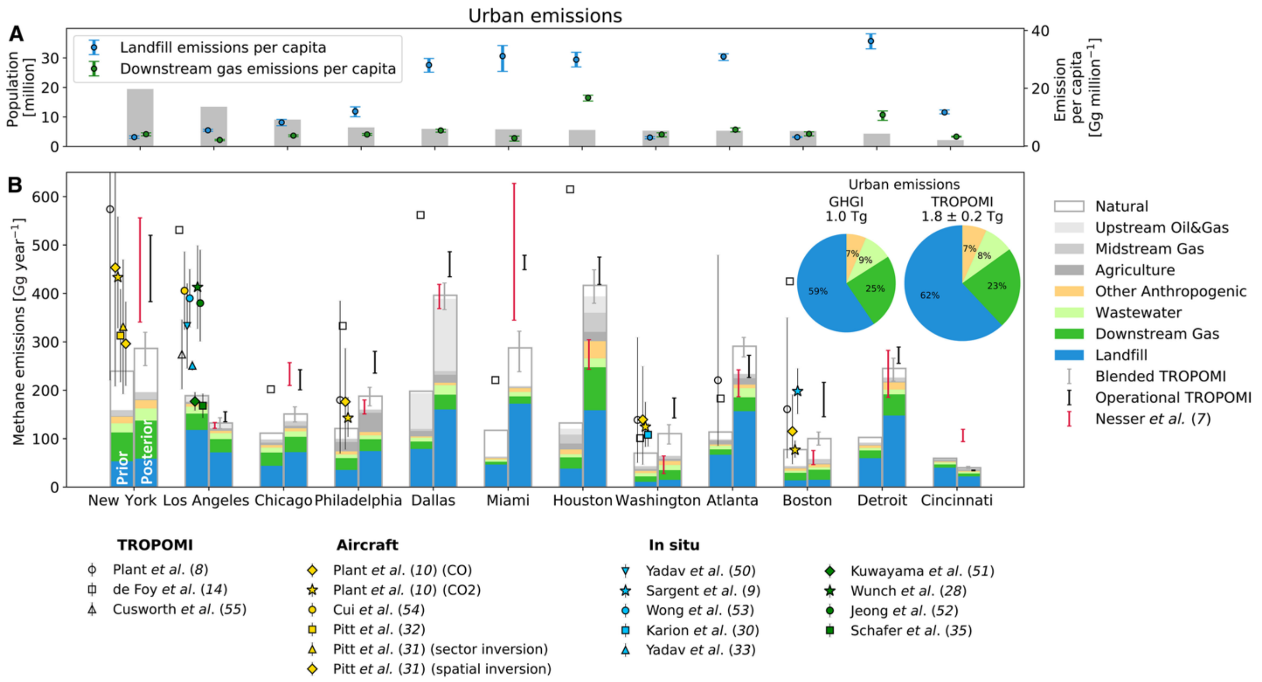
The atmospheric methane observations used in this study are from 2022 and were collected by the Tropospheric Monitoring Instrument (TROPOMI) on board the Sentinal-5P satellite. TROPOMI provides daily, global measurements of total atmospheric methane concentrations at a high level of spatial resolution, including contributions from both area and point sources. Applying version 2.0 of the Integrated Methane Inversion (IMI), an open-source cloud computing tool that incorporates the GEOS-Chem atmospheric transport model and prior estimates of methane emissions, the authors generate posterior estimates of surface methane emissions using an inversion of the TROPOMI observations with Bayesian inference. The inversion analysis is conducted at 12-kilometer spatial resolution, which allows for better separation of the contribution from different source sectors and makes it possible to estimate emissions from large individual landfills. Prior emissions estimates are taken from EPA's national Greenhouse Gas Inventory (GHGI). Uncertainty ranges were calculated for all emission results and are provided in the full study.

For purposes of this analysis, the authors define urban emissions as those from population-driven activities or sources including landfills, downstream gas distribution systems, wastewater treatment, and stationary fuel combustion (for example, by residential heating systems). Landfill emissions are mapped on the basis of facility coordinates and are spatially distinct from other sectors. Emissions from downstream gas, wastewater treatment, and stationary combustion (categorized as "other anthropogenic sources" in the GHGI) are all allocated on the basis of population, which means that the ability to separate the contribution from these three source categories in the inversion analysis is limited. Among them, however, downstream gas, which includes distribution from city gates to consumers and post-meter end use, is expected to dominate based on emissions estimates in the GHGI.

Results

Figure 1 summarizes results for the 12 U.S. urban areas included in the study, showing that (1) posterior estimates of methane emissions from this analysis are higher — in several cases, substantially higher — than prior emission estimates for all but two of the areas studied (Los Angeles and Cincinnati are the exceptions) and (2) landfills and natural gas distribution systems are the dominant sources of anthropogenic methane emissions in most of these large urban areas.

Fig. 1: Annual methane emissions in 12 U.S. urban areas ordered by population (largest to smallest)



__(A)__ Shows urban population (gray bars) and per capita posterior emissions from the TROPOMI inversion for downstream gas and landfills. Population data are from the Center for International Earth Science Information Network of Columbia University. __(B)__ Compares the authors' posterior estimates for 2022, subdivided by sector, to prior estimates from the US EPA GHGI and to previous studies. Prior estimates are shown on the left, and posterior estimates are shown on the right. Vertical bars are the uncertainty in total emissions estimated from the spread of the inversion ensemble in individual urban area. Pie charts show total emissions by sector for the 12 urban areas.

Combining results for the 12 urban areas in this study yields total estimated methane emissions of 1.8 Tg year $^{-1}$, from the following sources: 62% landfills, 23% downstream gas, 8% wastewater, and 7% other anthropogenic sources. Total emissions are highest in Houston, Detroit, Dallas, and Atlanta, despite their smaller populations than New York and Los Angeles. The contribution from landfills varies from 28% in Washington to 84% in Miami, whereas the contribution from downstream gas varies from 7% in Miami to 44% in Boston. Variations in per capita emissions are largely driven by landfill emissions and are lower in New York and Los Angeles than in other cities. In general, landfill emissions correlate more strongly with total waste-in-place than with population, whereas downstream gas emissions are strongly correlated with population and gas usage.

Consistent with previous research using atmospheric methane observations, the findings from this analysis suggest that anthropogenic methane emissions from urban areas in the United States are substantially underestimated in the current GHGI. The authors' 1.8 Tg year $^{-1}$ estimate of total emissions for the 12 urban areas studied is 80% higher than reflected in the GHGI, which indicates a total of 1.0 Tg year $^{-1}$ for these same areas. For example, the inversion estimate for Houston is 3.9 times *higher* than reported in EPA's national inventory, whereas estimated emissions for Los Angeles and Cincinnati are 32% and 37% *lower,* respectively, than in the GHGI. The authors find that landfills account for much of the difference between emission results obtained using atmospheric methane observations and estimates generated by bottom-up calculations. Their results also indicate that the GHGI understates emissions from downstream natural gas distribution systems in some urban areas — mainly Houston, Detroit, New York, and Washington.

Given the importance of landfills, both as absolute contributors to urban methane emissions and as a driver of discrepancies between current emission inventories and atmospheric methane measurements, the authors leverage the high spatial resolution enabled by the TROPOMI observations to analyze emissions for 53 large, individual landfills, including 9 landfills in Los Angeles and 44 landfills in other urban areas. Of these landfills, 43 have gas collection and control systems; 10 do not. For the landfills studied, the "recovery-first" estimation method most frequently used to report landfill emissions gives estimates far below the authors' posterior estimates, which are 3.7 times higher on average. An alternative "generation-first" estimation method produces results closer to the posterior estimates, although the authors' estimates remain about 1.3 times higher.[1] Gas collection efficiency is a major uncertainty in the recovery-first method. The results suggest that actual gas collection efficiencies for most landfills are far lower than assumed in the estimation methods used by landfill operators to report emissions to the EPA. Notably, Los Angeles landfills are an exception: results for these facilities suggest that their average gas collection efficiency is 85%, much higher than that of other landfills included in the analysis. As a consequence, the GHGI *overstates* emissions from these nine landfills relative to their actual contribution as estimated from the inversion analysis.

Excluding the nine Los Angeles landfills, the authors estimate gas collection efficiencies for the remaining 44 landfills in their sample range from 5% to 90%, with a mean collection efficiency of 38%. This is far lower than the 70% mean collection efficiency used to estimate emissions from these landfills for GHGI reporting purposes. Based on this result, a recent EPA proposal to reduce assumed landfill gas collection efficiencies in the GHGRP by 10% would not be sufficient to correct for the pattern of underestimation found when comparing reported landfill emissions to emissions inferred from atmospheric observations. However, the authors also find large variability in collection efficiencies for individual landfills, suggesting that no simple change to available bottom-up estimation methods is likely to fully correct for shortcomings in current landfill methane inventories.

Discussion

Using a high-resolution (12 km by 12 km) inversion of TROPOMI satellite observations, the authors quantify methane emissions by sector in 12 large U.S. urban areas and find that urban methane emissions are, on average, 80% higher than GHGI estimates. Landfills account for 62% of urban emissions in this analysis and drive most of the discrepancy with emission totals as reported in the GHGI. Estimated emissions from downstream natural gas distribution systems are also higher than in the GHGI but lower than in previous city-scale inverse studies — this discrepancy still needs to be resolved.

Investigating emissions from individual landfills, the authors find that landfills in Los Angeles have much higher gas collection efficiencies than landfills in other urban areas. This suggests that efforts by the state of California to reduce landfill emissions through enhanced gas collection and control measures have been successful. For example, the analysis indicates that gas collection efficiency at the Sunshine Canyon landfill in Los Angeles reached 92% by 2022. This follows substantial infrastructure upgrades at the facility that included the addition of gas wells and pumps and replacement of the final soil cover with closure turf and vegetative cover. The authors estimate that if mean gas collection efficiency for all landfills in the study were raised to the level achieved in Los Angeles (that is, from 38% to 85%), methane emissions from these landfills could be reduced by a factor of four.

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[1] Landfills with gas collection and control systems (GCCSs) can use the so-called recovery-first estimation method, which back-calculates methane emissions based on the quantity of gas collected by the GCCS and its assumed collection efficiency. This approach tends to produce lower emission totals and is the method used by most large landfill operators for emissions reporting purposes. In the generation-first estimation method, decay rates are applied to the degradable organic content of a landfill to generate emission estimates.

Reference to full paper, author affiliations, and acknowledgements

A more detailed account of the research on which this brief is based may be found in Xiaolin Wang, Daniel J. Jacob, Hannah Nesser, Nicholas Balasus, Lucas A. Estrada, Melissa P. Sulprizio, Daniel H. Cusworth, Tia R. Scarpelli, Zichong Chen, James D. East, and Daniel J. Varon. “Quantifying Urban and Landfill Methane Emissions in the United States Using TROPOMI Satellite Data.” *Science Advances* 12 (13). March 2026. eadz9308. https://doi.org/10.1126/sciadv.adz9308.

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About the Program

The Harvard Methane Initiative seeks meaningful and sustained progress in reducing global emissions of this very important greenhouse gas — through research and effective engagement with policymakers and key stakeholders. This Initiative is supported by the Salata Institute for Climate and Sustainability at Harvard University. The Harvard Methane Initiative and other Research Clusters supported by the Salata Institute comprise interdisciplinary teams of researchers from across Harvard’s schools, whose varied expertise is required to address the complexity of the climate-related problems that they seek to solve. Robert N. Stavins, A.J. Meyer Professor of Energy and Economic Development at Harvard Kennedy School, directs the Harvard Methane Initiative. The findings, views, and conclusions in this publication are those of the authors alone.