Supplement of Atmos. Chem. Phys., 25, 1513–1532, 2025
https://doi.org/10.5194/acp-25-1513-2025-supplement

Atmospheric Chemistry and Physics
Open Access

Supplement of

Small emission sources in aggregate disproportionately account for a large majority of total methane emissions from the US oil and gas sector

James P. Williams et al.

Correspondence to: James P. Williams (jamwilliams@edf.org) and Ritesh Gautam (rgautam@edf.org)

Table of contents:

Supplementary figures:

Page S3 – Figure S1: Total oil/gas methane emissions by basin and facility category

Page S4 – Figure S2: Spatial boundaries of remote sensing studies used for comparisons

Page S5 – Figure S3: Comparison to continuous emission distributions from Xia et al. (2024) and Kunkle et al. (2023)

Page S6 – Figure S4: Annual gas production by oil/gas basin

Page S7 – Figure S5: Annual combined oil and gas production by oil/gas basin

Page S8 – Figure S6: Facility-level emission distributions for remaining eleven oil/gas basins

Page S9 – Figure S7: Ranked cumulative percentage of methane emissions from production well sites versus cumulative oil and gas production

Page S10 – Figure S8: Sensitivity analysis on the limit of detection for empirical measurements

Page S11 – Figure S9: Sensitivity analysis on excluding empirical measurement data from oil/gas basins

Page S12 – Figure S10: Map of CONUS with oil/gas basins

Page S13 – Figure S11: Cumulative percentage of methane emissions by emission rate and percentage of cumulative facilities

Supplementary tables:

Page S14 – Table S1: Breakdown of cumulative methane emissions by emission rate magnitudes

Page S15 – Table S2: Description of methods used to gather ground-based empirical measurements used in this work.

Page S16 – Table S3: Description of the locations where ground-based empirical measurements used in this work were gathered.

Page S17-S18 – Table S4: Comparison of total oil/gas methane emissions from our facility-level inventory to the target regions from other aerial-based remote sensing studies

Page S19-S20 – Table S5: Description of remote sensing campaigns used for comparison to the facility-level model.

Page S21 – Table S6: Goodness-of-fit tests for empirical measurement data versus output facility-level emission rates

Page S22 – Table S7: Comparison of reported methane emissions between Sherwin et al. (2024) and Cusworth et al. (2022)

Supplementary Figures

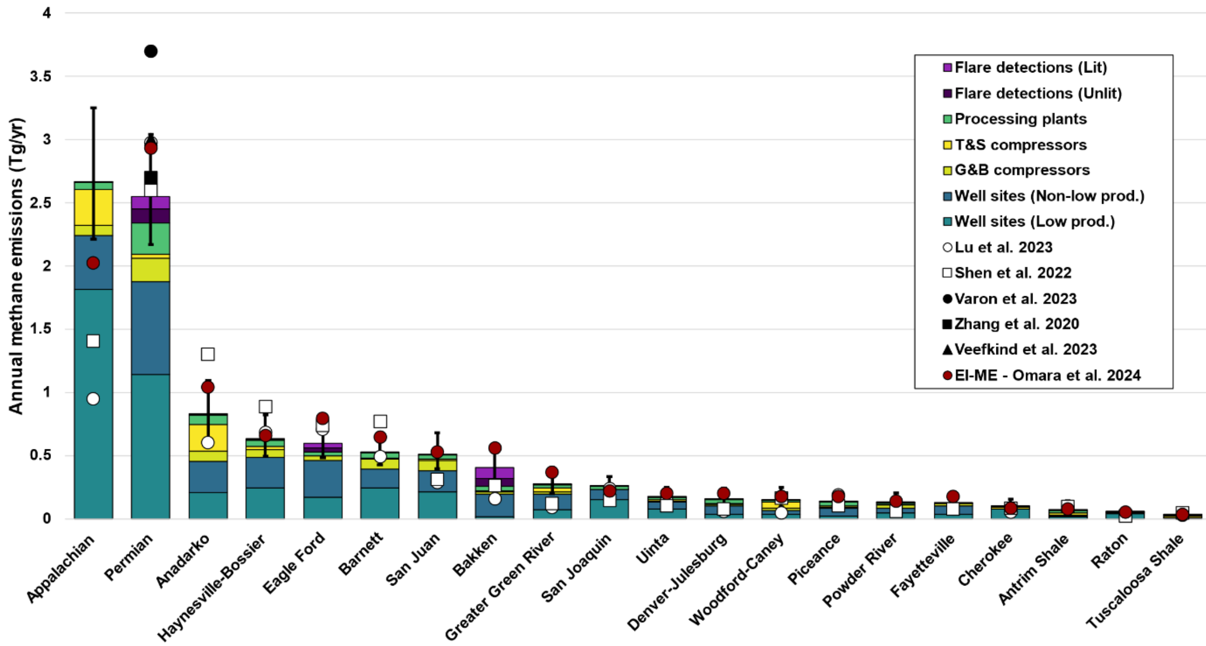

Figure S1: Total methane emissions for different oil/gas basin boundaries from our facility-level model results colored according to the emitting facility category with uncertainty bars (i.e., 95% c.i.) Other satellite-based studies are included for basin-level comparisons, except for the EI-ME (Omara et al., 2024) which estimates basin-level emissions using a measurement-based facility-level approach.

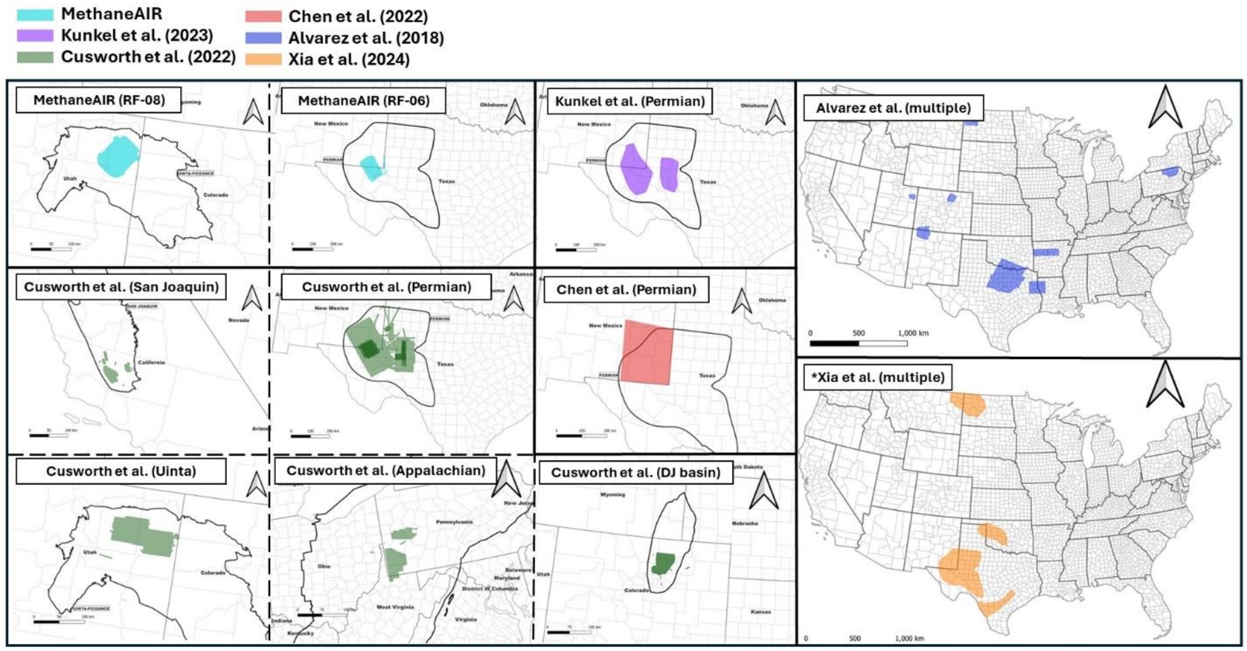

Figure S2: Spatial boundaries of remote sensing studies used for comparisons in Table S2, Fig. 7, and Fig. 8.

*Spatial boundaries outlined by Xia et al. (2024) represent the measured oil/gas basins in their work, but not specifically the outlines of the flown boundaries within those oil/gas boundaries.

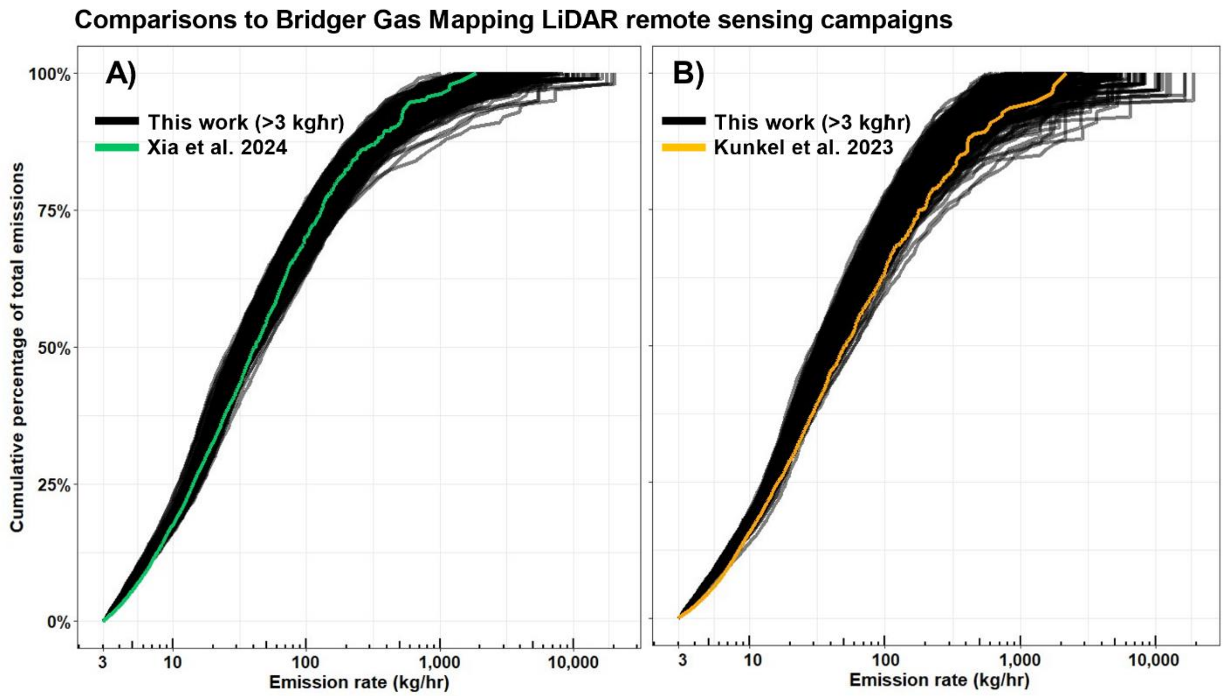

Figure S3: A) Comparison of our facility-level ensemble of methane emission distributions (n=500) to the measured emissions from A) Xia et al. (2024) and B) Kunkel et al. (2023) for sources emitting above 3 kg/hr which is the approximate Bridger GML limit of detection. Spatial domains used for the comparisons of emission distribution curves are identical in Kunkel et al. (2023), and for Xia et al. (2024) we estimate emissions within the entire four-basin aggregate identified in their study since the actual aerial surveyed regions in their study are kept anonymous. Maps of all spatial boundaries used for comparisons are provided in Fig. S2.

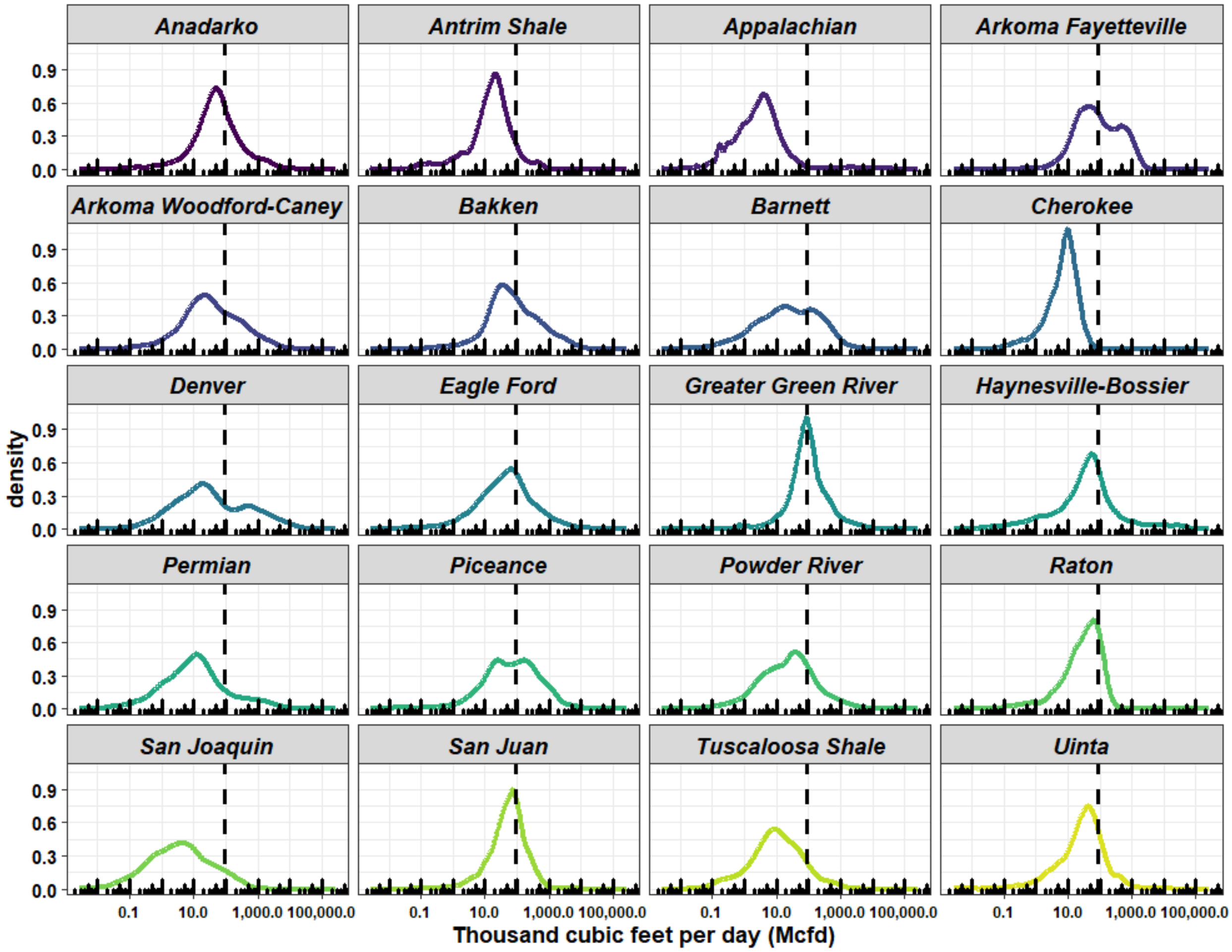

Figure S4: Kernal densities of well site level gas production (Mcf/day) for US oil/gas producing basins to illustrate differences in production characteristics among basins. For reference, the black segmented lines represent a gas production value of 90 Mcf/day, which corresponds to 15 boe/day. Unit conversions: 1 Mcf = 1,000 cubic feet of natural gas = 19.2 kg of methane at 15.6 ºC and 1 atmosphere; 1 boe = 1 barrel of oil equivalent = 6 Mcf; assumed methane content in natural gas of 80%.

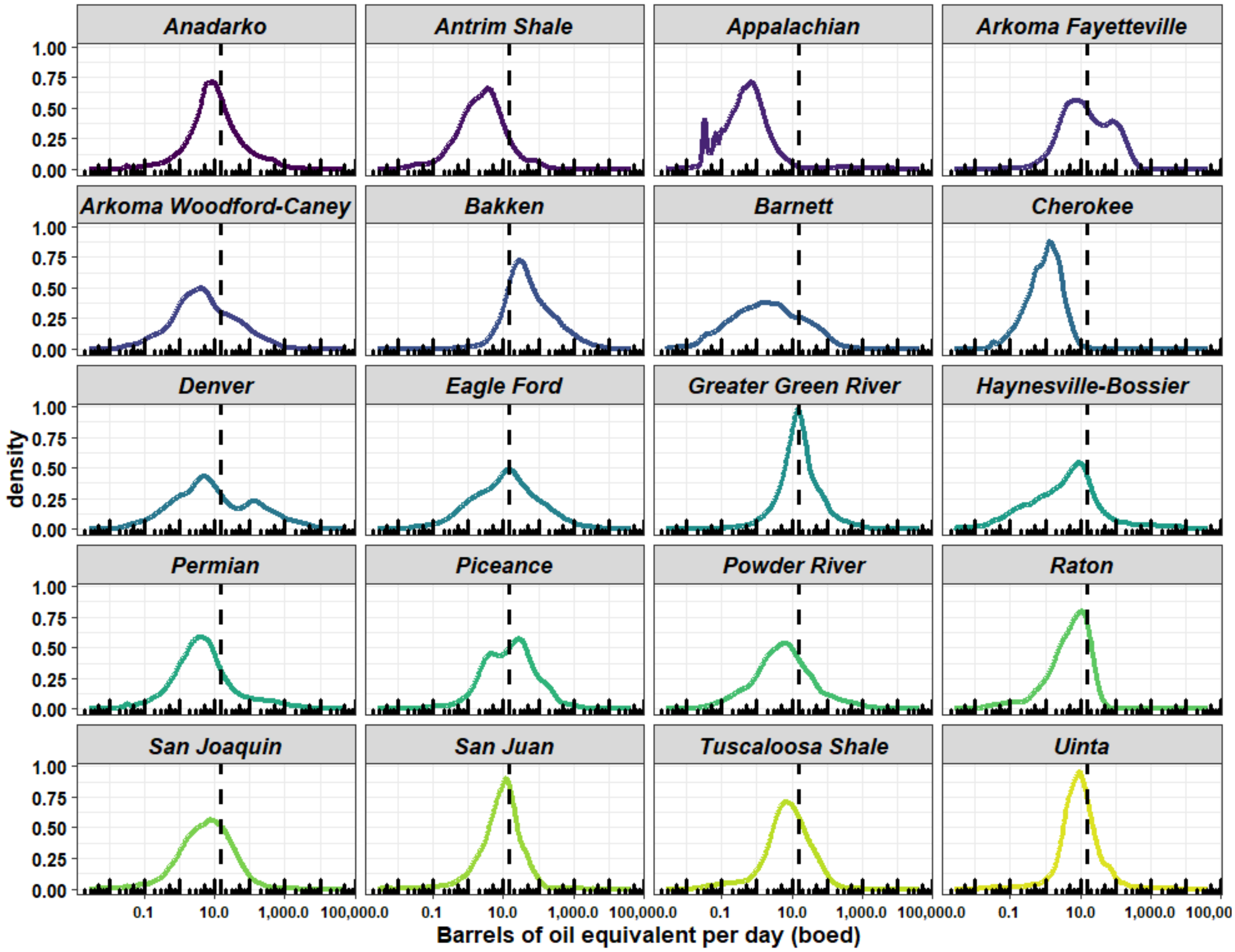

Figure S5: Kernal densities of well site level combined oil and gas production (boe/day) for US oil/gas producing basins to illustrate differences in production characteristics among basins. For reference, the black segmented lines represent a gas production value of 15 boe/day. Unit conversions: 1 Mcf = 1,000 cubic feet of natural gas = 19.2 kg of methane at 15.6 ºC and 1 atmosphere; 1 boe = 1 barrel of oil equivalent = 6 Mcf; assumed methane content in natural gas of 80%.

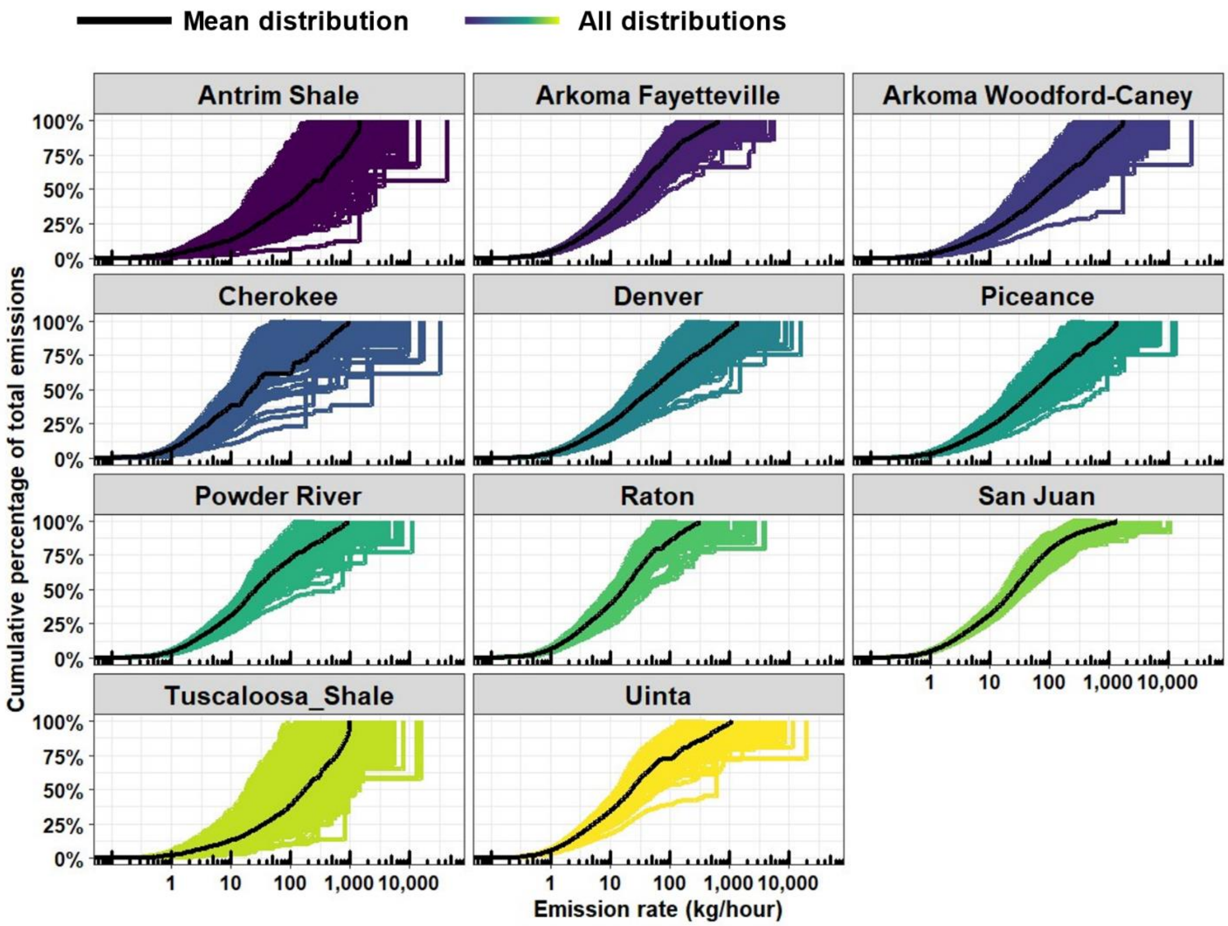

Figure S6: Results from 500 model simulations showing the cumulative methane emissions distribution curves for total upstream/midstream oil/gas methane emissions for the bottom eleven emitting oil/gas basins in the CONUS for 2021. The model averages for each basin are shown in the solid black lines. A map of the spatial boundaries used for the different oil/gas basins is shown in Fig. S10.

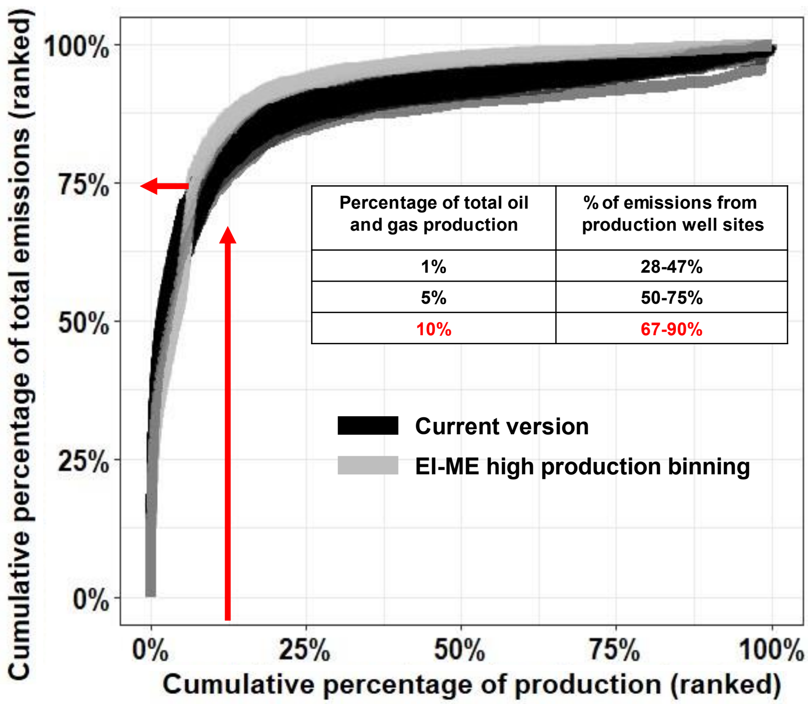

Figure S7: Results from 500 model simulations showing the cumulative methane emissions distribution curves for total well site oil/gas methane emission rates versus the percentage of cumulative combined oil and gas production using the well site production binning we present in this work (see Fig. 1), and the well site production binning used in Omara et al. (2024) for the EI-ME. The production bins used in this work are created based on equally distributing empirical measurement data for production well sites above an LOD of 0.1 kg/hr, and the EI-ME production bins are based on equally spaced log(e) jumps from log(5) to log(10). Results are ranked first by individual well-site emission rates, and then by well-site combined oil and gas production. The inset table shows the specific percentages of total emissions contributed from production well sites for cumulative well site production values of 1%, 5%, 10%, and 20%. The red arrows correspond to the percentage of total well site emissions contributed from well sites cumulatively producing 10% of total CONUS oil and gas production in 2021.

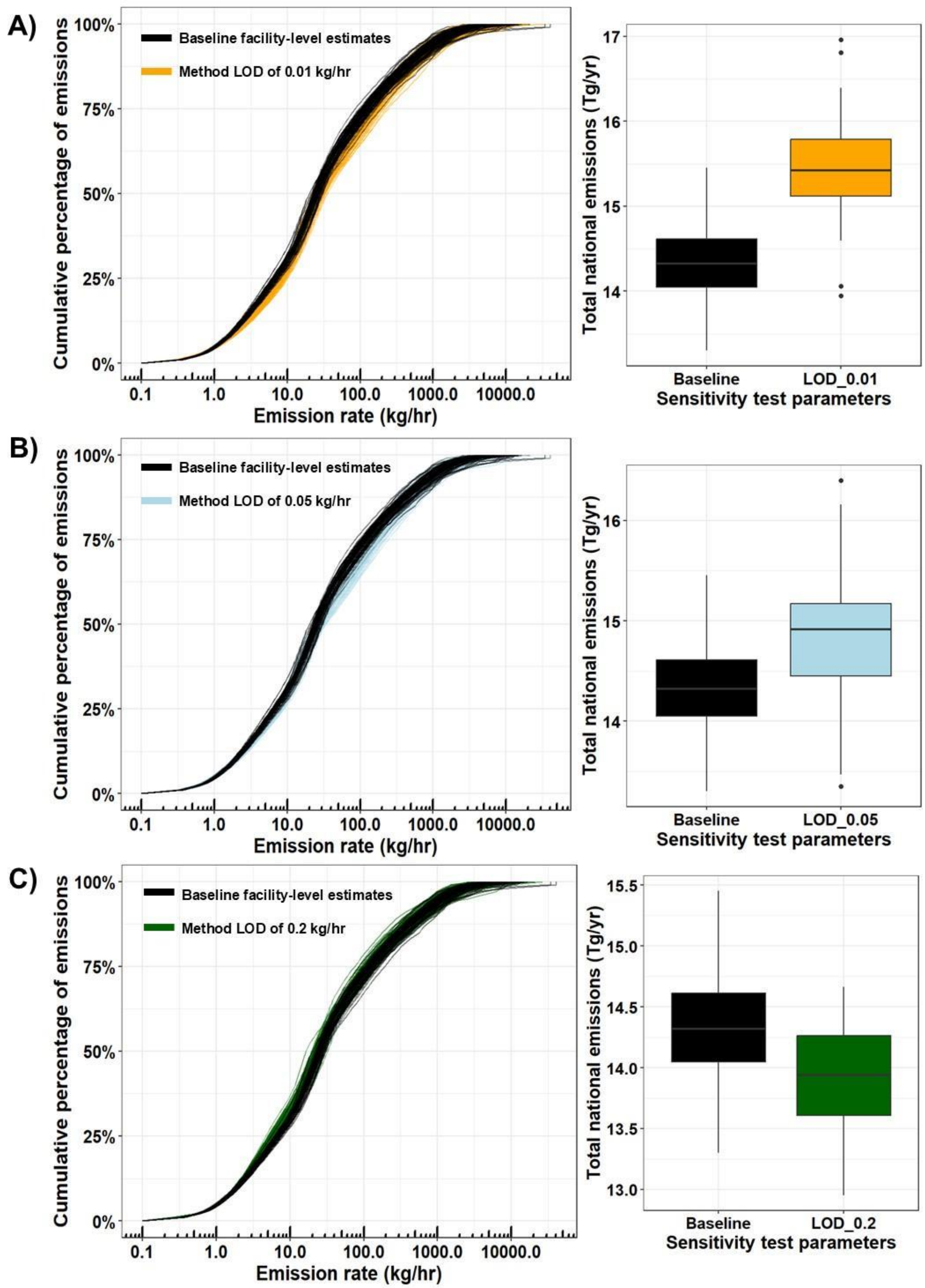

Figure S8: Results of a sensitivity analysis showing the impacts of modifying the method limit of detection used in the facility-level estimates for both the national-level oil/gas methane emission distributions (left) and total national methane emissions (right). Method LODs of A) 0.01 kg/hr, B) 0.05 kg/hr, and C) 0.2 kg/hr, were tested against the baseline LOD of 0.1 kg/hr.

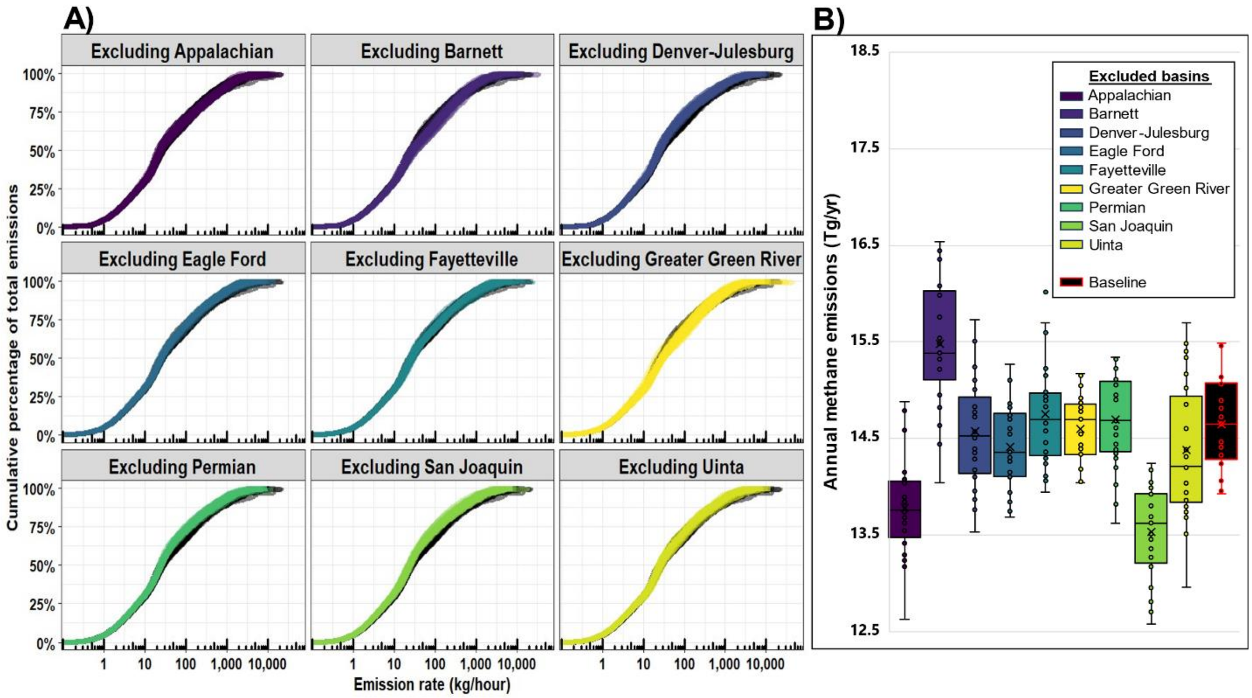

Figure S9: A) Sensitivity analysis of the effects of excluding empirical measurements from a single basin that shows the resulting impacts on oil/gas methane emission distributions for the CONUS. 25 emission distribution curves are presented for each basin (colored lines) exclusion scenario with comparisons to the entire dataset of empirical data (black lines). B) Sensitivity analysis of the effects of excluding empirical measurements from a single basin showing the impacts on total oil/gas methane emission estimates for the CONUS. Each box and whisker plot contains 25 estimates of total methane emissions colored according to the oil and gas basin from which empirical measurements were excluded. The black boxplot with red outlines shows the baseline scenario, which has no empirical measurement data removed.

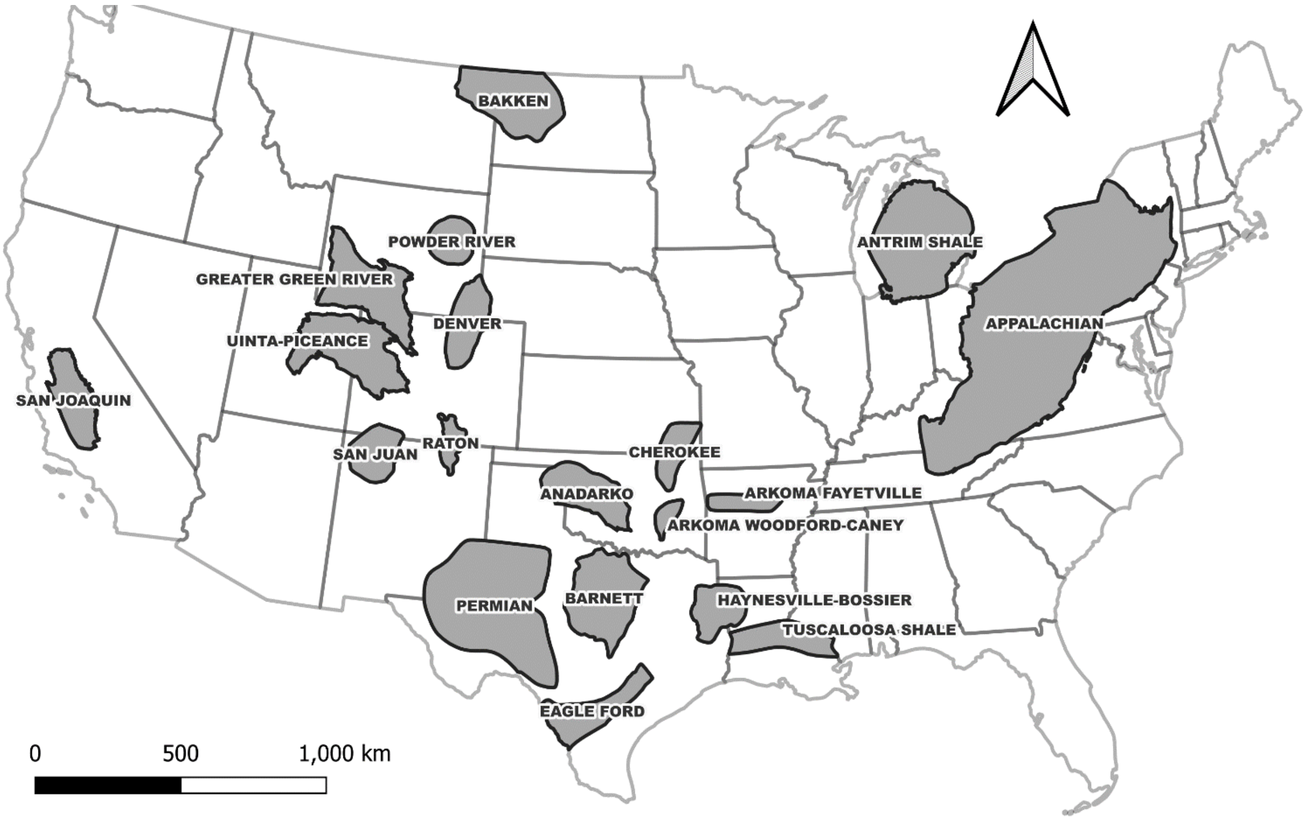

Figure S10: Map of contiguous United States (Alaska not shown) with oil/gas producing basins outlined in grey.

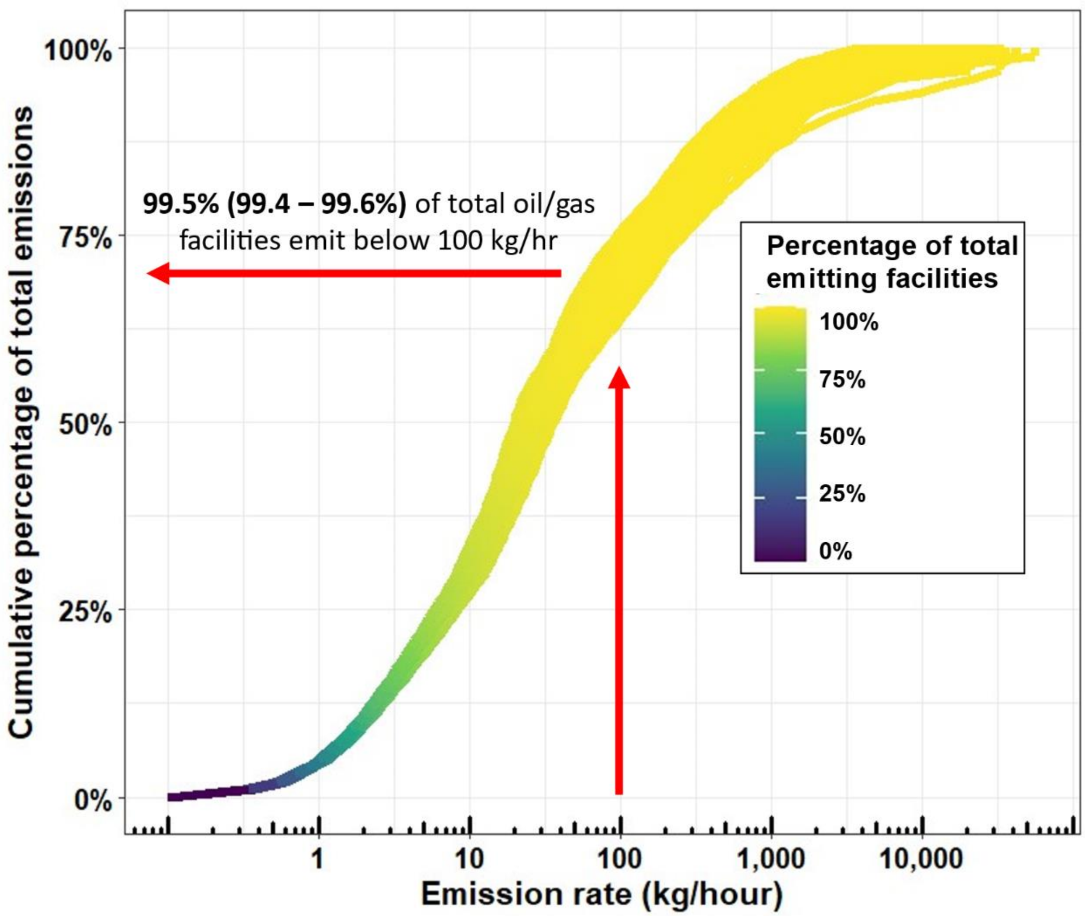

Figure S11: Results from 500 estimated facility-level emission distributions showing the cumulative percentages of total methane emissions contributed from facilities emitting below methane emission rate thresholds and colored according to the percentage of total emitting sites ranked by emission rate. The red arrows correspond to the cumulative emissions from facilities emitting <100 kg/hr, with the corresponding percentage of total facilities shown in the inset text.

Supplementary Tables

Table S1: Breakdown of total oil/gas methane emission for the CONUS in 2021 contributed from different magnitudes of methane emission rates with the corresponding percentage of total facilities responsible for those emissions. These results show a breakdown of the emission distributions curves presented in Figure 3 of the main text.

Emission rate threshold range (kg/hr)	Percentage of total emissions
≤0.1	**0.2% (0.1 - 0.3%)**
0.1 – 1	**4.4% (4.1 – 4.8%)**
1 – 10	**25% (24- 27%)**
10 – 100	**41% (39 – 42%)**
100 – 1,000	**22% (21 – 23%)**
>1,000	**7.2% (5.0 – 8.6%)**

Table S2: Description of methods used to gather ground-based empirical measurements used in this work.

Study	Measurement method	# of measurements	Facility category
Brantley et al. 2014	OTM33a	228	Well sites
Caulton et al. 2019	Gaussian	564	Well sites
Deighton et al. 2020	HiFlow	43	Well sites
Omara et al. 2016	Tracer release	35	Well sites
Omara et al. 2018	Gaussian OTM33a Tracer release	52 9 34	Well sites Well sites Well sites
Rella et al. 2015	Gaussian	185	Well sites
Riddick et al. 2019	Chamber	49	Well sites
Robertson et al. 2017	OTM33a	149	Well sites
Robertson et al. 2020	OTM33a	84	Well sites
Zhou et al. 2021	Gaussian	66	Well sites
Lan et al. 2015	Gaussian	32	Well sites
Goetz et al. 2015	Tracer release	3	Well sites
Mitchell et al. 2015	Tracer release	115	G&B compressors
Robertson et al. 2020	OTM33a	3	G&B compressors
Zimmerle et al. 2020	HiFlow	180	G&B compressors
Subramanian et al. 2015	Tracer release	45	T&S compressors
Yacovitch et al. 2015	Tracer release	5	T&S compressors
Mitchell et al. 2015	Tracer release	16	Processing plants
Yacovitch et al. 2015	Tracer release	4	Processing plants

Table S3: Description of the locations where ground-based empirical measurements used in this work were gathered.

			Production well bins (Mcf/day)*					
Oil/gas basin	**Facility category**	**Total # of measurements**	**(0 - 29)**	**(29 - 88)**	**(88 - 346)**	**(346 - 1,205)**	**(1,205 - 3,908)**	**(>3,908)**
Appalachian	Well sites	739	224	74	18	74	152	197
Barnett	Well sites	228	24	50	93	71	19	3
	T&S compressors	5						
	Processing plants	4						
Denver-Julesburg	Well sites	110	39	36	23	9	2	1
Eagle Ford	Well sites	4	-	1	2	-	1	-
Fayetteville	Well sites	52	3	4	11	22	12	-
Permian	Well sites	84	19	17	17	21	7	3
	G&B compressors	3						
San Joaquin	Well sites	66	26	30	10	-	-	-
Uinta	Well sites	60	14	22	16	6	2	-
Greater Green River	Well sites	158	9	22	44	33	38	12
All the U.S.**	T&S compressors	45						
	G&B compressors	295						
	Processing plants	16						

*Production well bins are determined by gas production cohorts corresponding to empirical measurement data gathered for production well sites (i.e., not applicable for T&S compressors, G&B compressors, and processing plants).

**All the US refers to empirical measurements sampled from multiple oil/gas producing regions in the US without data on the specific oil/gas basis from which the measurements were gathered.

Table S4: Comparison of total oil/gas methane emissions from our facility-level inventory to the target regions from other aerial-based remote sensing studies.

Remote sensing study comparison: total regional emissions						***This work***
Study	**Oil/gas basin(s)**	**Total emissions (t/hr)**	**Estimated percentage of non-oil/gas emissions**	**Estimated percentage of pipeline emissions**	**Adjusted oil/gas basin emissions (t/hr)**	**Total oil/gas basin emissions (t/hr)**
MethaneAIR	Permian (RF-06)	91 (62-115)	0%	30%	63 (43-80)	45 (38-55)
	Uinta (RF-08)	15 (12-23)	0%	24%	11 (7.7-17)	11 (9-19)
Cusworth et al. 2022	SJ (S-2020)	23 (20-26)	35%	45%	4.5 (3.8-5.2)	23 (19-31)
	SJ (F-2020)	22 (17-27)	0%	41%	13 (10-16)	24 (20-32)
	SJ (F-2021)	18 (16-20)	7%	23%	12 (11-14)	23 (19-31)
	Uinta (2020)	34 (28-40)	0%	34%	21 (18-25)	14 (13-19)
	Permian (F-2019)	415 (305-525)	0%	23%	320 (235-404)	226 (205-252)
	Permian (S-2020)	177 (118-236)	0%	20%	142 (94-189)	54 (45-68)
	Permian (S-2021)	181 (141-221)	0%	19%	147 (113-180)	57 (49-72)
	Permian (F-2021)	111 (83-139)	0%	9%	101 (66-136)	58 (50-72)
	Denver (S-2021)	21 (17-25)	44%	7%	10 (8.3-12)	14 (11-24)
	Denver (F-2021)	25 (18-32)	21%	28%	13 (9.4-16)	14 (11-24)
	App (2019)	109 (70-148)	67%	3%	33 (21-44)	44 (33-79)
Kunkel et al. 2023	Permian	112	NA		NA	NA
Xia et al. 2024	Anadarko, Bakken, Eagle Ford, Permian	162	NA		NA	NA
Alvarez et al. 2018	Appalachian	18 (4-32)	NA		NA	17 (10-43)
	Bakken	27 (14-40)				36 (30-46)
	Barnett	60 (49-71)				83 (72-100)
	Weld	19 (5-33)				14 (11-42)
	Fayetteville	27 (19-35)				9 (6-15)
	Haynesville	73 (19-127)				65 (53-91)
	San Juan	57 (3-111)				56 (47-66)
	West Arkoma	26 (0-56)				7 (5-10)

	Uinta	55 (24-86)				11 (9-19)
Chen et al. 2022	NM - Permian	194 (62-334)	NA	19%	157 (50-270)	76 (69-98)

Table S5: Description of remote sensing campaigns used for comparison to the facility-level model.

Study	Flight UID	Oil/gas basin	Survey year(s)	Regional estimate method	Measurement platform
MethaneAIR	RF-06	Permian	2021	MethaneAIR GIM inversions	MethaneAIR
	RF-08	Uinta	2021		
Cusworth et al. 2022	SJ (S-2020)	San Joaquin	Summer 2020	TROPOMI inversions	GAO and AVIRIS-NG
	SJ (F-2020)	San Joaquin	Fall 2020		
	SJ (F-2021)	San Joaquin	Fall 2021		
	Uinta (S-2020)	Uinta	Summer 2020		
	Permian (F-2019)	Permian	Fall 2019		
	Permian (S-2020)	Permian	Summer 2020		
	Permian (S-2021)	Permian	Summer 2021		
	Permian (F-2021)	Permian	Fall 2021		
	App (2019)	Appalachian	Spring 2019		
	Denver (S-2021)	Denver-Julesburg	Summer 2021		
	Denver (F-2021)	Denver-Julesburg	Fall 2021		
Alvarez et al. 2018	Appalachian	Appalachian	Spring 2015	-	Various mass-balance/tracer aircraft campaigns
	Bakken	Bakken	Spring 2014		
	Barnett	Barnett	2013		
	Weld	Denver-Julesburg	Spring 2012		
	Fayetteville	Fayetteville	Fall 2015		
	Haynesville-Bossier	Haynesville-Bossier	Summer 2013		
	San Juan	San Juan	Spring 2015		
	West Arkoma	West Arkoma	Summer 2013		
	Uinta	Uinta	Winter 2012		
Kunkel et al. 2023	Permian	Permian	-	-	Bridger GML

Chen et al. 2022	NM - Permian	New Mexico - Permian	2018-2020	Accounting of partial detections from aerial surveys	Kairos
Xia et al. 2024	Four-basin aggregate	Anadarko, Bakken, Eagle Ford, Permian	-	Combination of aerial measurements and simulations	Bridger GML

Table S6: Results of Kolmogorov-Smirnov tests for goodness of fit of our facility-level methane emissions distributions to empirical measurements for each facility category including high-emitter and low-emitter categories. Note that p-values above p=0.05 indicate that we cannot reject the null hypothesis that the empirical and our estimated methane emission distributions are significantly different.

Top 5% of emitters	**K-S test (p-value)**	**Bottom 95% of emitters**	**K-S test (p-value)**
Production wells (0 - 27 boe/day)	0.53	**Production wells (0 - 27 boe/day)**	0.24
Production wells (27 - 84 boe/day)	0.62	**Production wells (27 - 84 boe/day)**	0.57
Production wells (84 - 330 boe/day)	0.16	**Production wells (84 - 330 boe/day)**	0.73
Production wells (330 – 1,200 boe/day)	0.62	**Production wells (330 – 1,200 boe/day)**	0.77
Production wells (1,200 – 3,864 boe/day)	0.97	**Production wells (1,200 – 3,864 boe/day)**	0.53
Production wells (>3,864 boe/day)	0.71	**Production wells (>3,864 boe/day)**	0.89
G&B compressor stations	0.07	**G&B compressor stations**	0.37
T&S compressor stations	0.93	**T&S compressor stations**	0.25
Processing plants	0.28	**Processing plants**	NA

Table S7: Comparison of the aerially detected emissions and sub-aerial estimate emissions for seven sampling campaigns between Cusworth et al. (2022) and Sherwin et al. (2024). The sub-aerial detections for Cusworth et al. (2022) were calculated using the total TROPOMI estimated emissions subtracted by aerially detected emissions. Sub-aerial emissions for Sherwin et al. (2024) were calculated by Sherwin et al. (2024) using the OPGEE component-level model presented in Rutherford et al. (2021) for production well sites, and GHGI emission factors for midstream facilities. Percentage differences are calculated using the values from Sherwin et al. (2024) divided by the values of Cusworth et al. (2022). The seven campaigns were selected for comparison due to a predominance (i.e., >80%) of oil and gas sources in the regions, allowing for more direct comparisons.

Aerial campaign	***Aerial (Cusworth et al 2022.) (t/hr)***	***Below aerial (Cusworth et al. 2022) (t/hr)***	***Aerial (Sherwin et al. 2024) (t/hr)***	***Below aerial (Sherwin et al. 2024) (t/hr)***	***% difference in aerial (Sherwin / Cusworth)***	***% difference in sub-aerial (Sherwin / Cusworth)***
Permian 2019	246	169	449	108	+83%	-36%
Permian S-2020	72	105	96	38	+33%	-64%
Permian S-2021	72	109	83	47	+15%	-57%
Permian F-2021	68	43	80	51	+18%	+19%
Uinta 2020	6.1	28	8.4	12	+37%	-58%
SJ – F-2020	5.6	16	6.4	2.6	+14%	-84%
SJ – F-2021	2.2	16	2.6	2.4	+18%	-85%
				Average	**+31%**	**-52%**