Supplementary Figures

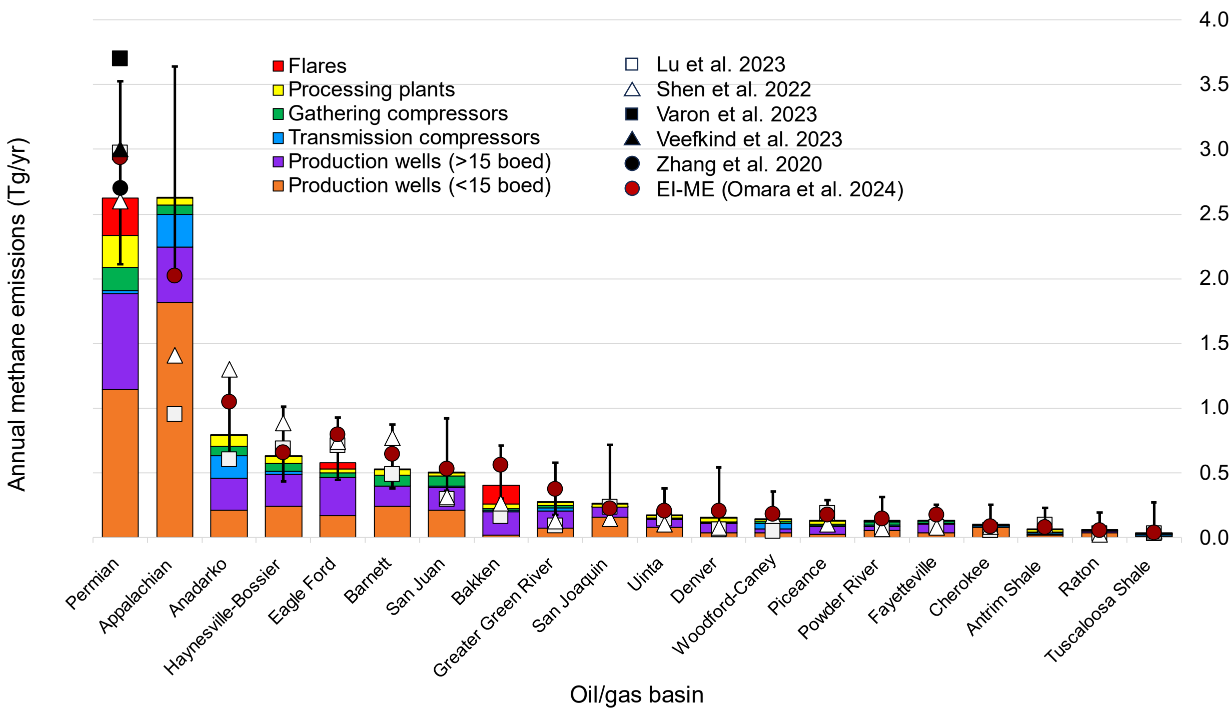

Figure S1: Total methane emissions for different oil/gas basin boundaries from our facility-level model results colored according to the emitting facility category with uncertainty bars (i.e., 95% c.i.) Other satellite-based studies are included for basin-level comparisons, except for the EI-ME (Omara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

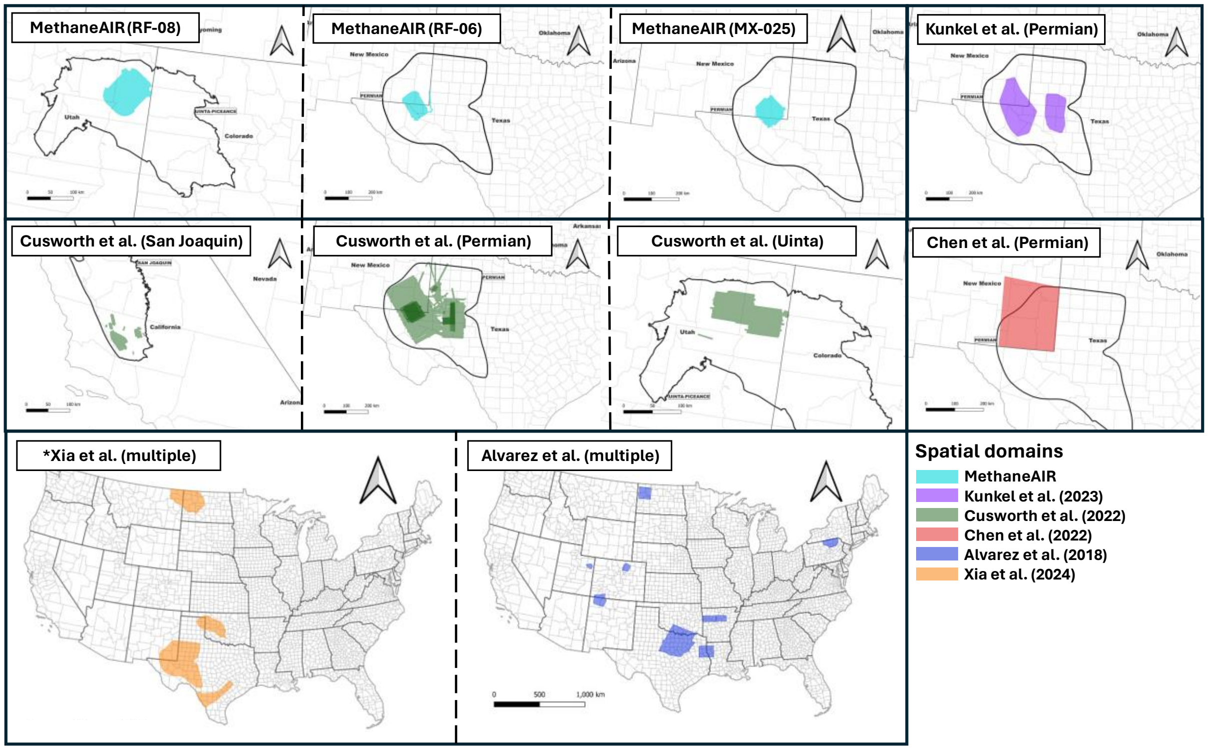

Figure S2: Spatial boundaries of remote sensing studies used for comparisons in Table S2, Fig. 7, and Fig. 8.

*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.

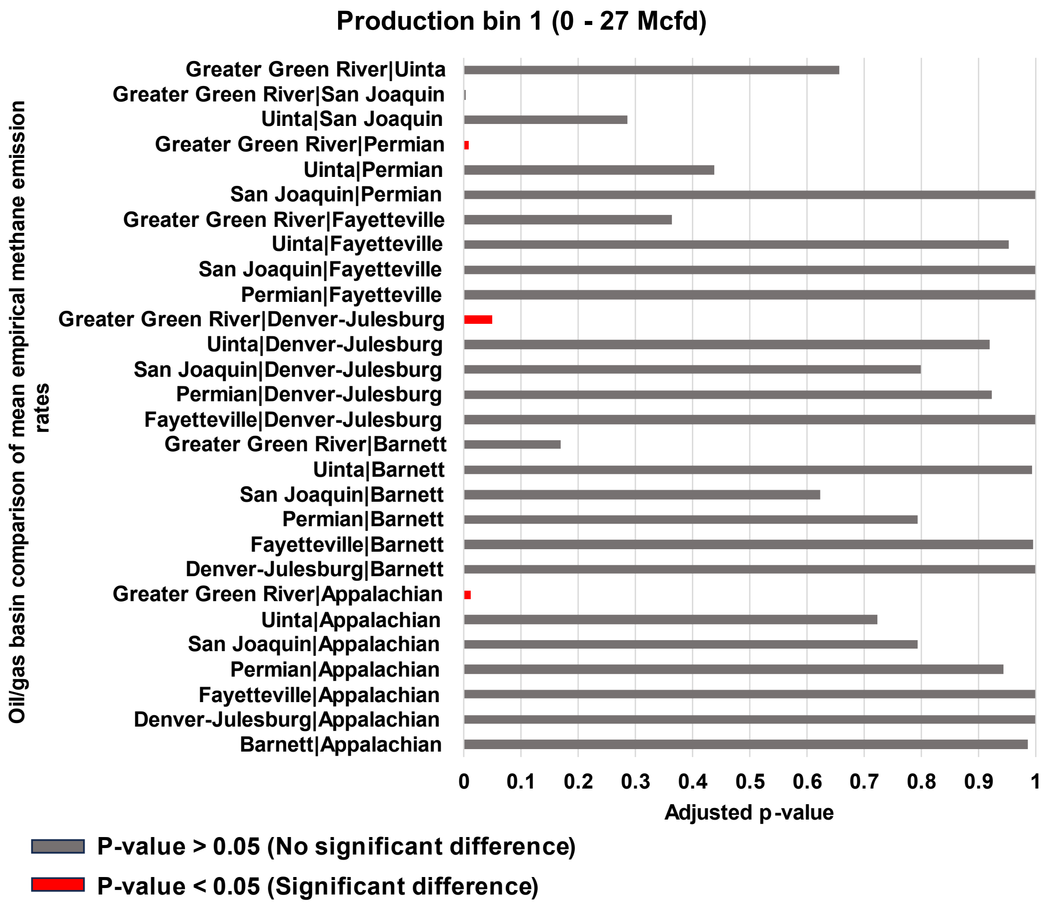

Figure S3: Results of Tukey honest significance test showing the significance of differences between mean well site empirical emission rates gathered from different oil/gas basins for the first production cohort of well sites (0 – 27 Mcfd). P-values below 0.05 imply a significant difference between mean emission rates for different oil/gas basins, and p-values above 0.05 imply no significant difference. The number of measurements available for each comparison can be found in Table S2.

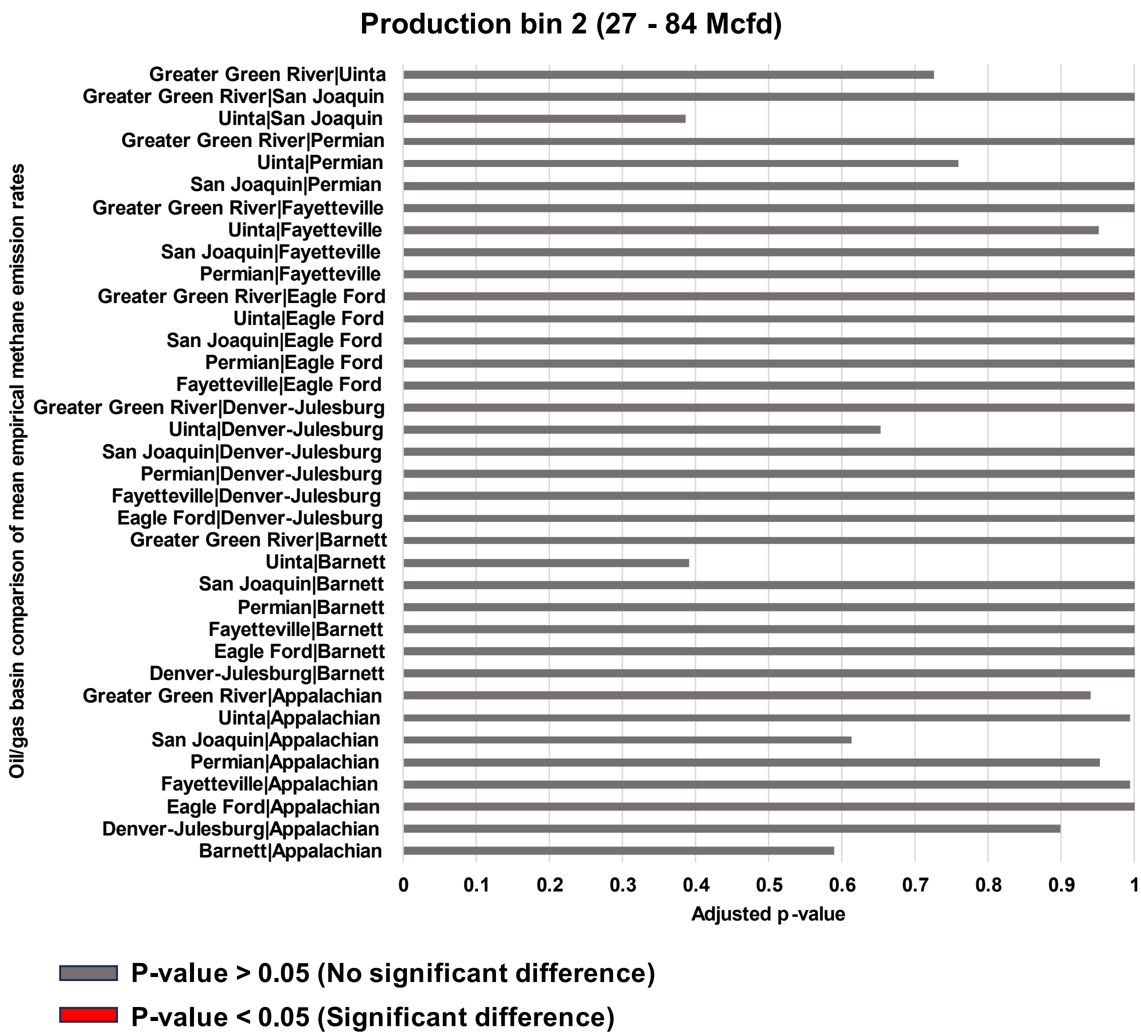

Figure S4: Results of Tukey honest significance test showing the significance of differences between mean well site empirical emission rates gathered from different oil/gas basins for the second production cohort of well sites (27 – 84 Mcfd). P-values below 0.05 imply a significant difference between mean emission rates for different oil/gas basins, and p-values above 0.05 imply no significant difference. The number of measurements available for each comparison can be found in Table S2.

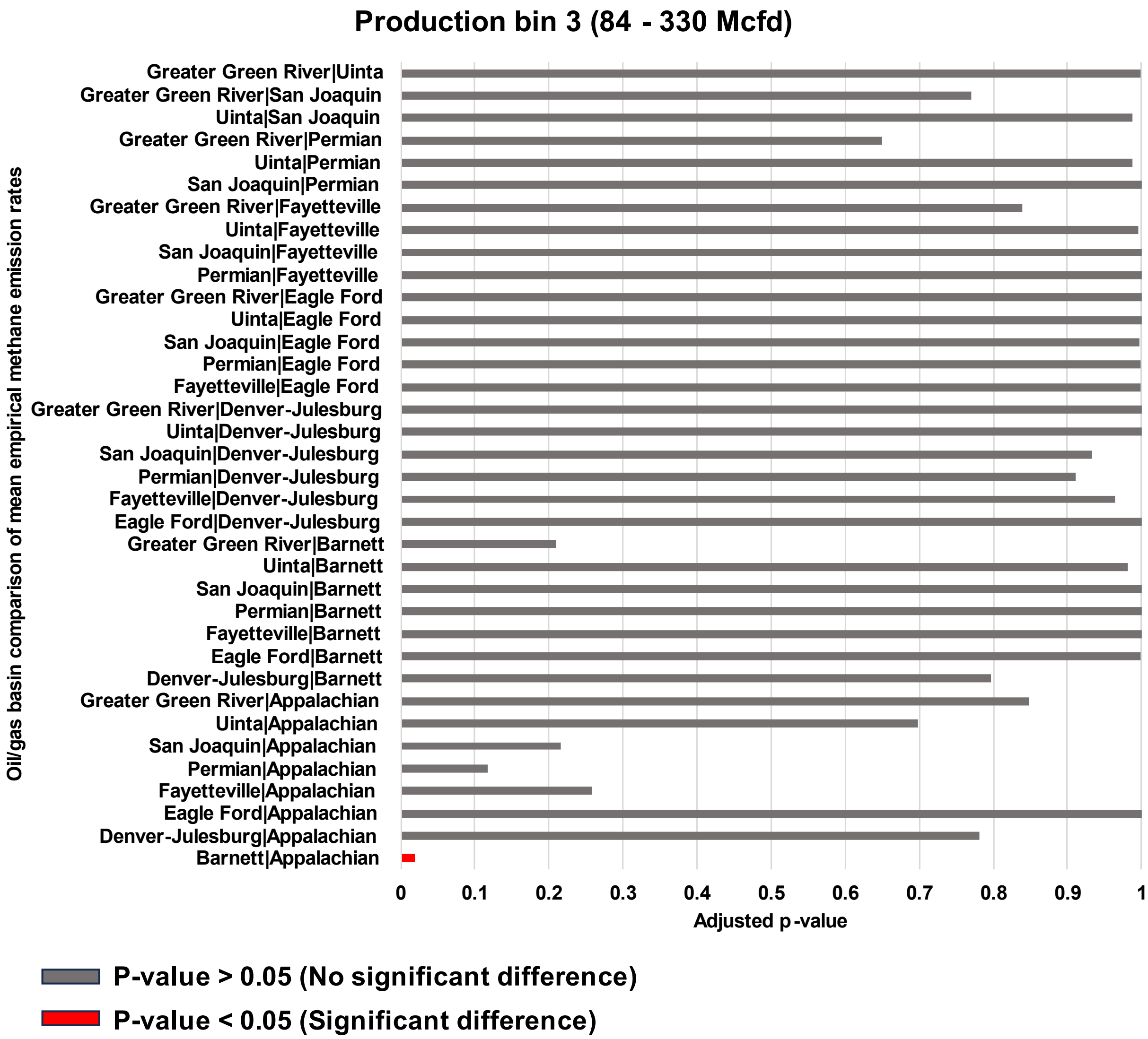

Figure S5: Results of Tukey honest significance test showing the significance of differences between mean well site empirical emission rates gathered from different oil/gas basins for the third production cohort of well sites (84 – 330 Mcfd). P-values below 0.05 imply a significant difference between mean emission rates for different oil/gas basins, and p-values above 0.05 imply no significant difference. The number of measurements available for each comparison can be found in Table S2.

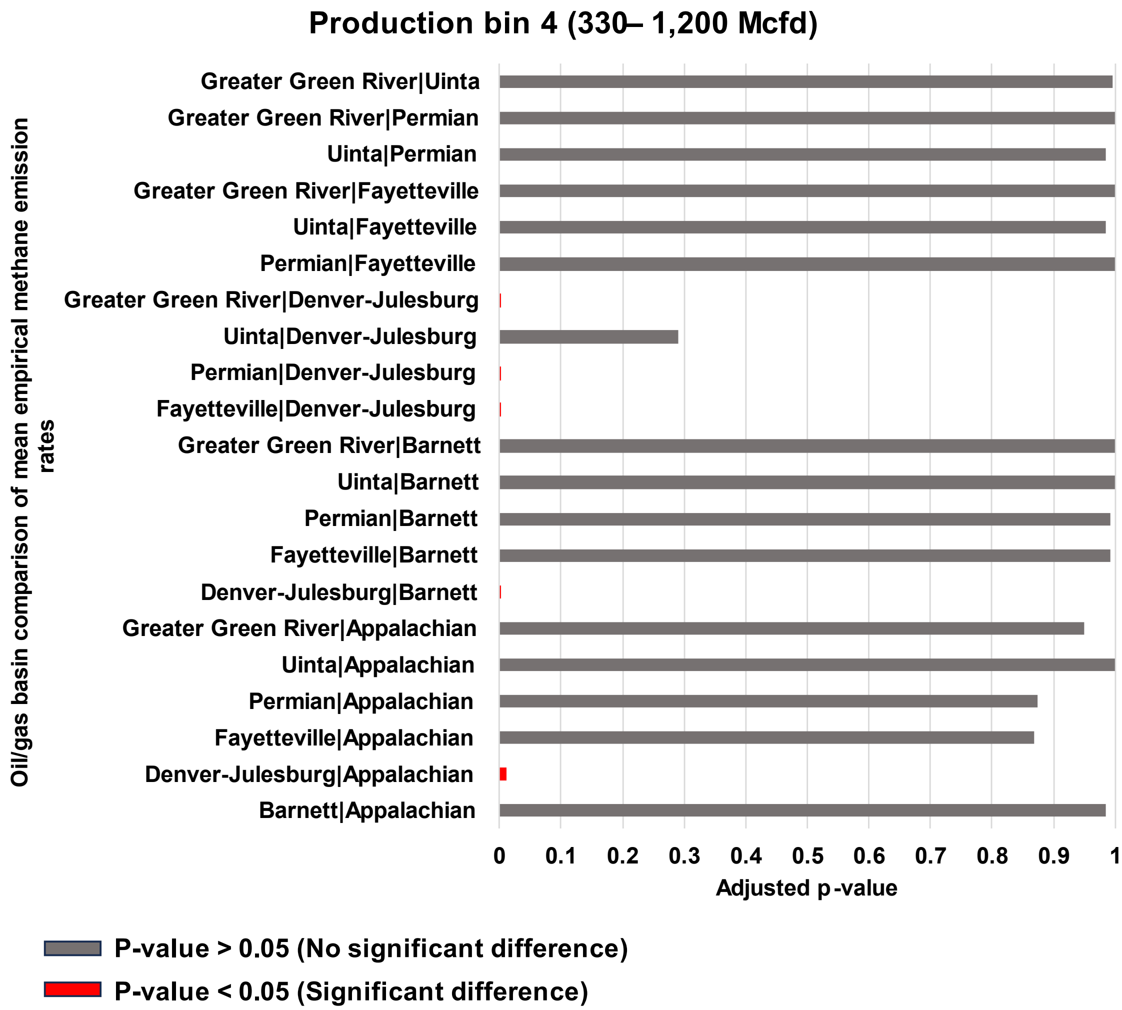

Figure S6: Results of Tukey honest significance test showing the significance of differences between mean well site empirical emission rates gathered from different oil/gas basins for the fourth production cohort of well sites (330 – 1,200 Mcfd). P-values below 0.05 imply a significant difference between mean emission rates for different oil/gas basins, and p-values above 0.05 imply no significant difference. The number of measurements available for each comparison can be found in Table S2.

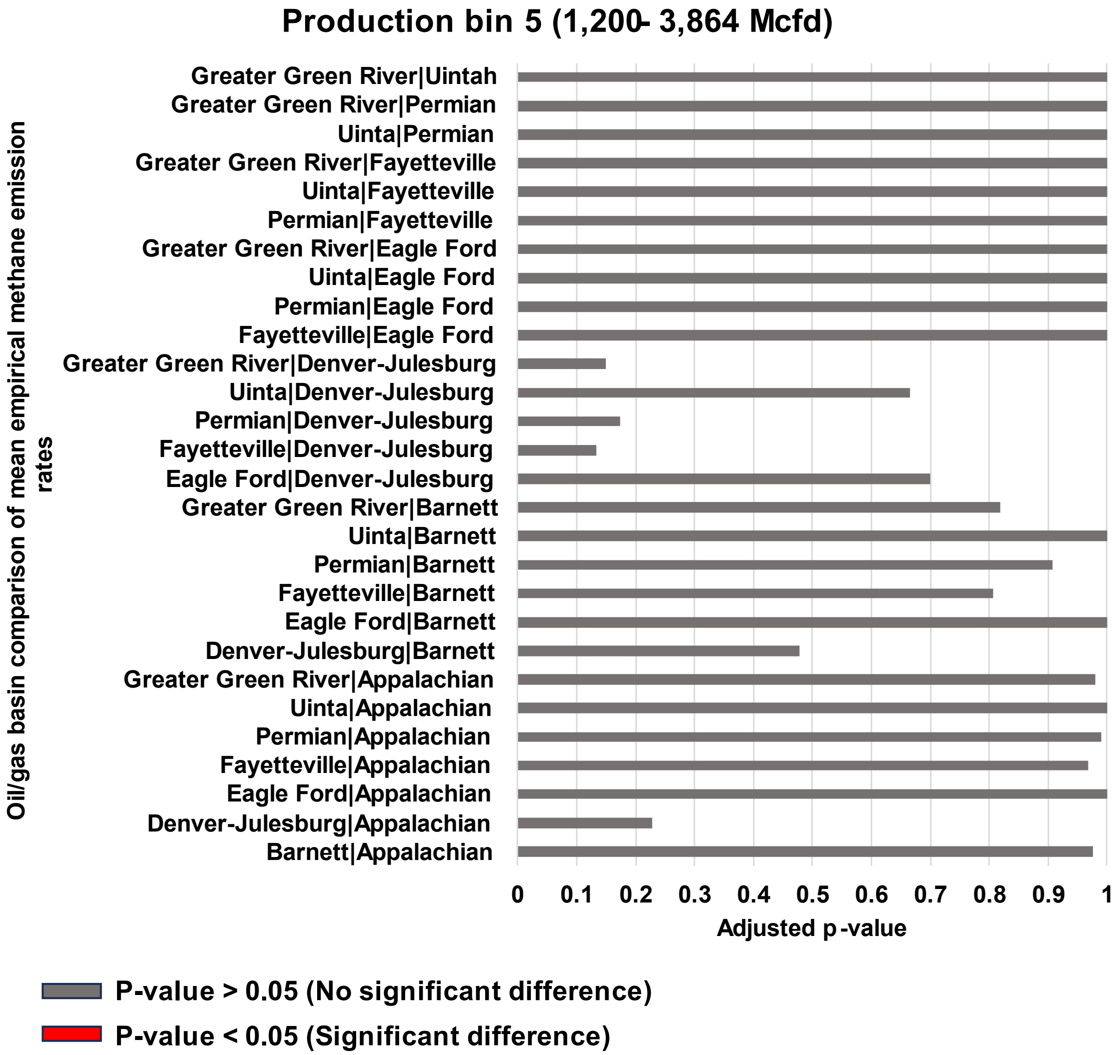

Figure S7: Results of Tukey honest significance test showing the significance of differences between mean well site empirical emission rates gathered from different oil/gas basins for the fifth production cohort of well sites (1,200 – 3,864 Mcfd). P-values below 0.05 imply a significant difference between mean emission rates for different oil/gas basins, and p-values above 0.05 imply no significant difference. The number of measurements available for each comparison can be found in Table S2.

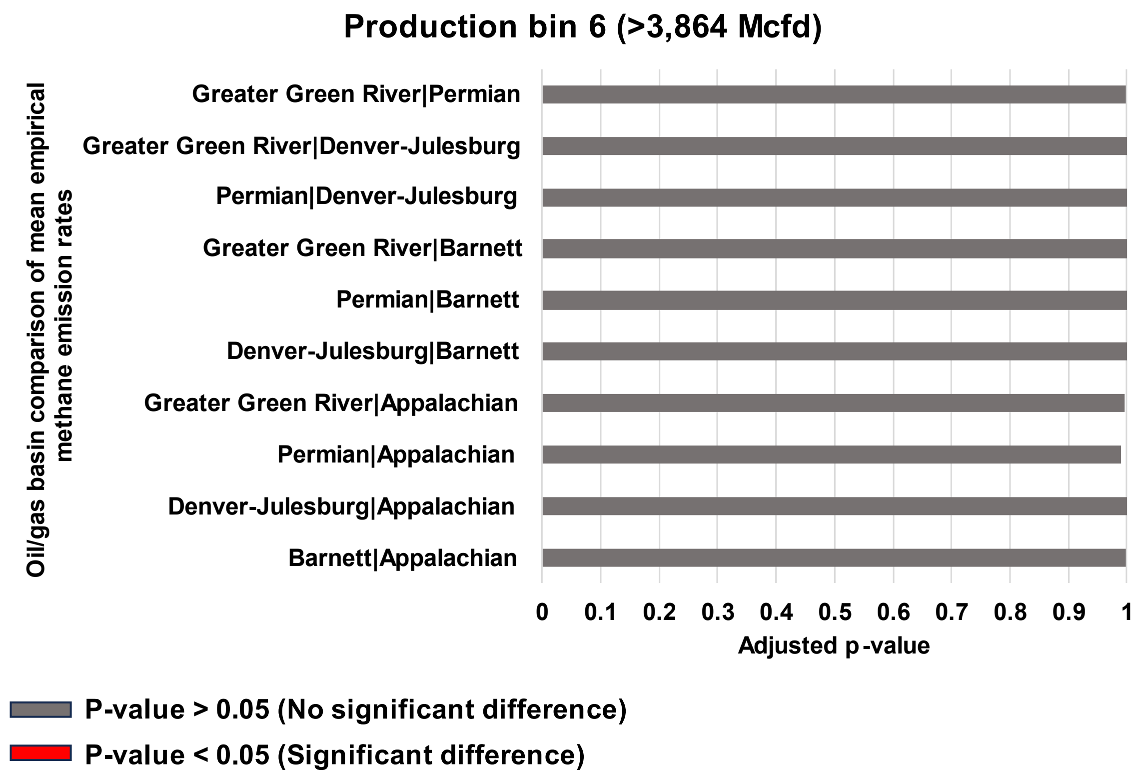

Figure S8: Results of Tukey honest significance test showing the significance of differences between mean well site empirical emission rates gathered from different oil/gas basins for the sixth and highest production cohort of well sites (> 3,864 Mcfd). P-values below 0.05 imply a significant difference between mean emission rates for different oil/gas basins, and p-values above 0.05 imply no significant difference. The number of measurements available for each comparison can be found in Table S2.

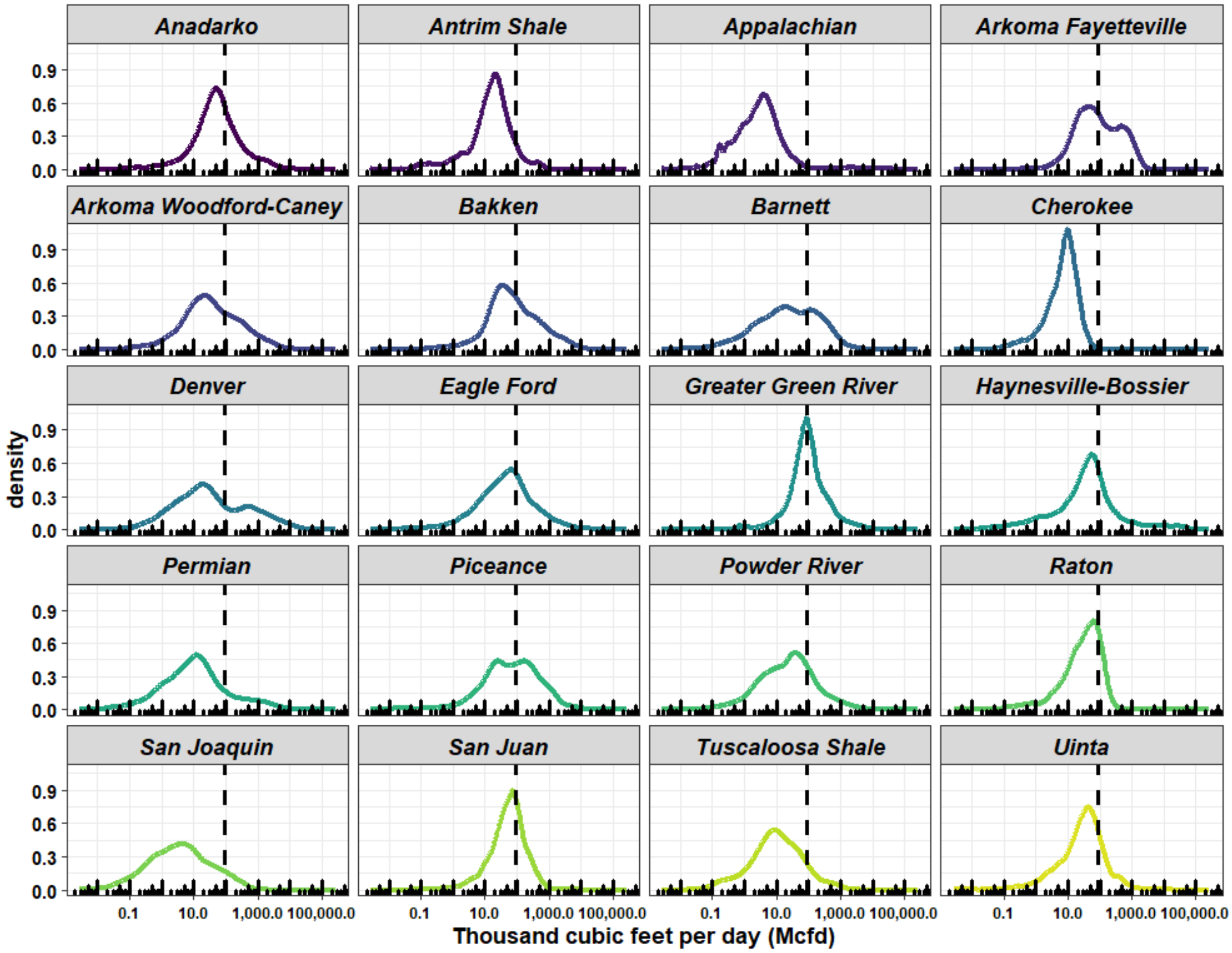

Figure S9: Kernal densities of well site level gas production (Mcfd) for US oil/gas producing basins to illustrate differences in production characteristics among basins. For reference, the black segmented lines represent a gas production value of 90 Mcfd, which corresponds to 15 barrels of oil equivalent per day.

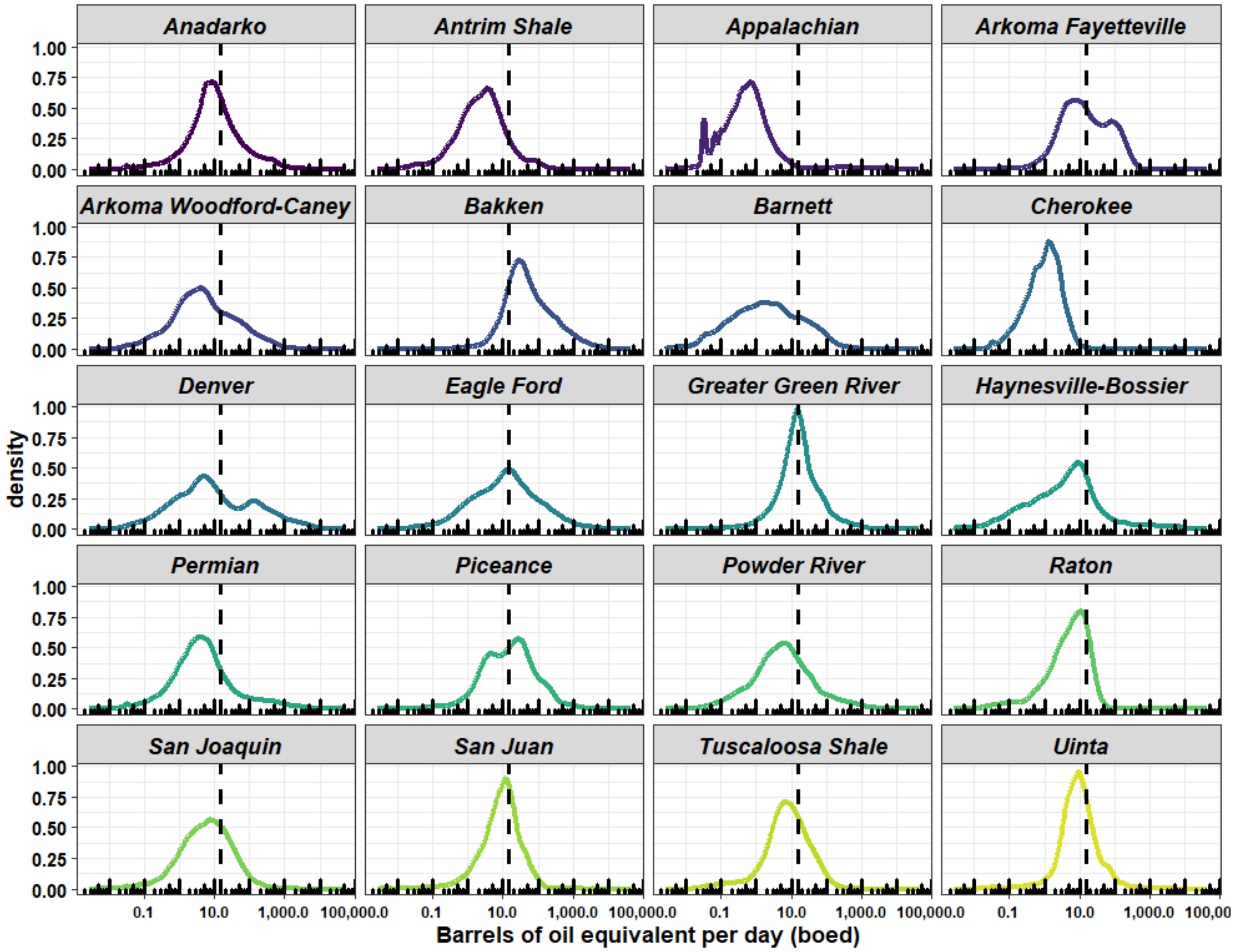

Figure S10: Kernal densities of well site level combined oil and gas production (boed) for US oil/gas producing basins to illustrate differences in production characteristics among basins. For reference, the black segmented lines represent a gas production value of 15 boed.

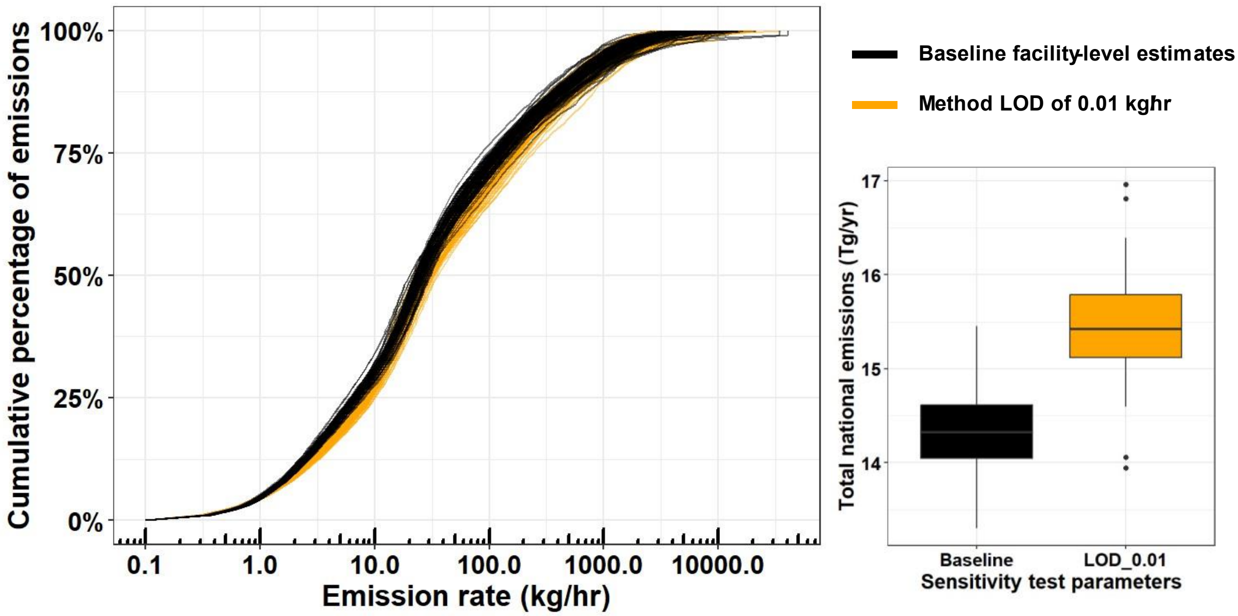

Figure S11: Results of a sensitivity analysis of the method limit of detection used in the facility-level estimates for both the national level oil/gas methane emission distributions (left) and total national methane emissions (right)..). A method LOD of 0.01 kg/hr was tested (orange) against the baseline LOD of 0.1 kg/hr (black) for 100 model estimates each.

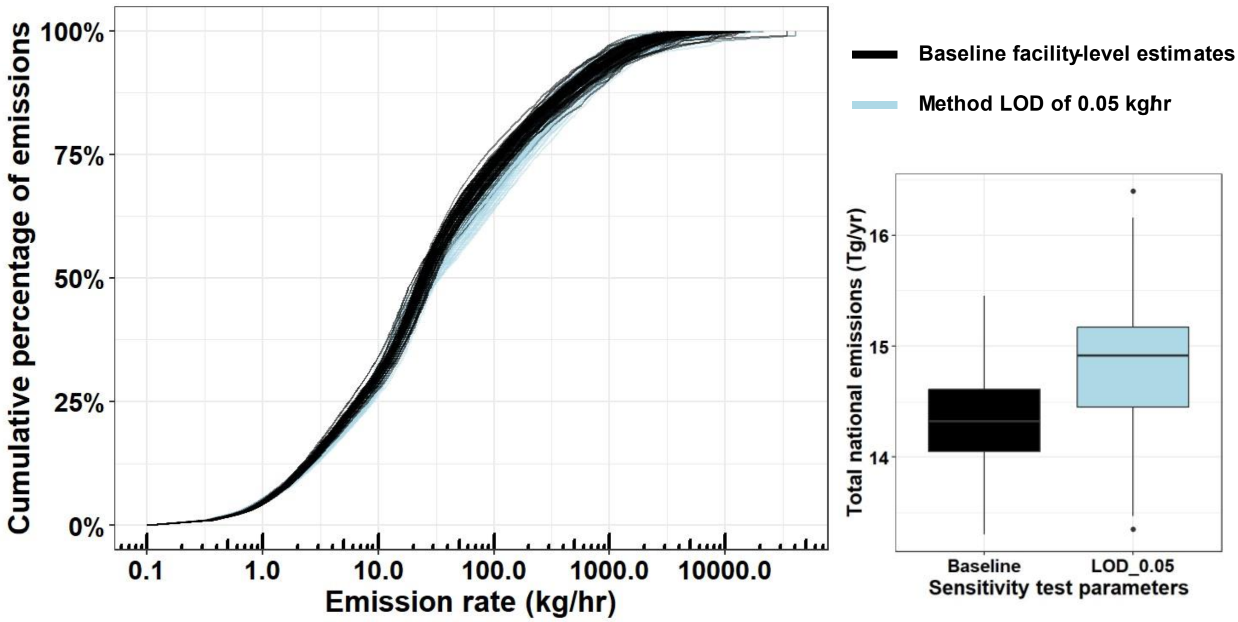

Figure S12: Results of a sensitivity analysis on the method limit of detection used in the facility-level estimates for both the national level oil/gas methane emission distributions (left) and total national methane emissions (right). A method LOD of 0.05 kg/hr was tested (light blue) against the baseline LOD of 0.1 kg/hr (black) for 100 model estimates each.

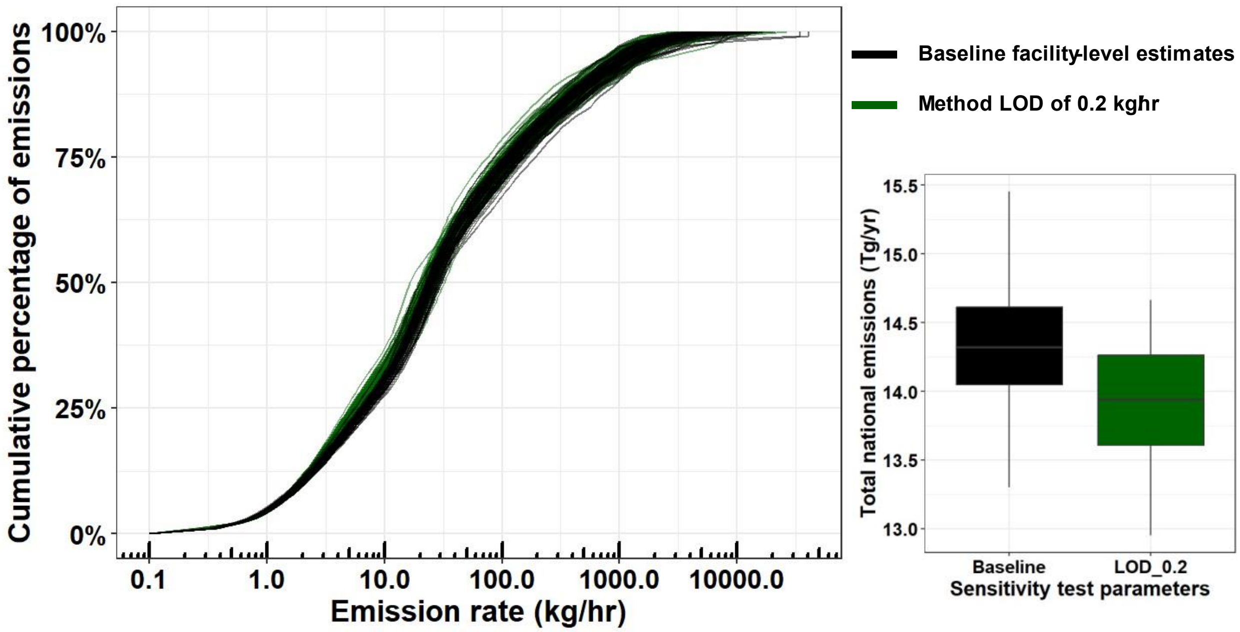

Figure S13: Results of a sensitivity analysis on the method limit of detection used in the facility-level estimates for both the national level oil/gas methane emission distributions (left) and total national methane emissions (right). A method LOD of 0.2 kg/hr was tested (dark green) against the baseline LOD of 0.1 kg/hr (black) for 100 model estimates each.

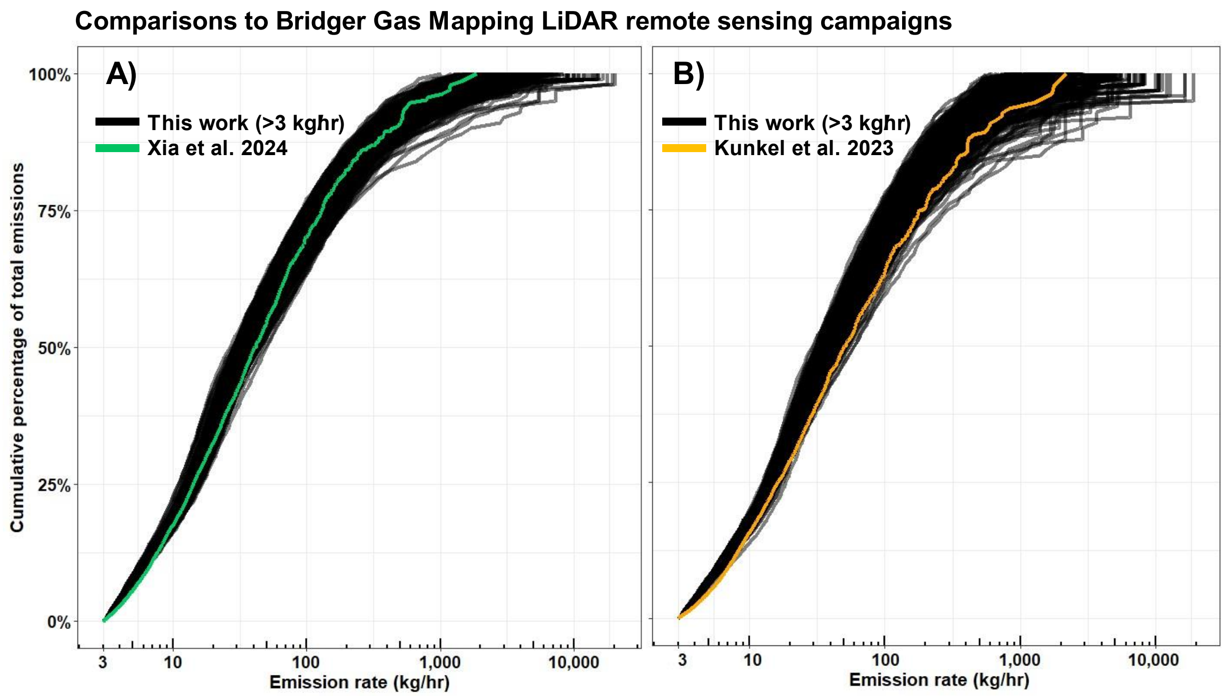

Figure S14: A) Comparison of our facility-level ensemble of methane emission distributions (n=500) to the measured emissions from A) Xia et al. (2024) and B) Kunkel et al. (2023) for sources emitting above 3 kg/hr which is the approximate Bridger GML limit of detection. Spatial domains used for the comparisons 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.

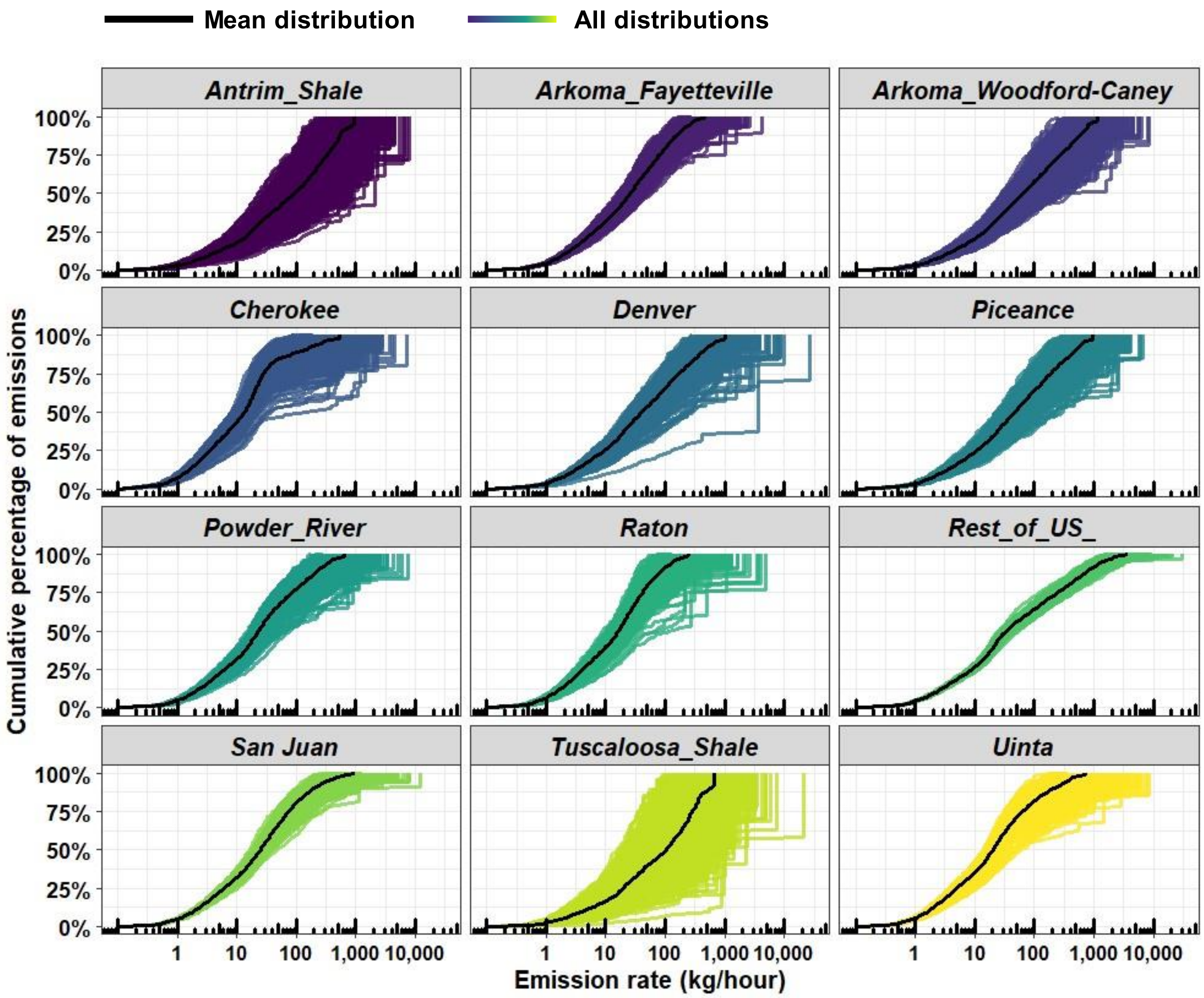

Figure S15: A) Results from 500 model simulations showing the cumulative methane emissions distribution curves for total upstream/midstream oil/gas methane emissions for the bottom eleven emitting oil/gas basins in the CONUS for 2021. The model averages for each basin are shown in the solid black lines. Inset dashed lines represent the percentage contributions of total emission from sources emitting <100 kg/hr. A map of the spatial boundaries used for the different oil/gas basins is shown in Fig. S16.

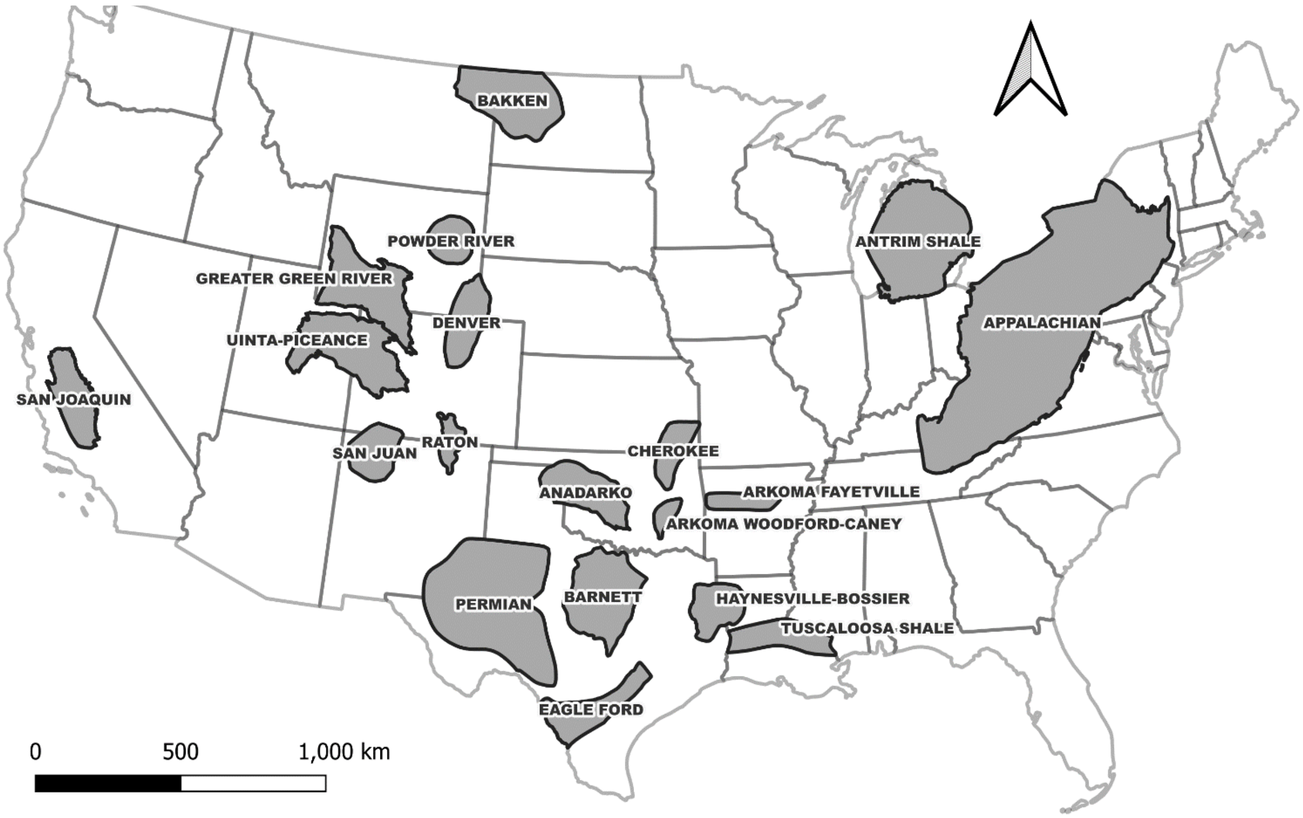

Figure S16: Map of contiguous United States (Alaska not shown) with oil/gas producing basins outlined in grey.

Supplementary Tables

Table S1: 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	52	Well sites
	OTM33a	9	Well sites
	Tracer	34	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
Mitchell et al. 2015	Tracer	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	45	T&S compressors
Yacovitch et al. 2015	Tracer	5	T&S compressors
Mitchell et al. 2015	Tracer	16	Processing plants
Yacovitch et al. 2015	Tracer	4	Processing plants

Table S2: Description of the locations where ground-based empirical measurements used in this work were gathered.

			Production well bins (Mcfd)*					
Oil/gas basin	**Facility category**	**Total # of measurements**	**(0 - 27)**	**(27 - 84)**	**(84 - 330)**	**(330 - 1,200)**	**(1,200 - 3,864)**	**(>3,864)**
Appalachian	Well sites	736	224	74	18	74	152	194
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 S3: Comparison of total ONG 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 oil/gas basin emissions (tonnes/hr)**	**Total oil/gas basin emissions (tonnes/hr)**
MethaneAIR	Permian (RF-06)[†]	91 (62-115)	45 (38-55)
	Permian (MX-025)[†]	125	42 (33-61)
	Uinta (RF-08)	15 (12-23)	11 (9-19)
Alvarez et al. 2018	Appalachian	18 (4-32)	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-Bossier	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)
*Cusworth et al. 2022**	San Joaquin	22 (17-27)	22 (18-29)
	Uinta	34 (28 – 40)	14 (11 – 21)
	Permian (Fall 2019)[‡]	415 (305-525)	226 (205-252)
	Permian (Summer 2020)[‡]	177 (118-236)	51 (43-73)
	Permian (Summer 2021)[‡]	181 (141-221)	55 (48-70)
	Permian (Fall 2021)[‡]	111 (83-139)	54 (46-65)
Chen et al. 2022	New Mexico - Permian	194 (126 - 266)	76 (65 – 89)
Kunkel et al. 2023	Permian	112	163 (146 - 194)
*Xia et al. 2024***	Anadarko, Bakken, Eagle Ford, Permian	162	478 (414 – 534)

* Only surveys where 100% of point source detections were attributed to oil/gas sources are shown for comparison.

** Simulations are based on total emissions from the entire four oil/gas basins, whereas the totals from Xia et al. 2024 are representative of the specific flown boundaries within these four basins which means the total emissions are likely not comparable.

† Both aerial surveys were combined for this oil/gas basin and study into one estimate presented in Fig. 7

⸸ Four aerial surveys were combined for this oil/gas basin and study into one estimate presented in Fig. 7

Table S4: 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	MethaneAIR
	MX-025	Permian	2023		
	RF-08	Uinta	2021		
Cusworth et al. 2022	San Joaquin (F 2020)	San Joaquin	Fall 2020	TROPOMI inversions	GAO and AVIRIS-NG
	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		
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	New Mexico - Permian	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 S5: Breakdown of total oil/gas methane emissions for the CONUS in 2021 contributed from different magnitudes of methane emission rates with the corresponding percentage of total facilities responsible for those emissions.

Emission rate threshold range (kg/hr)	***Percentage of total emissions***
≤0.1	0.2% (0.1 - 0.3%)
0.1 – 1	4.5% (4.0 - 5.1%)
1 – 10	26% (23- 29%)
10 – 100	42% (37 – 46%)
100 – 1,000	22% (18 – 26%)
>1,000	6.1% (2.6 – 13%)

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 boed)	0.53	**Production wells (0 - 27 boed)**	0.24
Production wells (27 - 84 boed)	0.62	**Production wells (27 - 84 boed)**	0.57
Production wells (84 - 330 boed)	0.16	**Production wells (84 - 330 boed)**	0.73
Production wells (330 – 1,200 boed)	0.62	**Production wells (330 – 1,200 boed)**	0.77
Production wells (1,200 – 3,864 boed)	0.97	**Production wells (1,200 – 3,864 boed)**	0.53
Production wells (>3,864 boed)	0.71	**Production wells (>3,864 boed)**	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