


Importance of Super-emitter Natural Gas Well Pads in the Marcellus Shale

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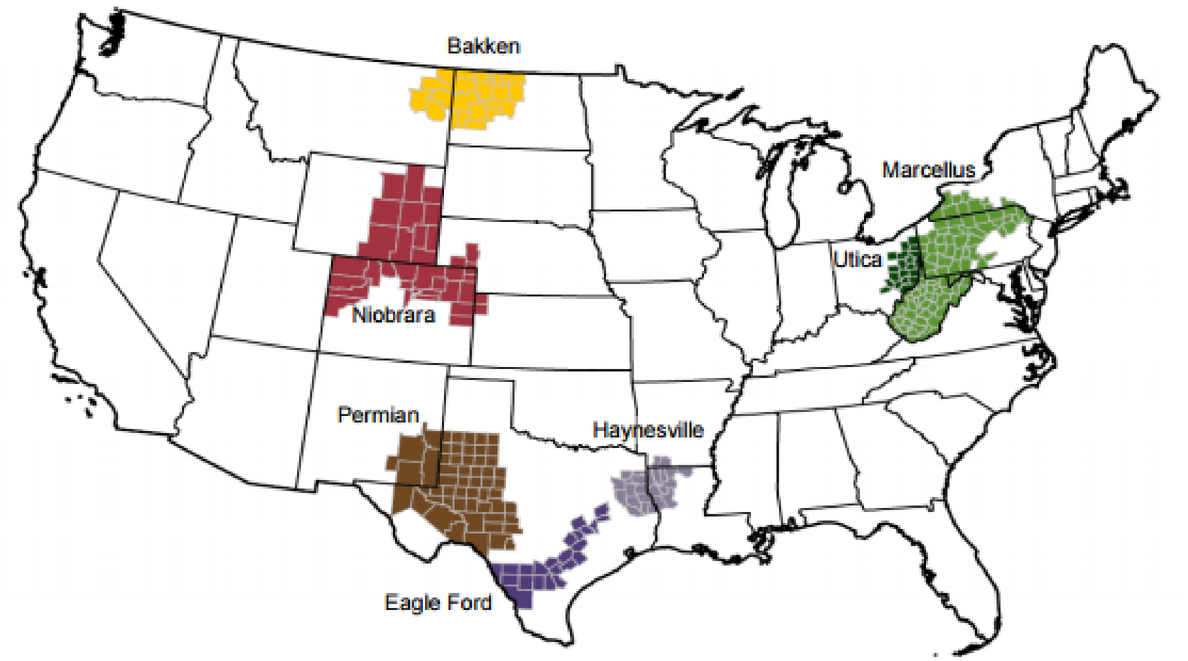
Marcellus/Appalachia

- Marcellus is the most productive natural gas play in the U.S.
- ~10,000 active unconventional gas wells in PA
- ~73,000 active conventional gas wells in PA
- Estimates of 300,00 to 900,000 orphaned, abandoned or plugged wells in PA.

U.S. Shale Plays

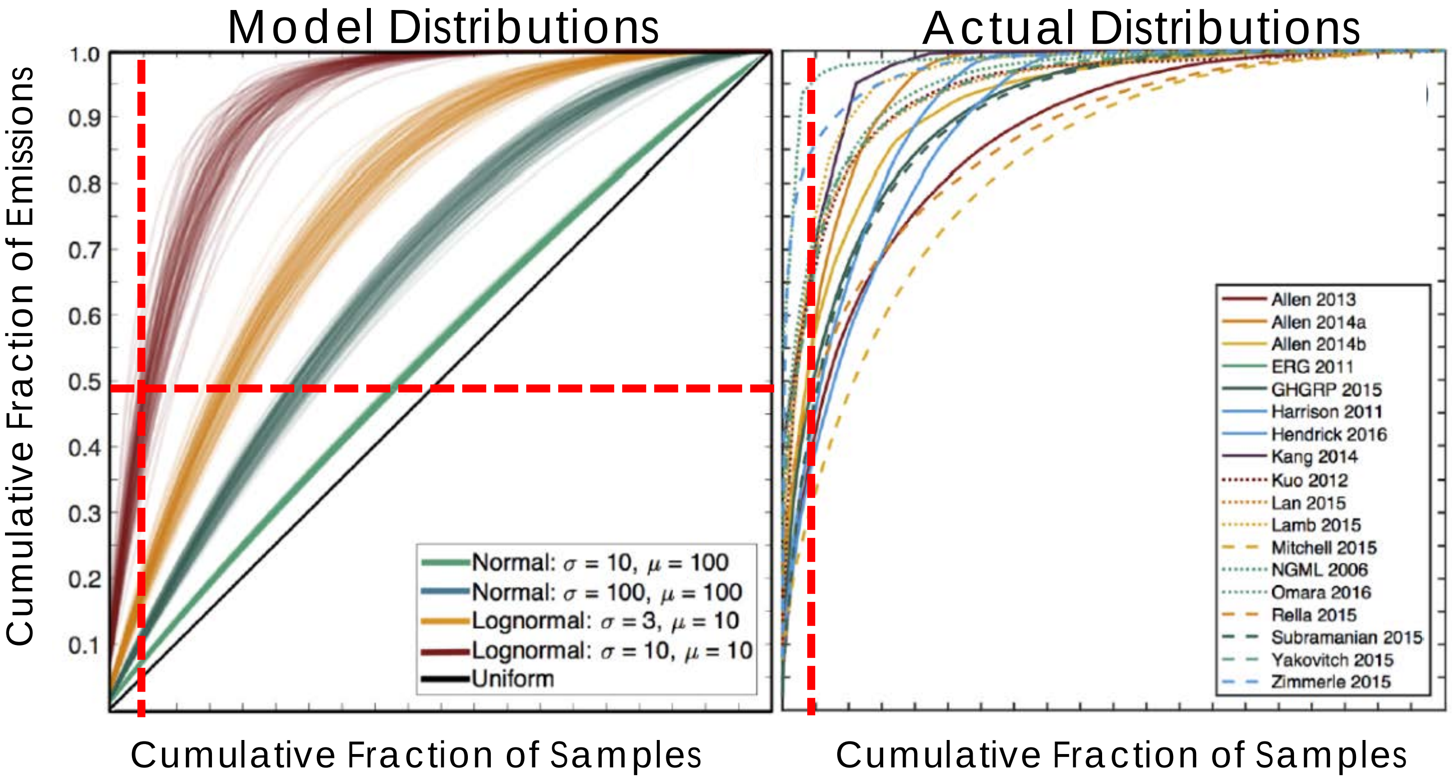


EIA, 2015.

PA DEP; Kang et al., 2014; Kang, 2014; Brandt et al. 2015.

Extreme Emissions Distributions

- Many natural gas studies show lognormal distribution.
- ~50% of emissions come from the top 5% of sites.
- Many studies have small (~100) sample size.
- Small sample sizes may not capture the largest emissions.

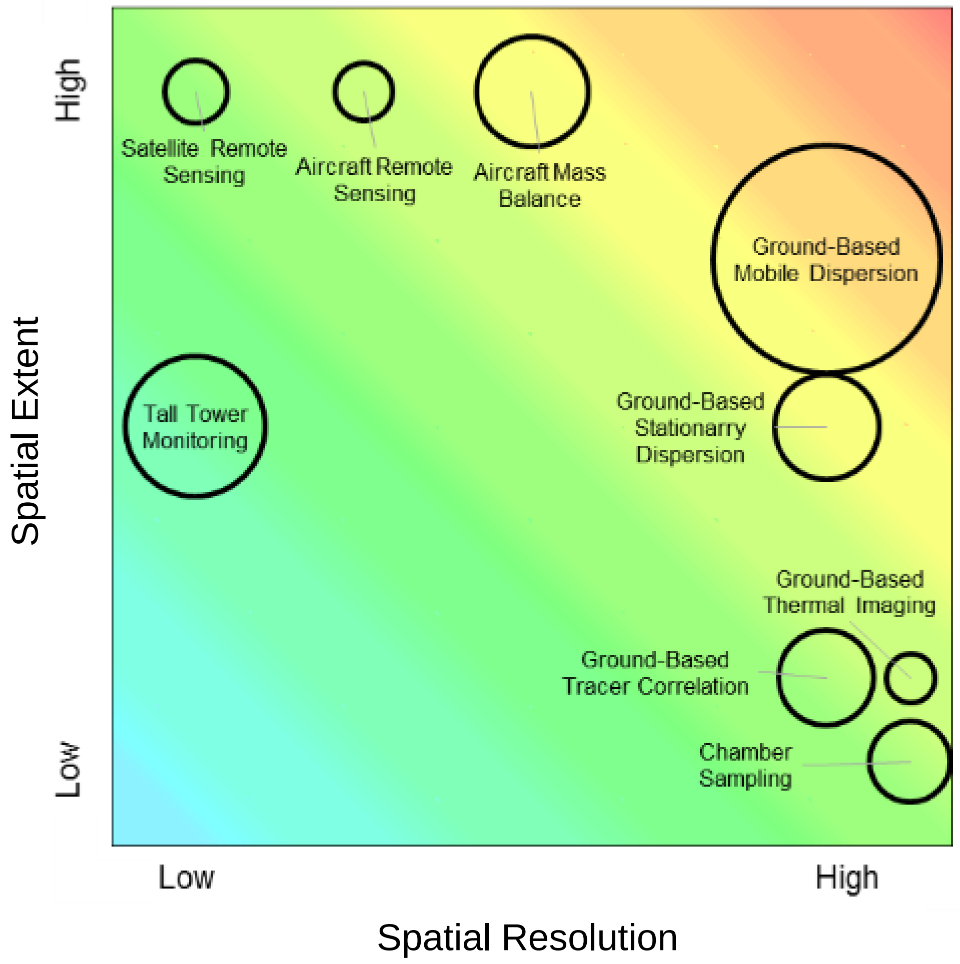


Brandt et al., 2016.

Ground-Based Mobile Dispersion

- Plethora of tools for emission monitoring.
- Ground-based mobile dispersion has some of the largest reported uncertainties.
- Robust methodology has not been available.
- Can the methodology by improved?

Well Pad Methodology Comparison



Gaussian Plume Model

- $C(x,y,z) = \frac{Q}{2\pi\sigma_y\sigma_z u} \cdot e^{\frac{-y^2}{2\sigma_y^2}} \cdot \left[e^{\frac{-(z-h)^2}{2\sigma_z^2}} + e^{-} \right.$

C = concentration

h = source height

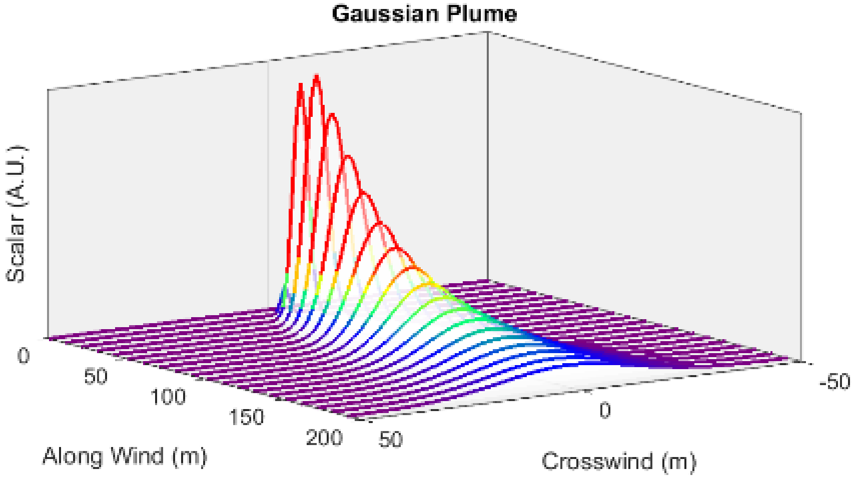
Q = reference emission rate

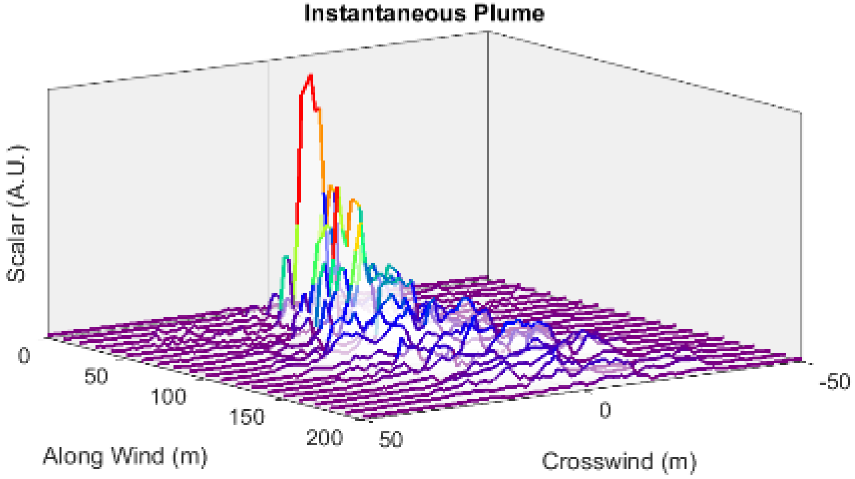
u = mean wind speed

σ_z = vertical dispersion

σ_y = horizontal dispersion

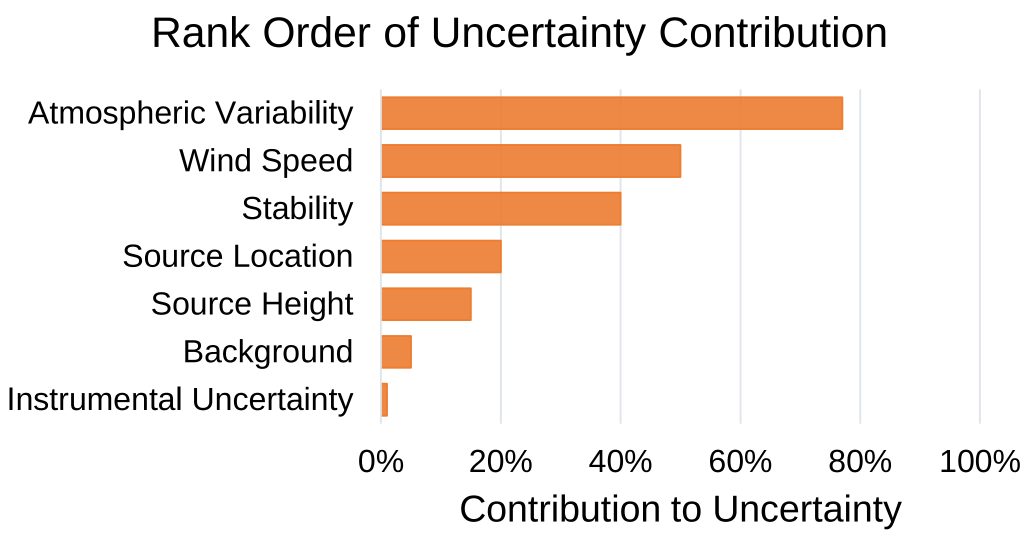
- $Q = \frac{\sum C_{Observation} - C_{Background}}{\sum C_{Model}} \times Q_{ref}$





Uncertainty Estimate

- Large uncertainty for single pass estimates.
- Large uncertainty than other studies.
- This may still be suitable when target sources span many orders of magnitude.
- Resampling is the best way to reduce uncertainty.

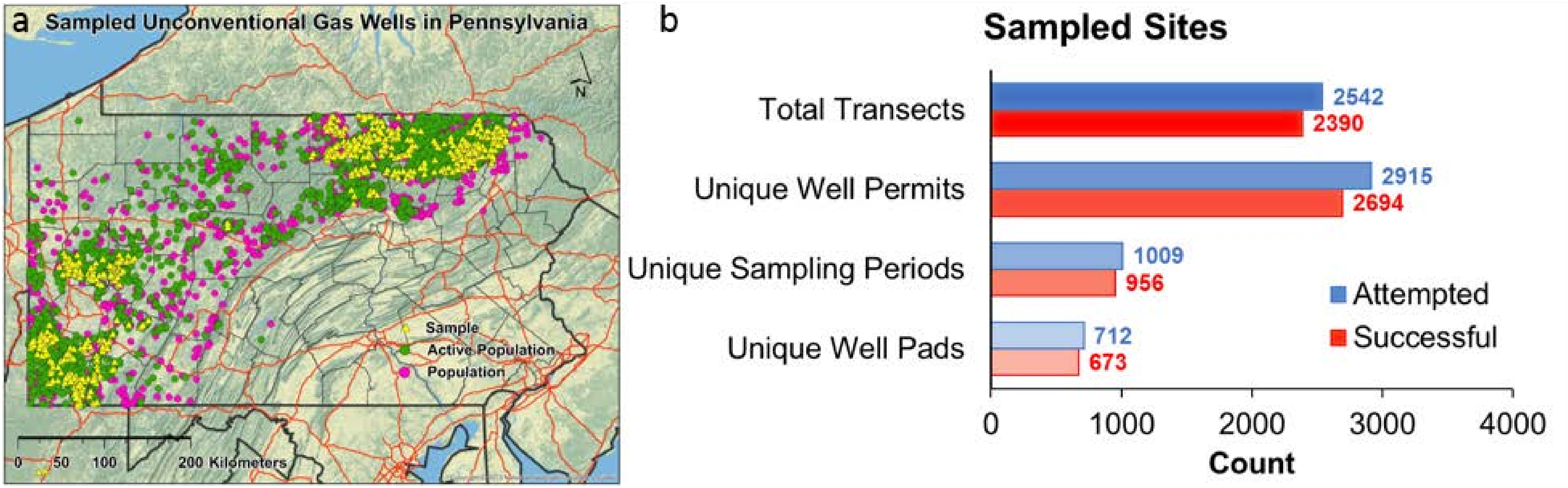


	Gaussian	Gaussian	Lower Limit
No. of Transects	1	10	1
Uncertainty Range (95% CI)	**0.05x-6.5x**	**0.5x-2.7x**	**0.5-1.5x**

Caulton et al., ACP, 2018.

Campaign Statistics

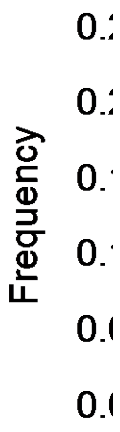
- Data collected in Summer 2015, Fall 2015 and Summer 2016.
- ~ 10,000 miles drives.
- ~ 200 hours of data collected.

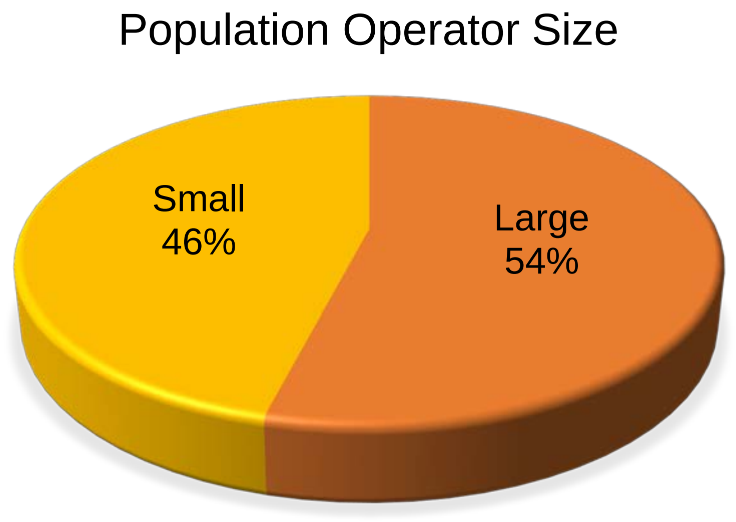


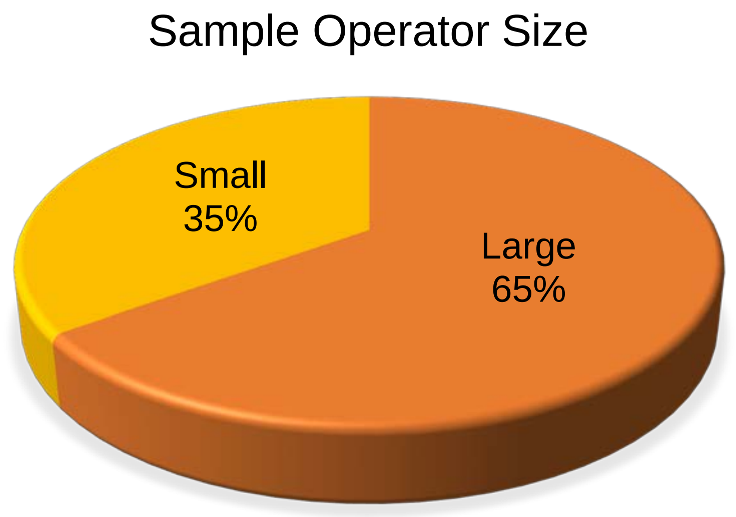
Caulton et al., ES&T, 2019.

Results: Representativeness

- Lifetime production distributions show no significant differences.
- Well age (spud date) of the sample population was slightly older than the population.
- Roughly the same number of sites measured in the northeast and southwest.
- Slight oversampling of sites with large operators (own >500 sites).



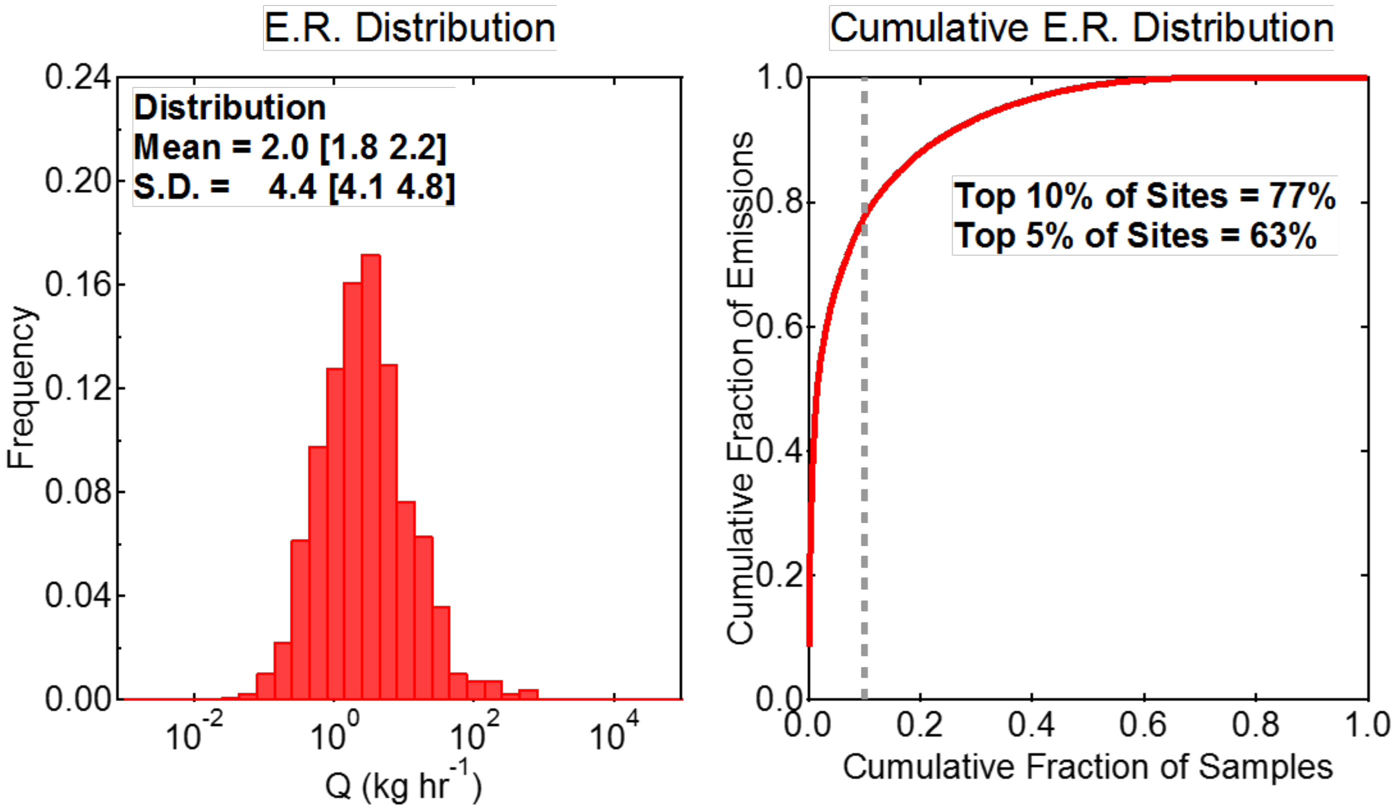




Pennsylvania Dept. of Environmental Protection, www.dep.pa.gov

Results: Distribution

- ~30% of sites had no emissions.
- Lognormal distribution observed.
- Contribution of top 10% of sites is 77%.
- Higher contribution than suggested in the literature.

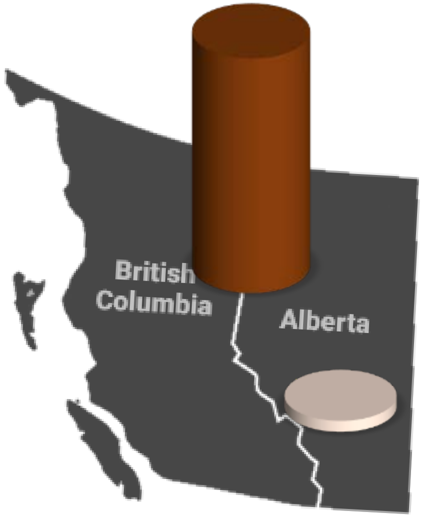


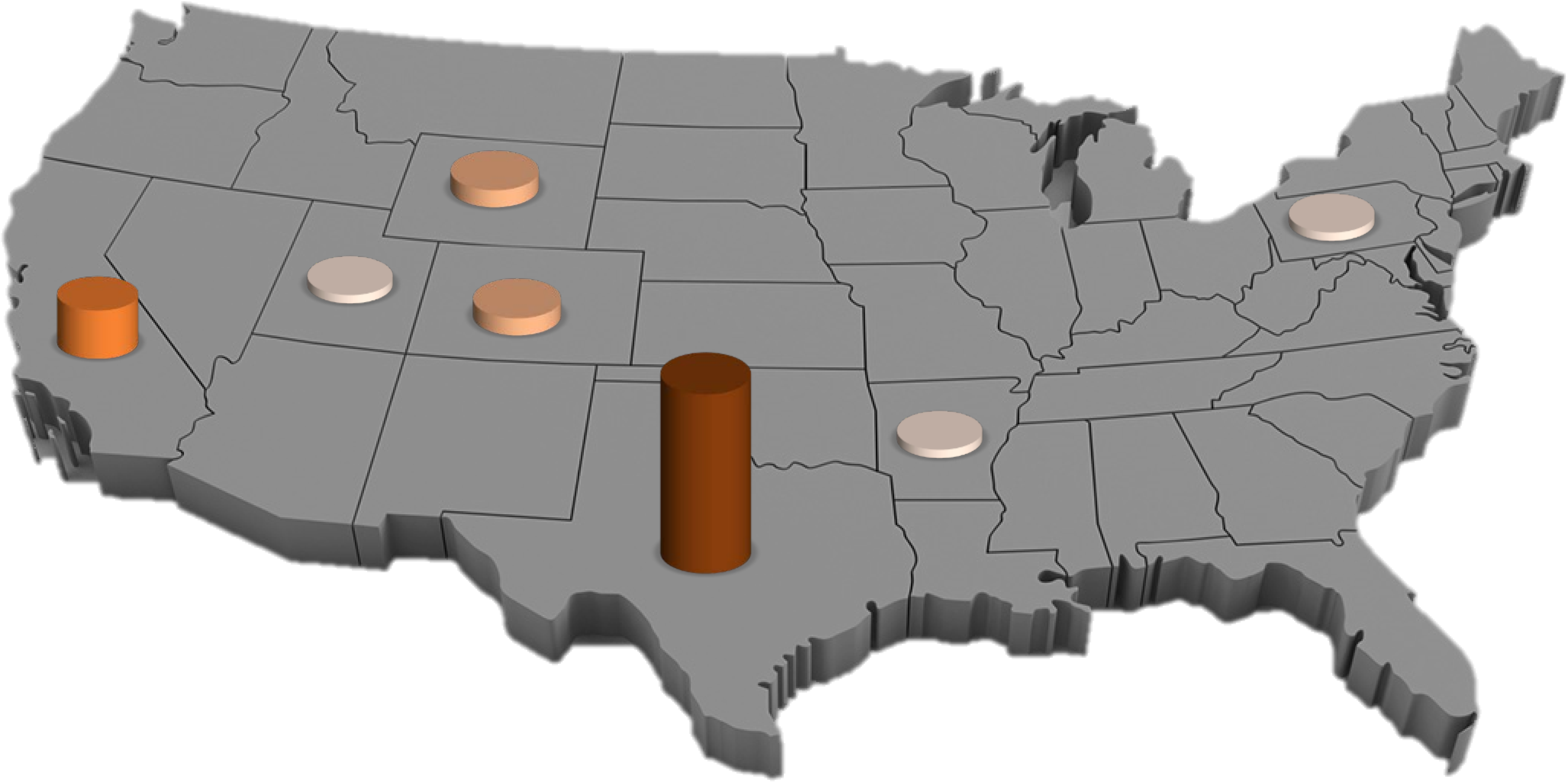
Comparison to Previous Work

- Relative to other studies in the Marcellus, this work suggests lower emission rates.
- Similar statistics to work from other basins.
- Higher contribution from top 10% of sites.

Study	Basin	Sample Size	Geometric μ (kg hr^{-1})	Geometric σ (kg hr^{-1})	Top 10% Contribution
This work	**Marcellus**	**956**	**2.0**	**4.4**	**77**
Omara et al. (2018)	**Marcellus**	**45**	**4.3**	**3.2**	**47**
Omara et al. (2016)	**Marcellus**	**13**	**5.7**	**4**	**50**
Goetz et al. (2015)	**Marcellus**	**3**	**8.7**	**--**	**--**
ERG (2011)	Barnett (TX)*	2126	0.05	24	23
Atherton et al. (2017)	British Columbia	1481	~2.1	--	--
Kuo et al. (2012)	California*	337	0.04	5.5	80
Rella et al. (2015)	Barnett (TX)	115	0.63	4.2	60
Brantley et al. (2014)	Pinedale (WY)	107	2.1	--	--
Robertson et al. (2017)	Denver-Julesberg	84	1.4	3.7	--
Brantley et al. (2014)	Denver-Julesberg	74	0.5	--	--
Robertson et al. (2017)	UGR (WY)	51	2.3	2.9	--
Yacovitch et al. (2015)	Barnett (TX)	43	9.5	6.8	50
Brantley et al. (2014)	Barnett (TX)	43	1.2	--	--
Lan et al. (2015)	Barnett (TX)	33	2.3	6.8	25
Robertson et al. (2017)	Fayetteville (AR)	53	0.68	7.3	--
Robertson et al. (2017)	Uintah (UT)	30	3.7	3.7	--
Zavala-Araiza et al. (2018)	Alberta	25	0.73	4.5	50
Yacovitch et al. (2018)	Fayetteville (AR)	10	1	--	--

Production and Sample Density by State





Ground Sampling
- > 1,000
- 300-1,000
- 100-300
- < 100

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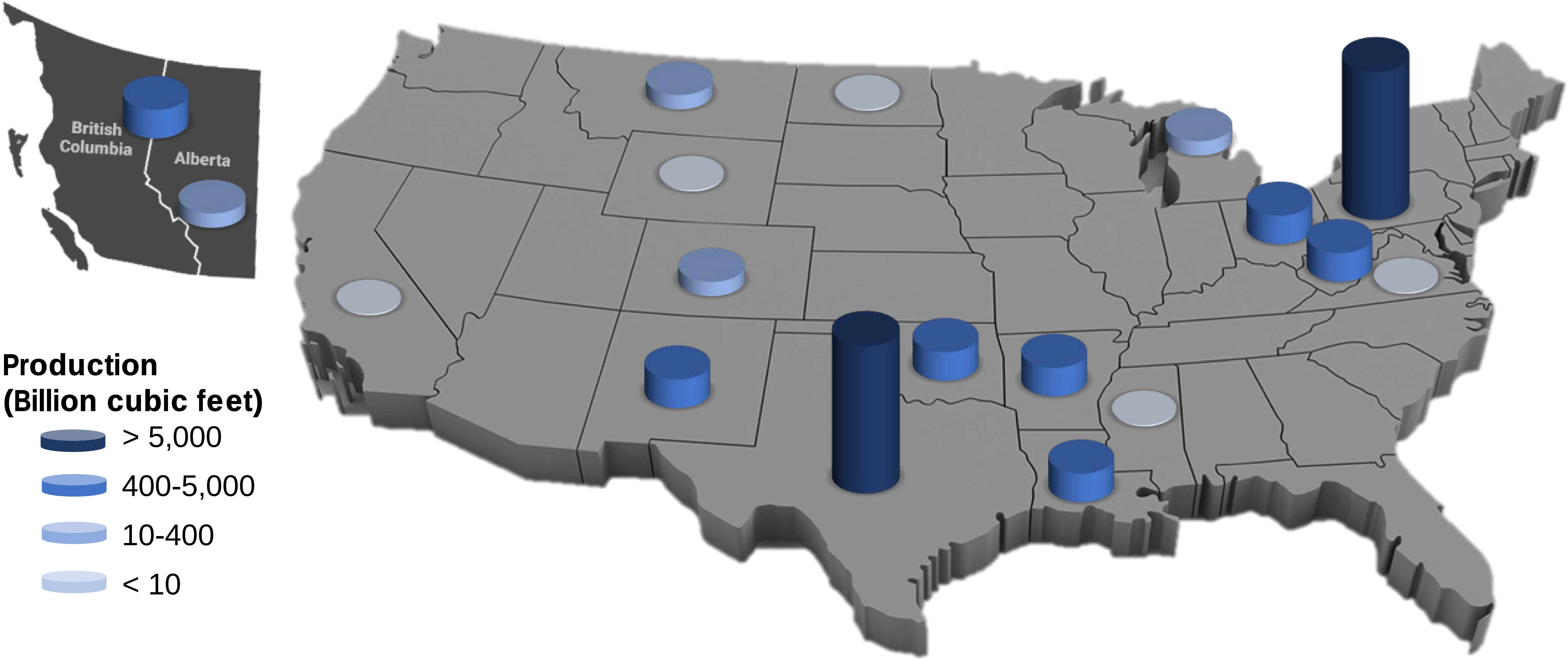

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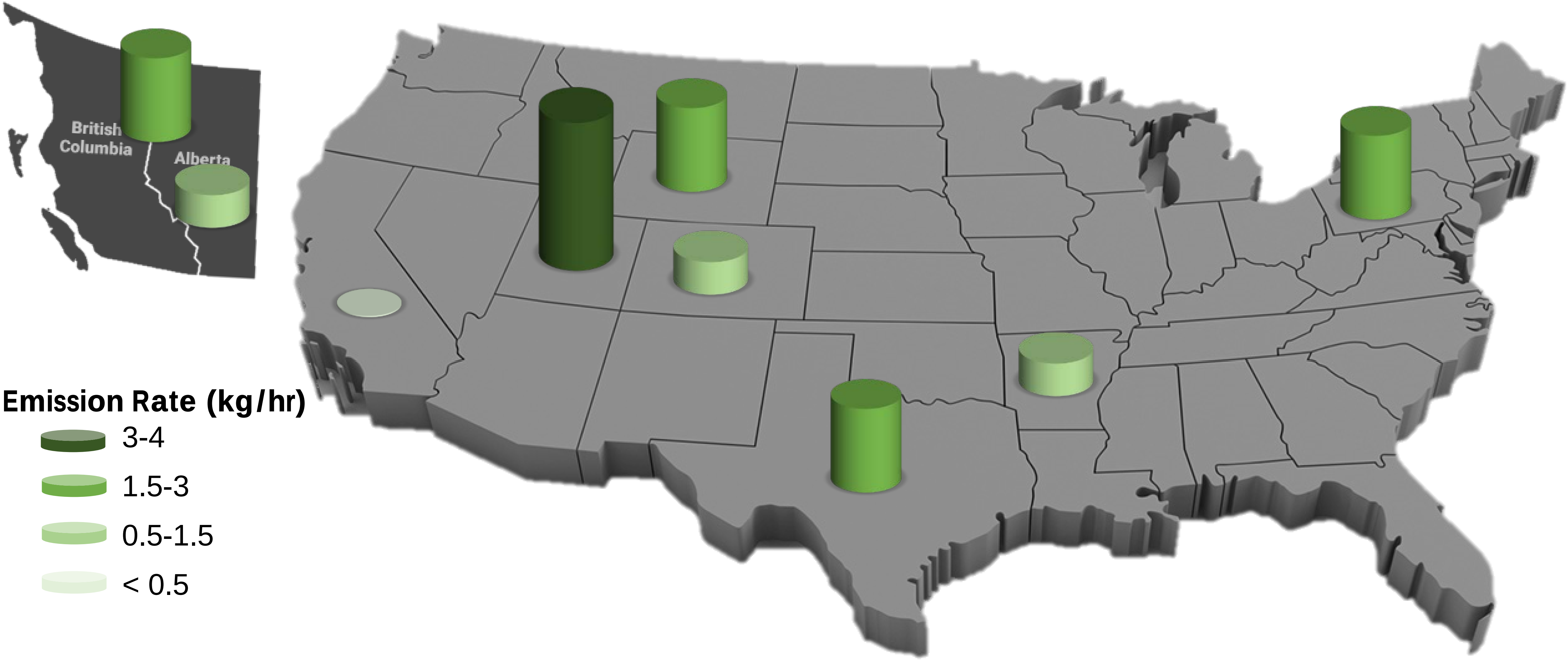
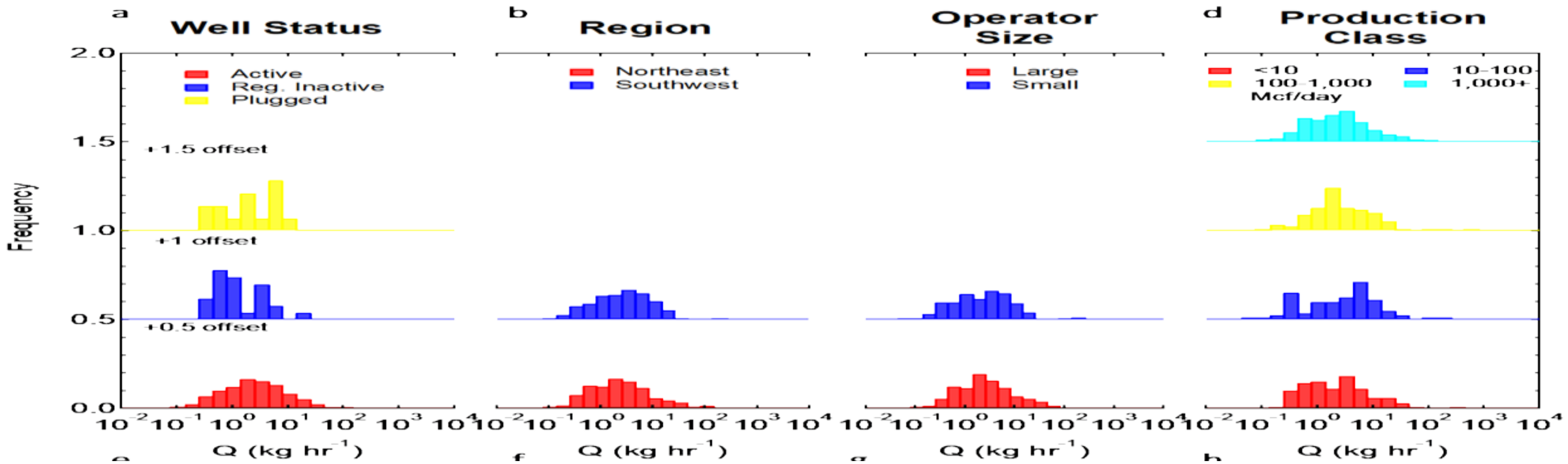


Trends

- Distributions were generally not different between cohorts.
- Active well pads showed the highest frequency of super-emitters.
- Plugged and active well pads had similar leak rates.
- Region, operator and production class showed no difference in mean emissions.

Well Status | Region | Operator Size | Production Class



Marcellus Natural Gas Emissions

- A representative sample of 20% of the Marcellus population.
- Geometric mean emission rate of 2.0 kg/hr.
- Top 10% of sites contribute 77% of emissions.
- Emissions uncorrelated to well age, production, or many other factors.
- Emissions are not predictable with available information.
- Continuous and widespread monitoring still needed to reduce emissions.

Thank you!

- Coauthors at Princeton Univeristy: Jessica Lu, Haley Lane, Mark Zondlo, Qi Li, Elie Bou-Zeid, Jeff Fitts, Levi Golston, Da Pan, Xuehui Guo, Jim McSpiritt, Lars Wendt, Bernhard Buchholz

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Improving Emissions Estimates