Improving estimates of U.S. O&G CH_4 emissions by comparing a custom bottom-up inventory with site-level and basin-level measurements

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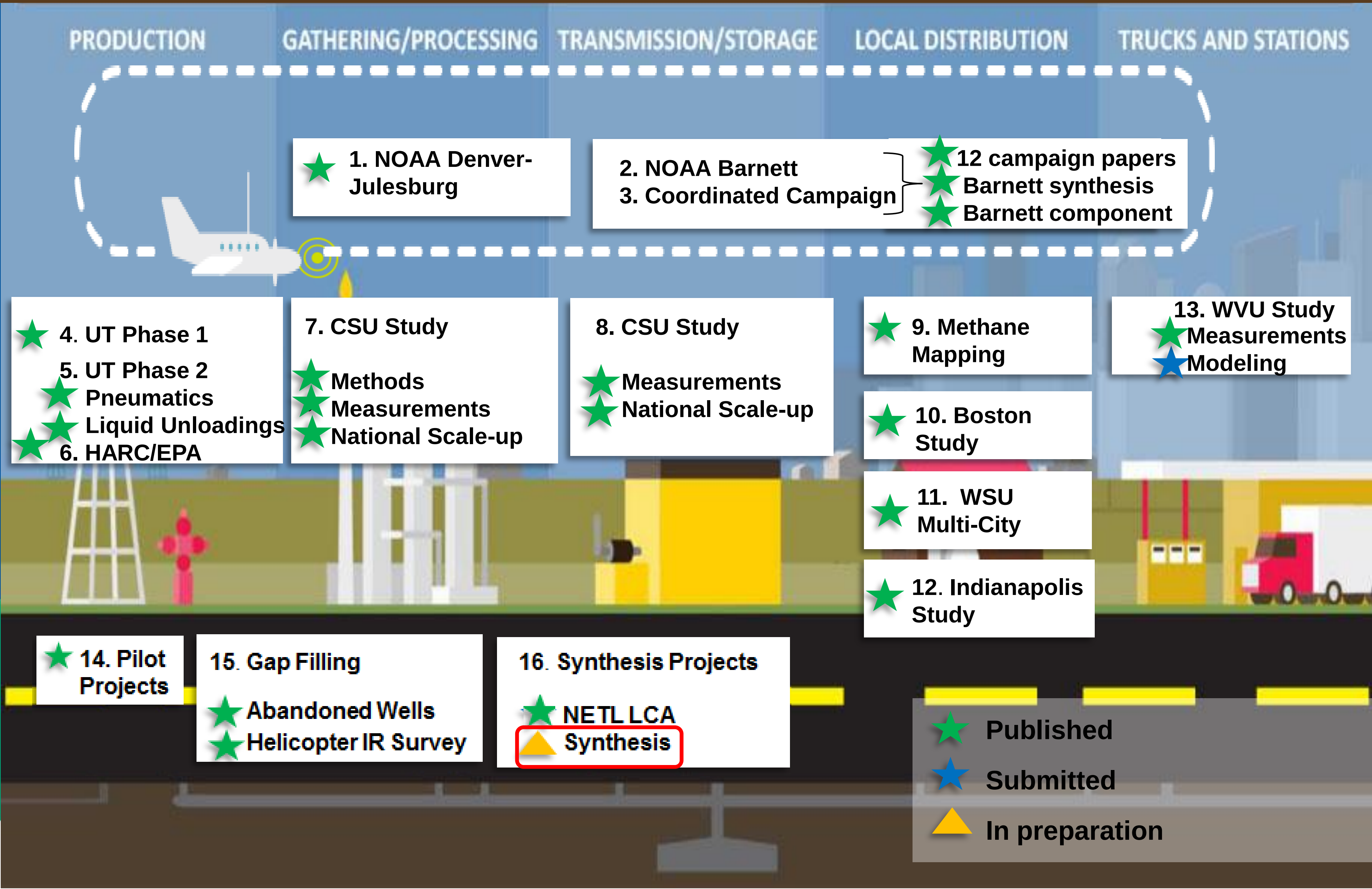
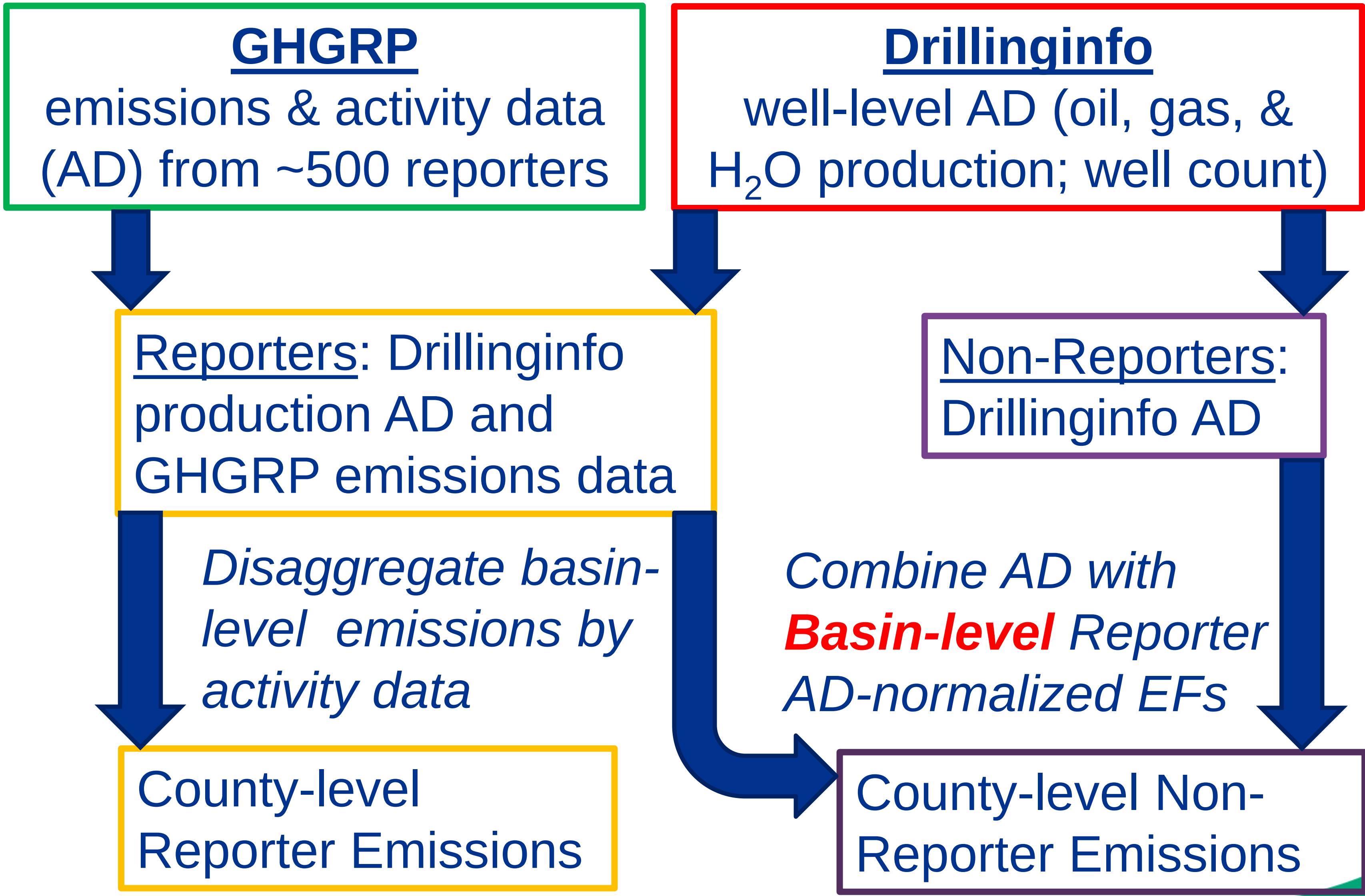
EDF Methane Studies



2015 county-level CH_4 inventory developed by integrating recent data sources

- Drillinginfo
  - 2015 well-level production data
- EPA Greenhouse Gas Reporting Program
  - 2015 onshore production emissions and activity data
- Harvard gridded GHG Inventory(Maasakkers et al 2016)
  - 2012 midstream & downstream emissions by 0.1° x 0.1° grid cells
- Measurement studies
  - Allen et al 2013 (equipment leaks & pneumatic pumps), Allen et al 2014 (pneumatic controllers), Marchese et al 2015 (gathering & processing), Zimmerle et al 2015 (transmission & storage), Townsend-Small et al 2016 & Kang et al 2014 (abandoned wells)
- Other sources
  - AP-42 (combustion exhaust), EPA O&G Tool (produced water), EPA GHG Inventory (gathering lines & offshore)

County-level emissions estimated from basin-level GHGRP data

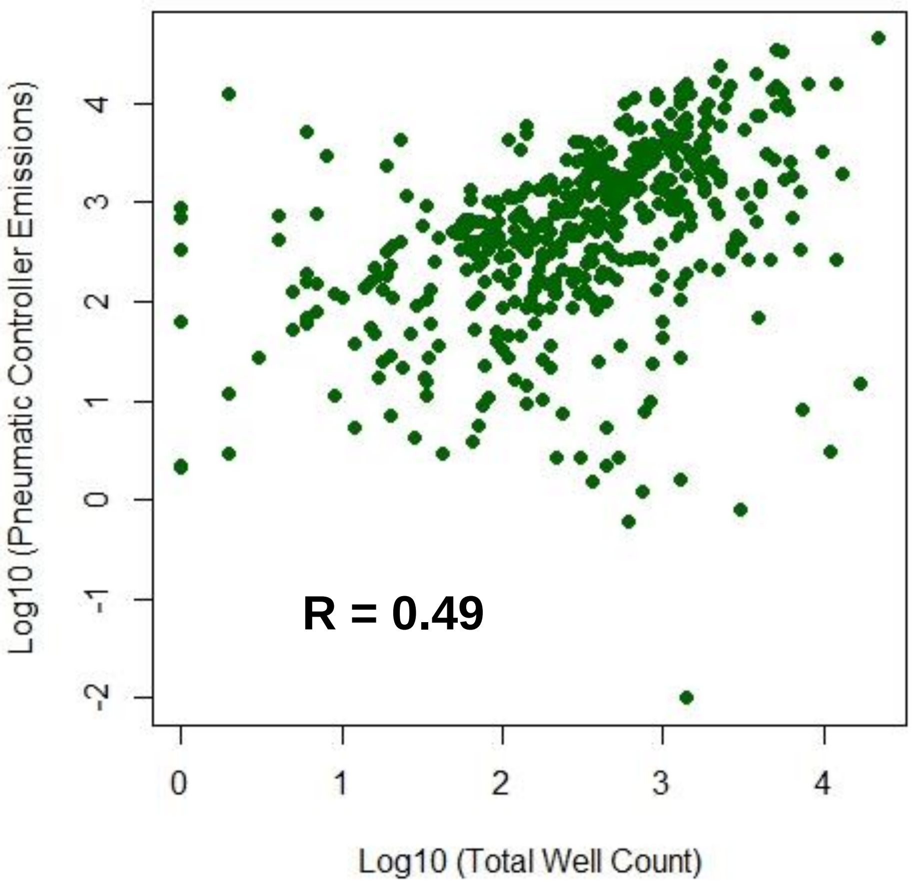


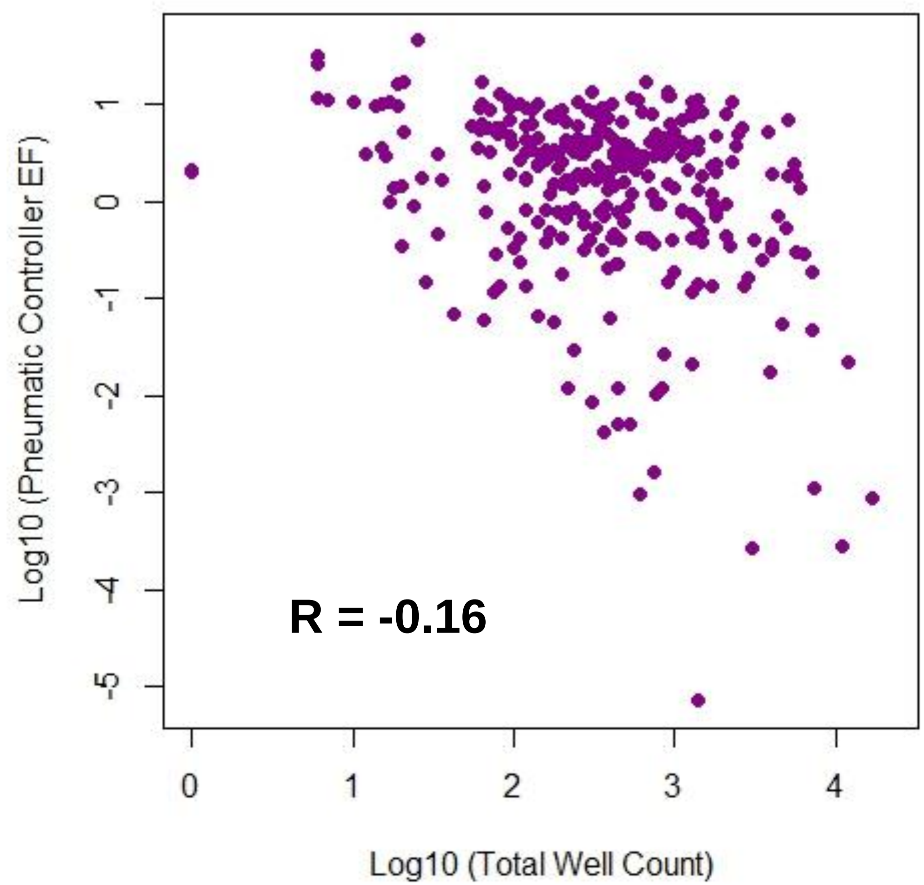
Are GHGRP onshore production data representative of the national population?

- GHGRP reporting facilities account for ~80% of U.S. O&G production and 50% of active wells
- Average O&G production per well is 4–5X higher for reporters than non-reporters
- Within reporters, most emission sources have low to moderate *positive* correlation between emissions and at least one activity data parameter
- Within reporters, most emission sources have a *negative* correlation between activity data and activity data normalized EFs

Example: Pneumatic Controllers

Within GHGRP reporters, total well count is positively correlated with emissions and negatively correlated with emissions/well





Are GHGRP onshore production data representative of the national population?

- GHGRP reporters account for a large fraction of the population but tend to have higher production

- GHGRP reporter derived production-normalized EFs will tend to <u>underestimate</u> non-reporter emissions

Which activity data parameters are best for extrapolating emissions?

Correlation between GHGRP emissions and Drillinginfo Activity Data			
Emission Source	**Activity Data**	**R**	**$p < 0.05$**
Pneumatic Controllers	Total Well Count	0.49	*
Pneumatic Pumps	Total Gas Production	0.13	*
Dehydrators	Total Gas Production	0.07	
Liquids Unloading	Gas Well Count	0.51	*
HC Tanks	Total Oil Production	0.12	*
Associated Gas Venting & Flaring	Gas Producing Well Oil Production	0.32	*
Flares	Gas Producing Well Oil Production	0.20	*
Reciprocating Compressors	Gas Producing Well Count	0.42	*
Centrifugal Compressors	Gas Producing Well Count	0.00	
Combustion Exhaust	Gas Producing Well Count	0.22	*
Leaks - Gas Service	Gas Well Count	0.77	*
Leaks - Light Crude Service	Oil Well Count	0.62	*
Leaks - Heavy Crude Service	Oil Only Well Count	0.57	*

Problem: Choice of activity data can greatly affect non-reporter estimates

Solution: Estimate emissions using multiple AD parameters

Pneumatic Pump GHGRP Non-Reporter Emission Estimates		
Extrapolation AD	R	MT CH_4 y^{-1}
Gas Production	0.13	32,200
Oil Production	0.09	42,700
Well Count	0.11	139,000

Final estimates blend individual source estimates based on AD with statistically significant linear models, weighted by the inverse relative confidence interval of the linear model slopes

$$Emissions_N = m_N\ (\pm sd_N) * AD_N$$

$$Weight_N = m_N / sd_N$$

$$\frac{Estimate_1 * Weight_1 + Estimate_2 * Weight_2 + Estimate_N * Weight_N}{Weight_1 + Weight_2 + Weight_N}$$

Source Estimation Methods

- Basic GHGRP approach (EFs based on reported emissions normalized by activity data)
  - Associated gas flaring
  - Associated gas venting
  - Centrifugal compressors
  - Dehydrators
  - Flares
  - Hydrocarbon tanks
  - Liquids Unloading
  - Reciprocating compressors
  - Well Testing

Source Estimation Methods

- **Pneumatic controllers**
  - GHGRP activity factors (type-specific controllers per AD)
  - Allen et al 2014 emission rates (377 controllers)
  - High-, low-, intermittent-bleed, and malfunctioning controllers EFs = 12, 4, 1, and 43 scfh CH_4
  - 7% of devices assumed to be malfunctioning
- **Pneumatic pumps**
  - GHGRP activity factors (pumps per AD)
  - Allen et al 2013 emission rates (62 chemical injection pumps)
  - EF = 12 scfh CH_4

Source Estimation Methods

- **Equipment leaks**
  - Approach used in Zavala-Araiza et al 2017 for Barnett Shale
  - Allen et al 2013 emission rates (278 leaks)
  - Wells aggregated to pads based on location & 50 m cluster radius
  - For gas producing well pads, site-level EFs based on Allen et al leak rate distribution and number of leaks per site (by well count)
  - For oil only pads, well-level EF based on GHGRP heavy crude leak emissions
- **Completions & workovers**
  - GHGRP No Hydraulically Fractured C&W assumed to be workovers (8% of reported wells)
  - GHGRP HF C&W assumed to be new well completions
  - Oil well completions assumed to have the same potential emissions & control efficiency as gas well completions

Source Estimation Methods

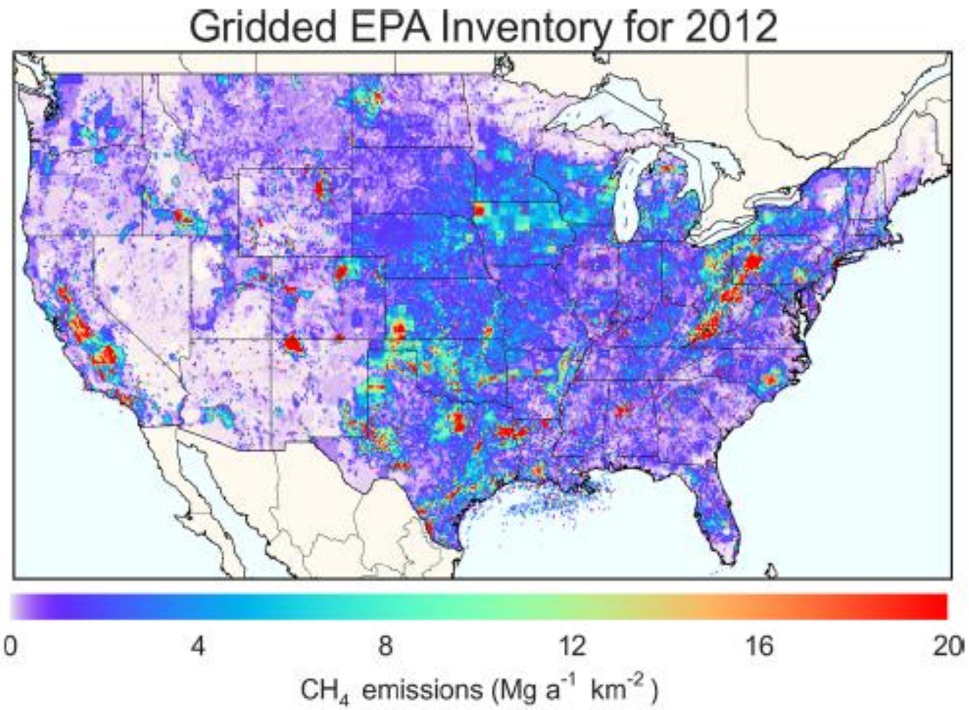
- **Produced Water Flashing**
  - Drillinginfo water production
  - State-level H_2O well^{-1} used for states without well-level data
  - EPA O&G Tool EFs (0.74 – 2.6 scf bbl^{-1})
- **Abandoned Wells**
  - Drillinginfo inactive well counts and Townsend-Small et al 2016 & Kang et al 2014 EFs
- **Combustion Exhaust**
  - GHGRP approach used on reported CO_2 emissions
  - CH_4 emissions converted from CO_2 with AP-42 natural gas compressor and turbine EF CH_4:CO_2

Source Estimation Methods

- **Gathering Stations**
  - Marchese et al 2015 state-specific loss rates
  - Station emissions augmented by ~10% based on Barnett Synthesis (Zavala et al 2016) to account for super-emitters
- **Gathering blowdowns**
  - Marchese et al 2015 episodic emissions (10% of operational emissions)
- **Gathering lines**
  - EPA GHGI leaks $mile^{-1}$ and emissions $leak^{-1}$ factors

Source Estimation Methods

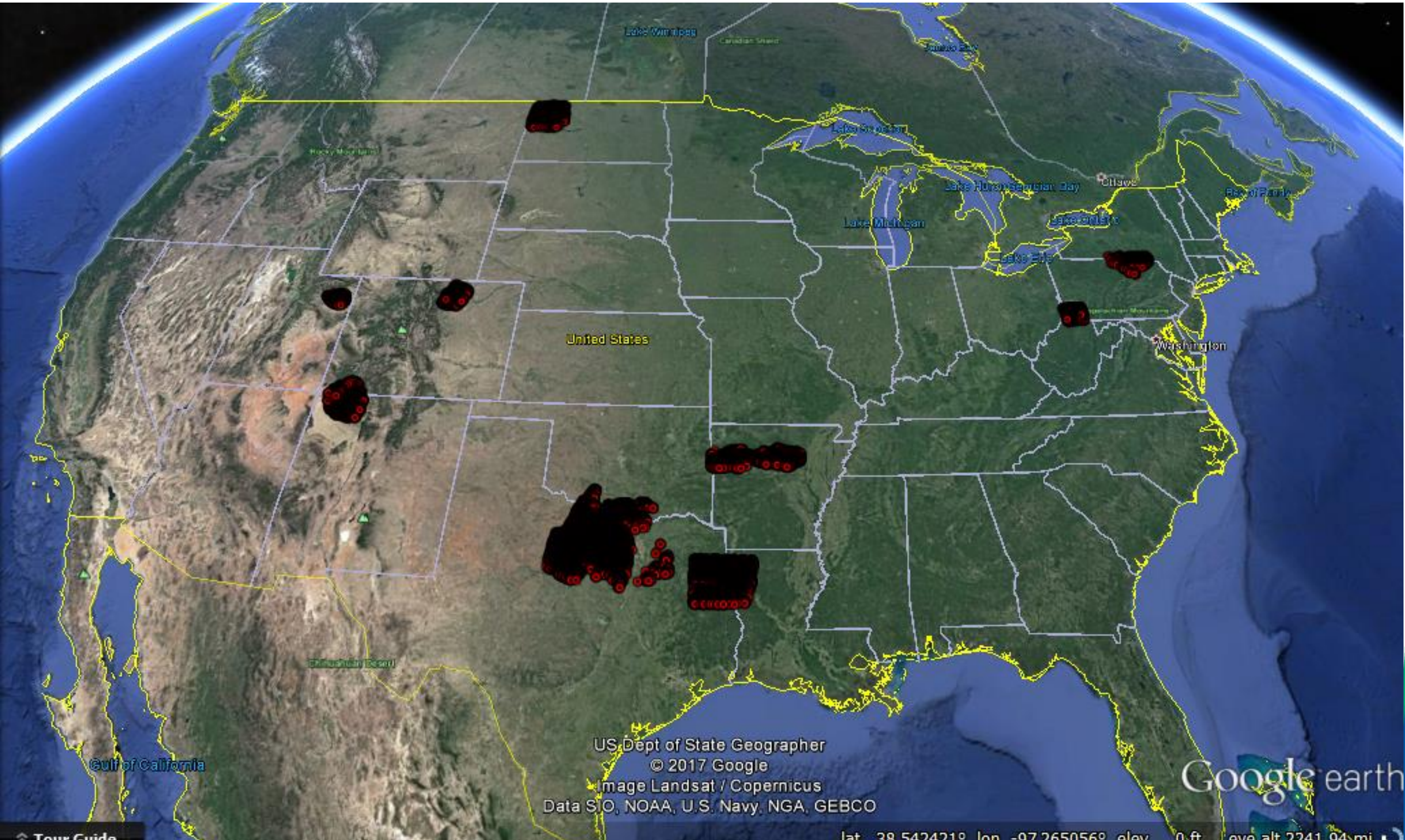
- Maasakkers et al 2016 gridded GHGI used for natural gas processing, transmission & storage, local distribution, other fossil (e.g., coal), and biogenic sources (e.g., landfills)
- Processing and T&S gridded emissions adjusted based on best estimate of national emissions
  - Processing: Marchese et al 2015 (~0.6 Tg), augmented by 22% for super-emitters
  - T&S: Zimmerle et al 2015 including super-emitters (~1.8 Tg)



Uncertainty Analysis

- Monte Carlo model used to estimate emission central estimates & 95% confidence intervals by source and area (county, basin, US, top-down domains)
- Reporter variability
  - EFs for non-reporters developed by randomly drawing from combination of basin-specific and national reporter data weighted by AD
- Extrapolation uncertainty
  - Central estimates: individual estimates blended by statistical weights
  - Lower and upper bounds based on minimum and maximum individual estimates
- Measurement uncertainty
  - Monte Carlos used for measurement data
  - Reported uncertainty used when available

Top-Down studies have quantified emissions in U.S. O&G basins accounting for ~40% of gas and 20% of oil production



Top-Down/Bottom-Up Comparison

- Bottom-up emissions of 10 top-down flight envelopes were estimated by adjusting 2015 county-level inventory for spatiotemporal differences in AD
  - Bakken (Peischl et al 2016)
  - Barnett (Karion et al 2015)
  - Fayetteville (Peischl et al 2015; Schwietzke et al 2017)
  - Western Arkoma (Peischl et al 2015)
  - Haynesville (Peischl et al 2015)
  - Uintah (Karion et al 2014)
  - Denver-Julesburg (Petron et al 2014)
  - San Juan (Smith et al 2017)
  - Southwest PA (Ren et al 2017)
  - Northeast PA (Barkley et al, in review)

Potential Causes of TD:BU Discrepancy

- Top-down O&G flux uncertainty
  - spatiotemporal domain
  - source apportionment
- Temporal patterns in emission sources
  - In the Fayetteville, liquids unloading events are concentrated during time of TD flights
- Inaccurate or missing bottom-up data
  - Lower control efficiencies for tanks and flaring
  - High uncertainty for sources with little empirical data such as gathering blowdowns and pipelines
  - Super-emitters not fully accounted for in EFs

Conclusions

- Our inventory model estimate of total O&G emissions is similar to EPA 2017 GHGI
  - differences for some sources (e.g., lower pneumatic controller and higher equipment leak emissions)
- Both top-down and site-level data indicate that inventory underestimates emissions
  - Production super-emitters most likely are the largest missing source
- Forthcoming synthesis paper will estimate national emissions, inform mitigation strategies, and suggest research priorities

Acknowledgements

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EDF CH_4 Study Papers

1. **December 2013:** UT Production study: http://www.pnas.org/lookup/doi/10.1073/pnas.1304880110
2. **May 2014:** NOAA DJ Basin Flyover: http://onlinelibrary.wiley.com/doi/10.1002/2013JD021272/pdf
3. **November 2014:** HARC/EPA Fence-line study: http://pubs.acs.org/doi/abs/10.1021/es503070q
4. **December 2014:** UT Production Pneumatics study: http://pubs.acs.org/doi/abs/10.1021/es5040156
5. **December 2014:** UT Production Liquids Unloading study: http://pubs.acs.org/doi/abs/10.1021/es504016r
6. **January 2015:** Harvard Boston Urban Methane study: http://www.pnas.org/content/early/2015/01/21/1416261112
7. **February 2015:** CSU Transmission and Storage study, measurements: http://pubs.acs.org/doi/abs/10.1021/es5060258
8. **February 2015:** CSU Gathering and Processing study, measurements: http://pubs.acs.org/doi/abs/10.1021/es5052809
9. **March 2015:** WSU Local Distribution study: http://pubs.acs.org/doi/abs/10.1021/es505116p
10. **May 2015:** CSU Gathering & Processing study, methods: http://www.atmos-meas-tech.net/8/2017/2015/amt-8-2017-2015.html
11. **July 2015:** CSU Transmission & Storage study, national results: http://pubs.acs.org/doi/abs/10.1021/acs.est.5b01669
12. **August 2015:** CSU Gathering & Processing study, national results: http://pubs.acs.org/doi/abs/10.1021/acs.est.5b02275

Barnett Coordinated Campaign Papers (July 2015) papers 13-24:

13. Overview: http://pubs.acs.org/doi/abs/10.1021/acs.est.5b02305
14. NOAA led Top-down study: http://pubs.acs.org/doi/abs/10.1021/acs.est.5b00217
15. Bottom-up inventory: http://pubs.acs.org/doi/abs/10.1021/es506359c
16. Functional super-emitter study: http://pubs.acs.org/doi/abs/10.1021/acs.est.5b00133
17. Michigan airborne study: http://pubs.acs.org/doi/abs/10.1021/acs.est.5b00219
18. WVU compressor study: http://pubs.acs.org/doi/abs/10.1021/es506163m
19. Princeton near-field study: http://pubs.acs.org/doi/abs/10.1021/acs.est.5b00705
20. Purdue aircraft study: http://pubs.acs.org/doi/abs/10.1021/acs.est.5b00410
21. Aerodyne mobile study: http://pubs.acs.org/doi/abs/10.1021/es506352j
22. U of Houston mobile study: http://pubs.acs.org/doi/abs/10.1021/es5063055
23. Picarro mobile flux study: http://pubs.acs.org/doi/abs/10.1021/acs.est.5b00099
24. Cincinnati tracer apportionment: http://pubs.acs.org/doi/abs/10.1021/acs.est.5b00057

25. **December 2015:** Barnett Synthesis: http://www.pnas.org/content/112/51/15597.abstract
26. **March 2016:** Abandoned & Orphaned Wells: http://onlinelibrary.wiley.com/doi/10.1002/2015GL067623/full
27. **April 2016:** Aerial Infrared Survey: http://pubs.acs.org/doi/abs/10.1021/acs.est.6b00705
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30. **January 2017:** Barnett component paper: https://www.nature.com/articles/ncomms14012