Declining Methane Emissions in Colorado in the Last Decade Suggest Observable Impact of Early Adoption of Oil and Gas Methane Regulations

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Since the first oil and gas methane regulations were passed in Colorado in 2014, regulations have been a key strategy to reduce methane emissions from the oil and gas sector. However, direct evidence of the efficacy of these regulations has hitherto been lacking, in part because of the lack of consistent measurement data—a necessity to reliably track changes in emissions over time. The Greenhouse Gases Observing Satellite (GOSAT), launched in 2009, is one of the earliest satellites to measure methane concentrations. GOSAT observations, as well as some data points from ground and aircraft studies, are our only view into methane trends during these early days of oil and gas methane regulations. These data sources allow us to examine trends in methane emissions and overlay them with the adoption of regulations to see if the regulations had an observable impact. Colorado, the leading state in regulating oil and gas methane emissions, provides an excellent case study in using measurement-based data to examine trends in methane emissions.

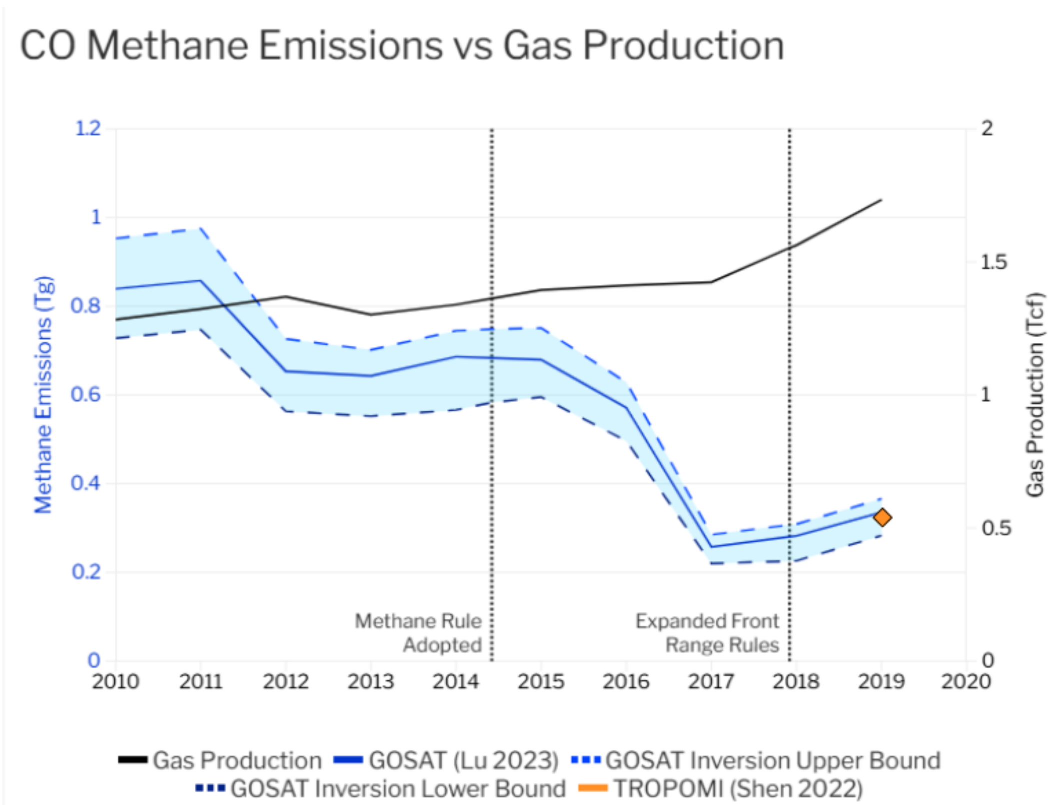


Figure 1: Absolute oil and gas methane emissions for Colorado (excluding tribal lands), plotted along with gas production for the state (also excluding tribal lands). GOSAT emission estimates use the inversion done by Lu et al. 2023, extracted at the state level using the files available in the data repository. See Methodology for more details about how tribal lands were excluded. The GOSAT upper and lower bounds are derived from the 12-member inversion ensemble (see Methodology for more details). The TROPOMI estimate is derived from Shen et al., extracted at the state level using the files available in the data repository. Gas production for the state is pulled from Enverus. Effective dates for the first two oil and gas methane regulations in Colorado are shown with vertical grey lines.

As shown with the GOSAT estimates in Figure 1, Colorado's absolute oil and gas methane emissions show a clear decline in 2011 (close to a 25% decrease between 2011 and 2012) and another clear decrease starting in 2015 (with an overall ~70% decrease in emissions between 2010 and 2017). These decreases in emissions occurred despite increasing gas and oil production in the state (graph of oil production shown in the Methodology).

This significant decrease in absolute methane emissions is quite unique among oil and gas producing states. Using the same GOSAT inversion, absolute emissions in Texas increase by over 30% over the same period. States such as Louisiana and North Dakota have varying emissions over the same period but end in 2019 close to their starting 2010 emissions. Total absolute oil and gas methane emissions for the United States remained relatively flat during this time period. While some states such as Arkansas and Montana also have decreasing emissions, most of the states with decreasing emissions also have decreasing gas production. The only other major oil and gas producing state that shows decreasing emissions without corresponding decreasing gas production from 2010 to 2019 is New Mexico (see discussion and graph in the Methodology for explanation).

In Colorado, it is not immediately obvious what may have caused the first decrease in methane emissions from 2011 to 2012. Oil and gas VOC regulations were passed for the ground-level ozone nonattainment area of Colorado in 2004, 2006, and 2008. These VOC regulations targeted tanks, dehydrators, and compressors, many of which emit substantial amounts of methane in addition to VOCs. Though intended to reduce VOC emissions, these regulations may have had the secondary impact of reducing methane emissions from the oil and gas sector as well, as found in Alberta, Canada.

The second decreasing emissions trend lines up very well with the initial regulation of methane emissions from the oil and gas industry in Colorado. The first oil and gas methane regulations in Colorado took effect in mid-2014, and additional methane and VOC regulations took effect in late 2017 and early 2020. Among other requirements, these regulations established a leak detection and repair program, adopted pneumatic controller requirements, and limited venting during maintenance activities.

The emission trends shown above suggest that particularly the first regulations may have significantly decreased methane emissions in the state. GOSAT data shows a decrease starting in 2015 with a faster rate of decrease in 2016 and 2017, perhaps indicating that time was needed for the effects of the regulation to be fully observable. (As one illustration, several consent decrees were reached between the state of Colorado and oil and gas companies for failure to comply with various regulations several years after they were passed). There is a small increase in emissions from 2017 to 2019, possibly tied to the sharper increase in gas production during those years.

Though the GOSAT inversion from Lu et al.—as with all satellite inversions—has uncertainties that must be considered when relying on its estimates, nonetheless there is sufficient evidence to support the insights from this analysis. The GOSAT instrument itself has a coarse resolution (0.5x0.625°) and low temporal sampling, making evaluations of smaller domains difficult. The GEOS-CHEM model used for the inversion has been shown to have a low bias at surface sites, which may mean the absolute emissions estimated by this inversion are low. However, because the bias of the model does not change appreciably with time (see Figure S7 of the supplement of Lu et al.), the emission trend should be more robust than the absolute emission estimates. Inversions can show a dependence on the assumed prior emissions. Note however that the Lu et al. states: "The same prior emissions in North America are used for all years, effectively assuming no trend as a prior assumption." This indicates that the oil and gas methane trend in Colorado is due to observations, not changing assumptions in the inversion. Note also that estimates for other sectors (including livestock) are estimated by the inversion to have remained constant over this decade, and that total methane emissions for the state are observed in the inversion to decrease. This fact signifies that the decrease in oil and gas methane emissions is not being driven by a predicted increase in emissions from other sectors, but by an overall decrease in methane emissions. The sectoral breakdown of emissions is explained further in the Methodology.

Focus on the Denver-Julesburg Basin

The Denver-Julesburg ("DJ") Basin is an oil and gas basin in Eastern Colorado, primarily located under the Denver Metro Area but extending into Wyoming. Because many measurement campaigns have taken place in the DJ Basin over the last decade, we can focus on this basin to incorporate additional measurement data to validate the trend observed by GOSAT even if at a smaller spatial domain. Figure 2 below shows the methane loss rate (i.e., methane emissions as a fraction of methane produced) in the DJ Basin, as estimated by GOSAT as well as several different measurement studies. The loss rate is shown in this graph instead of absolute emissions because the specific domains for these measurement studies differ, making comparison of absolute emissions challenging.

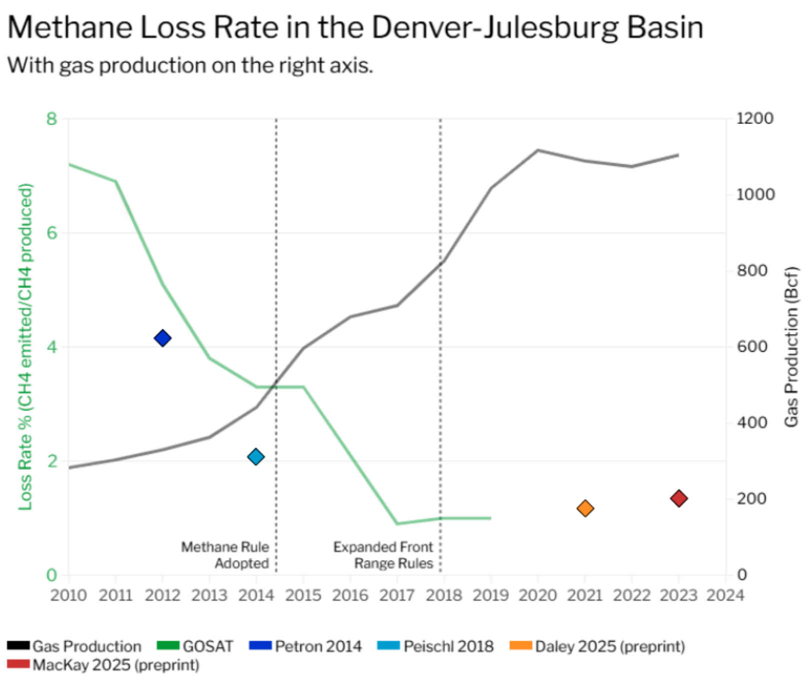


Figure 2: Methane loss rate for the Denver-Julesburg Basin. The loss rate is defined as mass of methane emitted divided by mass of methane produced (calculated as mass of natural gas produced multiplied by the percent methane content in natural gas). The methane loss rate from GOSAT is calculated by extracting emissions using the EIA basin definition for the DJ within Colorado, combined with gas production for equivalent years in the same domain form Enverus. Loss rates as reported in Petron 2014, Peischl 2018, and MacKay 2025 are also shown. The loss rate for Daley 2025 is calculated using the emission rates presented in that paper, combined with gas production data for the flight domains pulled from Enverus.

The airborne studies, along with the GOSAT inversion, show a clear declining trend of methane loss rate in the DJ Basin. Although the absolute emission trend in the DJ Basin as estimated by

GOSAT is similar to that of the state of Colorado (with a moderate decline starting in 2010 and a larger decline starting in 2015), the increasing gas production of the DJ Basin leads to a more significant drop in methane loss rate when compared to the rest of the state. The coarse resolution (0.5x0.625º) of this GOSAT inversion makes characterization of a basin like the DJ challenging, with its low absolute emissions and small spatial scale. Furthermore, the multiple sources of methane in this basin make sectoral breakdowns difficult. However, despite these uncertainties, the close alignment of GOSAT estimates with the independent airborne studies lends more confidence to the longer trend that GOSAT provides, both for the DJ Basin and for the wider state of Colorado.

Another recent study analyzed methane retrievals in the DJ Basin from a different satellite-based instrument (the Atmospheric Infrared Sounder (AIRS) instrument on the NASA Aqua satellite) from 2003 to 2020. After subtracting background methane concentrations, they observe a clear reduction in methane enhancement from 2012 to 2020. This enhancement was strongly correlated with surface measurements of ethane (considered a tracer for oil and gas emissions) in the same domain. Although this method is subject to its own uncertainty, it provides additional support for the overall narrative of decreasing emissions in the DJ Basin, in alignment with GOSAT and the airborne studies shown above.

More Uncertainty in the Piceance Basin

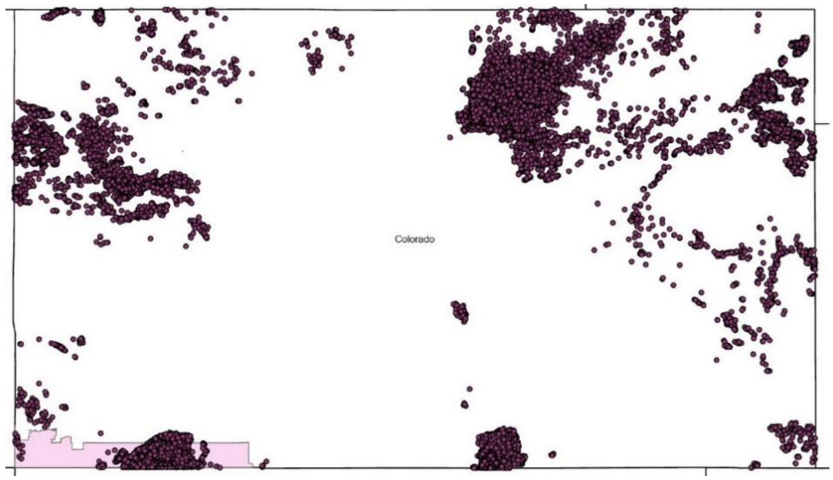
Unlike the Denver-Julesburg basin, the Piceance Basin is significantly understudied. Furthermore, the topography of the Piceance basin can make mass balance analyses difficult. The recent MethaneAIR flights in 2023 analyzed in MacKay 2025 surveyed two distinct regions of the Piceance and found very high emissions: 64 metric tons per hour of methane for the combined flight domains. If this emission rate is assumed to be constant throughout the year, it would equal 0.6 Tg/yr, significantly higher than GOSAT or TROPOMI estimates for the entire state of Colorado. However, because the MethaneAIR flights in the Piceance were collected over a relatively short timeframe and did not resample the same domains multiple times, it is difficult to determine if this emission rate reflects episodic emissions and is thus only robust for the day and time sampled, or if it can be extrapolated to the entire year. Future studies in the Piceance Basin will allow better reconciliation of the MethaneAIR estimate for this basin with the satellite observations.

Conclusion

Integration of measurement-based data in Colorado points to decreasing trends in oil and gas methane emissions in alignment with the implementation of robust regulations. More work focused on comparing between states with and without regulations may be able to provide stronger causal evidence for the efficacy of regulations.

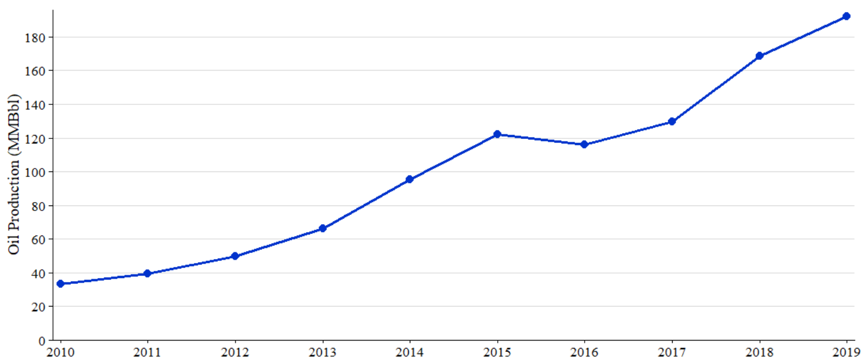
Methodology

Boundary for Analysis
Because tribal lands are not under Colorado's Air Pollution Control Division (APCD) jurisdiction, regulations passed by that agency do not apply to tribal lands. Therefore, in order to isolate the impact of regulations, tribal lands must be excluded from the analysis. A shapefile from the Census Bureau was used to clip out tribal lands for both emissions and production, leading to this map, where tribal lands are shown in pink shading in the southwest corner of the state (oil and gas wells included for reference):

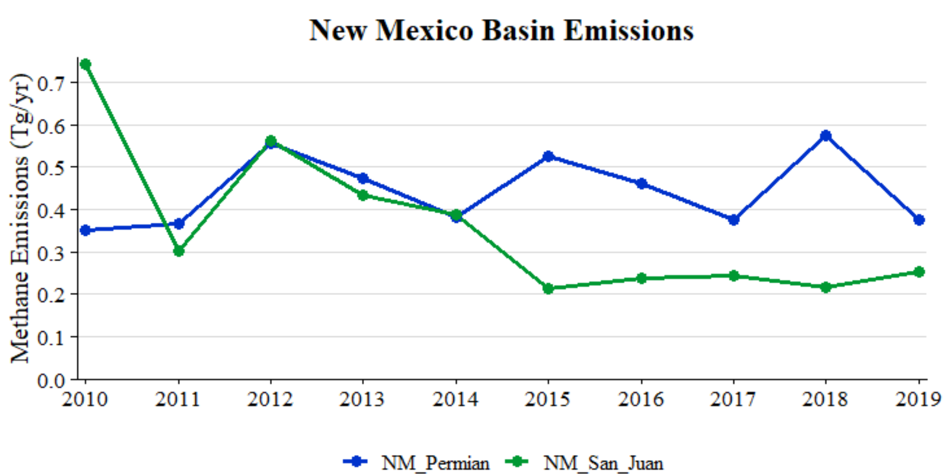


GOSAT Upper and Lower Bounds
The GOSAT upper and lower bounds for Colorado are calculated using basin-level uncertainties from Lu et al. 2023 for the DJ and San Juan for Colorado (uncertainties for Piceance basin are not available), as provided in the data repository. Emissions outside those basins rely on country-wide uncertainties. Because the majority of emissions in Colorado come from outside DJ and San Juan, the uncertainty ranges for this state may not be as robust.

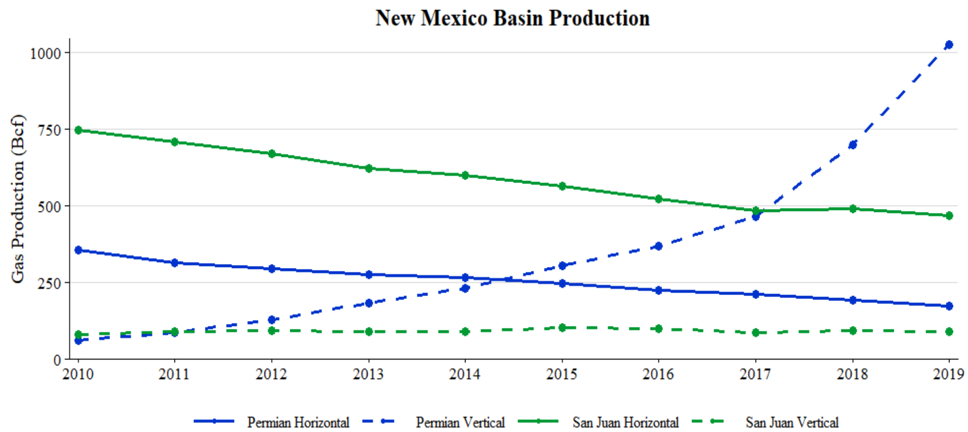
Oil Production in Colorado



Basin Breakdown of Emissions in New Mexico
GOSAT emissions and gas production for the two main basins in New Mexico are shown here. Gas production for the state, broken out by basin and drilling direction, is pulled from Enverus. In New Mexico, the two main basins (the Permian and the San Juan) have starkly different trends, which is obscured when looking at the entire state. Gas production in the San Juan Basin from older, vertically-drilled wells declines by 37% over the decade, with a corresponding decrease in emissions in that basin (as estimated by GOSAT).



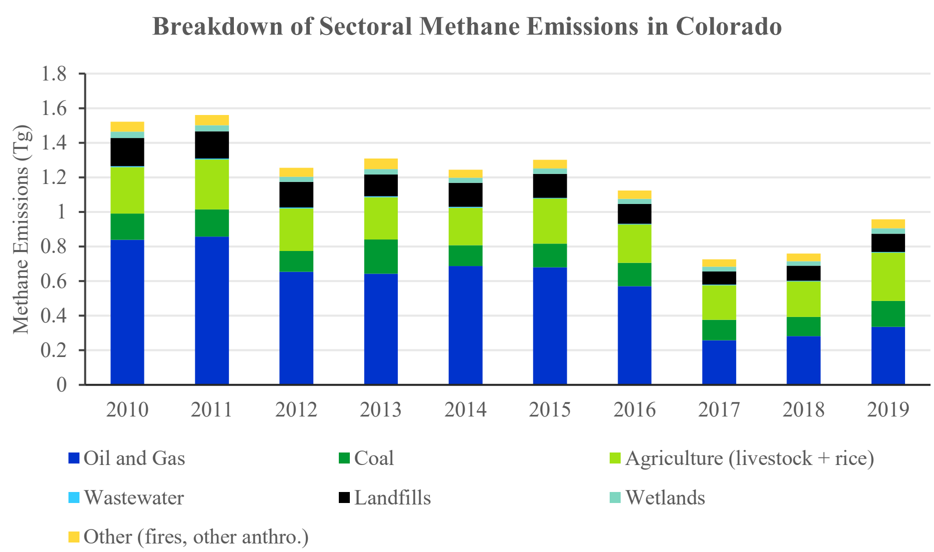
Production in the Permian from newer, more productive, horizontally-drilled wells skyrockets over the same time period, with only a small increase observed in emissions. Omara et al. demonstrated that vertically-drilled wells have a much higher loss rate than horizontally-drilled wells, which is why the increasing production in the Permian doesn't lead to a proportional increase in emissions. Thus, the overall trend in New Mexico results from decreasing emissions due to the decreasing emissions in the San Juan, with overall increasing production due to the increased production in the Permian.



GOSAT Sectoral Breakdown

Posterior methane emissions for all sectors are provided in the data repository and shown for the state of Colorado below. As explained above, the trend in decreasing methane emissions in Colorado is estimated by the inversion to primarily come from the oil and gas sector, while other sectors are estimated by the inversion to have much less variation over the time series.

In Lu et al., the main inversion results yield a posterior correction factor, which is applied to the total emission estimates in each grid cell, for each year. To disaggregate these total emissions by sector, two approaches based on prior inventory distribution are used.



The base approach optimizes the correction factors taking into consideration the error statistics for each sector: the prior error standard deviation for each grid cell, assumed to be 50%, and the error standard deviation on the prior estimate for each sector assumed to be proportional to the prior national uncertainty. The other approach assumes that the sectoral distribution in the prior inventory is accurate and applies the sectoral fractions from the prior directly to the posterior total emissions.

Both approaches contribute to a 12-member ensemble inversion which yields 24 estimates used to calculate the mean posterior emissions, allowing for the evaluation of different assumptions in the inversion process. Analysis of sectoral error correlation shows that the inversion is sufficiently sensitive to separate oil and gas emission from other sectors.