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DOI
10.1029/2023JD038566

Publication date
2023

Document Version
Final published version

Published in
Journal of Geophysical Research: Atmospheres

AGU ADVANCING EARTH AND SPACE SCIENCE

JGR Atmospheres

RESEARCH ARTICLE
10.1029/2023JD038566

COVID-19 Impact on the Oil and Gas Industry NO_2 Emissions: A Case Study of the Permian Basin

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Key Points:

- The NO_2 emissions calculated using TROPOMI data and the divergence method coincide with the downturn of O&G activity in the Permian basin
- Average NO_2 tropospheric column concentrations show a weaker decrease (−4%) in comparison to the significant reductions (~30%) observed in emissions during the COVID-19 lockdown
- We demonstrate a positive spatial and temporal relationship between oil and gas activity rates and emissions of NO_2 in the Permian basin

Supporting Information:

Supporting Information may be found in the online version of this article.

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Citation:

Serrano-Calvo, R., Veefkind, J. P., Dix, B., de Gouw, J., & Levelt, P. F. (2023). COVID-19 impact on the oil and gas industry NO_2 emissions: A case study of the Permian basin. *Journal of Geophysical Research: Atmospheres*, *128*, e2023JD038566. https://doi.org/10.1029/2023JD038566

Received 25 JAN 2023
Accepted 16 JUN 2023

Abstract

COVID-19 caused a historic collapse in fossil fuel demand, a general decline in economic activity, and hydrocarbon price volatility. This resulted in an unprecedented scenario to evaluate the contribution of the O&G (Oil and Gas) industry NO_2 (nitrogen dioxide) emissions in the Permian basin (United States), currently the second largest hydrocarbon-bearing area on Earth. TROPOMI (Tropospheric Monitoring Instrument), on board the Sentinel-5P satellite, has captured the impact of the oil and gas industry emissions during the COVID-19 lockdown. A generalized drop (~30%) of NO_2 emissions derived using the divergence method in comparison with 2019 was observed following the decline in production and drilling (13% and 68% respectively) during the lockdown. NO_2 tropospheric columns were less impacted with a smaller decrease (~4%) across the basins. This study demonstrates that the impact of the COVID-19 lockdown on NO_2 emissions was not only present in urban areas but also in vast O&G production regions, which shows the potential of TROPOMI to assess future pollution mitigation strategies for this industry.

Plain Language Summary

The COVID-19 pandemic caused a big impact on the oil and gas industry, not only in production but also in price and demand. This situation was a good opportunity to analyze one of the most common gas emissions of this industry, nitrogen dioxide, in one of the biggest oil and gas production areas, the Permian basin. Using satellite imagery, it was observed a generalized drop in nitrogen dioxide emissions during the lockdown period of the pandemic. This study not only shows that the impact of the COVID-19 pandemic on nitrogen dioxide emissions was present in other environments apart from the urban for example, the oil and gas production regions, but also the capability to monitor it using satellite imagery.

1. Introduction

The COVID-19 lockdown has been an exceptional scenario to evaluate NO_2 emissions change due to the limitation of the human activity.

Since the appearance of the virus at the end of January 2020 in Wuhan (China), the COVID-19 impact on the energy industry was present in all aspects of this sector, from production to consumption. With the spread of the virus and the increase of cases around the world, strict lockdown policies were imposed on nearly 3 billion people globally (Rume & Islam, 2020), leading to an unprecedented reduction in fossil fuel demand and consumption. According to Le Quéré et al. (2020), aviation activity decreased by 75%, surface transport by 50%, and industry activity by 35%, producing a collapse in oil and gas consumption. Due to the decrease in consumption, the stockpile of gas and crude oil arrived at the limit in most of the productive countries which produced a decline in the barrel price to almost negative numbers. In response to this situation, OPEC (Organization of the Petroleum Exporting Countries) agreed to cut oil and gas production to recover the price of the barrel (Figure 1; Figure S1 in Supporting Information S1).

Linked to the decrease in fossil fuel consumption and COVID-19 lockdown policies, emissions of air pollutants and greenhouse gases were impacted worldwide (Archer et al., 2020; Barré et al., 2020; Ding et al., 2020; Gaubert et al., 2021; Keller et al., 2021; Tang et al., 2021; Turner et al., 2020). This included the emission of nitrogen dioxides ($NO_x = NO + NO_2$), which is emitted by the production, storage, and transportation of oil and gas. NO_x (Nitrogen oxides) is generated by combustion engines used to generate power, drilling, flaring, and for transportation of equipment and consumables. It is important to monitor and reduce NO_x emissions because, they affect

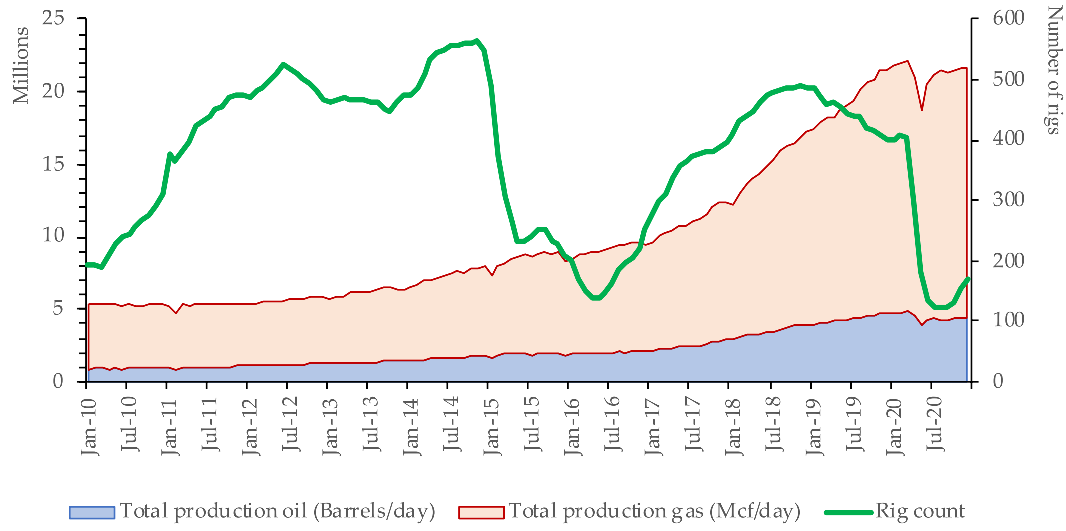

Figure 1. Time series of gas production, oil production and rig count in the Permian basin (U.S.) from January 2010 to August 2020 (Source of the data used: U.S. Energy Information Administration).

human health, vegetation, the chemistry balance in soils and waters and NO_2 is a precursor gas for tropospheric ozone and aerosols (Honour et al., 2009; Huang et al., 2021).

COVID-19 provides an unprecedented scenario to evaluate the NO_x emission of the oil and gas (O&G) industry for the largest oil and gas-producing region of the United States. In this study, we use satellite data collected by TROPOMI (TROpospheric Monitoring Instrument) (Veefkind et al., 2012) on board of Sentinel-5P and O&G activity data from the Permian basin region from January 2019 to October 2020. This research shows for the first time the impact of drastically reducing the oil and gas activity on concentrations and emissions of NO_2 in the Permian basin, not only in quantitative values but also in spatial and time relationships with the source.

2. Materials and Methods

2.1. Study Area: The Permian Basin

The Permian basin is the largest O&G production region in the United States and the second-largest hydrocarbon-bearing area in the world. It is located in the south of the country, between Texas and New Mexico with an extension of 160,000 km^2 (Robertson et al., 2020). The basin is formed by different production sub-basins that can be classified as the most productive sub-basins (Delaware, Central, and Midland) and the ones still in exploration and development (Ozona Arc and Valverde) (Figure 2).

The oil production in the basin increased from 900 thousand barrels per day in 2010 to 4,177 thousand barrels per day in 2019 (U.S. Energy Information Administration, 2019). In the case of gas, the increase in production over the last 10 years has been from 4,000 million cubic feet per day to 17,000 million cubic feet per day at the beginning of 2020.

O&G exploration in the Permian basin is primarily done using non-conventional techniques, including hydraulic fracturing (fracking) and horizontal drilling. The region is covered with thousands of active and abandoned wells, while continuously new wells are drilled. During drilling, heavy machinery, and engines, which amongst others emit NO_x, are used to create hydraulic fractures. Drilling is the step in the oil and gas production which can respond relatively quickly to market changes (Dix et al., 2020). A drop in demand therefore results in a strong decrease in the rig count (see Figure 1).

2.2. Data

This research is based on multiple sources of data: (a) NO_2 tropospheric vertical column densities, (b) wind data, (c) O&G production rates, and (d) drilling activity.

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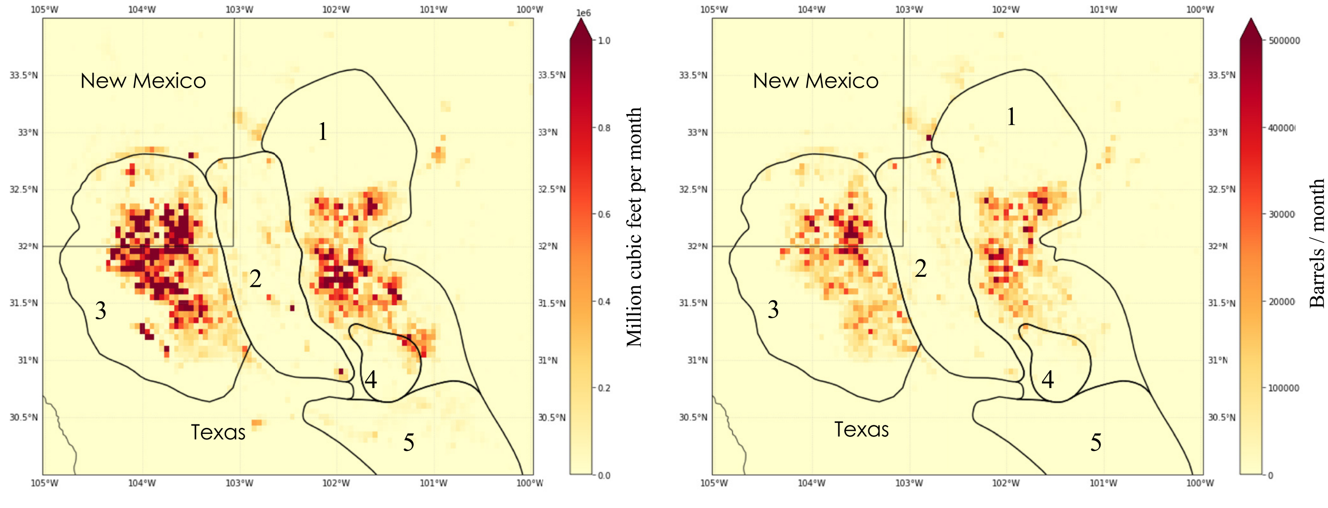


(a)

(b)

Figure 2. Monthly average of gas (a) and oil (b) production distribution in the Permian basin in 2020. The numbers are related to the different sub-basins of the Permian: 1-Midland, 2-Central, 3-Delaware, 4-Ozona Arc, and 5-Valverde.

We have used TROPOMI NO_2 Version 1.3 data (European Space Agency, 2021; Sentinel-5P Pre-Operations Data Hub, 2021; Van Geffen et al., 2020) with a quality indicator (qa_value) of at least 0.75. This ensures filtering for good quality NO_2 tropospheric columns for conditions with low cloud fractions. The NO_2 TROPOMI data processors were upgraded after October 2020, which causes jumps in the data records. Therefore, we limit our analysis to data until October 2020.

Monthly gas production, oil production, and drilling activity data were acquired from Enverus DrillingInfo (https://www.enverus.com), last accessed (30 October 2021).

In the case of drilling activity, the data provided by ENVERUS is reported in "drilling days." Drilling-days-counts can implicate more than one rig in the well pad, for example, three rigs drilling 20 days each, will be 60 days of drilling in total. The maximum number of rigs per well pad is 9, therefore the maximum number of days per month of drilling activity is 270.

2.3. Processing of TROPOMI Data

The TROPOMI orbit-based data files were filtered to the area of interest, in this case, the Permian basin, using the shapefile provided by the U.S. Energy Information Administration (E.I.A, 2017). From these files daily gridded NO_2 data was produced on $0.025° \times 0.025°$ (approximately 2.5 km × 2.1 km) latitude/longitude grids. Subsequently, monthly mean and median NO_2 data were derived from the daily data, for the period January 2019 to October 2020. This study is focus in three different monthly time series: (a) COVID-19 lockdown (March–April), (b) whole year (January–October), and (c) before and after the lockdown (January–June).

2.4. Divergence Method for NO_2 Emissions Estimation

To estimate the NO_2 emissions using the total NO_2 columns, the divergence method was applied following the steps described by Beirle et al. (2019) and Dix et al. (2022). The divergence method was applied to the daily gridded NO_2 data set. For the wind speed and direction, the average value over the boundary layer height is used. Both the wind data and the boundary layer height are obtained by spatial and temporal interpolation in the publicly available ECMWF (European Centre for Medium Range Weather Forecasts) ERA 5 data set (ECMWF, 2021; Hersbach, H. et al., 2018). For the boundary layer height, a minimum value of 200 m was applied. The NO_2 lifetime is estimated from the average OH (hydroxyl radical) concentration in the boundary layer, using:

$$t_{NO2} = ([OH]\,k)^{-1}$$

where t_{NO2} is the lifetime in s, [OH] in mol cm^{-3} and k a constant of 3×10^{-11} s mol^{-1} cm^3 (Atkinson et al., 2004; IUPAC, 2022). The concentration of OH was obtained for the CAMS (Copernicus Atmosphere monitoring Service) global forecast (Peuch et al., 2022). Dix et al. (2022) concluded that using the divergence method, NO_x emissions from oil and gas production areas can be calculated on an annual basis within an uncertainty of 50%. Furthermore, the NO_x emission maps derived with the divergence method provide a high level of spatial detail with a precision that likely exceeds the accuracy of the total NO_x quantification.

2.5. Source Attribution and Spatial Analysis

A source attribution analysis was performed for the entire Permian basin and separately for each sub-basin. The method of this analysis is to combine the TROPOMI NO_2 emission data with the activity information. Each grid box in the monthly data set is classified using a combination of the NO_2 emission data and the activity data. To this end, 30 classes were defined (Figure S2, Tables S1 and S2 in Supporting Information S1) with the combination of different thresholds for production, drilling, and emission data. The segmentation of the different thresholds was selected having into account the average, the standard deviation, and the maximum for each data set. For example, for the emissions segmentation:

$$\text{Mean emissions in the Permian (Mean)} : 2.3\,e^{-9}\ \text{mol} \cdot s^{-1} \cdot m^2$$

$$\text{Standard deviation (SD)} : 1.9\,e^{-9}\ \text{mol} \cdot s^{-1} \cdot m^2$$

$$\text{Maximum Emissions (MaxE)} : 1.47\,e^{-8}\ \text{mol} \cdot s^{-1} \cdot m^2$$

The split of the thresholds:

$$\text{Average emissions} : \text{Mean} - \text{SD} \leq \text{Emissions} \leq \text{Mean} + \text{SD}$$

$$\text{Low emissions} : \text{Emissions} \leq \text{Mean} - \text{SD}$$

$$\text{High emissions} : \text{Mean} + \text{SD} < \text{Emissions} < \text{MaxE} - [(\text{Mean} + \text{SD}) - (\text{MaxE})/2]$$

$$\text{Very high emissions} : \text{Emissions} > \text{MaxE} - [(\text{Mean} + \text{SD}) - (\text{MaxE})/2]$$

	Threshold ($mol \cdot s^{-1} \cdot m^2$)	Description
Emissions	Emissions $\leq 3.5\ e^{-10}$	Low emissions
	$3.5\ e^{-10} \leq$ Emissions $\leq 4.3\ e^{-9}$	Average emissions
	$4.3\ e^{-9} <$ Emissions $< 9.3\ e^{-9}$	High emissions
	Emissions $> 9.3\ e^{-9}$	Very high emissions

In addition, emissions located in cities (Texas Department of Transportation, 2021c; U.S. Geological Survey, 2019), airports (Analysis Center Earth Data, 2019; Texas Department of Transportation, 2021a), highways and, secondary roads (Program New Mexico 911 (NM911), 2021; Texas Department of Transportation, 2021b) were omitted for the reason that significant emissions sources other than from the O&G industry are expected for these locations. Grid boxes for which the emission data contained fill values were classified as “no production/drilling.”

3. Results

3.1. Spatial Distribution of NO_2 Tropospheric Concentrations During the COVID-19 Lockdown in the Permian Basin

The monthly median of NO_2 is shown in Figure 3 for the months of January to June for 2019 and 2020. NO_2 concentrations are higher in winter due to the longer lifetime of NO_2 during these months. The impact of COVID-19 on NO_2 concentrations is analyzed by comparing the same periods between 2019 and 2020. The period

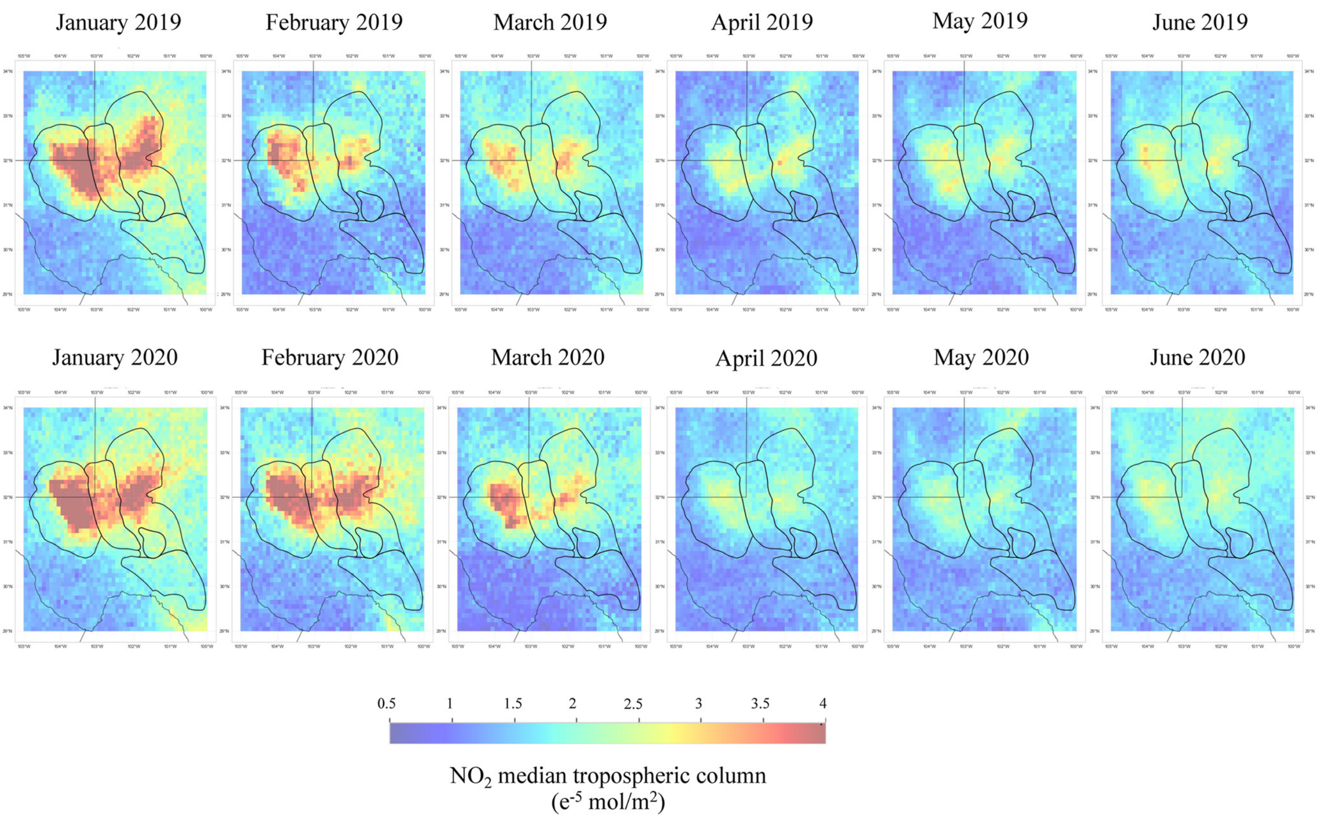


Figure 3. Time series of median nitrogen dioxide tropospheric column from January to June 2019 and 2020 in the Permian basin.

January to March 2020 is not impacted by any COVID-19 policy measures, whereas during the period April to June 2020, there were policy measures in the region as well as around the world. In this analysis, we used a 3-month period to reduce the effects of differences in meteorology in 2019 versus 2020.

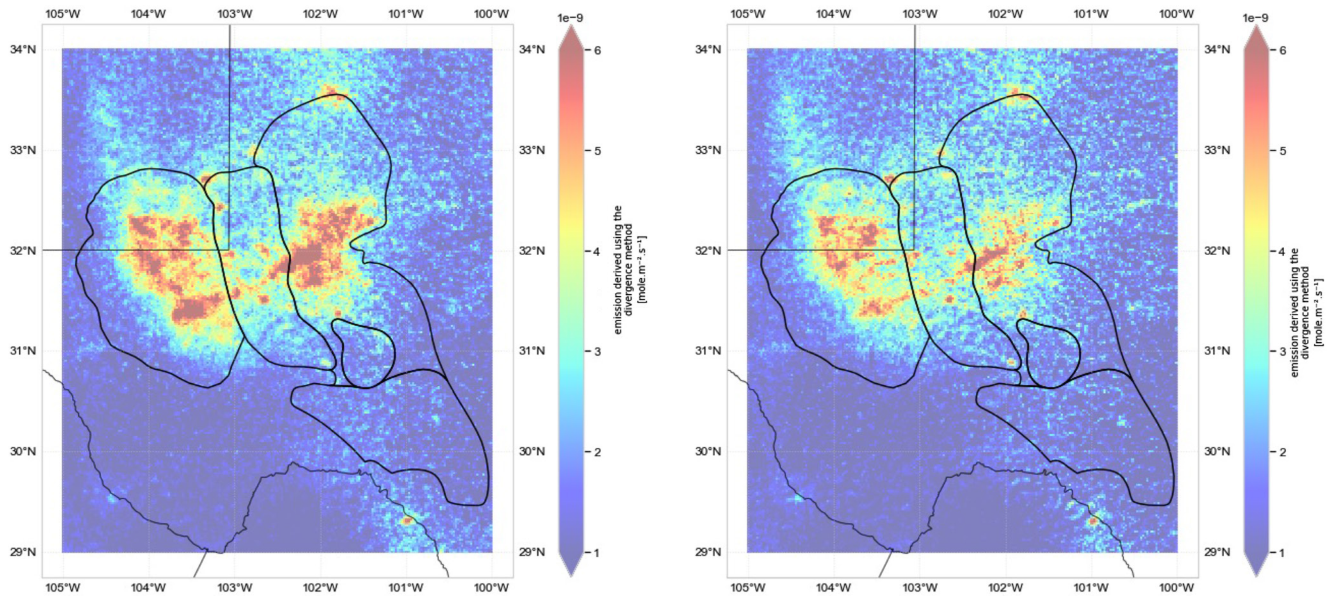
As compared to the same period in 2019, the NO_2 tropospheric concentrations show an increase during the winter months of 2020 (from January 2020 to March 2020) of an average 9%, where Midland and Central sub-basins show the largest increases (13.3% and 13.2%, respectively). A decrease is found during the lockdown months (April to June 2020) of an average of −4% (Table 1; Figure S3 in Supporting Information S1), which is quite similar across the most productive sub-basins (Delaware, Central, and Midland).

Sources of the variability of NO_2 concentrations include meteorology (cloud cover, wind, etc.), the atmospheric chemistry (chemical reaction rates and photolysis) which can change the lifetime of NO_2, and measurement noise

Table 1
Changes in NO_2 Concentration Average, Minimum, Maximum, Interquartile Range, Average ±95% Confidence Interval, and Standard Deviation Across All the Sub-Basins in the Permian Basin

Sub-basin	Average % of change (%)	Min % of change (%)	Max % of change (%)	Interquartile range (50%) (%)	Average and 95% confidence interval (NO_2 in μmol/m^2)	Standard deviation of the mean (NO_2 in μmol/m^2)
Delaware	−4.4	−5	0	−5.9	5.1 ≤ 18.1 ≤ 33.0	7.0
Midland	−4.6	21	−28	−0.3	5.1 ≤ 18.6 ≤ 33.0	7.6
Central	−4.6	−76	12	−3.3	4.1 ≤ 18.0 ≤ 32.7	7.1
Ozona Arc	−6.3	30	0	8.4	5.1 ≤ 14.6 ≤ 33.0	5.9
Valverde	0.0	0	55	1.3	1.3 ≤ 14.1 ≤ 26.7	7.5

Note. The percentages are related to April to June 2020 with respect the April to June 2019.



(a) (b)

Figure 4. Median nitrogen dioxide emissions in 2019 (a) and 2020 (b) from January to October obtained using TROPOMI NO_2 tropospheric columns and the divergence method.

from the instrument. The similarity in the standard deviations of all the sub-basins during the lockdown period demonstrates that the data variability is comparable. The uncertainty in the measurement of the mean in all the basins is comparable with only the Delaware basin having a 95% confidence interval higher than the other basins (Table 1).

3.2. Analysis of NO_2 Emissions During the COVID-19 at Basin and Sub-Basin Level in the Permian Basin

The median of NO_2 emissions derived from the TROPOMI concentrations using the divergence method, are shown in Figure 4 for the period January to October 2019 and January to October 2020. The regions with the highest NO_2 emissions are the ones that show the major reductions in 2020 with respect to the same period in 2019.

The variability of the emissions between February and June 2019 (Figure S8 in Supporting Information S1; Figure 5) is considerably smaller as compared to the concentrations for the same period (Figure 3). This indicates that the chemical loss of NO_2, which is the main driver for the seasonal variations in the concentrations, and the meteorology are generally well represented in the divergence method. The emissions for 2020 show a different behavior, with a strong decrease after March 2020. Comparing NO_2 median emissions during the COVID-19 lockdown period (April to June 2020) with the same period in 2019, an average of 30% decrease was observed in all the sub-basins that compose the Permian basin, with Midland as the sub-basin with the largest decrease (−33%) (Figure S8 in Supporting Information S1).

Reference regions outside the boundaries of the Permian basin with background conditions (areas without the presence of O&G industrial activities) were also analyzed (Figure S4 in Supporting Information S1). The NO_2 median emissions decreased between 1% and 10%, except for regions on the East of the Permian basin where large cities like Dallas, San Antonio, or Austin are located. This analysis of the background regions verifies that the decrease of the NO_2 emissions is not related to artifacts in the data or the methods, but to reduced emissions in the area (an average decrease of 30%). The decreased emissions during the lockdown period were found in regions dominated by O&G industrial activities, as well as in areas with emissions not dominated by the O&G, such as the Interstate 20 Frontage Road and the major cities of the basin (Pecos, Odesa, Midland, and Carlsbad).

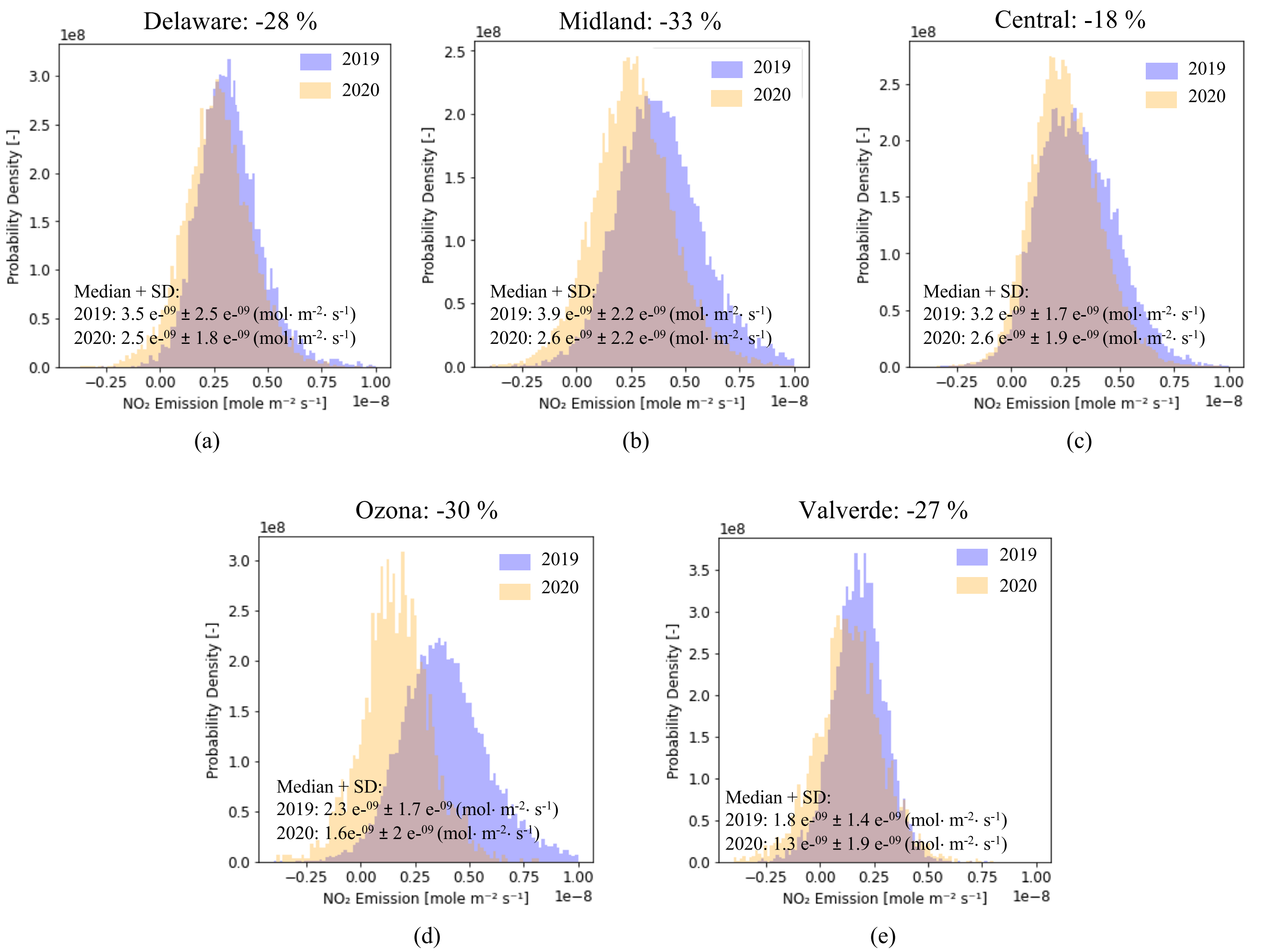


Figure 5. Histograms of the NO_2 emissions for the most productive sub-basins (a, b, and c) and the less productive (d and e) in the Permian basin during the period April-May in 2019 and 2020. The percentages in the plot title are related to the reduction of NO_2 emissions between 2019 and 2020 (SD: Standard deviation).

3.3. Source Attribution of NO_2 Emissions in the Permian Basin Before and During the COVID-19 Lockdown

NO_2 emissions calculated with the divergence method were combined with O&G production, drilling, and other activities. Figure 6 shows the mean emission for the grid boxes associated with these activity categories, as a function of the month in 2019 and 2020. NO_2 associated with production and drilling in the same place, and places with only drilling activities were the most impacted during and after the COVID-19 lockdown. Decreases of 67% with respect to 2019 are found during the period from April to June 2020 (Table 2). According to Dix et al. (2020), the number of active drilling wells responds quickly to economic changes but places with only production activity more gradual, which can explain the large decrease in places with significant drilling activities.

In a longer time-series analysis (January to October 2020), the impact of COVID-19 was also most pronounced in production and drilling regions (−32%), and only an impact of −3% decrease for the other categories (Table 2), mainly related to the rapid response of the industry (reduction of drilling activities and production intensity). The entire Permian basin showed an impact of −7% if we compare 2020 with 2019, but if the comparison is limited to the lockdown period changes in emissions of up to −19% was found. Excluding the impact of other sources of emissions, the effect of the COVID-19 lockdown was −24% for NO_2 emissions which were associated with the O&G industry.

The same analysis was performed for the main sub-basins of the Permian basin (Table S3 in Supporting Information S1). For the period January to October, NO_2 emissions associated to places with production and drilling

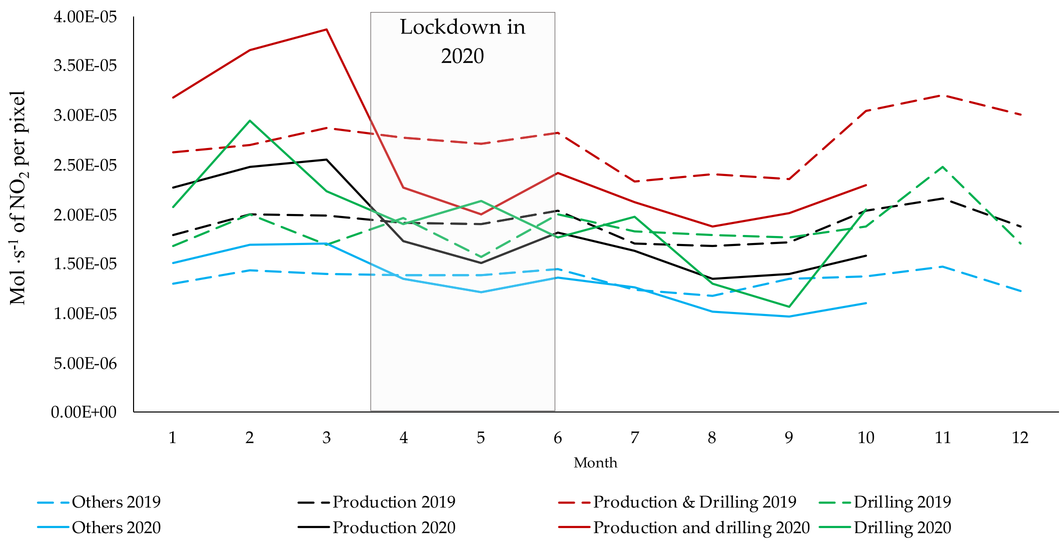


Figure 6. Normalized NO_2 emission for each month in areas with only production, production and drilling, drilling, and other activities not related to the O&G. NO_2 emissions were normalized by the number of pixels attributed to each activity on the entire Permian basin.

activity on the same site showed an important decrease in the Delaware, Midland, and Central sub-basins. As the number of locations with NO_2 emissions associated to only production activities did not change significantly (Figures S5 and S9 in Supporting Information S1), this decrease appears to be driven by the intensity of the activities.

Finally, we analyzed the production rates in locations with high levels of NO_2 emissions (4.3 e^{-9} mol·s^{-1}·m^{-2} < NO_2 emissions < 9.3 e^{-9} mol·s^{-1}·m^{-2} of NO_2) and places with average levels (3.5 e^{-10} mol·s^{-1}·m^{-2} < emissions < 4.3 e^{-9} mol·s^{-1}·m^{-2}) during the COVID-19 lockdowns (Figure 7; Figures S7 and S9 in Supporting Information S1). As can be seen in Figure 7 and in Figure S9 in Supporting Information S1, in March 2020 average NO_2 emissions from oil and gas production locations were mainly associated with low production places (Production < 5,000 Mcf/month in the case of gas and between 0 < Production < 800 barrels a month for oil) and high NO_2 emissions to locations with high production (40,000 Mcf/month < Production < 600,000 Mcf/month for gas and 12,000 < Production < 100,000 barrels in the case of oil). With the COVID-19 lockdown, a significant decrease in high NO_2 emissions (4.3 e^{-9} mol·s^{-1}·m^{-2} < NO_2 emissions < 9.3 e^{-9} mol·s^{-1}·m^{-2} of NO_2) associated with places with high production rates can be observed in the Delaware basin and Central basin, and an increase in average NO_2 emissions (3.5 e^{-10} mol·s^{-1}·m^{-2} ≤ emissions ≤ 4.3 e^{-9} mol·s^{-1}·m^{-2}) in the same locations. In May 2020, just after the peak of the lockdown, the total NO_2 emission from places classified as high emitter location were reduced from 0.17 mol·s^{-1} of NO_2 to 0.03 mol·s^{-1} in the Permian basin (Figure 7; Figure S7 in Supporting

Table 2
Total NO_2 Emission Rate of Each O&G Activity in the Permian Basin in 2019 and 2020 (January to October and April to June) for Areas With Only Production, Production + Drilling, Drilling and Other Activities

		Production	Production + drilling	Drilling	Others	Total Permian
January to October	Permian basin 2019 (mol·s^{-1} of NO_2)	2.17	0.42	0.009	1.47	4.08
	Permian basin 2020 (mol·s^{-1} of NO_2)	2.09	0.27	0.009	1.42	3.81
	% Difference	−3.7%	−32%	−2.8%	−3.4%	−7%
April to May	Permian basin 2019 (mol·s^{-1} of NO_2)	0.70	0.135	0.003	0.48	1.33
	Permian basin 2020 (mol·s^{-1} of NO_2)	0.60	0.044	0.001	0.43	1.07
	Decrease due to lockdown (mol·s^{-1} of NO_2)	0.11	0.095	0.002	0.06	0.257
	% Difference	−16%	−67%	−66%	−12%	**−19%**

Note. The emissions were normalized to the number of pixels for each category.

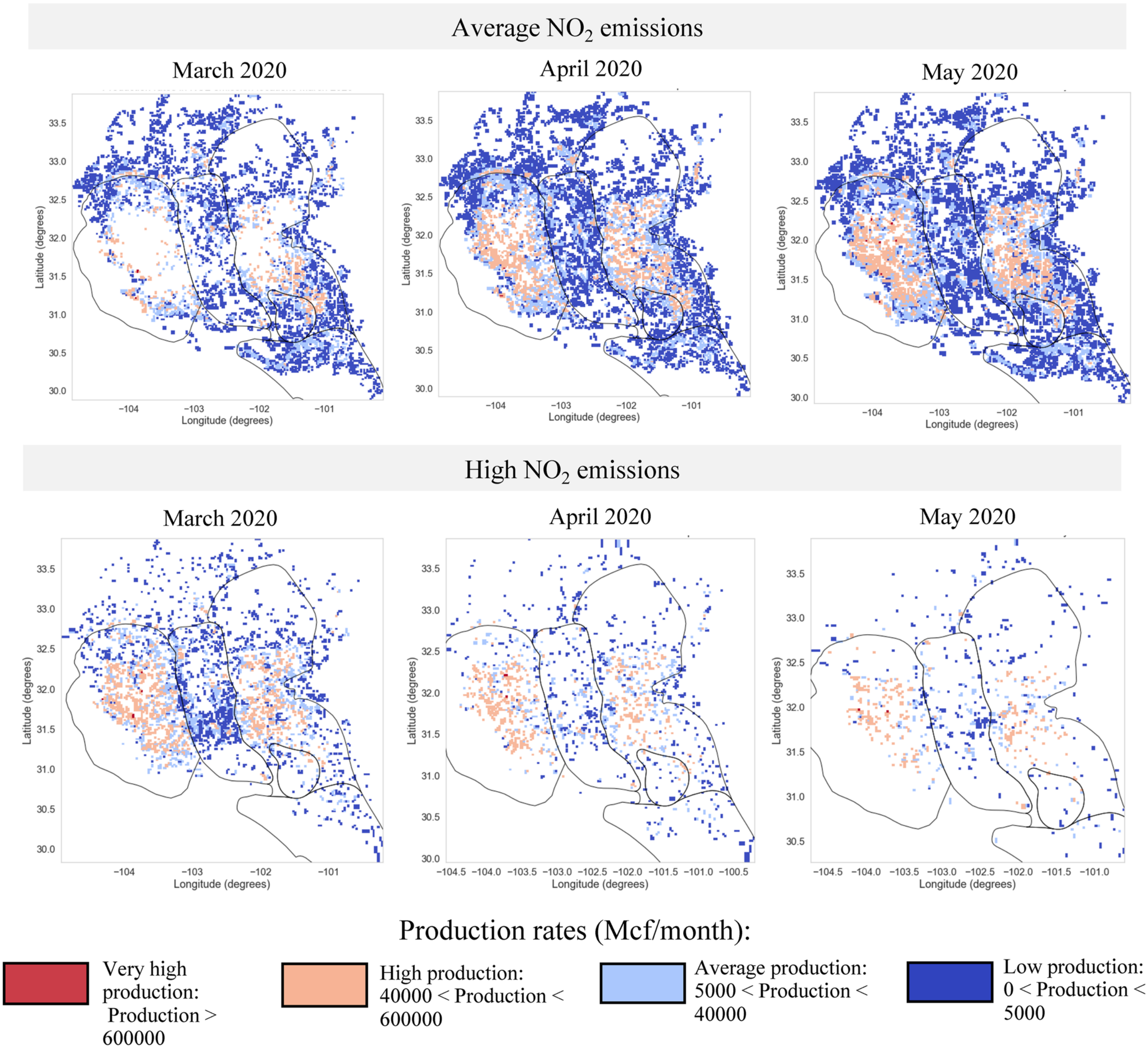


Figure 7. NO_2 high emissions (4.3 e^{-9} mol·s^{-1}·m^{-2} < NO_2 emissions < 9.3e^{-9} mol·s^{-1}·m^{-2}) (Bottom) and average emissions (3.5 e$-^{10}$ mol·s^{-1}·m^{-2} ≤ emissions ≤ 4.3 e^{-9} mol·s^{-1}·m^{-2}) (Top) related to gas production rates in the Permian basin from March to May 2020.

Information S1). Although gas and oil production were analyzed separately the results related to the emissions attribution are similar because in the Permian basin most of the wells can produce oil and gas at the same time.

4. Discussion

The observed decrease NO_2 concentrations and emissions in the Permian basin corresponded in time with the decline in demand for fossil fuels, due to the COVID-19 lockdowns and travel bans. For the period between April and June 2020, we report decreases of NO_2 tropospheric column concentrations of 4% and emissions derived using the divergence method of 30%, compared to the same period in 2019. This difference in reduction between concentrations and emissions in the same location has been also reported by (Misra et al., 2021). The average decrease (4%) in tropospheric concentrations from March to May 2019 was also observed by Qu et al. (2021), justifying this weaker decrease in NO_2 concentrations because of the inability of TROPOMI to capture the decrease in seasonal progression periods due to the dampening effect from the NO_2 background. This research also demonstrates the ability of TROPOMI to capture the larger reductions of NO_2 in small areas where there are high levels of NO_2 emissions (as it was observed in the maximum values in the Midland basin—28%) which is also in agreement with Qu et al. (2021). Although other uncertainties can be present in concentrations (e.g., measurement noise, chemical reaction rates, or meteorology), the use of temporal and spatial averaging during only 3 months of the COVID-19 lockdown can reduce the random errors and impacts of the seasonal variations of the NO_2 lifetime.

The decreases in emissions are driven by decreased O&G industry activity which we quantified as a decrease of 68% in drilling activities and 16% in production activities. However, not all O&G activities decreased in the same way: in the case of production, the number of active wells remained the same (Table S4 in Supporting Information S1), and just reducing the production rate (−13% respect to 2019) caused a 16% reduction of NO_2, and consequently a reduction in the emission rate per meter squared (from high emission rates (4.3 e^{-9} $mol \cdot s^{-1} \cdot m^2$ < NO_2 emissions < 9.3 e^{-9} $mol \cdot s^{-1} \cdot m^2$ of NO_2) to what it was categorized as average emission rates (3.5 e^{-10} $mol \cdot s^{-1}$ m^2 ≤ emissions ≤ 4.3 e^{-9} $mol \cdot s^{-1} \cdot m^2$). The relationship between changes in production rates and NO_2 enhancements detected by OMI (Ozone Monitoring Instrument) was demonstrated by Majid et al. (2017), indicating an increase of approximately 0.15 e^{-15} mol cm^{-2} of NO_2 for an increase of 1 million barrels daily.

Drilling activities, especially the ones located at the same location as production, reduced the number of active drilling rigs drastically instead of decreasing the drilling intensity (reducing the number of days drilling per month). The absolute largest reduction in NO_2 emissions was associated with locations with only production (0.108 $mol \cdot s^{-1}$ of NO_2). However, the number of emitting locations (48% (Figure S6 in Supporting Information S1)) is much higher than the places having drilling + production on the same location (7% (Figure S6 in Supporting Information S1)). In the case of drilling activities in the same place as production, the reduction of NO_2 emissions (0.091 $mol \cdot s^{-1}$) was similar to the one associated with places with only production activity, but for 40% fewer locations (Figure S6 in Supporting Information S1). Therefore, the fact that having a similar level of emissions but much less locations, makes the reduction of drilling activity a powerful mitigation action to reduce NO_2 emissions in the Permian basin.

Several authors have shown the relationship between lockdown policies and the decrease in NO_2 at different scales of analysis: at the global scale (Venter et al., 2020; Zhang et al., 2021), country (Archer et al., 2020; Qu et al., 2021) and cities (Barré et al., 2020). In the case of urban areas, Barré et al. (2020) shows an overall reduction in European cities between 20% and 40%. Misra et al. (2021) presented the decrease in NO_2 emissions in urban areas (−73%) and power plants (−53%) in the North of India with the use of the divergence method. The divergence method has been also applied to detect missing NO_2 emissions from the O&G industry inventories (Dix et al., 2021), demonstrating the suitability of the method to detect emissions caused by the O&G industry. The impact of the COVID-19 lockdowns in the Permian basin, which is predominantly driven by changes in O&G industrial activities, is therefore on the low side as compared to reductions in urban areas.

5. Conclusions

The exceptional scenario of the COVID-19 pandemic created an opportunity to assess the contribution of the oil and gas sector to nitrogen dioxide emissions in the biggest production area of the United States, the Permian basin. This research shows for the first time the impact of reducing the activity source of NO_2 emissions in a dynamic spatial and time analysis of an area characterized by widespread source points and illustrating a different scenario from studies in urban areas (Barré et al., 2020; Zhang et al., 2021).

The influence of lockdown policies had an impact on global energy trends, causing a major drop in oil and gas demand. This decrease in the oil and gas activity also observed in the Permian basin (13% of production and 68% in drilling activities) caused a significant reduction in NO_2 emissions (∼30%) and a weaker decrease in tropospheric concentrations (−4%) masked by the impact of the NO_2 background. However, stronger reductions of NO_2 tropospheric concentrations can be observed in smaller areas where the emissions suffered a strong decrease. During the lockdown period, locations with both production and drilling activity at the same place showed a similar decrease in NO_2 emissions as places with only production, even having less amount of source points across the Permian basin. The reduction of drilling activity can be a good strategy for NO_2 emission reduction in the Permian basin.

This research has revealed the potential of TROPOMI NO_2 observations and derived emissions to track variations of the O&G production and drilling activities.

Data Availability Statement

Main data sets used in this publication are:

- TROPOMI NO_2 Version 1.3 data available at https://s5phub.copernicus.eu/dhus/#/home.
- ERA-5 meteorological information available at https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5.

Acknowledgments

We acknowledge the free use of the tropospheric nitrogen dioxide column data available on the Copernicus S5p Open Access Hub: https://scihub.copernicus.eu/. We acknowledge helpful discussions with Rutger IJzermans, Richard Eyers, Bas van de Kerkhof, David Randell, and Matthew Jones. This work was financially supported by Shell Global Solutions International B.V. with grant reference number CW284766. Drilling and production activity data were provided by Enverus DrillingInfo. B.D. and J.dG were financially supported by the NASA ACMAP program under award number 80NSSC19K0979, and by the Rocky Mountain Institute and Blue Sky Resources.

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