COVID-19 impact on the oil and gas industry emissions: a case study of methane and nitrogen dioxide in the Permian basin

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November 28, 2022

Abstract

COVID-19 caused an historic collapse in fossil fuel demand, a general decline in economic activity and hydrocarbon price volatility. This resulted in an unprecedent scenario to evaluate the contribution of the oil and gas industry (O&G) to methane (CH_4) and nitrogen dioxide (NO_2) emissions in the Permian basin (U.S.), 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 during the COVID-19 lockdown. Production and drilling declined (13 % and 68 % respectively) during the lockdown, causing a generalized drop (˜30 %) of NO_2emissions derived using the divergence method in comparison with 2019. NO_2 tropospheric columns were less impacted with a smaller decrease (˜4 %) across the basins. On the other hand, the impact of the lockdown in methane (increase of 0.1 % to 0.3 % across the basins) was not as evident as in the NO2, because of the large background cause by the long lifetime (12 years), the variability of the meteorology, and the limited temporal sampling due to the strict thresholds of the retrieval algorithm. This study demonstrates that the impact of the COVID-19 lockdown on NO_2 and CH_4emissions 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.

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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.
- NO_2 emissions show significant reductions (~30 %) during the COVID-19 lockdown, meanwhile CH_4 seems to increase.
- We demonstrate a positive spatial correlation between oil and gas activities and emissions of CH_4 and NO_2 in the Permian basin.

Abstract

COVID-19 caused an historic collapse in fossil fuel demand, a general decline in economic activity and hydrocarbon price volatility. This resulted in an unprecedent scenario to evaluate the contribution of the oil and gas industry (O&G) to methane (CH_4) and nitrogen dioxide (NO_2) emissions in the Permian basin (U.S.), 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 during the COVID-19 lockdown. Production and drilling declined (13 % and 68 % respectively) during the lockdown, causing a generalized drop (~30 %) of NO_2 emissions derived using the divergence method in comparison with 2019. NO_2 tropospheric columns were less impacted with a smaller decrease (~4 %) across the basins. On the other hand, the impact of the lockdown in methane (increase of 0.1 % to 0.3 % across the basins) was not as evident as in the $NO_{2,}$ because of the large background cause by the long lifetime (12 years), the variability of the meteorology, and the limited temporal sampling due to the strict thresholds of the retrieval algorithm. This study demonstrates that the impact of the COVID-19 lockdown on NO_2 and CH_4 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 in the oil and gas industry, not only in production but also in the price and demand. This situation was a good opportunity to analyse two of the most common gas emissions of this industry, methane and 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. In the case of methane, the impact of the pandemic lockdown was not as evident as nitrogen dioxide due to other factors related to chemistry characteristics of methane and how the satellite selects the data. This study shows that the impact of the COVID-19 pandemic in methane and nitrogen dioxide emissions was present in other environments a part from the urban e.g., the oil and gas production regions, but also the capability to monitor it using satellite imagery.

1 Introduction

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 the aspects of this sector, from production to consumption. With the spread of the virus and increase of cases around the world, strict lockdown policies were imposed to nearly 3 billion people globally (Rume & Islam, 2020), leading to an unprecedent reduction of fossil fuel demand and consumption. According to Le Quéré et al., (2020), aviation activity decreased by 75 %, surface transport with 50 % and industry activity with 35 %, producing a collapse in oil and gas consumption. Due to the decrease in consumption, the stockpile of gas and crude oil arrived to the limit in most of the productive countries which produced a decline of the barrel price to almost negative numbers. In response to this situation, the OPEC (Organization of the Petroleum Exporting Countries) agreed to cut the oil and gas production with the intention to recover the price of the barrel (Figure 1 and figure S1).

Linked to the decrease in fossil fuel consumption and 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). Production, storage and transportation of oil and gas are linked to different emissions, including nitrogen dioxide (NO_2) and methane (CH_4). Nitrogen dioxide is generated by combustion engines used to generate power, for drilling and for transportation of equipment and consumables. NO_2 affects human health and is the precursor gas for tropospheric ozone and aerosols. CH_4 originates mainly in flaring, releases in the wellhead due to hydraulic fracturing, during processing and by venting. CH_4 is the second most important greenhouse for global warming (Dlugokencky, 2021).

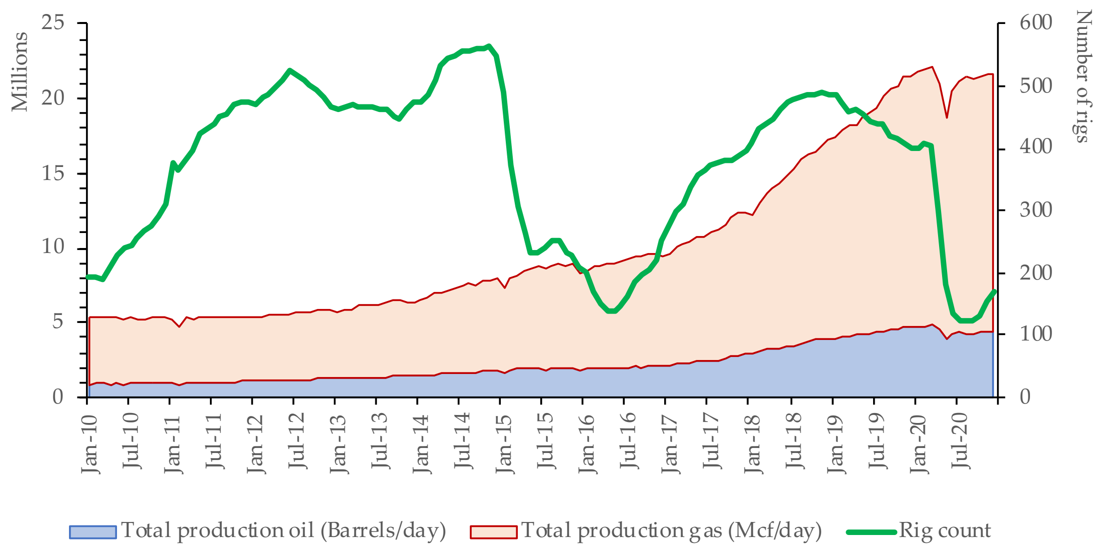

Figure 1 Time series of gas production, oil production and rig count in the Permian basin (U.S) from January 2010 to August 2020. (Source of the data used: U.S Energy Information Administration).

COVID-19 provides an unprecedent scenario to evaluate the contribution of the oil and gas (O&G) industry to these emissions 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 December 2020. This research shows for the first time the impact of drastically reducing the oil and gas activity on concentrations and emissions of methane and nitrogen dioxide 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, 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 of 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.

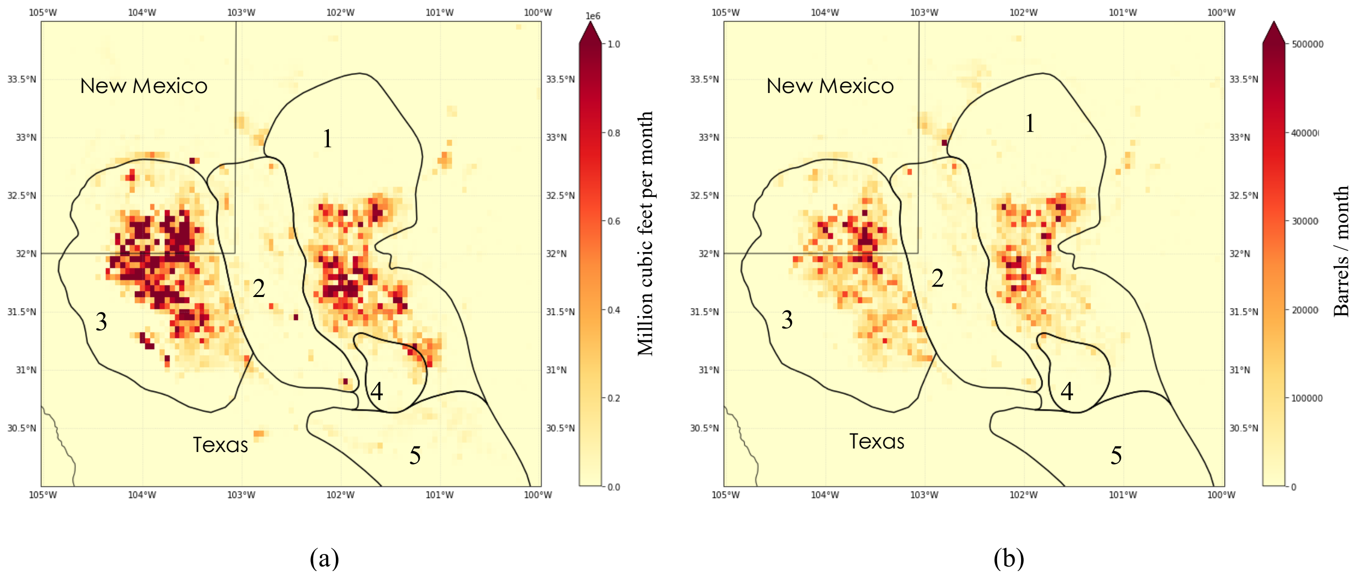

Figure 2 Monthly average of gas (a) and oil (b) production distribution in the Permian basin in 2020. The numbers are related to the different sub-basins of the Permian: 1-Midland, 2-Central, 3-Delaware, 4-Ozona Arc and 5-Valverde.

2.2 Data

This research is based on multiple sources of data: (i) NO_2 tropospheric vertical column densities, (ii) methane column mixing ratios, (iii) wind data, (iv) O&G production rates, and (v) drilling activity.

We have used TROPOMI NO_2 Version 1.3 data (European Space Agency, 2021b; Van Geffen et al., 2020) with a quality indicator (qa_value) of at least 0.75 (Eskes et al., 2021). This ensures filtering for good quality NO_2 tropospheric columns for conditions with low cloud fractions. For the TROPOMI CH_4 column mixing ratios (Lorente et al., 2021), we also used version 1.3 (European Space Agency, 2021a) with the recommended quality indicator filtering of larger than 0.5. The NO_2 and CH_4 TROPOMI data processors were upgraded after October 2020, which causes jumps in the data records. Therefor 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 (30-10-2021).

In the case of drilling activity, the data provided by ENVERUS was reported in "drilling days". Drilling days counts can implicate more than one rig in the well pad e.g., 3 rigs drilling 20 days each will be 60 days of drilling in total. The maximum number of rigs per well pad is 9, making the maximum number of days per month of drilling activity 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 and CH_4 data were produced on a 0.020° x 0.025° (approximately 2.2 km x 2,8 km) and 0.1° x 0.1° (approximately 9 km x 11 km) latitude/longitude grids. Subsequently, monthly mean and median NO_2 and CH_4 data were derived from the daily data, for the period January 2019 to October 2020.

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). The divergence method was applied on 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 ECMWF ERA 5 data set (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 concentration in the boundary layer, using:

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

Where t_{NO2} is the lifetime in s, [OH] in molecules cm^{-3} and *k* a constant of $3x10^{-11}$ s molecules^{-1} cm^3 (Atkinson et al., 2004; IUPAC, 2022).

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 goal 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, Table S1, Table S2) with the combination of different thresholds for production, drilling and emission data. 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 NO_2 and CH_4 tropospheric concentrations

The monthly median of NO_2 and CH_4 concentrations are shown in Figure 3 for the months 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. Compared to NO_2, the monthly CH_4 maps show much more variability, which is mainly caused by the sparse sampling of the data, as the CH_4 data are only available for strictly cloud free conditions. The impact of the COVID-19 on NO_2 and CH_4 concentrations is analysed by comparing the same periods between 2019 and 2020. The period 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 three-month period to reduce the effects of differences in meteorology in 2019 versus 2020 and to increase the data coverage for CH_4. 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 %, and a decrease during the lockdown months (April to June 2020) of an average -4 % (Table 1 and figure S3). This decrease during the lockdown period is quite consistent for the most productive sub-basins Delaware, Central and Midland. For winter months the largest increase was found for the Midland and Central sub-basins increase (13.3 % and 13.2 %, respectively).

In the case of methane, an increase in concentrations can be observed in 2020 with respect to 2019 for the entire period of January to June. For the months April to June, we find increases between 0.1 to 0.3 % between 2019 and 2020 (Table 1 and figure S4). The increase in the CH_4 global background concentrations is estimated between 0.5 and 0.8 % in the same period (Dlugokencky, 2021). High concentration of methane (between 1900 and 1920 ppb) is found in both years in the most productive basins of the Permian (Delaware and Midland) (Figure 3).

Table 1 Changes in NO_2 and CH_4 average, minimum, maximum, interquartile range, average ± 95 % confidence interval and standard deviation across all the sub-basins in the Permian basin. The percentages are related to April to June 2020 with respect the April to June 2019.

	Sub-basin	Average % of change	Min % of change	Max % of change	Interquartile range (50 %)	Average and 95 % confidence interval (NO_2 in mol/m^2 and CH_4 in ppbv)	Standard deviation of the mean (NO_2 in mol/m^2 and CH_4 in ppbv)
NO_2	Delaware	-4.35 %	-5 %	0 %	-5.88 %	$5.121e^{-06} \leq 1.807e^{-05} \leq 3.295e^{-05}$	6.99e-06
	Midland	-4.55 %	21 %	-28 %	-0.34 %	$5.121e^{-06} \leq 1.861e^{-05} \leq 3.295e^{-05}$	7.55e-06
	Central	-4.55 %	-76 %	12 %	-3.31 %	$4.183e^{-06} \leq 1.8\ e^{-05} \leq 3.265e^{-05}$	7.06 e-06
	Ozona Arc	-6.25 %	30 %	0 %	8.41 %	$5.121e^{-06} \leq 1.461e^{-05} \leq 3.295e^{-05}$	5.9 e-06
	Valverde	0 %	0 %	55 %	1.3 %	$1.308e^{-06} \leq 1.408\ e^{-05} \leq 2.672e^{-05}$	7.54e-06
CH_4	Delaware	0.26 %	1.54 %	0.25 %	0.72 %	1852.14 ≤ 1885.20 ≤ 1922.96	17.61
	Midland	0.17 %	0.57 %	-0.32 %	0.39 %	1846.33 ≤ 1874.01 ≤ 1902.21	14.13
	Central	0.1 %	0.57 %	-1.02 %	0.68 %	1850.20 ≤ 1878.42 ≤ 1903.82	13.99
	Ozona Arc	0.12 %	0.49 %	-0.54 %	1 %	1848.92 ≤ 1874.76 ≤ 1899.71	12.86
	Valverde	0.15 %	0.55 %	-1.55 %	0.75 %	1846.61 ≤ 1872.55 ≤ 1897.13	12.75

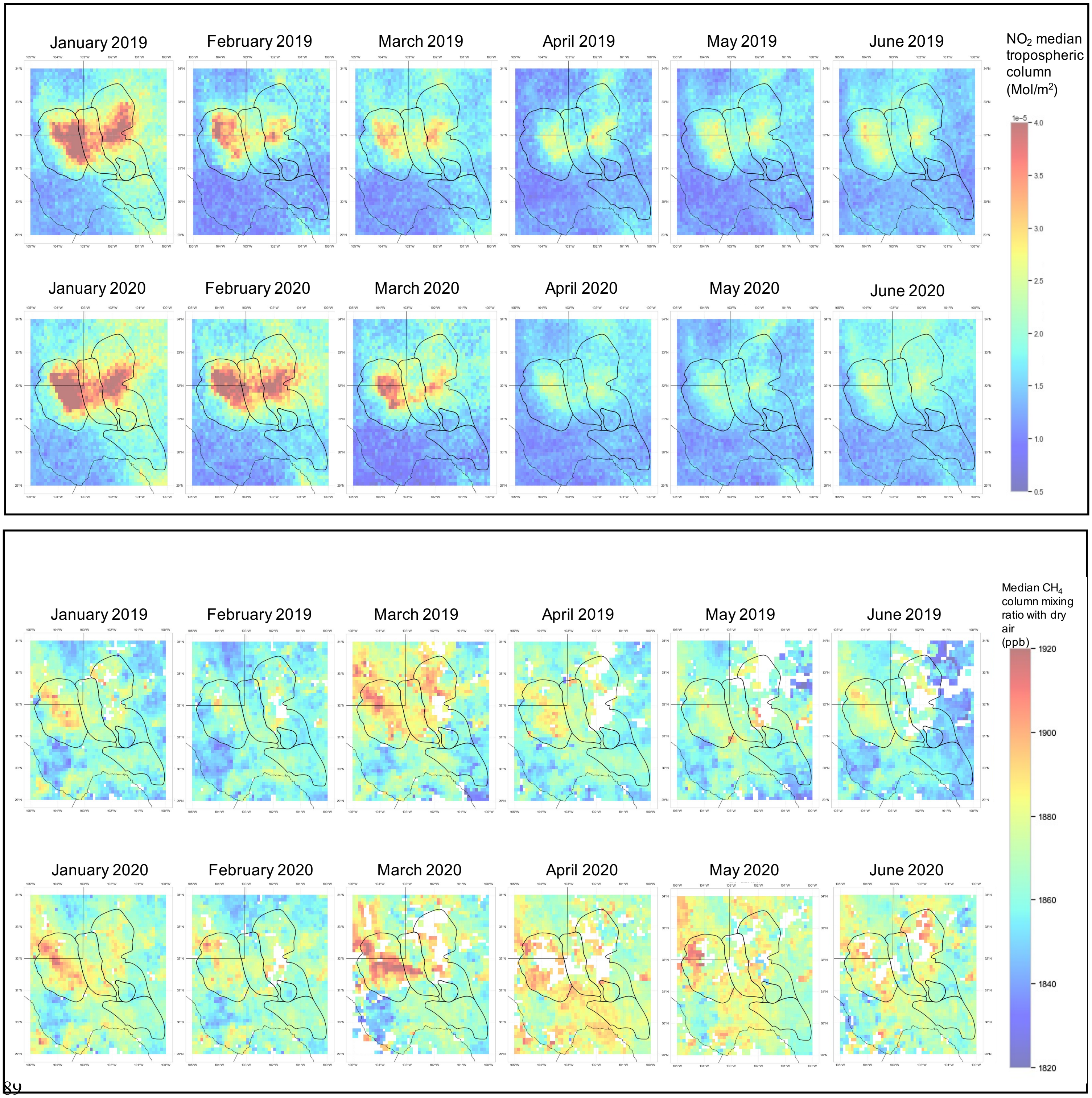

Figure 3 Time series of nitrogen dioxide tropospheric column (**top**) and methane column mixing ratio with dry air (**bottom**)from January to June in 2019 and 2020 in the Permian basin.

Sources of variability of NO_2 can be the meteorology (cloud cover, wind, etc.), the atmospheric chemistry (chemical reaction rates and photolysis) which can change the lifetime of NO_2, and measurement noise from the instrument. In the case of CH_4, the difference with NO_2 will remain in the lifetime, which in this case because of the long of it (12 years) can induce to background variability. The similarity on 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 in both NO_2 and CH_4 with only the basin of Delaware having a 95 % confidence interval higher than the other basins.

3.2 NO_2 emissions during the COVID-19

The median of NO_2 emissions derived from the TROPOMI concentrations using the divergence method, are shown in figure S5 for the period January to October 2019 and January to October 2020. A general decrease in NO_2 emissions is found in 2020 with respect to the same period in 2019, in particular for higher emissions.

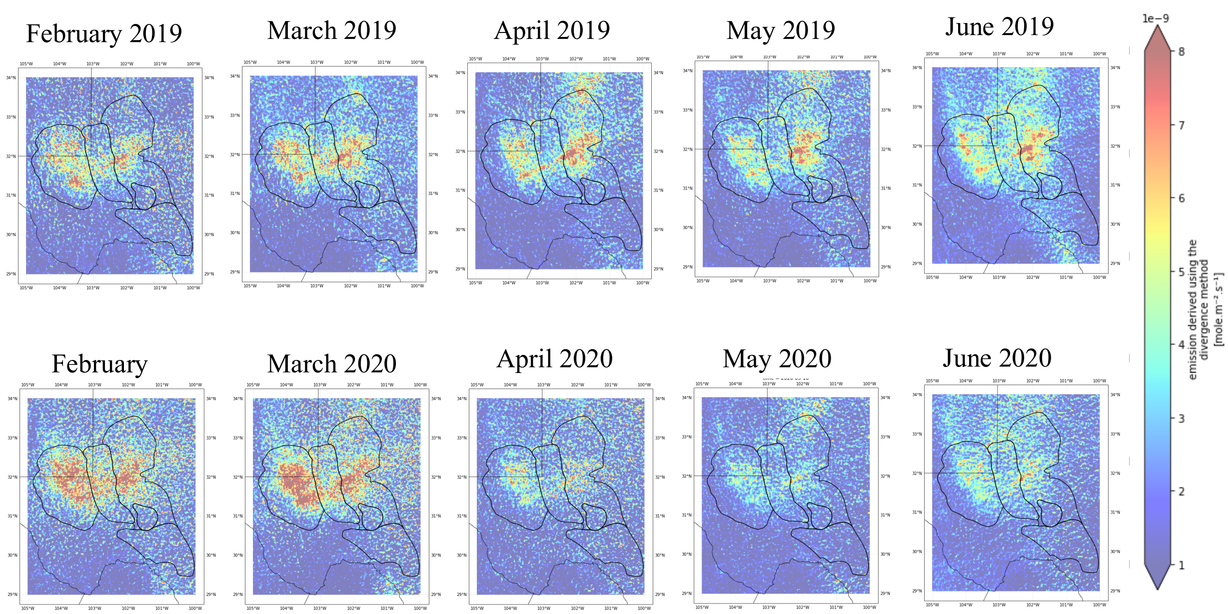

Figure 4 Nitrogen dioxide emissions time series derived from TROPOMI NO_2 tropospheric columns and the divergence method during the months before the lockdown (February to March) and lockdown months (April to June) in 2019 and 2020.

The variability of the emissions between February and June 2019 (

Figure 4) is considerably smaller as compared to the concentrations for the same period (Figure 3). This indicates that the chemical loss of NO_2, that is the main driver for the seasonal variations in the concentrations, is 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 5).

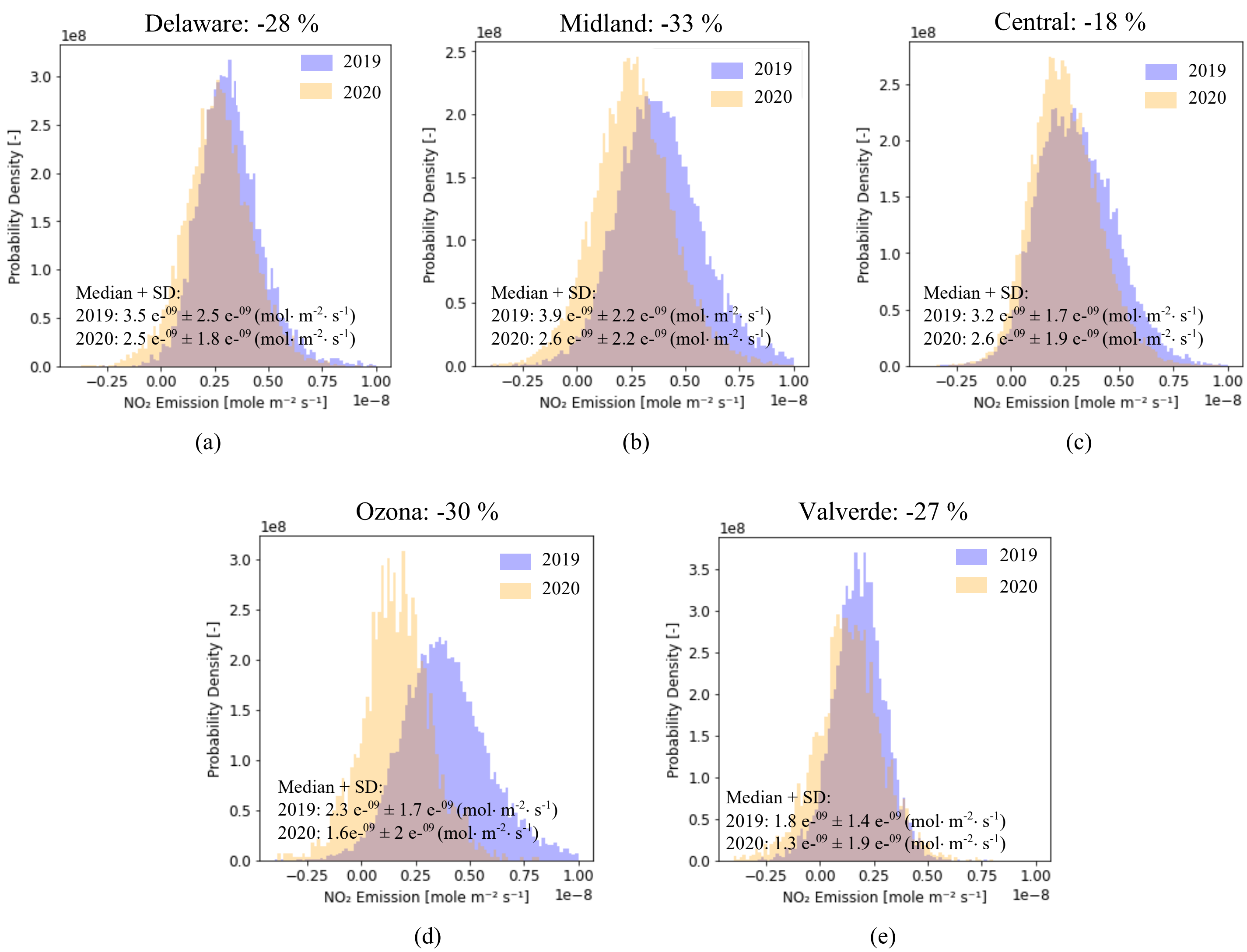

Figure 5 Histograms of the NO_2 emissions for the most productive sub-basins (**a, b,** and **c**) and the less productive (**d** and **e**) in the Permian basin during the period April-June in 2019 and 2020. The percentages in the plot title are related to reduction of NO_2 emissions between 2019 and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

Reference regions outside the boundaries of the Permian basin with background conditions were also analysed (Figure S6). The NO_2 median decreased between 1-10 %, 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 artefacts in the data or the methods, but to reduced emissions in the area. 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).

3.4 Source attribution of NO_2 emissions

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 to production + drilling and 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 April to June 2020 (

Table **2**). According to Dix et al., (2020), the number of active wells responds quickly to economic changes and sites with only production activity more slowly, which can explain the large decrease in places with significant drilling activities.

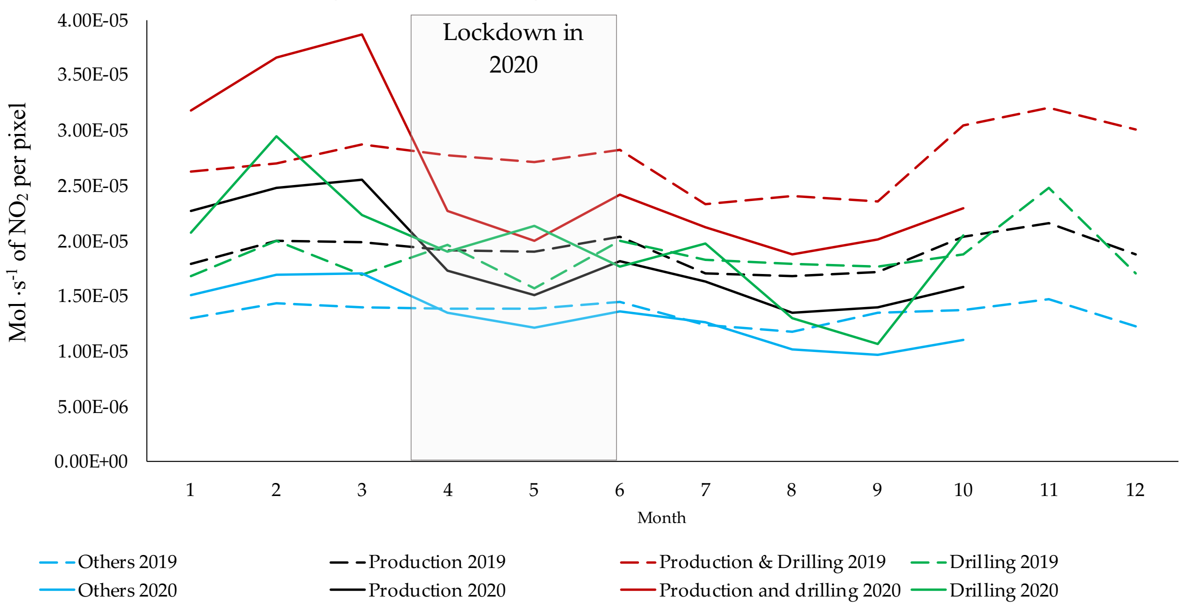

Figure 6 Normalized NO_2 emission for each month in areas with only production, production + drilling, drilling and other activities not related to the O&G. NO_2 emissions were normalized by the number of pixels attributed to each activity.

In a longer time-series analysis, (January to October 2020), the impact of COVID-19 was also most pronounced in production + drilling zones (-32 %), and only an impact of ~3 % decrease for the other categories (

Table **2**). The entire Permian basin showed an impact of the 7 % if we compare 2020 with 2019, but if the comparison is limited to the lockdown period reduction in emissions up to 19 % were found. Excluding the impact of other sources of emissions, the effect of the COVID-19 lockdown resulted in a decrease of 24 % with respect to 2019 in NO_2 emissions which were associated to the O&G industry.

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 (Mole×s^{-1} of NO_2)	2.173	0.424	0.009	1.473	4.079
	Permian basin 2020 (Mole×s^{-1} of NO_2)	2.092	0.286	0.009	1.423	3.81
	% Difference	-3.7 %	-32.5 %	-2.8 %	-3.4 %	**-7 %**
April to June	Permian basin 2019 (Mole×s^{-1} of NO_2)	0.704	0.135	0.003	0.483	1.325
	Permian basin 2020 (Mole×s^{-1} of NO_2)	0.596	0.044	0.001	0.427	1.068
	Decrease due to lockdown (Mole×s^{-1} of NO_2)	0.108	0.095	0.002	0.056	0.257
	% Difference	-16 %	-67 %	- 66 %	-12 %	**-19 %**

*In Figure S8 and table S4 of the supplementary there are the average percentage of pixels categorized as the different activities analysed.

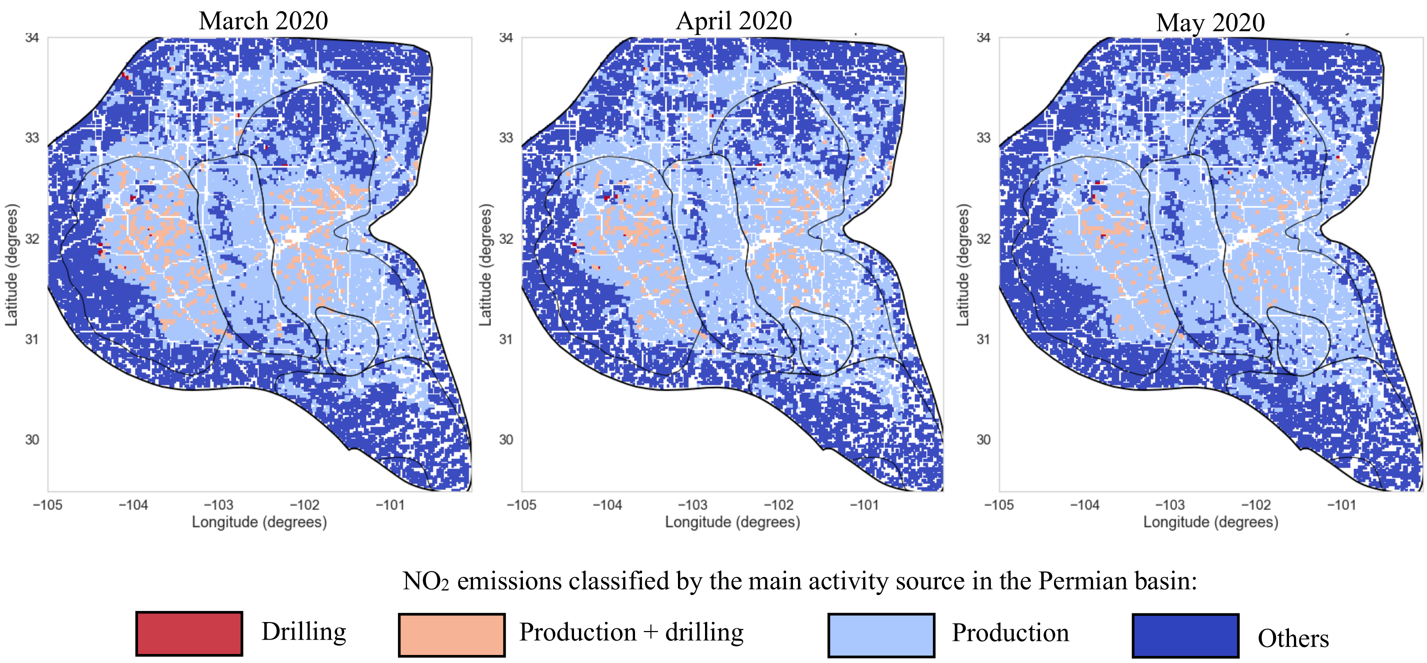

Figure 7 NO_2 emissions calculated from Tropomi data and the divergence method between March 2020 and May 2020 and classified according to different activities related and non-related to the O&G industry.

The same analysis was done for the main sub-basins of the Permian basin (Figure 7 and Table S3). NO_2 emissions associated to production + drilling areas showed an important decrease from March to April 2020 in Delaware, Midland, and Central sub-basins. On the other hand, if the period January to October is compared between 2019 and 2020, the number of locations with NO_2 emissions associated to only production did not change significantly, but it did it the emission rate on them (Figure 8 and figure S7). Thus, the production + drilling locations are where the major changes were found.

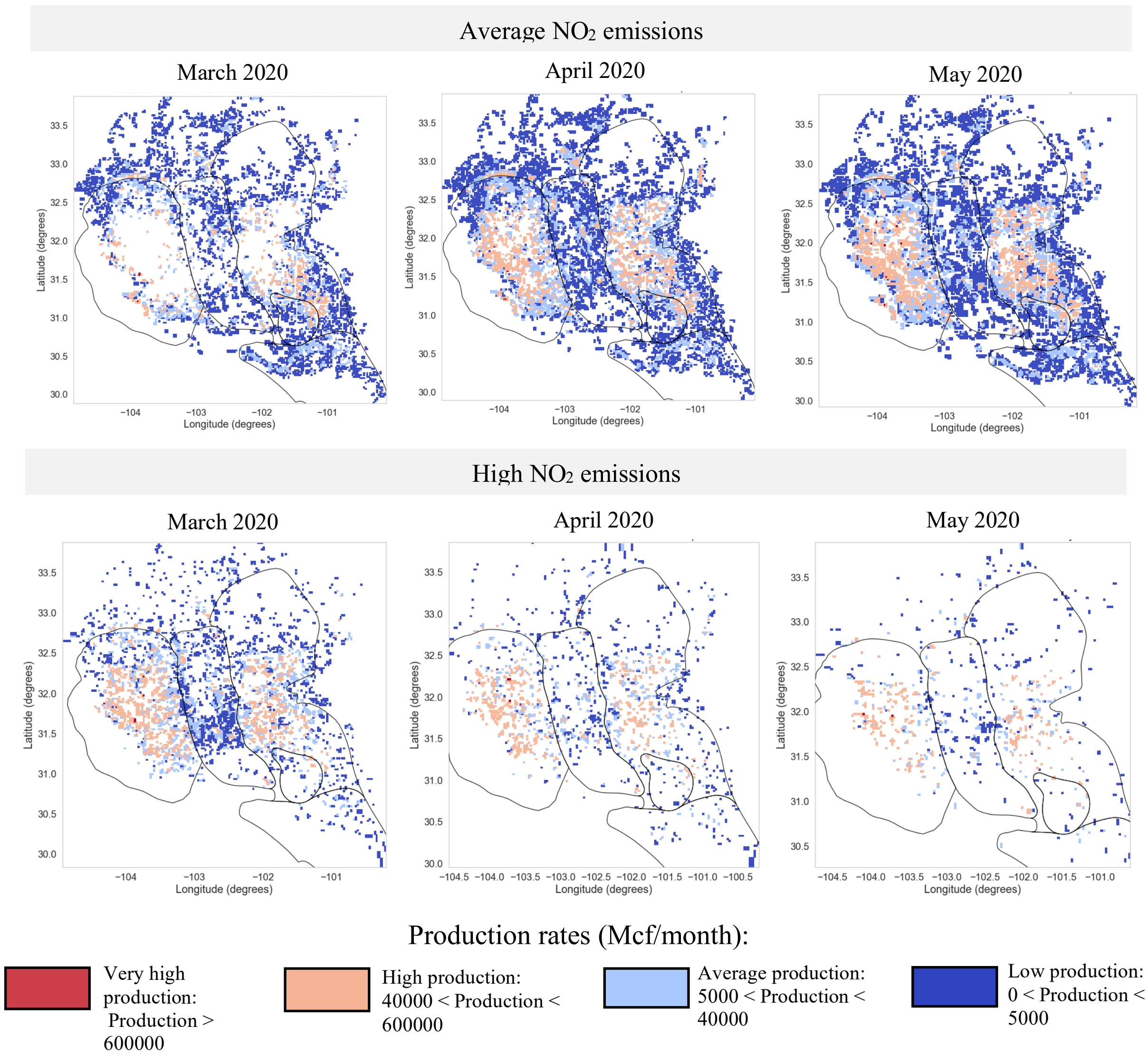

Figure 8 NO_2 high emissions ($4.3e^{-9}$ mol s^{-1} < NO_2 emissions < $9.3e^{-9}$ mol s^{-1}) (**Bottom**) and average emissions (3.5 e^{-10} mol s^{-1} < = emissions < = 4.3 e^{-9} mol s^{-1}) (**Top**) related to gas production rates in the Permian basin from March to May 2020.

Finally, we analyzed the production rates in locations with elevated levels of NO_2 emissions (4.3 e^{-9} mole·s^{-1} < NO_2 emissions < 9.3 e^{-9} mole·s^{-1} of NO_2) and places with average levels (3.5 e^{-10} mole·s^{-1} < = emissions < = 4.3 e^{-9} mole·s^{-1}) during the COVID-19 lockdowns (Figure 8 and Figure S9). As it can be seen in Figure 8 and in figure S9, low NO_2 emissions from oil and gas production places were mainly associated to 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 high production locations (40,000 Mcf/month < Production < 600,000 Mcf/month for gas and 12000 < Production < 100000 barrels in the case of oil) in March 2020. Although gas and oil production were analyzed separately the results are similar due to the fact that in the Permian basin most of the wells can produce oil and gas at the same time. With the COVID-19 lockdown, a significant decrease in high NO_2 emissions associated with high production can be observed in Delaware basin and Central basin, and an increase in average NO_2 emissions on the same locations. In May 2020, just after the peak of the lockdown, the total NO_2 emissions of the grid boxes classified as high emission was reduced from 1.7 10^{-1} mole·s^{-1} of NO_2 to 2.8 10^{-2} mole·s^{-1} in the Permian basin (Figure S9).

5 Discussion

5.1 The influence of the lockdown in nitrogen dioxide emissions

The downward trend in NO_2 concentrations corresponded in time with the demand decline of fossil fuels due to the lockdowns and travel bans.

For the Permian basin for the period April until June 2020, we report decreases of NO_2 tropospheric column concentrations of 4 % and emissions derived using the divergence method of 30 %, as compared to the same period in 2019. This difference in magnitude of reduction between concentrations and emissions in the same location has been also reported by (Misra et al., 2021) during the COVID-19 lockdown. This can be attributed to the implementation of the wind field in the emission computation. 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 error and not be impacted by the seasonal variation of 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) and just reducing the production intensity (-13 % respect to 2019) caused a 16 % reduction of NO_2. Drilling activities, especially the ones located on the same location as production, reduced the number of active drilling rigs drastically instead of decreasing the intensity (decreasing the number of days drilling per month). The total largest reduction in NO_2

emissions was associated with locations with only production (0.108 mole·s^{-1} of NO_2) but the number of possible source points (48 % (Figure S9)) is much more higher than the drilling + production (7 % (Figure S9)). In the case of drilling activities in the same place as production, the reduction of NO_2 emissions (0.091 mole·s^{-1}) was similar to the one associated only with production having 40 % less of possible source points, making the reduction of drilling 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 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 the European cities between 20 % and 40 %. Misra et al., (2021) presented the decrease of NO_2 emissions over 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 emission suitability of the method to detect emission 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 over urban areas.

5.2 The response of methane to the COVID-19 lockdown

During the COVID-19 lockdown period (April to June 2020) CH_4 concentrations did not decrease in comparison to the same period of 2019 and even appeared to increase, which is the opposite of what it is observed with NO_2. This positive trend has been observed by Mcnorton et al., 2022 finding an increase of 150 kt yr^{-1} in the overall background and a global trend of 05 - 0.8 % per year. Deriving the local changes in the CH_4 emissions from the total column satellite observations is challenging because of the large and increasing background concentration, in combination with a poor temporal sampling. Lyon et al., (2021) analyzed the variation of CH_4 concentrations from airborne and tower measurements, highlighting a declining in methane concentrations from 176 Mg CH_4 hr^{-1} before the lockdown to 55 Mg CH_4 hr^{-1} between April and May 2020 in a defined area on the East of Delaware basin. Observations done in this research and the observations in Lyon et al., (2021) can be linked to the results from Crosman (2021), who describes the meteorological drivers which contribute to a western CH_4 enhancement anomaly in the Permian basin (which can be observed in Figure 3). If we reduce the study area to the one described by Lyon et al., (2021), we can interpret the impact of the COVID-19 as a decrease in CH_4 but, if we increase the area, enhancements of CH_4 can be observed towards the west of Delaware. In addition, the results found by Stevenson et al., (2021) about the impact of COVID-19 in CH_4 increments due to NO_x reductions will also explain the enhancements observed with respect to 2019 in other areas of the Permian basin e.g., the north of the Midland basin.

6 Conclusions

The exceptional scenario of the COVID-19 pandemic created an opportunity to assess the contribution of the oil and gas sector to methane and nitrogen dioxide emissions in the biggest production area of the United States, the Permian basin. This research shows for the very first time the impact of reducing the activity source of NO_2 and CH_4 emissions in a dynamic spatial and time analysis of an area characterised 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 in the global energy trends, causing a major drop in the 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 slighter drop in tropospheric concentrations. During the lockdown period, locations with both production and drilling activity on the same place showed a similar decrease in NO_2 emissions as places with only production, even having less amount of source points. The reduction of drilling activity can be a good strategy for NO_2 emission reduction in the Permian basin.

In the case of CH_4, the lockdown impact seems to increase the concentration in the most productive regions of the Permian basin (Delaware basin 0.26 % the average and 0.72 % the interquartile 50) between April to June 2020 which agrees with Mcnorton et al., (2022). Other aspects e.g., methane lifetime, sampling and meteorological and transport phenomena are important for the observed concentrations. Indications of decrease were found when reducing the region.

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. For CH_4, this could not be demonstrated and will require further analysis to remove the large background and to overcome the poor temporal sampling of the current TROPOMI data set.

Acknowledgments, Samples, and Data

We acknowledge the free use of tropospheric nitrogen dioxide column and methane 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.

Open research

Main data sets used in this publication are:

- TROPOMI NO_2 Version 1.3 and TROPOMI CH4 column mixing ratios 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

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Journal of Geophysical Research Atmospheres

Supporting Information for

COVID-19 impact in the oil and gas industry emissions: a case study of methane and nitrogen dioxide in the Permian basin

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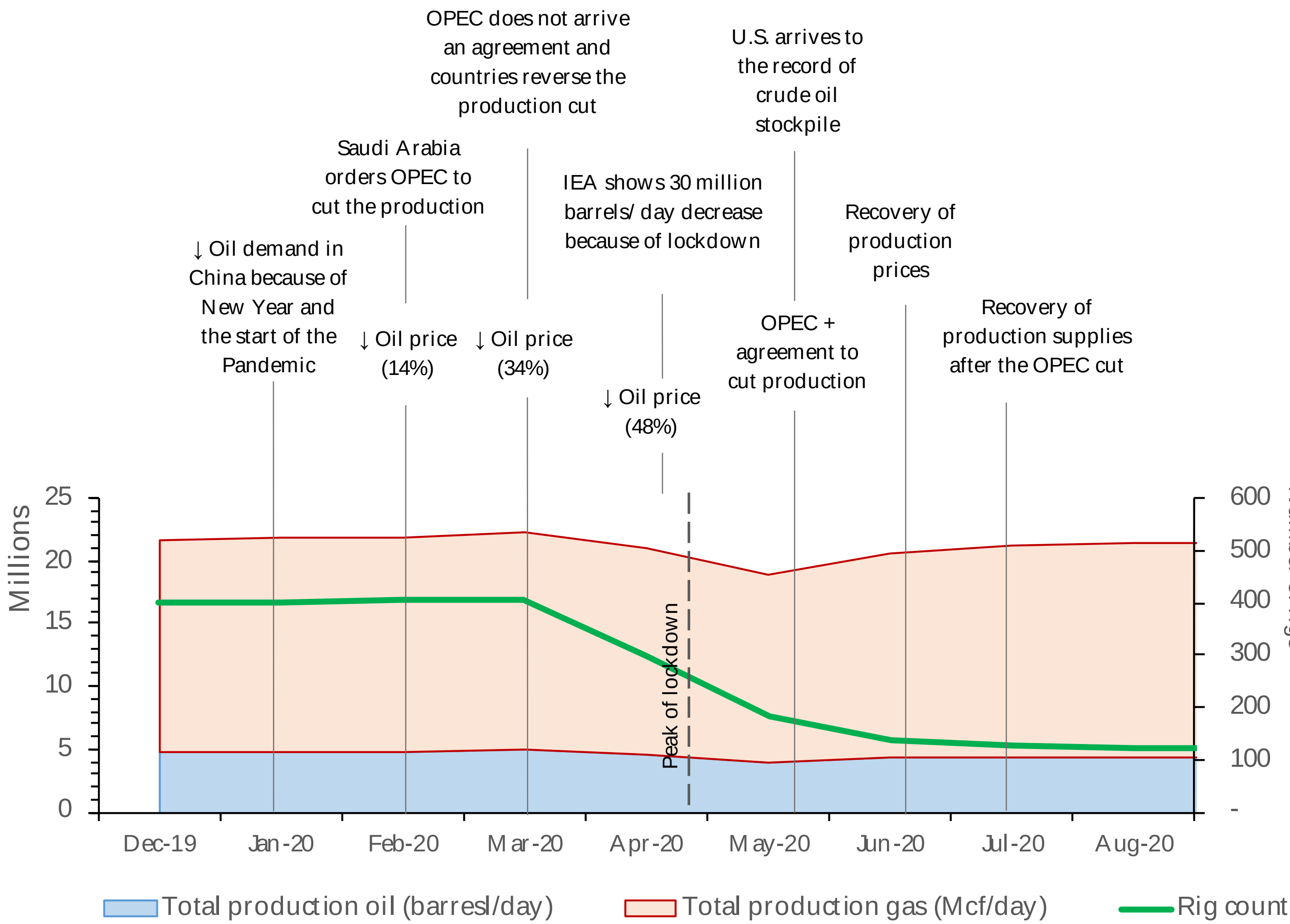


Figure S1 Main events occurred in oil and gas industry related to the oil price, production and OPEC from December 2019 to August 2020. The line chart is a detail section of Figure S1 from the same period. The green shaded part of the time ax highlights the COVID-19 lockdown period.

Table S1 Thresholds applied in the custom classified algorithm for emissions, drilling activity, oil production and gas production in the Permian basin.

	Threshold	*Description*
Emissions	Emissions < = 3.5 e^{-10}	Low emissions
	3.5 e^{-10} < = Emissions < = 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
Drilling	Drilling = 0	No drilling
	Drilling < = 25 days	Low drilling activity
	25 days < = Drilling < = 60 days	Average drilling activity
	60 days < Drilling < = 120 days	High drilling activity
	Drilling > 120 days	Very high drilling activity
Oil production	Production = 0	No production
	0 < Production < = 800	Low production
	800 < Production < = 12,000	Average production
	12,000 < Production > =100,000	High production
	Production > 100,000	Very high production
Gas production	Production = 0	No production
	0 < Production < = 5,000	Low production
	5,000< Production < = 40,000	Average production
	40,000< Production > =600,000	High production
	Production > 600,000	Very high production

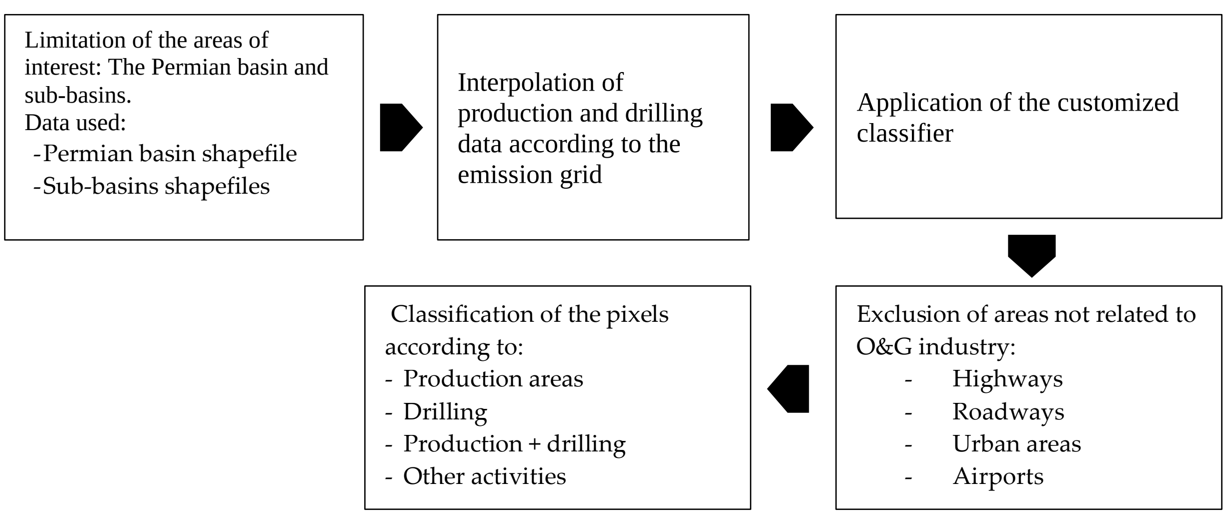
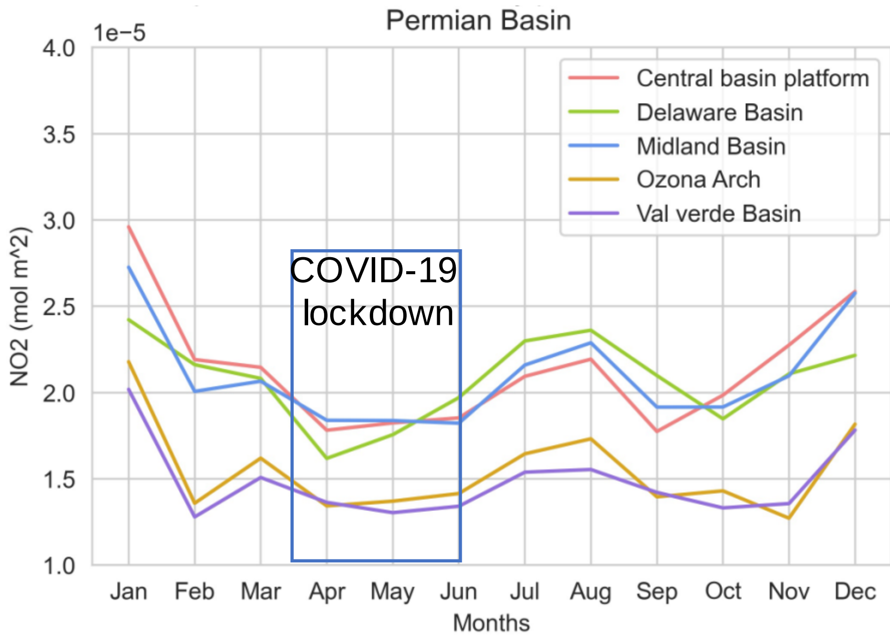


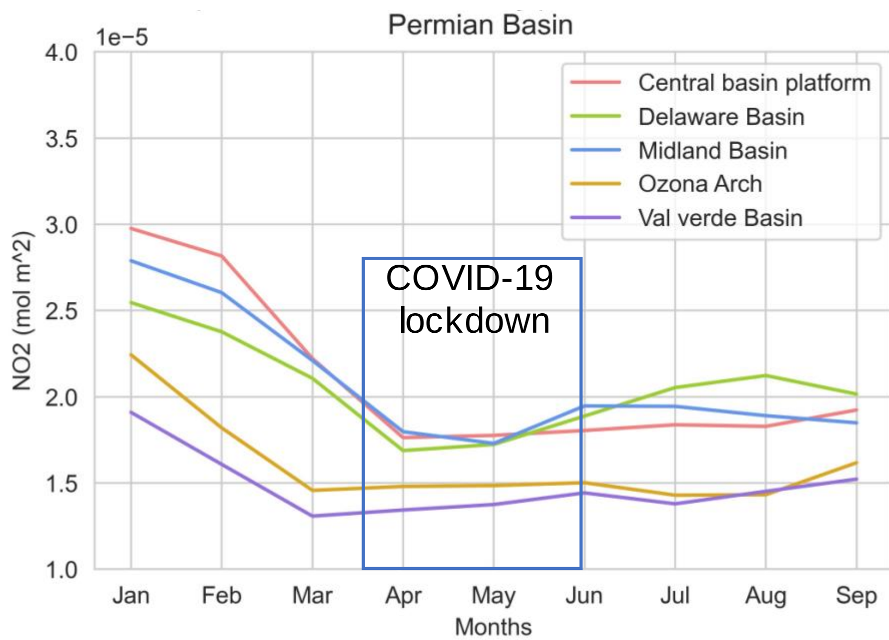
Figure S2 Workflow applied for the investigation of the emission source in the Permian basin.

Table S1 Classification details and interpretation for source attribution of NO2 emissions calculated using the divergence method in the Permian basin.

Code	Emissions	Production	Drilling	Interpretation of source attibution
0	Low	No	No	Area not in the influence of NO2 emissions
1	Average	No	No	Background
2	Average	Yes	No	Low emission pads/ low production?
3	Average	Yes	Low	Low emission pads/ low production?
4	Average	Yes	Average	Low emission pads/ low production-drilling?
5	Average	Yes	High	Low emitter rigs or production / High winds in the area?
6	Average	Yes	Very high	Low emitter rigs or production / High winds in the area?
7	Average	No	Low	
8	Average	No	Average	Low emitter rigs / High winds in the area?
9	Average	No	High	Low emitter rigs / High winds in the area?
10	Average	yes	Very high	Low emitter rigs / High winds in the area?
11	High	no	no	Other industrial activity, cities, roads?
12	High	yes	no	Production activity
13	High	Yes	Low	Production activity
14	High	Yes	Average	
15	High	Yes	High	Drilling + production at the same time
16	High	Yes	Very high	Drilling + production at the same time
17	High	No	Low	High emitter rig
18	High	No	Average	Low emitter rigs
19	High	No	High	Drilling
20	High	No	Very high	Drilling
Code	**Emissions**	**Production**	**Drilling**	**Interpretation of source atttribution**
21	Very high	No	No	Other industrial activity
22	Very high	Yes	No	Production
23	Very high	yes	Low	High emitter rigs or production
24	Very high	Yes	Average	High emitter rigs or production
25	Very high	Yes	High	Drilling + production at the same time
26	Very high	Yes	Very high	Drilling + production at the same time
27	Very high	No	Low	High emitter rigs
28	Very high	No	Average	High emitter rigs
29	Very high	No	High	Drilling
30	Very high	No	Very high	Drilling

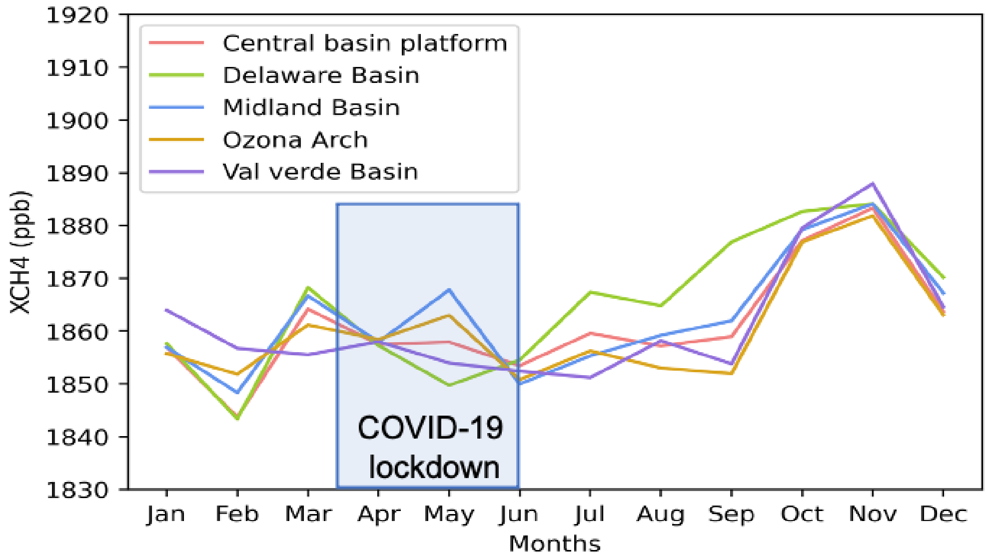


(a)

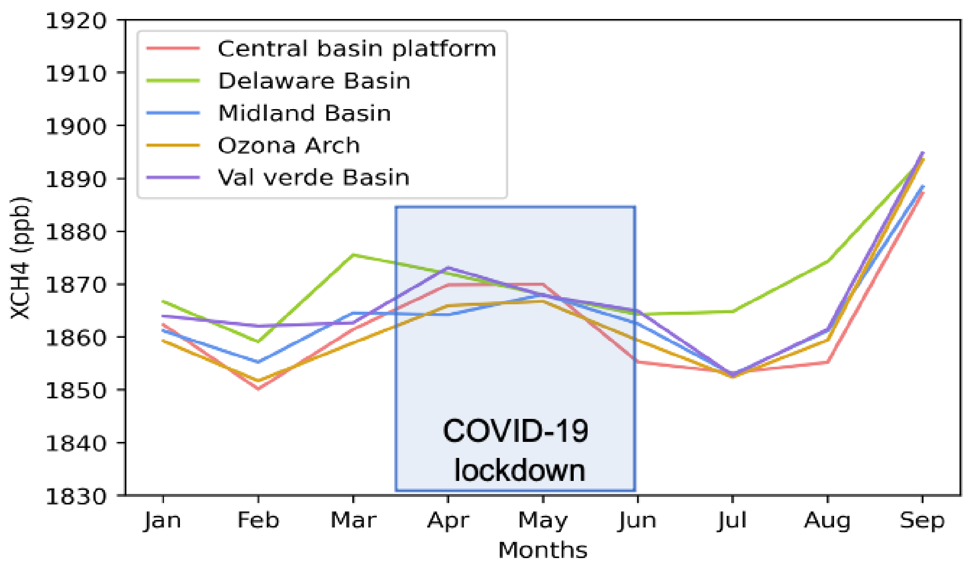


(b)

Figure S3 Nitrogen dioxide median for each sub-basin for each month in 2019 (a) and in 2020 (b). In blue is highlighted the lockdown period in both years.

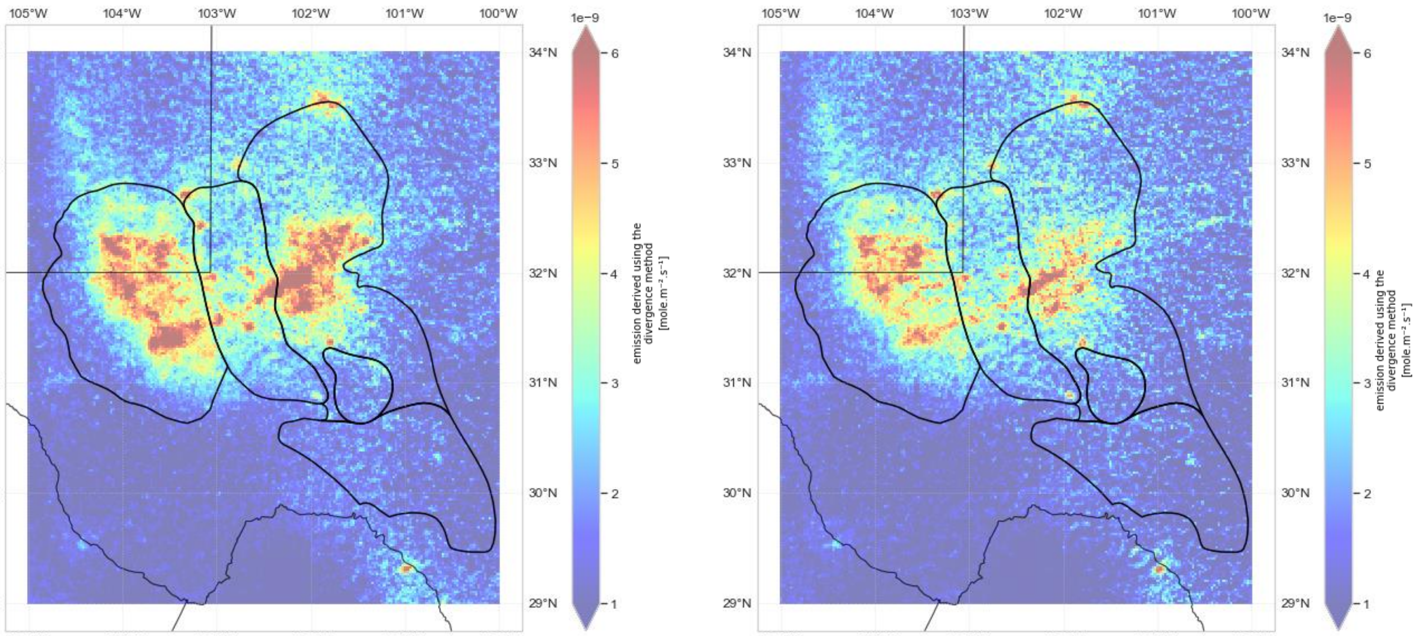


(a)



(b)

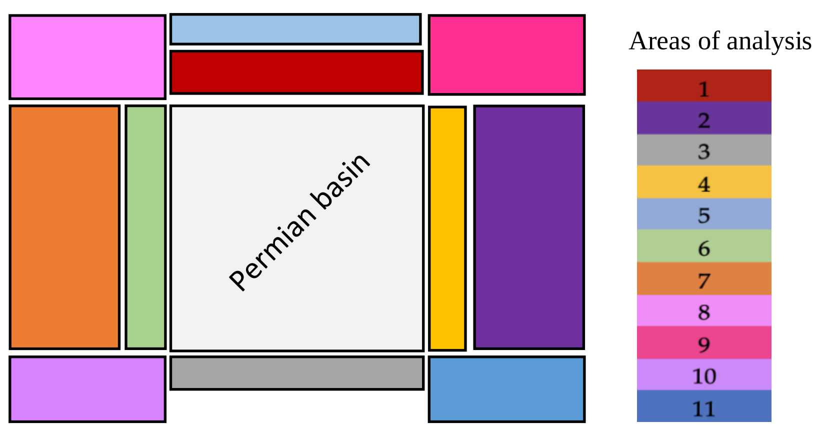
Figure S4 Methane median concentrations for each sub-basin for each month in 2019 (a) and in 2020 (b). In blue is highlighted the lockdown period in both years.



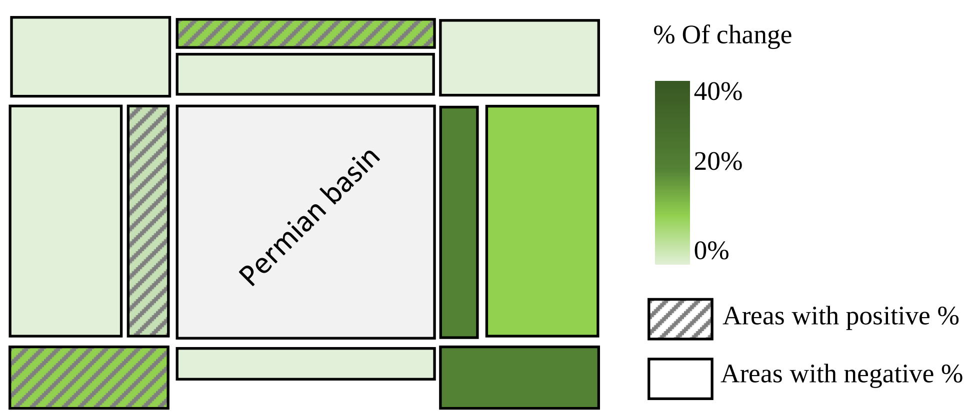
(a) (b)

Figure S5 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.

AREA	LON (degrees)		LAT(degrees)		2019 median NO_2 emissions (mole · $m^2 \cdot s^{-2}$)	2020 median NO_2 emissions (mole · $m^2 \cdot s^{-2}$)	% CHANGE
1	-105	-100	34	36	2.09e-09	2.04e-09	-2.24
2	-99	-95	29	34	3.21e-09	2.85e-09	-12.52
3	-105	-100	26	28	1.01e-09	1.01e-09	-0.23
4	-100	-99	29	34	1.52e-09	1.18e-09	-28.90
5	-105	-100	36	38	1.71e-09	1.91e-09	10.37
6	-108	-106	29	34	1.07e-09	1.12e-09	4.85
7	-112	-108	29	34	1.17e-09	1.14e-09	-2.51
8	-112	-106	29	36	1.20e-09	1.19e-09	-1.01
9	-100	-95	29	36	2.68e-09	2.64e-09	-1.75
10	-112	-106	26	28	6.09e-10	6.87e-10	11.36
11	-100	-95	26	28	2.53e-09	1.87e-09	-35.69



(a)



(b)

Figure S6 Top table summarizes coordinates of the areas surrounding the Permian basin used to calculate the median of NO_2 emissions, the median from 2019 and 2020, and the percentage of change. (a) Diagram of the location of the different areas and (b) with a colour scheme representing the change in NO_2 median emissions between 2019 and 2020.

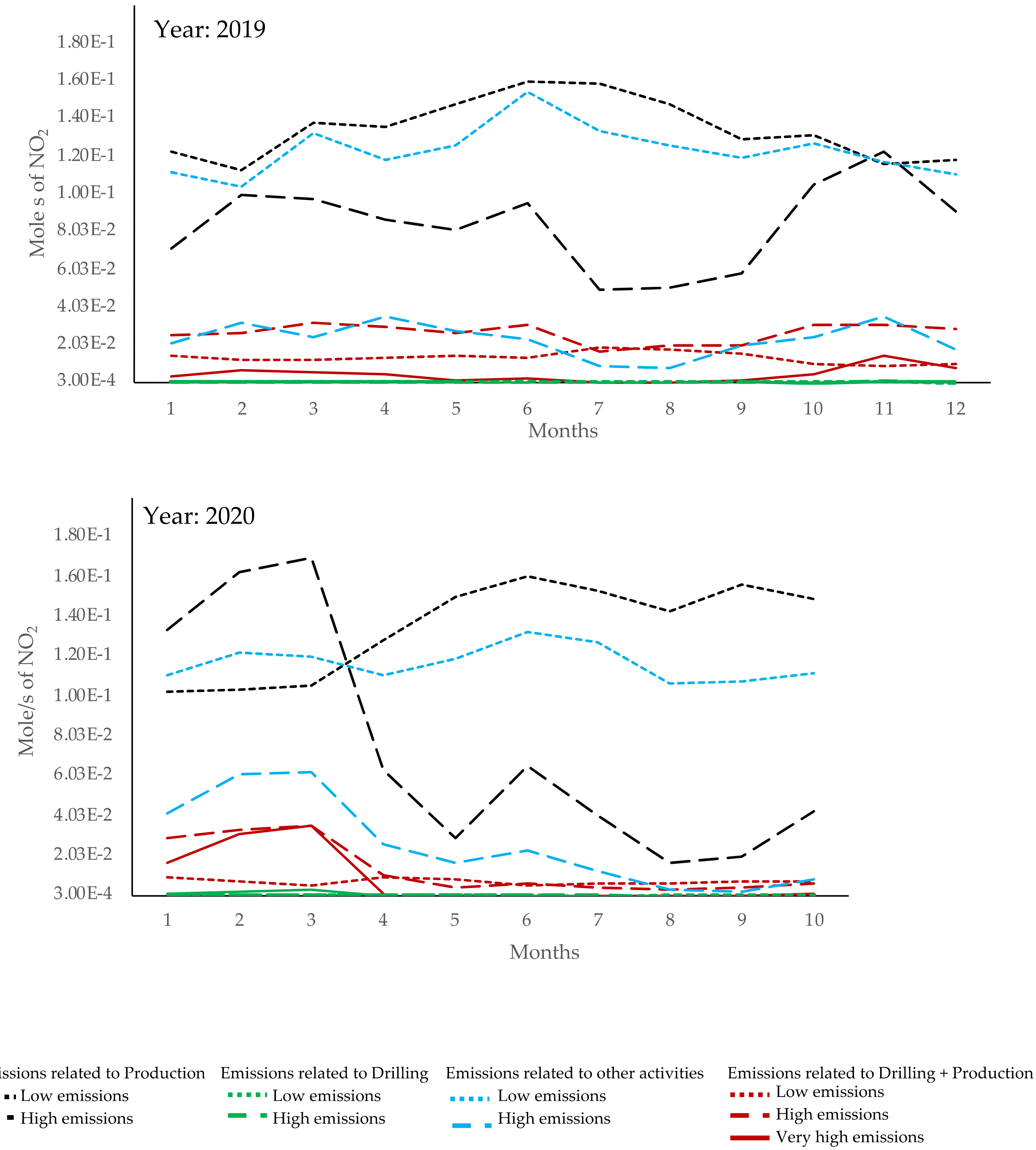


Figure S7 NO_2 emissions time-series in 2019 (a) and 2020 (b) classified according to emission level and source of the emission in the Permian basin.

Table S2 Total NO2 emission rate of each O&G activity in each basin of the Permian basin in 2019 and 2020 (from January to October) for areas with only production, production + drilling, drilling and other activities.

		Delaware (mole·s^{-1} of NO_2)	**Midland** (Mole·s^{-1} of NO_2)	**Central** (Mole·s^{-1} of NO_2)	**Valverde** (Mole·s^{-1} of NO_2)	**Ozona Arc** (Mole·s^{-1} of NO_2)
2019	Production	0.535	0.618	0.376	0.057	0.055
	Production + Drilling	0.238	0.143	0.022	0.00001	0.002
	Drilling	0.004	0.001	0.001	0.001	0.000
	Others	0.224	0.194	0.068	0.224	0.006
2020	Production	0.560	0.576	0.359	0.049	0.050
	Production + Drilling	0.168	0.094	0.012	0.0002	0.001
	Drilling	0.003	0.002	0.0004	0.0004	0
	Others	0.221	0.179	0.069	0.202	0.006

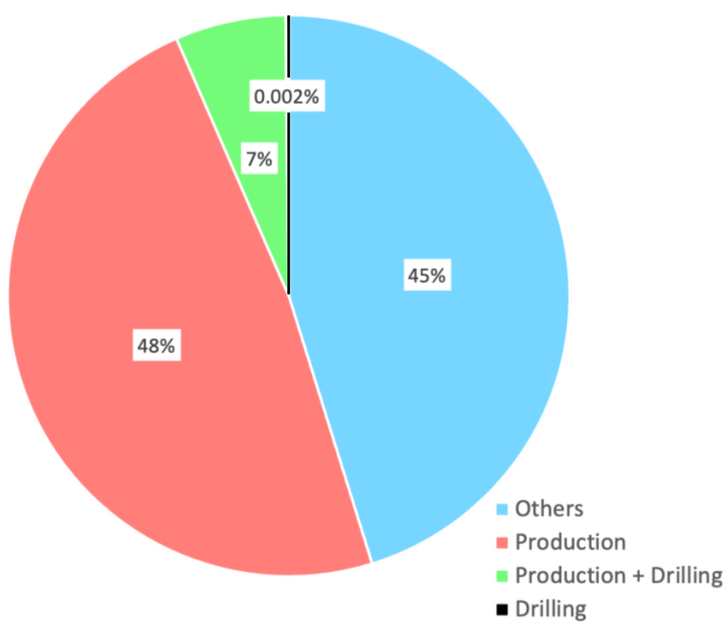


Figure S8 Average percentage of number of pixels classified as production, production + drilling, drilling and other activities in the Permian basin.

Table S4 Total number of pixels of each O&G activity in the Permian basin in 2019 and 2020 from January to October and for the COVID-19 lockdown period.

		Production	Production + drilling	Only drilling
January to October	Permian basin 2019 (Total num pixels)	35371	4282	139
	Permian basin 2020 (Total num pixels)	35592	2313	64
	% Difference	0.6 %	-45%	-53.96%
April to June	Permian basin 2019 (Total num pixels)	10583	1288	44
	Permian basin 2020 (Total num pixels)	10593	581	14
	% Difference	0.09 %	-54.8%	-68.18%

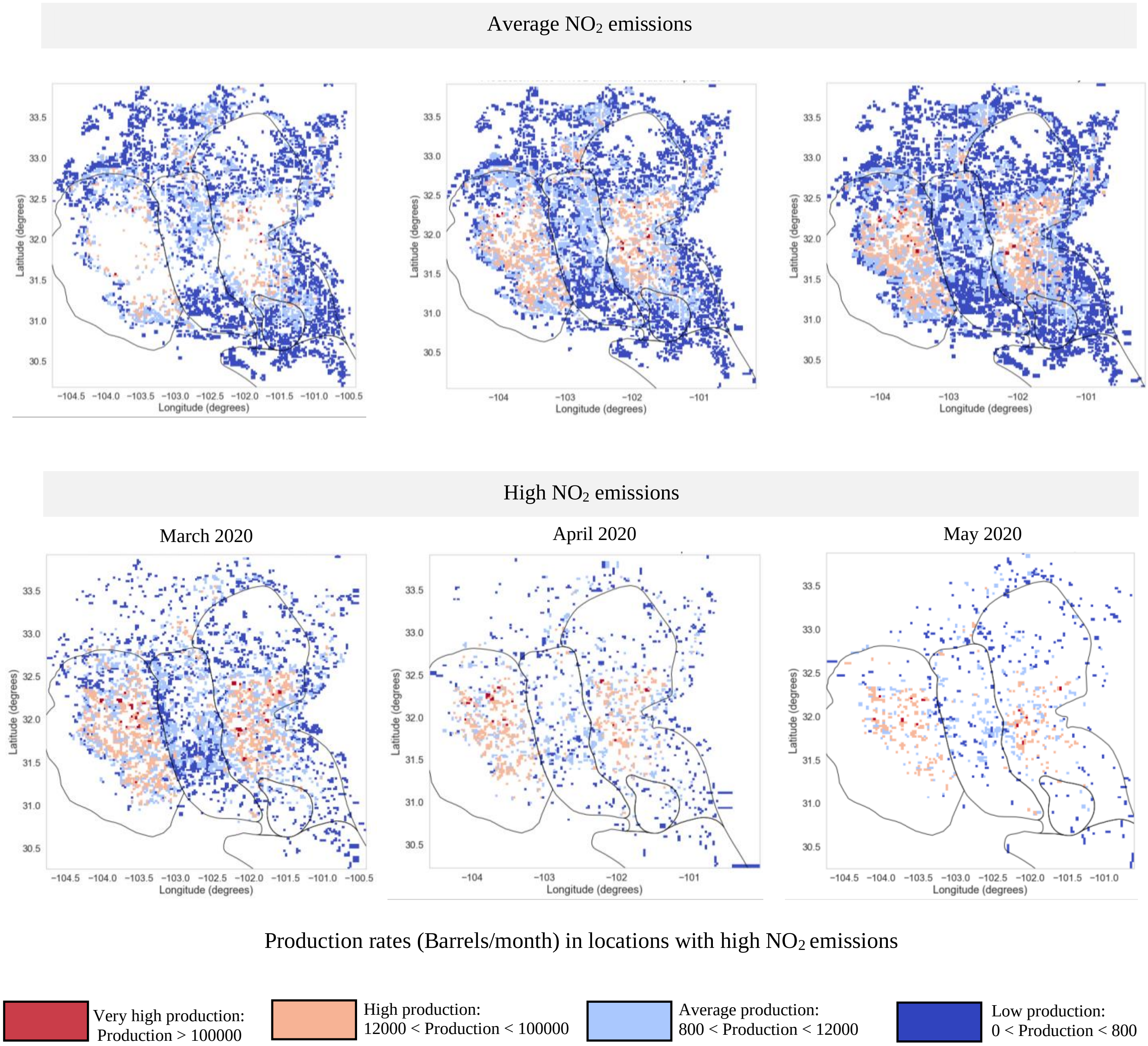


Figure S9 NO2 high emissions ($4.3e^{-9}$ mol s^{-1} < NO2 emissions < $9.3e^{-9}$ mol s^{-1}) and average emissions (3.5 e^{-10} mol s^{-1} < = emissions < = 4.3 e^{-9} mol s^{-1}) related to oil production rates in the Permian basin from March to May 2020.