Title: Upstream oil and gas production and ambient air pollution in California

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Abstract

Background. Prior studies have found that residential proximity to upstream oil and gas production is associated with increased risk of adverse health outcomes**.** Emissions of ambient air pollutants from oil and gas wells in the preproduction and production stages has been proposed as conferring risk of adverse health effects, but the extent of air pollutant emissions from wells is not clear.
Objectives. We examined the effects of upstream oil and gas preproduction (count of drilling sites) and production (total volume of oil and gas) activities on concentrations of five ambient air pollutants in California.
Methods. We obtained data on approximately 1 million daily observations from 314 monitors in the EPA Air Quality System, 2006-2019, including daily concentrations of five routinely monitored ambient air pollutants: $PM_{2.5}$, CO, NO_2, O_3, and VOCs. We obtained data on preproduction and production operations from Enverus and the California Geographic Energy Management Division (CalGEM) for all wells in the state. For each monitor-day, we assessed exposure to upwind preproduction wells and total oil and gas production volume within 10 km. We used a panel regression approach in the analysis and fit adjusted fixed effects linear regression models for each pollutant, controlling for geographic, seasonal, temporal, and meteorological factors.
Results. We observed higher concentrations of $PM_{2.5}$ and CO with exposure to preproduction wells within 3 km, NO_2 for wells at 1-2 km, and O_3 with exposure at 2-4 km. Monitor-days with exposure to increases in production volume had higher concentrations of $PM_{2.5}$, NO2, and VOCs within 1 km and higher O_3 concentrations at 1-2 km. Results were robust to sensitivity analyses.
Conclusion. Adjusting for geographic, meteorological, seasonal, and time-trending factors, we observed higher concentrations of ambient air pollutants at air quality monitors in proximity to preproduction wells within 4 km and producing wells within 2 km.

Introduction

Recent studies have found that residing in proximity to oil and gas wells is associated with adverse cardiovascular, psychological, reproductive, and other health outcomes (Casey et al. 2015, 2018; Currie et al. 2017; Denham et al. 2021; McKenzie et al. 2014, 2018, 2019; Tang et al. 2020; Whitworth et al. 2017). Studies in California have found higher risk of preterm birth and low birthweight with exposure to upstream oil production, as well as impaired lung function and higher asthma prevalence (Gonzalez et al. 2020; Johnston et al. 2021; Shamasunder et al. 2018; Tran et al. 2020). Several possible mechanisms have been hypothesized for the observed associations between proximity to wells and adverse health outcomes, including emissions of ambient air contaminants during various stages of upstream oil and gas production (Adgate et al. 2014; Allshouse et al. 2019; Gonzalez et al. 2020; Johnston et al. 2019; McKenzie et al. 2012). There is a potential for widespread risk of exposure to air pollutant emissions from upstream oil and gas development, with an estimated 17.6 million U.S. residents, including 2.1 million Californians, living within 1.6 km (1 mile) of at least one active well (Czolowski et al. 2017).

Despite widespread potential exposure to wells and reported health risks, the effects of upstream oil and gas production on ambient air quality are still not well understood (Johnston et al. 2019). Under the Clean Air Act and its amendments, local regulatory agencies are responsible for maintaining networks of *in situ* air pollution monitors (Grainger et al. 2017). Agencies routinely monitor criteria air pollutants, which are statutorily regulated under the Clean Air Act and which include fine particulate matter with an aerodynamic diameter less than 2.5 μm ($PM_{2.5}$), carbon monoxide (CO), nitrogen dioxide (NO_2), and ozone (O_3). Other hazardous pollutants are also routinely monitored, including non-methane volatile organic compounds (VOCs) such as acetaldehyde, benzene, chloroform, dichloromethane, formaldehyde, and tetrachloroethylene. In prior studies, such as *in situ* monitoring campaigns conducted in California, Colorado, and Texas, investigators have reported elevated concentrations of $PM_{2.5}$, CO, NO_2, O_3, and VOCs near wells (Allshouse et al. 2019; Arbelaez and Baizel 2015; Garcia-Gonzales et al. 2019a; Schade and Roest 2016, 2018). Sources of $PM_{2.5}$ emissions associated with upstream oil and gas production may include combustion of diesel fuel from on-site equipment and heavy trucks, dust from construction sites and unpaved roads, and secondary formation in the atmosphere (Adgate et al. 2014); emissions of CO and NO_2 may also be associated with fossil fuel combustion in vehicles and off-road equipment (Holloway et al. 2000; Jackson et al. 2014); O_3 may be formed as a secondary pollutant in photochemical reactions involving nitrous oxides (such as NO_2) and VOCs in the presence of sunlight (Mauzerall et al. 2005; Rodriguez et al. 2009).

Studies have found elevated concentrations of harmful pollutants near oil and gas wells (Garcia-Gonzales et al. 2019b). However, prior studies have been geographically and temporally constrained and often do not mirror methods applied by population health researchers. In particular, exposure characterization is often spatial in nature, whereas population health researchers often seek to exploit temporal variation to isolate the role of exposure to oil and gas wells from exposure to other spatially correlated activities may affect pollution and health. Additionally, the unique geological conditions of California may constrain external validity of air quality studies that investigate oil and gas production-related emissions in other settings (Garcia-Gonzales et al. 2019a). Population health studies investigating exposure to upstream oil and gas production typically use proximity to wells as the indicator of exposure without directly measuring concentrations of air pollutant emissions or other potential hazards, such as noise and water pollution (Casey et al. 2015; Currie et al. 2017; Gonzalez et al. 2020; McKenzie et al. 2014; Rasmussen et al. 2016; Tang et al. 2020; Tran et al.

2020). Improved understanding of pollutants emitted during upstream oil and gas production, including the classes of pollutants emitted (or secondarily produced) and the distances to which they are transported could help population health scientists more accurately parameterize exposure assessments and determine which aspects of exposure to production activities may adversely affect human health.

In our prior study (Gonzalez et al. 2020), we found that proximity to wells was associated with higher preterm birth risk, but we were not able to measure specific chemical pollutants women were potentially exposed to during their pregnancy, or to separate proximity to wells from other activities that may also affect preterm birth risk. Our objectives in the current study were to examine how upstream oil preproduction and production activities affected ambient air quality in California from 2006 to 2019, with the aim of validating and informing population health studies of exposure to upstream oil and gas production. We investigated whether marginal changes in preproduction and production activities resulted in increased concentrations of $PM_{2.5}$, CO, NO_2, O_3, and VOCs. Where we observed marginal increases in pollutant concentrations with exposure to wells, we also aimed to determine the distance at which elevated concentrations decay to background levels. To address these objectives, we applied a quasi-experimental design using a panel of publicly available air quality monitoring data.

Methods

Study design

We constructed a panel dataset with repeated daily measures of ambient air pollutant concentrations as well as upstream oil and gas production across California from January 1, 2006, to December 31, 2019. We made use of geospatial and temporal variation in oil and gas extraction activities, including well preproduction (defined as the interval between spudding, or initiation of drilling, and completion) and production (total monthly volume of oil and gas produced), and leveraged daily variation in wind direction as a source of exogenous variation. The type and magnitude of emissions may vary by stage due to differences in activities related to preproduction and production, and the intensity of well pad activity varies within each stage (Allshouse et al. 2017). For each monitor, we assessed daily exposure to upwind wells in preproduction and production during the study period. Then we used a fixed effects regression approach to assess the effect of exposure to preproduction and producing wells on the concentrations of each pollutant, accounting for geographic, seasonal, and time-trending, and meteorological factors.

Data

We obtained air quality data from the U.S. Environmental Protection Agency (EPA) Air Quality System (AQS). This dataset comprised daily measurements of seven air pollutants, with daily mean concentrations of $PM_{2.5}$ ($\mu g\ m^{-3}$) as well as daily max concentrations of CO (ppm), NO_2 (ppb), O_3 (ppb), and non-methane VOCs (ppb C). We included data for all 314 AQS monitors in California that were operating during the study period and that monitored for the five pollutants of interest (Figure 1). Due to the sparse monitoring of VOCs compared to other pollutants, we included data on VOC measurements for 1999-2005; we excluded pre-2006 measurements for other pollutants because data for wildfire smoke plumes, described below, were not available before 2006.

Data on the oil and gas wells, including development dates and monthly production volume, was obtained from the California Geologic Energy Management Division (CalGEM) and Enverus, a private data aggregation service. The analytic dataset included 38,157 wells that were in the preproduction and 90,697 wells in production in California during the study period (Table S1). We defined the preproduction stage of the well as starting with the reported spud date and ending with the completion date. Preproduction wells were included in the study if the preproduction interval (spudding to completion) occurred during the study period. For wells missing data on the spud date, we assumed that the preproduction interval began 30 days before completion; for wells missing completion date, we assumed the preproduction stage ended 30 days after spudding. Wells in the production stage were included for all sites with any reported oil or gas production during the study period. Because oil and gas are frequently produced from the same wells, we used a combined metric of oil and gas production reported as barrels of oil equivalent (BOE). The dataset comprised 8,064,549 well-month observations of a total of approximately 3.8 billion BOE.

We obtained meteorological data from the North American Regional Reanalysis (NARR), a product developed by the National Centers for Environmental Prediction. This dataset included modeled daily mean wind direction and speed, reported as vectors (*u* and *v*), as well as observations of mean daily surface temperature (°C) and total daily precipitation (mm). We also obtained administrative shapefiles for air basins across the state from the California Air Resources Board (CARB). We used data from the 2010 decennial census to determine whether monitors were located in urban or rural areas, with urban areas classified as urban clusters with 2,500 to 50,000 residents or densely inhabited areas with at least 50,000 people. To control for potential effects of wildfire smoke on daily concentrations ambient air pollutants, we used data on the daily location of wildfire smoke plumes from the Hazard Mapping System of the National Oceanic and Atmospheric Administration (NOAA), which assessed the number of overhead smoke plumes at the zip code level (Schroeder et al. 2008).

Exposure assessment

We constructed a panel dataset where, for each monitor and each day with a pollutant observation, we summed (a) the number of upwind wells in preproduction and (b) the total volume of upwind oil and gas production (BOE) in 1 km increments out to 10 km (Figure 2). We determined the wind direction for each monitor-day from the *u* and *v* vector components from the NARR wind product. The resultant of the *u* and *v* vector components convey wind direction and speed (magnitude). Preproduction and production wells that intersected the upwind quadrant on each day for each monitor comprised the primary exposure variables; wells outside the quadrant were excluded.

As sensitivity analyses, we also assessed exposure to wells in the downwind quadrant as a placebo exposure. Additionally, we assessed exposure to all preproduction wells and production volume in 1 km annuli (or rings) radiating out from the monitor, i.e., without taking wind into account.

Identification strategy

We leveraged daily variation in wind direction as a plausibly exogenous source of variation, uncorrelated with well preproduction and production activities as well as other sources of pollution. This strategy allowed us to, by design, isolate the marginal contributions of additional preproduction wells and production volume to ambient air pollutant concentrations.

Statistical analyses

We used adjusted fixed effects linear regression models to assess how marginal changes in (a) the count of wells in preproduction or (b) the volume of oil and gas production affects concentrations of each observed pollutant ($PM_{2.5}$, CO, NO_2, O_3, and VOCs). For each combination of pollutants and well stage (preproduction or production), we fit the following model:

$$Y_{md} = U_{mda} + D_{mda} + O_{mda} + C_{md} + \gamma_{mn} + \delta_{by} + \lambda_{m},$$

where Y is the observed daily concentration of the pollutant at monitor *m* on day *d*; U is a vector of either the (a) upwind count preproduction wells or (b) upwind sum oil and gas production on day *d* in annulus *a* (0-1 km, 1-2 km, … 9-10 km) radiating from monitor *m*; D is similar to U but for downwind wells; O is also similar to U, but were wells in the two quadrants orthogonal to the upwind quadrant (i.e., lateral wells); C is a vector of covariates (day of week, precipitation in mm, temperature in °C, wind speed in ms^{-1}, and the count of overhead smoke plumes) at monitor *m* on day *d*; γ is a fixed effect for monitor by month, *n*; δ is a fixed effect for air basin, *b*, by year, *y*; and λ is a fixed effect for the monitor. We fit additional models with polynomial terms for each exposure bin to examine whether the response was nonlinear.

We compared the point estimates for upwind wells with downwind placebos. As sensitivity analyses, we also modified the fixed effects in the model, using monitor-by-year and air basin-by-month-by-year fixed effects in the model. Additionally, we fit models as described above in the primary analysis but using exposure assessment data that did not take wind into account (i.e., the sum of all preproduction wells or production volume within each annulus). Finally, as an additional sensitivity analysis for co-exposure to wildfire smoke, we fit models for $PM_{2.5}$ where monitor-day observations that had smoke plumes overhead were omitted.

In total we fit 27 models, and, as the primary analysis, we focused on the adjusted fixed effects regression models for exposure to preproduction wells and production volume. In particular, we were interested in the point estimates for exposure to upwind wells and production within 5 km of the monitor.

All data preparation and analyses were conducted using R v. 4.0 (R Core Team 2020).

Results

Descriptive statistics

The analytic dataset comprised 1,058,230 daily observations of the five pollutants from 314 monitors across California collected from 2006 to 2019, with additional observations for VOCs from 1999-2005 (Table 1). Most (208) monitors were located in urban areas and approximately half (158) were in the four air basins with the majority of oil and gas wells (96.4%) and production (87.2%): Sacramento Valley, San Joaquin Valley, South Central Coast, and South Coast (Table S1). Not all monitors collected data for all pollutants. The majority (79.5%) of monitor-days included observations for O_3, with 43% of monitor-days including data for NO_2 and $PM_{2.5}$. Some 31% of monitor-days included CO observations and 8.9% included observations of VOCs. For each pollutant, there were more observations at monitors more than 10 km from wells than monitors near wells. There were slightly more observations collected in the later years of the study period compared to earlier in the study period. The number of monitors in operation throughout the study period was relatively consistent from year to year; the minimum number of monitors in operation was 223 in 2006 and the maximum was 245 in both 2012 and 2014, with a median of 239 (Figure S4). The number of monitors that assessed $PM_{2.5}$ concentrations increased throughout the study period. At monitoring sites within 10 km of wells, the average concentrations of $PM_{2.5}$ and VOCs were higher than at monitoring sites further than 10 km. Monitors further than 10 km of wells had slightly higher mean NO_2 concentrations.

Preproduction and production wells were concentrated in the San Joaquin Valley, which includes Kern County, with substantial production in the South Coast air basin, which includes Los Angeles County (Table S1). Among the 314 monitors included in the analytic dataset, 79 (25.2%) were within 10 km of at least one oil or gas well, 33 (10.5%) were within 3 km, and 11 (3.5%) were within 1 km. Of the monitor-days included in the analysis, 46,477 (4.4%) were exposed to at least one preproduction or production well within 1 km, 115,648 (10.9%) were within 3 km, and 239,764 (22.7%) were within 10 km. For monitor-days with data for $PM_{2.5}$ and VOCs, there were no preproduction wells within 1 km.

Among exposed monitor-days, the median number of preproduction wells within each upwind 1-km bin was between 1 and 4, with a maximum of 41 (Table S2). For producing wells, median upwind exposure spanned 7.2 to 166.9 BOE, with a right-skew and a maximum of 24,166.1 BOE. There was both seasonal and geographic variation in wind direction: in the San Joaquin Valley, the wind predominantly originated in the northwest; in the South Coast basin, wind predominantly came from the southwest (Figure S1). Exposure to preproduction wells was correlated with exposure to production volume for all annuli beyond 1 km. Across producing wells, daily production volume was right-skewed, with a median of 7.3 BOE per day and mean (± SD) of 17.1 (± 50.6) BOE per day. Exposure to preproduction wells was highly correlated for adjacent annuli and moderately correlated with further annuli; we observed a similar trend for production volume (Table S3). Within 1-km annuli, exposure to preproduction wells was moderately correlated with exposure to production volume except for exposures within 1 km.

Primary analyses

In the primary analysis, we observed increased concentrations of $PM_{2.5}$, CO, NO_2, and O_3 with exposure to preproduction wells (Figure 3). For $PM_{2.5}$, we observed an increase of 2.35 $\mu g\ m^{-3}$ (95% CI: 0.81, 3.89) for each additional upwind preproduction well site within 2 km of the monitor, and 0.97 $\mu g\ m^{-3}$ (0.52, 1.41) for an additional well within 2-3 km. For CO, increase of 0.09 ppm (-0.0004, 0.18) with an additional upwind well within 2 km and 0.02 (0.004, 0.032) for a well at 2-3 km. Concentrations of NO2 increased 2.27 with well at 0-1 km, 2.91 (0.99, 4.84) for a well at 1-2 km, and 0.65 (0.31, 0.99) for a well at 2-3 km upwind. For O_3, there were no significant changes for an additional well within 2 km, an increase of 0.31. (0.20, 0.42) with an additional well at 2-3 km, and an increase of 0.14 (0.05, 0.23) with a well at 3-4 km. There were no increases in concentration with upwind exposure to VOCs, though there was no exposure to preproduction wells within 1 km. Across all pollutants, we did not observe any substantial increased concentrations beyond 4 km. In the placebo test with exposure assessed to downwind wells, we did not observe any substantial increases in pollutant concentrations.

We observed increased concentrations of $PM_{2.5}$, NO_2, O_3, and VOCs with higher exposure to upwind production (Figure 4). We estimated the marginal effect of exposure to an additional 100 BOE of daily total oil and gas volume within each 1-km annulus. This degree of exposure roughly corresponds with median upwind production volume within each annulus among exposed monitor-days (Table S2) and is comparable to cutoffs used in recent population health work (Tran et al. 2020). For each additional 100 BOE of total oil and gas production within 1 km, we observed an increase of 1.93 $\mu g\ m^{-3}$ (95% CI: 1.08, 2.78) in the concentration of $PM_{2.5}$. For NO_2, we observed an increase of 0.62 ppb (0.37, 0.86) with an additional 100 BOE within 1 km. The concentration of O_3, increased by 0.11 ppb (0.08, 0.14) with for each 100 additional BOE at 1-2 km. There was an increase in VOC concentrations of 0.04 (0.01, 0.07) ppb C for an additional 100 BOE of production within 1 km. We did not observe any substantial changes in CO concentrations with upwind exposure to production volume. In the downwind placebo tests, we observed an increase in $PM_{2.5}$ concentrations for exposure to increased production within 1 km, a small increase in NO_2 concentrations at 1-2 km, and an increase in O_3 at 3-4 km.

Sensitivity analyses

We performed several sensitivity analyses. Fitting models that included exposure variables for both preproduction and production did not qualitatively change the results. In models with polynomial term for exposure we did not see evidence of non-linear responses to upwind exposure. Changing model specification in the primary analysis for preproduction wells (Table S4) or for production volume did not qualitatively change findings (Table S5). In a sensitivity analysis, we fit the model as described above but omitted the 35,422 monitor-days with smoke plumes overhead, comprising 7.8% of the $PM_{2.5}$ analytic dataset. The results were similar to the smoke-adjusted results for exposure to wells in both the preproduction and production stages (Figure S3).

Discussion

We observed higher concentrations of ambient air pollutants at monitoring sites exposed to wells in both the preproduction and production stages. Concentrations of $PM_{2.5}$ increased substantially on days when a preproduction well was within 3 km and when production volume increased within 1 km. We observed increases in $PM_{2.5}$ within 1 km of producing wells with and without wind direction taken into account, which may be attributable to high volume of producing wells near monitors in San Joaquin Valley orthogonal to the upwind direction, imperfect wind data, or shifting winds within the day that are not captured by our daily aggregated wind direction model.

Concentrations of O_3 increased at 1-4 km downwind of wells. Exposure to CO, which increased within 3 km of preproduction wells, is associated with symptoms including fatigue, dizziness, headache, confusion, and nausea, as well as adverse chronic cardiovascular and cardiorespiratory outcomes (Dydek 2008; Raub et al. 2000). For both new and producing wells, NO_2 exposure increases risk of adverse respiratory outcomes and impaired immune function (Costa et al. 2014). We observed higher concentrations of VOCs with increases in production volume within 1 km. In the current study, VOCs comprised non-methane organic compounds including acetaldehyde, benzene, chloroform, dichloromethane, ethylene, formaldehyde, and tetrachloroethylene. People exposed to VOCs emitted from oil and gas production may have higher risk of cancer and adverse neurological or developmental outcomes (McKenzie et al. 2018).

Findings from the current study indicate both primary emission and secondary formation of pollutants from upstream oil and gas production activities. However, identifying specific processes that resulted in observed pollutant emissions was outside the scope of the study. Results from the current study suggest that O_3 is a secondary pollutant resulting from preproduction and production activities. We observed significant increases in O_3 concentrations the started at 1 to 3 km downwind of preproduction and production wells, which may be attributable to secondary formation from primary pollutants emitted from well sites. Ground-level O_3 may be secondarily formed from photochemical reactions involving CO, NO_x, and VOCs, pollutants that we also observed to were emitted from wells (Real et al. 2007; Rodriguez et al. 2009).

Our findings validate exposure assessment methods employed in many population health studies, where exposure may be estimated acutely (e.g., on a day-to-day basis) or for some longer duration, such as a trimester of pregnancy. Chronic exposure is also a concern for residents near oil fields, where wells may have been in production for years or decades. We observed differences in the type and intensity of emissions between wells in preproduction and production. Future studies should consider the potential for risks associated with both stages, and potentially also for exposure to idle and postproduction wells. The five pollutants we examined in this study represent a subset of potential hazards associated with exposure to oil and gas wells, which may include other air pollutants as well as water and noise pollution (Adgate et al. 2014; Jackson et al. 2014). Recent studies from California have reported fugitive methane from idle and unplugged wells, as well as urban oil and gas infrastructure, which may correlate with emissions of benzene, toluene, ethylene, xylene, and other air toxics (Lebel et al. 2020; Okorn et al. 2021). To differentiate risks conferred by air pollutants, population health researchers could utilize variations in wind direction.

The siting of air quality monitors is delegated to local authorities and prior studies have found evidence of bias in where monitors are sited (Grainger et al. 2017; Grainger and Schreiber 2019). For example, in counties just marginally in attainment for National Ambient Air Quality Standards (NAAQS), regulators had an incentive to place new monitors far from pollution sources, whereas in areas already in non-attainment, the regulators were incentivized to place monitors close to polluting sources (Grainger et al. 2017). This could lead to biased estimates of emissions from oil and gas wells, as monitors may be sited away from the most intensively producing oil fields. There is also evidence that monitors are less likely to be located in communities with racially and socioeconomically marginalized populations, which could lead to underestimation of oil and gas-related emissions if oil production in excluded areas was more intensive and polluting (Grainger and Schreiber 2019). In the current study, the majority of oil and gas production was concentrated in Kern and Los Angeles Counties, both of which were in non-attainment for $PM_{2.5}$ throughout the study period (Environmental Protection Agency 2021).

Prior field studies have found emissions of pollutants from upstream oil and gas facilities. Studies in Texas have found high concentrations of nitrous oxides and saturated hydrocarbons associated with oil and gas production in the Eagle Ford Shale (Schade and Roest 2018). A recent study in Colorado, which combined *in situ* monitoring and cancer risk assessment, found higher exposure to non-methane hydrocarbons and elevated risk of cancer and other adverse health outcomes with close proximity to oil and gas facilities (McKenzie et al. 2018). Garcia-Gonzales et al. (Garcia-Gonzales et al. 2019a) found higher concentrations of VOCs downwind of a well site in Los Angeles. A study in Pennsylvania found that exposure metrics used in prior epidemiological studies were poorly correlated with observed pollutant concentrations (Wendt Hess et al. 2019). However, this study assessed exposure to wells at distances greater than 10 km, where we would not expect to detect increases in pollution, and the authors did not account for meteorological factors that may affect pollutant concentrations (Buonocore et al. 2020).

The current study had several limitations. Data for many pollutants that may be emitted during upstream oil and gas production operations are not routinely monitored and reported in the EPA Air Quality System. Therefore, the results of the current study reflect only a subset of pollutants potentially emitted from upstream oil and gas production. We did not have sufficient data to investigate specific VOC constituents. Additionally, there were relatively few monitor-days with exposure to preproduction wells within 1 km. None of the monitors that measure concentrations of $PM_{2.5}$ and VOCs were within 1 km of a preproduction well. We found evidence that drilling sites up to 3 km upwind increased $PM_{2.5}$ concentrations; however, we did not expect to observe changes in VOC concentrations further than 1 km. Prior work has reported decay of VOCs within 100-200 m from well sites (Garcia-Gonzales et al. 2019a; Zielinska et al. 2014), and consequently we were unable to make any inferences about the effect of preproduction activities on VOCs. In the primary analyses, we adjusted for exposure to wildfire smoke plumes to account for potential contributions of smoke to the pollutants of interest. Exposure was assessed as the number of overhead plumes for each monitor-day, but this method may not accurately indicate conditions at ground level. A sensitivity analysis for $PM_{2.5}$ omitting smoke days from the analysis yielded similar results to the smoke-adjusted models, suggesting that statistical adjustment for smoke exposure the plumes was sufficient. For the analyses of wells in the production stage, data on total oil and gas production volume were available at the monthly level. In the exposure assessment, we assumed that production occurred evenly throughout the month, which could lead to exposure misclassification if production was concentrated in certain days of the month. We were not able to differentiate between drilling or production methods, and consequently we were not able to determine whether certain methods resulted in higher emissions.

Strengths of this study include the large panel dataset, comprising over 1 million daily observations from high quality air monitors with broad geographic and temporal variation. We were able to control for unobserved potential confounders through the study design, using wind as a plausibly exogenous source of variation uncorrelated to both upstream oil production and other sources of pollution. Additionally, we conducted several tests to validate the robustness of the results.

Further research on hazards associated with upstream oil and gas production would improve understanding of potential health and environmental risks. Acute emissions of particular pollutants may be associated with specific steps of oil and gas preproduction or production, and more work is needed to determine if this is the case and, if so, which processes produce high emissions. Researchers could leverage data with high temporal resolution, such as hourly measurements of air pollutant concentrations and wind direction. A study by Halliday et al. (Halliday et al. 2016) found diurnal variation in benzene concentrations, indicating that integrating pollutant concentrations into 24-hour periods may obscure effects for some pollutants. Future studies may also benefit from community-based participatory methods, with, for example, monitoring in locations identified as priorities by residents of affected communities. Further research is also needed to examine emissions from other aspects of upstream oil production, such as flaring. Also, future studies could investigate how emissions from upstream oil production affects the health of non-human animals, ecosystem functioning, and agricultural productivity.

Exposure to oil and gas wells in both preproduction and production increased concentrations of $PM_{2.5}$, CO, NO_2, O_3, and VOCs. These findings indicate that proximity to wells is an appropriate metric for air pollution-related exposures in population health studies of oil and gas wells. Increases in exposure to $PM_{2.5}$ is associated with a range of adverse health outcomes, including higher risk of respiratory disease, such as hospitalization for asthma, as well as higher risk of death from ischemic heart disease (Hayes et al. 2020; Zheng et al. 2015). Exposure to $PM_{2.5}$ is also associated with substantial increases in risk of preterm birth, impaired fetal growth, and stillbirth, though associations were not consistent across all studies (Bekkar et al. 2020). Increases in $PM_{2.5}$ concentrations near wells could be a mediating factor for previously reported increases in risk of adverse birth outcomes with proximity to wells in California (Gonzalez et al. 2020; Tran et al. 2020). Ozone is also a risk factor for adverse birth outcomes, as well as impaired lung function and risk of other respiratory disease (Bekkar et al. 2020; Environmental Protection Agency 2006). Mitigating exposure to oil and gas wells would likely reduce exposure to ambient air pollutants.

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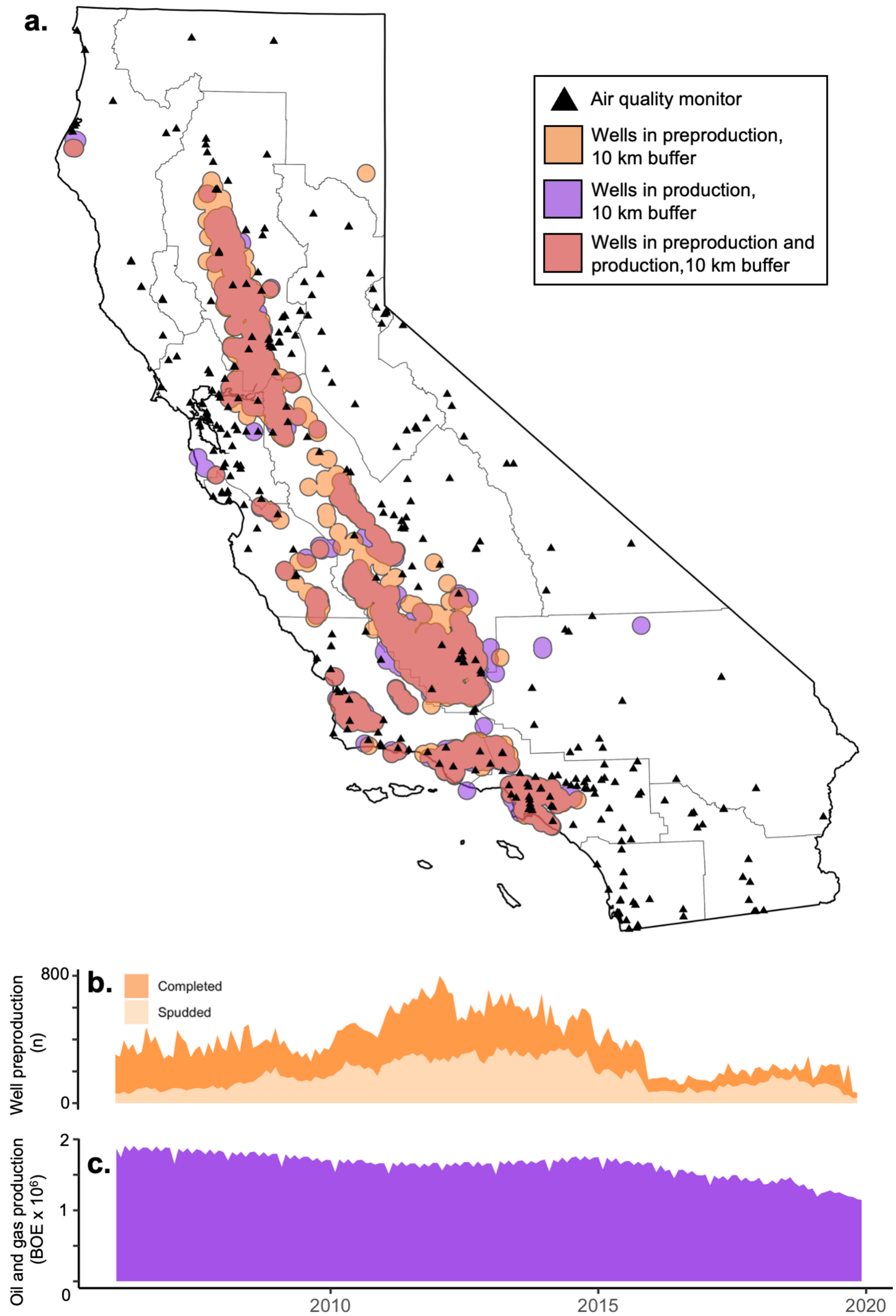

Figure 1. (a) A map of the study region, showing air basins, air quality monitor locations, and 10 km buffers around wells in preproduction (orange) and production (purple), as well as the overlap (red). (b) Count of wells spudded and completed by month across California, including recompletions of previously drilled wells. (c) Total oil and gas production by month for all wells in California, reported as million barrels of oil equivalent (BOE).

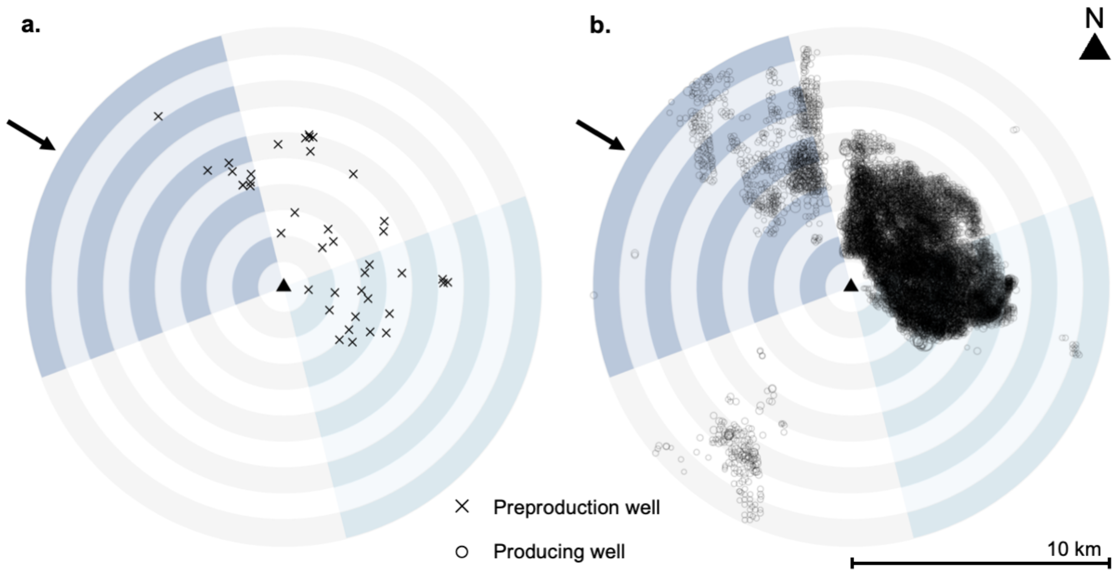

Figure 2. A visualization of the exposure assessment method at a monitor located in Bakersfield, California, using sample data from July 1, 2009, when the wind was blowing from the northwest (arrow). For each monitor-day, we assessed exposure to (a) the count of wells in preproduction and (b) the total volume of oil and gas produced upwind (darker shaded area) of the monitor. As a placebo test, we assessed exposure to wells downwind (lighter shade) of the monitor.

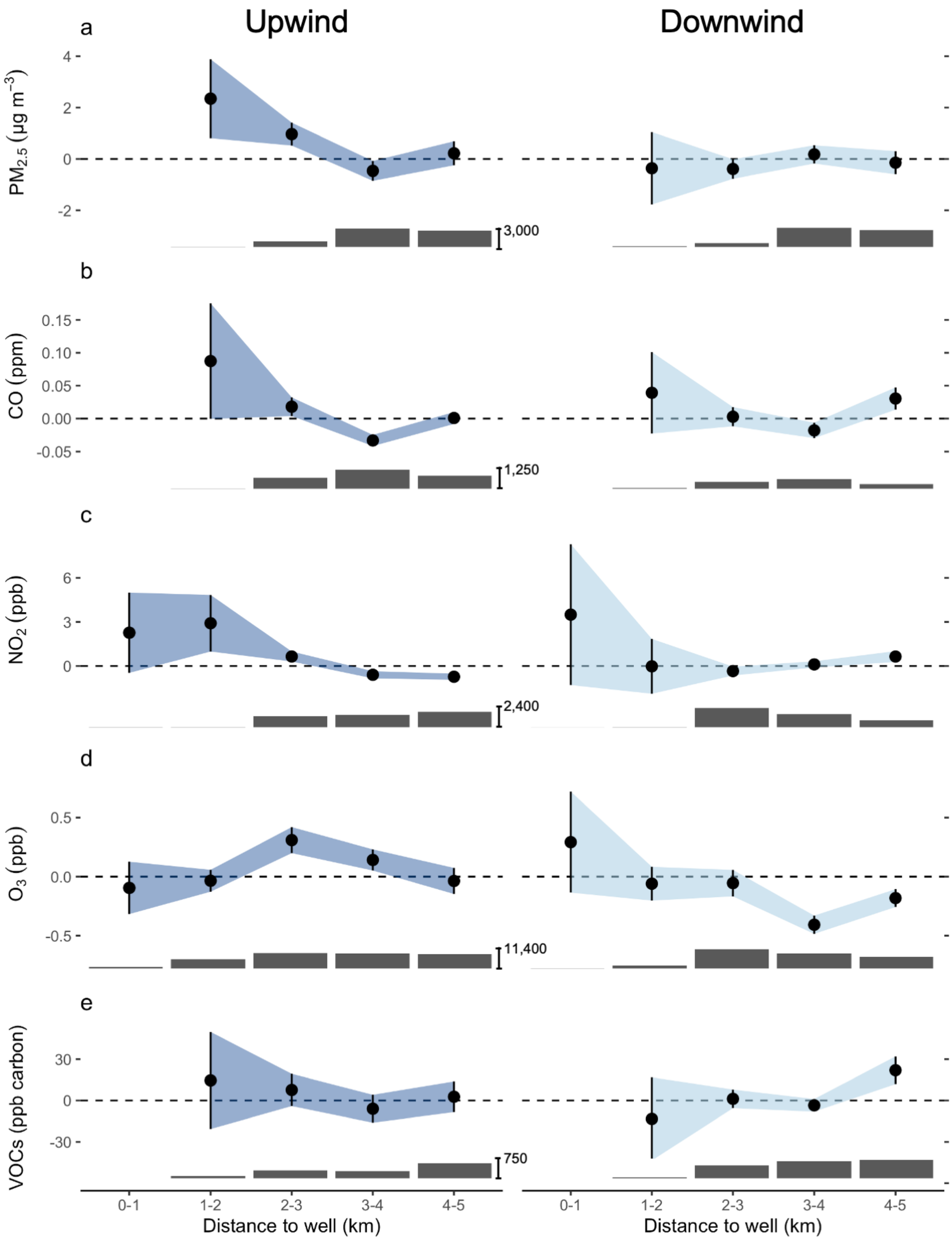

Figure 3. Point estimates (95% CIs) for the marginal effect of one additional preproduction well upwind (left column) and downwind (right column) of the monitor. The bar plots show the number of monitor-days with exposure at least one preproduction well within each distance bin.

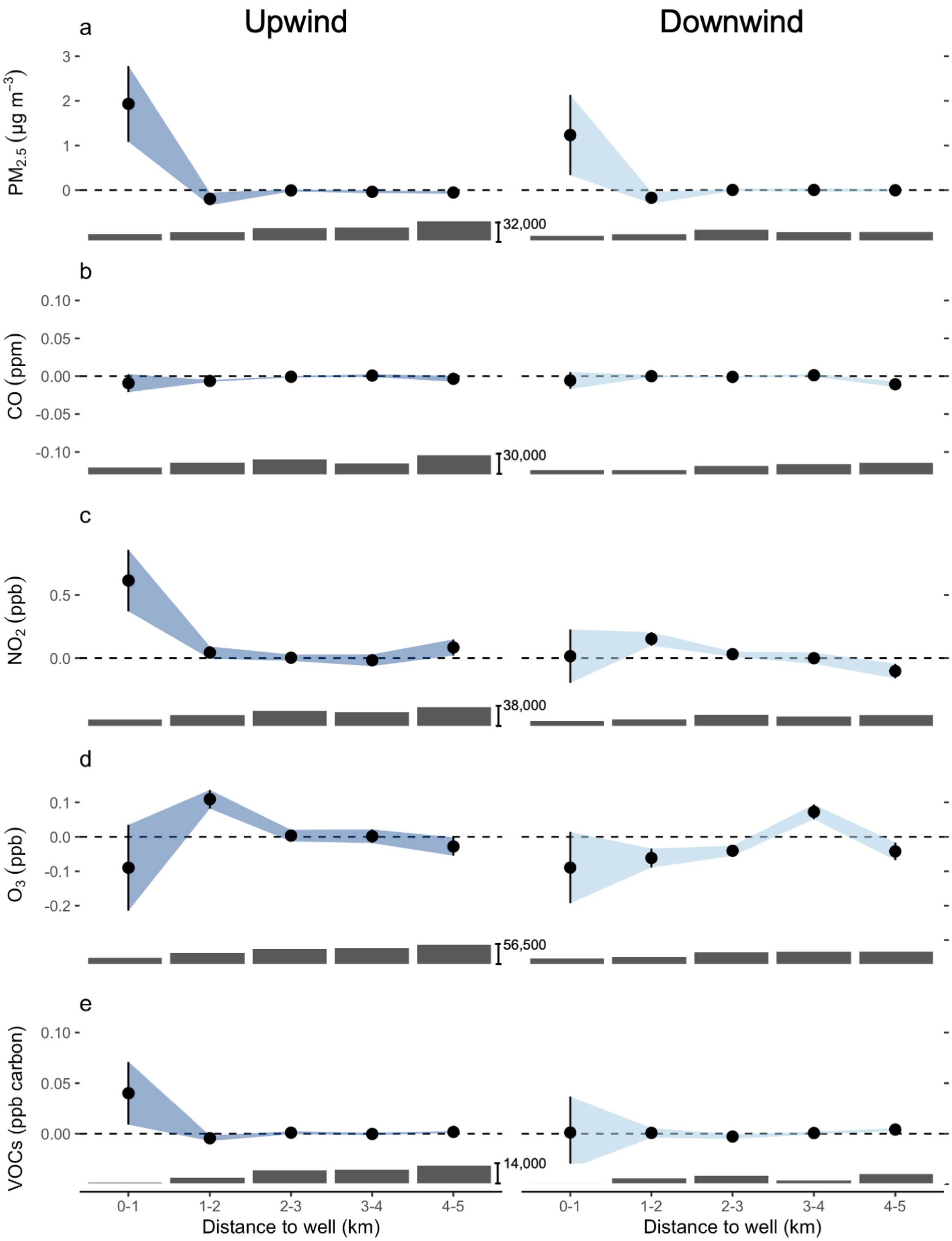

Figure 4. Point estimates (95% CIs) for the marginal effect of 100 additional barrels of oil equivalent (BOE) of daily production volume, for wells upwind (left column) and downwind (right column) of the monitor. The bar plots show the number of monitor-days with exposure at least 1 BOE of daily production volume within each distance bin. Note that more monitor-days had exposure to production volume than preproduction wells.

Table 1. Descriptive statistics of the air monitors, pollutant concentrations, and meteorological factors. The unit of observation is the monitor-day; some monitors observe multiple pollutants. VOCs in the dataset comprise non-methane volatile organic compounds.

	≤ 10 km to wells	> 10 km to wells	All
Monitors, *n* (column %)	79 (25.2)	235 (74.8)	314 (100)
Urban	57 (72.2)	151 (64.3)	208 (66.2)
Rural	22 (27.8)	84 (35.7)	106 (33.8)
Sacramento Valley	16 (20.2)	26 (11.1)	42 (26.6)
San Joaquin Valley	18 (22.8)	24 (10.2)	42 (26.6)
South Central Coast	15 (19.0)	14 (6.0)	29 (18.4)
South Coast	15 (19.0)	30 (12.8)	45 (28.5)
$PM_{2.5}$	43 (54.4)	155 (66.0)	198 (63.1)
CO	34 (43.0)	76 (32.3)	110 (35.0)
NO_2	45 (57.0)	94 (40.0)	139 (44.3)
O_3	65 (82.3)	172 (73.2)	237 (75.5)
VOCs	24 (30.4)	24 (10.2)	48 (15.3)
Observations, *n* (column %)	307,095 (29.0)	751,135 (71.0)	1,058,230 (100)
Urban	214,011 (69.7)	507,287 (67.5)	721,298 (68.2)
Rural	93,084 (30.3)	243,848 (32.5)	336,932 (31.8)
$PM_{2.5}$	137,657 (44.8)	317,065 (42.2)	454,722 (43.0)
CO	98,165 (32.0)	229,646 (30.6)	327,811 (31.0)
NO_2	157,567 (51.3)	297,197 (39.6)	454,764 (43.0)
O_3	252,572 (82.2)	588,448 (78.3)	841,020 (79.5)
VOCs	44,992 (14.7)	49,357 (6.6)	94,349 (8.9)
2006–2009	77,013 (25.1)	200,404 (26.7)	277,417 (26.2)
2010–2014	104,839 (34.1)	264,066 (35.2)	368,905 (34.9)
2015–2019	107,248 (34.9)	268,876 (35.8)	376,124 (35.5)
Smoke plume overhead	21,780 (7.1)	54,299 (7.2)	76,079 (7.2)
Pollutant concentrations, daily mean ± SD			
$PM_{2.5}$ (μg/m³)	10.6 ± 9.5	9.9 ± 9.0	10.1 ± 9.1
CO (ppm)	0.5 ± 0.4	0.5 ± 0.4	0.5 ± 0.4
NO_2 (ppb)	21.4 ± 14.6	22.1 ± 14.5	21.9 ± 14.5
O_3 (ppm)	0.04 ± 0.01	0.04 ± 0.02	0.04 ± 0.02
VOCs (ppb C)	120 ± 166	104 ± 142	112 ± 155
Meteorological factors, daily mean ± SD			
Precipitation (mm)	0.9 ± 4.0	1.2 ± 5.1	1.1 ± 4.8
Temperature (°C)	18.6 ± 7.8	17.2 ± 9.1	17.6 ± 8.8
Wind speed (m/s)	3.0 ± 2.1	3.2 ± 2.0	3.1 ± 2.0

Supplemental Material

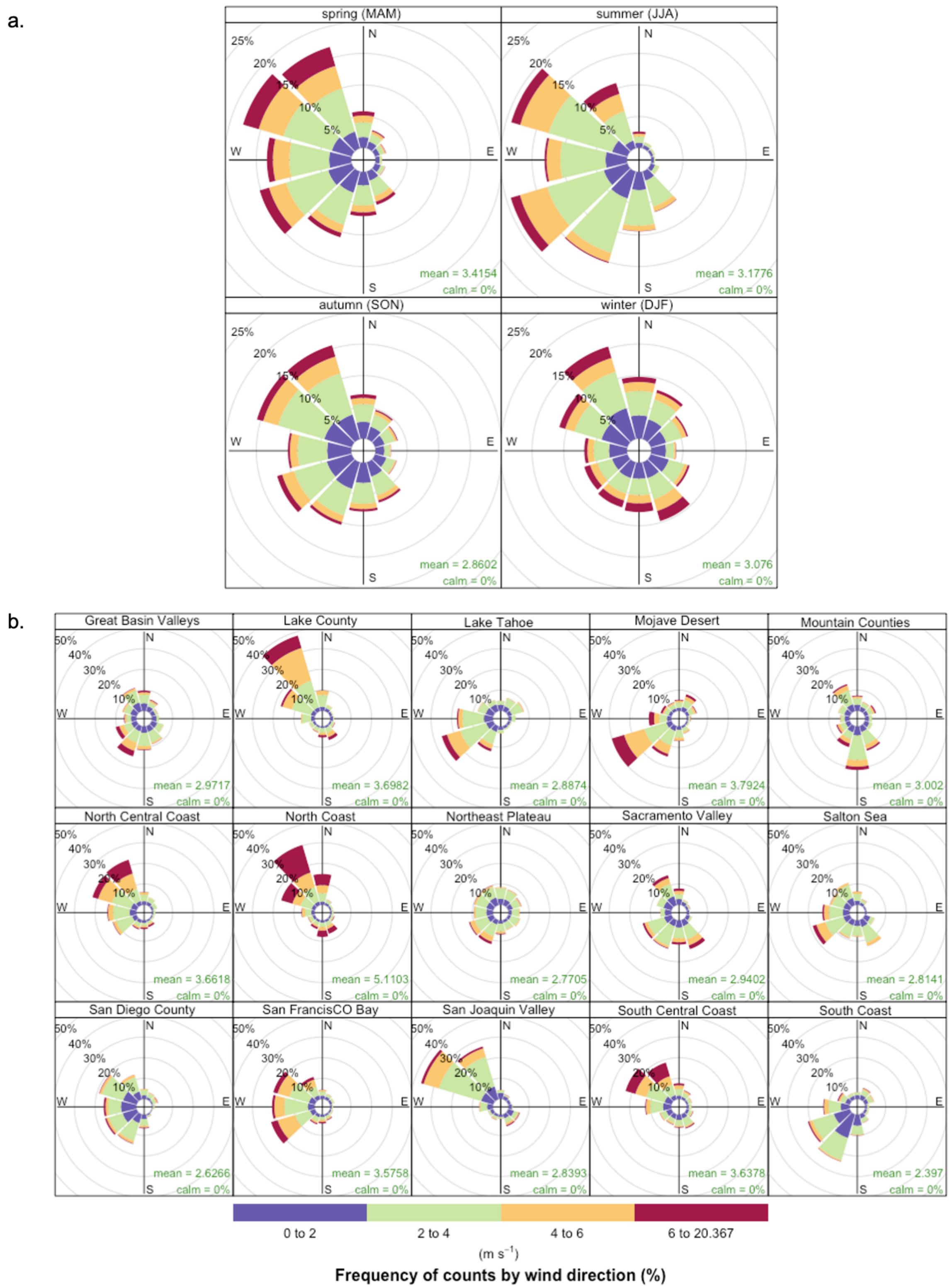

Figure S1. Wind roses for all monitor-days in the analytic dataset, stratified by (a) season and (b) CARB air basin.

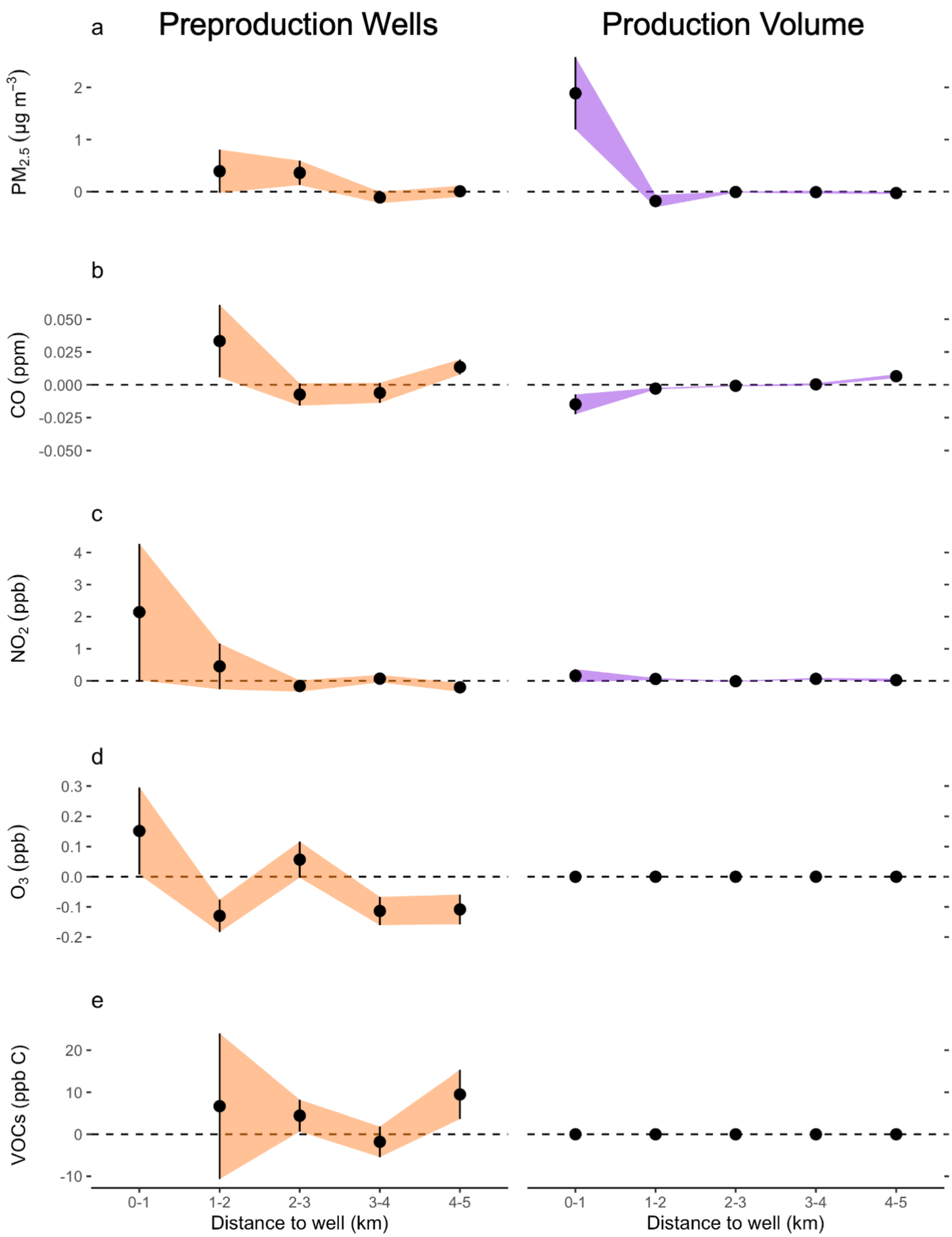

Figure S2. Results using exposure assessment without wind taken into account, i.e., point estimates (95% CIs) for the marginal effect of one additional preproduction well (left column) or 100 additional BOE production volume (right column). The analysis was otherwise similar to the primary analysis, results of which are presented in Figures 3 and 4.

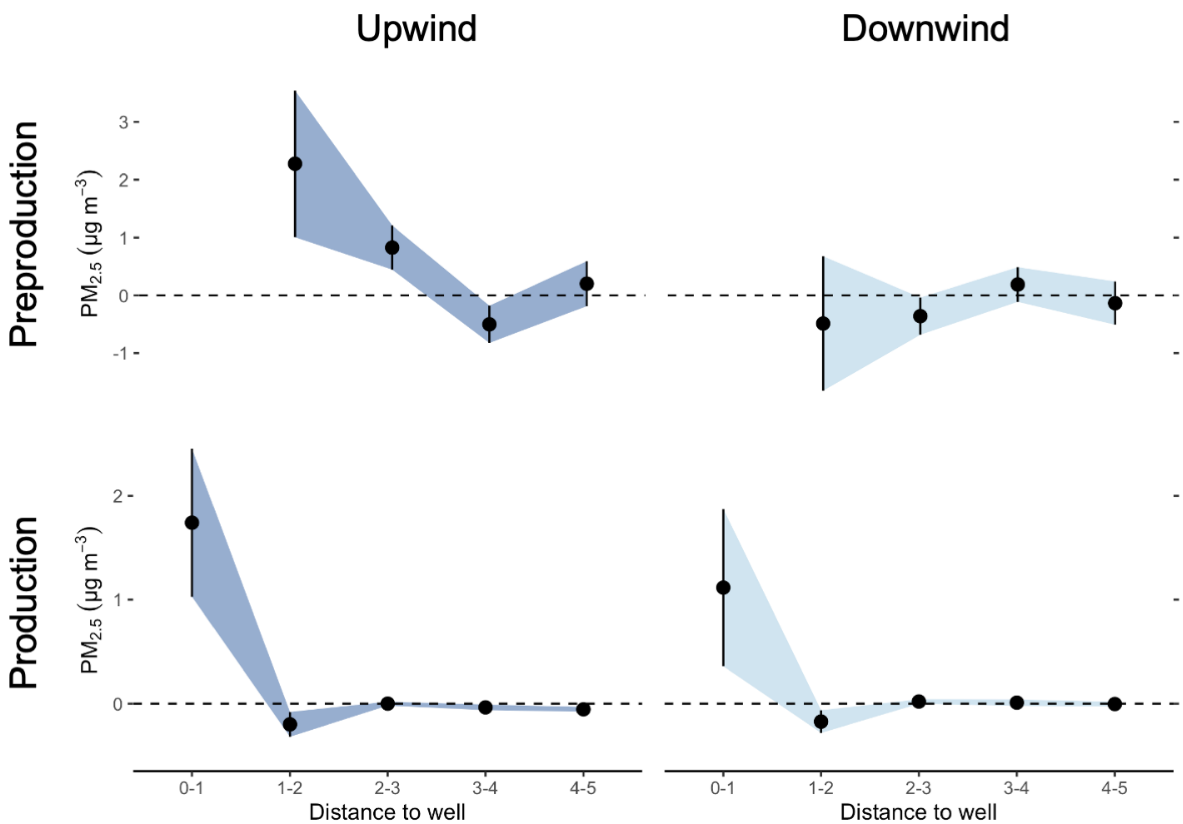

Figure S3. Results for a sensitivity analysis estimating the marginal effect of exposure to preproduction wells (top row) or production volume (bottom row), upwind of the monitor (left column) and (b) in the downwind placebo. The analysis is similar to the primary results presented in Figures 3 and 4, except for the exclusion of monitor-days with overhead smoke plumes.

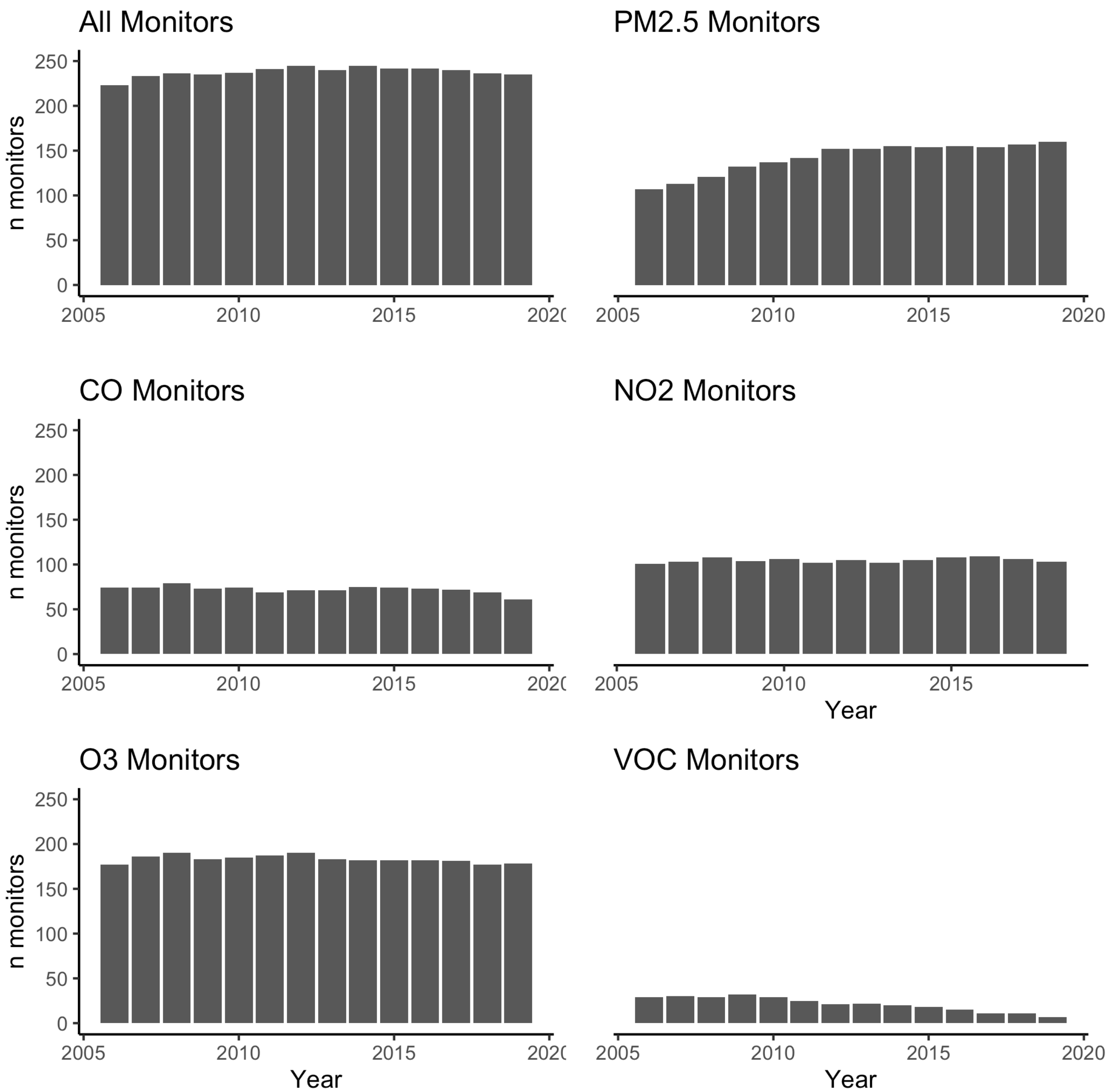

Figure S4. The distribution of the number of air quality monitors in operation by year and pollutant. Some monitors observed multiple pollutants.

Table S1. Descriptive statistics for wells in the preproduction and production stages, as well as total production volume (both oil and gas in barrels of oil equivalent, BOE). The preproduction interval may intersect with multiple time spans and producing wells may have been in operation during multiple time spans.

	Preproduction wells, n (% total)	Production wells, n (% total)	Production volume, BOE (% total)
n	38,157 (100)	90,697 (100)	3,751,850,237 (100)
Distance to monitor			
≤ 10 km	9,366 (24.5)	34,767 (38.3)	2,115,781,785 (56.4)
>10 km	28,791 (75.5)	55,930 (61.7)	1,636,068,452 (43.6)
Setting			
Urban	1,508 (4.0)	7,412 (8.2)	334,077,828 (8.9)
Non-urban	36,649 (96.0)	83,285 (91.8)	3,417,772,409 (91.1)
CARB Basin			
Sacramento Valley	974 (2.6)	2,476 (2.7)	172,665,258 (4.6)
San Joaquin Valley	33,740 (88.4)	71,260 (78.6)	2,474,879,984 (66.0)
South Central Coast	1,012 (2.7)	6,116 (6.7)	213,675,928 (5.7)
South Coast	1,243 (3.3)	7,450 (8.2)	407,828,298 (10.9)
Other	1, 188 (3.1)	3,395 (3.7)	482,800,769 (12.9)
Time			
2006-2009	12,668 (33.2)	59,899 (66.0)	939,575,749 (25.0)
2010-2014	18,592 (48.7)	62,376 (68.8)	1,286,600,953 (34.3)
2015-2019	8,579 (22.5)	71,670 (79.0)	1,183,983,473 (31.6)

Table S2. Descriptive statistics for monitor exposure among monitor-days with any exposure, reported as: median; mean ± SD (range).

	Preproduction wells, n			Production volume, BOE		
Distance (km)	Upwind	Downwind	All	Upwind	Downwind	All
0-1	2; 2.8 ± 2.4 (1; 14)	1, 2.5 ± 2.3 (1; 13)	2; 3.0 ± 2.5 (1; 14)	7.2; 65.2 ± 157.3 (0.1; 2,013.2)	12.9; 136.1 ± 229.2 (0.1; 1,391.3)	30.9; 180.0 ± 312 (0.1; 2,054.0)
1-2	2; 4.0 ± 4.5 (1; 41)	2; 3.5 ± 3.8 (1; 32)	2; 5.5 ± 6.5 (1; 41)	34.6; 328.5 ± 950.9 (0.1; 10,060.5)	61.1; 662.4 ± 1,261.1 (0.1; 9,538.1)	102.9; 1,163.4 ± 2703 (0.1; 13,677.8)
2-3	1; 1.9 ± 2.0 (1; 19)	1; 1.9 ± 1.8 (1; 19)	2; 3.2 ± 3.4 (1; 21)	107.2; 492.2 ± 1,433.8 (0.1; 24,166.1)	128.0; 855.0 ± 2,313.6 (0.1; 23,858.8)	324.0; 1613.0 ± 4118 (0.1; 24,166.1)
3-4	4; 3.9 ± 2.6 (1; 20)	3; 3.8 ± 3.0 (1; 23)	5; 5.3 ± 4.3 (1; 36)	166.9; 942.8 ± 1,999.0 (0.1; 20,120.2)	124.5; 1,115 ± 2,690.8 (0.1; 19,545.3)	293.6; 2,117.3 ± 4674 (0.4; 26,238.8)
4-5	2; 2.9 ± 2.2 (1; 17)	3; 3.6 ± 3.2 (1; 23)	3; 4.4 ± 4.2 (1; 31)	103.0; 703.2 ± 15.3 (0.1; 17,799.5)	228.7; 987.0 ± 2060.2 (0.1; 17,151.2)	242.2; 1,703.9 ± 3803 (0.1; 21,764.8)

Table S3. Pearson's correlation coefficients for exposure to preproduction wells and production volume within each 1 km annulus (ring), for exposure within 5 km of the monitor.

		Preproduction, n					Production, volume				
	km	0-1	1-2	2-3	3-4	4-5	0-1	1-2	2-3	3-4	4-5
Preproduction, n	0-1	1	0.73	0.33	0.31	0.25	0.04	0.23	0.17	0.20	0.30
	1-2	–	1	0.40	0.41	0.31	0.08	0.32	0.24	0.29	0.41
	2-3	–	–	1	0.41	0.32	0.16	0.39	0.39	0.35	0.38
	3-4	–	–	–	1	0.67	0.10	0.29	0.29	0.38	0.48
	4-5	–	–	–	–	1	0.12	0.33	0.37	0.38	0.44
Production, vol.	0-1	–	–	–	–	–	1	0.53	0.40	0.25	0.24
	1-2	–	–	–	–	–	–	1	0.81	0.62	0.60
	2-3	–	–	–	–	–	–	–	1	0.78	0.61
	3-4	–	–	–	–	–	–	–	–	1	0.81
	4-5	–	–	–	–	–	–	–	–	–	1

Table S4. Point estimates (standard error) for the marginal effect of exposure to an additional upwind preproduction well within each distance bin, 2006-2019. Each row presents results for each pollutant in annuli bins out to 4 km, with different model specifications (1-3); model 3 is the primary model discussed in the text. Note that for $PM_{2.5}$, CO, and VOCs, there were no monitor-days with a preproduction well within 1 km.

Dependent variable (units)	n	0-1 km			1-2 km			2-3 km			3-4 km		
		(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)
$PM_{2.5}$ (μg/m³)	454,722	–	–	–	1.92· (0.98)	1.88* (0.93)	2.35** (0.78)	3.24*** (0.26)	2.90*** (0.25)	0.97*** (0.23)	-0.78*** (0.23)	-1.07*** (0.22)	-0.46* (0.20)
CO (ppm)	327,811	–	–	–	0.16* (0.07)	0.12· (0.06)	0.09· (0.04)	-0.08*** (0.01)	-0.08*** (0.01)	0.02* (0.007)	-0.05*** (0.01)	-0.06*** (0.006)	-0.03*** (0.004)
NO_2 (ppb)	454,764	-10.75*** (0.02)	-9.28*** (2.11)	2.27 (1.40)	3.58* (1.62)	2.42 (1.51)	2.91** (0.98)	-2.44*** (0.28)	-2.22*** (0.26)	0.64*** (0.18)	-0.71*** (-0.20)	-1.00*** (0.18)	-0.60*** (0.17)
O_3 (ppb)	841,020	-0.31 (0.19)	0.16 (0.16)	-0.10 (0.11)	0.09 (0.08)	-0.08 (0.06)	-0.03 (0.05)	0.86*** (0.09)	0.83*** (0.08)	0.31*** (0.06)	0.45*** (0.07)	0.31*** (0.06)	0.14** (0.05)
VOCs (ppb C)[a]	94,349	–	–	–	-111.8*** (18.31)	-102.4*** (17.95)	14.59 (17.98)	22.04** (7.08)	13.43· (6.94)	7.69 (5.96)	43.20*** (6.19)	43.52*** (6.06)	-5.94 (5.16)
Controls[b]		N	Y	Y	N	Y	Y	N	Y	Y	N	Y	Y
Monitor-mo. + basin-yr. FE		N	N	Y	N	N	Y	N	N	Y	N	N	Y

·p < 0.1; *p < 0.05; **p < 0.01; ***p< 0.001
[a] VOCs data were for 1999-2019
[b] Controls include daily precipitation, mean temperature, wind speed, day-of-week, and number of overhead smoke plumes

Table S5. Point estimates (standard error) for the marginal effect of exposure to an additional 100 barrels of oil equivalent (BOE) of total upwind oil and gas production within each distance bin, 2006-2019. Each row presents results for each pollutant in annuli bins out to 4 km, with different model specifications (1-3); model 3 is the primary model discussed in the text. Note that for $PM_{2.5}$, CO, and VOCs, there were no monitor-days with a preproduction well within 1 km.

Dependent variable (units)	n	0-1 km			1-2 km			2-3 km			3-4 km		
		(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)
$PM_{2.5}$ (μg/m³)	454,722	0.34 (0.34)	0.23 (0.32)	1.93*** (0.43)	-0.33** (0.06)	-0.33*** (0.06)	-0.20** (0.07)	-0.02 (0.01)	-0.03* (0.01)	-0.01 (0.01)	0.16*** (0.01)	0.17*** (0.01)	-0.04* (0.02)
CO (ppm)	327,811	0.01*** (0.003)	0.01*** (0.003)	-0.01 (0.006)	0.002** (0.001)	0.003*** (0.001)	-0.01*** (0.001)	0.004*** (0.001)	-0.003*** (0.0005)	-0.001· (0.0004)	-0.01*** (0.001)	-0.01*** (0.001)	0.001 (0.001)
NO_2 (ppb)	454,764	0.46*** (0.11)	0.42*** (0.10)	0.62*** (0.12)	0.48*** (0.03)	0.50*** (0.03)	0.04· (0.02)	0.08*** (0.02)	-0.05** (0.02)	0.003 (0.01)	-0.36*** (0.03)	-0.03 (0.03)	-0.02 (0.02)
O_3 (ppb)	841,020	-0.82*** (0.08)	-0.87*** (0.07)	-0.09 (0.06)	0.04* (0.02)	0.09*** (0.02)	0.11*** (0.01)	-0.21*** (0.01)	-0.11*** (0.01)	0.004 (0.009)	0.24*** (0.01)	0.12*** (0.01)	0.002 (0.01)
VOCs (ppb C)[a]	94,349	0.09*** (0.02)	0.09*** (0.02)	0.04* (0.02)	-0.01*** (0.002)	-0.01*** (0.002)	-0.004** (0.001)	0.009*** (0.0001)	0.01*** (0.007)	0.001 (0.001)	-0.005*** (0.0006)	-0.003*** (0.0006)	-0.0002 (0.0006)
Controls[b]		N	Y	Y	N	Y	Y	N	Y	Y	N	Y	Y
Monitor-mo. + basin-yr. FE		N	N	Y	N	N	Y	N	N	Y	N	N	Y

·p < 0.1; *p < 0.05; **p < 0.01; ***p< 0.001
[a] VOCs data were for 1999-2019
[b] Controls include daily precipitation, mean temperature, wind speed, day-of-week, and number of overhead smoke plumes