**Supplemental Material**

**Model Predicted Distribution of PM2.5 Exposure-Related Health Effects from Marcellus Shale Gas Development in Pennsylvania, 2005-2017**

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This section provides the supplementary material which supports the demonstrated methodology in the manuscript titles as “Model Predicted Distribution of PM2.5 Exposure-Related Health Effects from Marcellus Shale Gas Development in Pennsylvania, 2005-2017”.

1. **Methodology**

In this analysis, we took advantage of the Gaussian dispersion model which was developed by Banan and Gernand (2020) to simulate the concentration of air pollutants caused by shale gas development. For the purpose of this study, we modified that model to conduct the estimation of relative risk and changes in health outcomes associated to simulated concentrations

In this study, Gaussian plume model is the method to simulate dispersion of PM emissions at local scale (within 50 km from the source). Equation (1) formulates the Gaussian plume equation as follows:

$$C\left(x,y,z;t\right)= \frac{Q}{2πuσ\_{y}σ\_{z}} exp\left(-\frac{y^{2}}{2σ\_{y}^{2}}\right)\left[ exp\left(-\frac{(z-H\_{eff})^{2}}{2σ\_{z}^{2}}\right)+ exp\left(-\frac{(z+H\_{eff})^{2}}{2σ\_{z}^{2}}\right)\right] (1)$$

where $C$ is the substance concentration as a function of $x$, $y$, and $z$ at a specific time $t$, $x$ is the distance downwind from the well, $y$ is the crosswind distance from the plume centerline, $z$ is the vertical distance from the ground level, $Q$ is the emission rate from emission source, $u$ is the average wind speed at wellsite height,$ H\_{eff}$ is the effective wellsite height, $σ\_{y}$ is dispersion coefficient in the crosswind direction, and $σ\_{z}$ is dispersion coefficient in the vertical direction. This model assumes no dry and wet deposition.

According to Roy et al. (2014), diesel engines are the main sources of PM2.5 emissions associated to shale gas development activities which are typically placed at the same level as the operation site. Accounting for elevation of wellpad (typically up to 2 meters) and plume rise, we simulated concentrations at the same vertical height ($z$) of 2 meters and the same $H\_{eff}$ value of 1 meter for all wellpads.

We categorized stability for each hour based on Pasquill stability categories using wind data, cloud coverage data, and time of the day (Turner, 1970) and used Pasquill-Gifford equations to calculate parameters $σ\_{y}$ and $σ\_{z}$ at different distances down the wind from the wellsites (EPA, 1995). For the purpose of defining stability, we considered daytime between 5 am to 8 pm and the rest of the day was set as night-time.

To estimate the rates of PM2.5 emissions originated from diesel engines used in shale gas development, we applied the approach developed by Roy et al. (2014). Roy et al. (2014) conducted a Monte Carlo simulation (based on the specific distribution of each variable) to estimate the emission rate of PM2.5 and two other air pollutant caused by shale gas development. They used emission factors reported in EPA’s inventory models (AP-42) and values in the literature reported for diesel engines similar to those being used in drilling and fracturing of Marcellus shale gas wells. Equation (2) was used in their simulation to estimate PM2.5 emissions rate from drilling operation for one well ($Edrilling$ in tons/well), as follows:

$$Edrilling=EF×HP×LF×t\_{drilling}×\% in use (2)$$

where $EF$ is emission factor from the engine on a drilling rig, $HP$ is the horsepower of the engine, $LF$ is the load factor or fraction of the total horsepower being used, $t\_{drilling}$ is the time to drill one well, and $\% in use$ is the fraction of drilling time the drilling equipment operates.

Roy et al. (2014) also used equation (3) to estimate PM2.5 emissions rate from hydraulic fracturing of one well ($Efracking$ in tons/well), as follows:

$$Efracking=EF×HP×LF×N\_{Stages} (3)$$

where $EF$ is emission factor from one fracking pump engine, $HP$ is the required horsepower for one stage of fracturing, $LF$ is the average load factor of the fracking pump engine, and $N\_{Stages}$ is the total number of stages needed to fracture one well.

Detailed information about activities timing is not accessible by public. Available literature and technical reports have estimated a drilling rate of 1000 feet per day based on the average drilled depth (12,546 ft., from well dataset) and the common drilling time (Facts about Canada’s Oil and Natural Gas Industry, 2019). According to these resources, it also takes one day in average to fracture 1000 feet in three stages (McKeon, 2011; Facts about Canada’s Oil and Natural Gas Industry, 2019; Coloradans for Responsible Energy Development, 2019). This provided the medium to calculate the emission rate per hour of fracturing.

Based on these estimates, we recalculated the emission rates for the drilling and fracking steps in kilograms per hour (instead of tons per year per well drilled) using the approach by Roy et al. (2014). For this purpose, we omitted the terms for “time to drill one well” (i.e., $t\_{drilling}$) and “number of stages” (i.e., $N\_{Stages}$) from equation (2) and equation (3), respectively, and repeated the Monte Carlo simulations. Results from our Monte Carlo simulations were the hourly rates of drilling and hydraulic fracturing.

Data on drilled depth and/or length of fracking is not available for some wells, despite reported “SPUD Date” implies that operation has been started on these wells. We used a bootstrapping method to simulate the drilled depth for these wells (582 wells, equal to 4% of all wells), using the available drilled depth data from nearby wells and other wells developed in the same county in the same year. In one case, no such a data was available from neighbor wells and we used the average of drilled depth values for all Marcellus shale gas wells in Pennsylvania (almost 12000 feet). For the cases with missing data on the length of fracking (almost half the wells, equal to 47% of all wells), we took advantage of simple linear regression by Banan and Gernand (2020) on the wells with reported data to model the relation between total drilled depth (feet) and length of fracking (feet), as formulated below:

$$Fracking Length = 0.7313 × Total Drilled Depth - 4371.3 (4)$$

Refer to Banan and Gernand (2020) for more details regarding the well and weather data as well as corresponding data preparation.

This model accounts only for PM2.5 emissions from diesel engines operating at development sites. Therefore, we assumed that all emissions are originated from point sources located at the center of each wellsite. It simulates PM2.5 concentration at distances farther than the setback distance (152.4 m) from the well location. These locations are specified by a grid size of 25-by-25 meters. The model simulates PM2.5 concentration associated with shale gas emissions at each grid and estimate the population density at each of the grids using Census data for the closest census block to that grid. The model assumes even distribution of population for each census block. Thus, expected number of affected people is equal to the product of population density (persons per area of the block) at each grid and the grid size (625 m2).

We used this model to simulate PM2.5 emission concentrations at any point up to 8 km downwind from every shale gas wellsite at each hour of drilling and hydraulic fracturing operations. These values are then averaged over a year to calculate the annual mean PM2.5 concentration. The annual mean concentrations serve as inputs to the CRF model which models relative risk associated with each mean value. The health impact function calculates the change in the number of each health impact based on the relative risk values from the CRF model.

1. **Supplemental References**
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