Evaluation of gas well setback policy in the Marcellus Shale region of Pennsylvania in relation to emissions of fine particulate matter

Article *in* Journal of the Air & Waste Management Association · April 2018

DOI: 10.1080/10962247.2018.1462866

2 authors:

Zoya Banan
Pennsylvania State University
4 PUBLICATIONS **12** CITATIONS
SEE PROFILE

Jeremy Gernand
Pennsylvania State University
33 PUBLICATIONS **110** CITATIONS
SEE PROFILE

Evaluation of Gas Well Setback Policy in the Marcellus Shale Region of Pennsylvania in Relation to Emissions of Fine Particulate Matter

Zoya Banan, Jeremy M. Gernand*
Department of Energy and Mineral Engineering, Pennsylvania State University, University Park, PA 16802, USA
* Corresponding author: Tel.: +1(814)865-5861, E-mail address: jmgernand@psu.edu

Introduction

During the past decade, shale gas development has become more economical due to recent technological achievements (Jacoby et al., 2011). Many consider natural gas as a bridging fuel toward a cleaner energy system which allows the electrical generation system to continue using fossil-based infrastructures and help to reduce greenhouse gas emissions from the coal use. Shale gas can also provide an improvement in public and occupational health, and reduce average environmental impacts from energy production as it replaces coal-produced electricity (Jenner et al., 2013). The U.S. holds large reserves of shale gas, and so exploitation of this resource is expected to continue for many decades. Some of the most famous reserves are the Barnett Shale in Texas, the Denver-Julesberg Basin in Colorado, and the Marcellus Shale in the northeast. Shale gas production in Pennsylvania started in 2007 and increased to more than 4 trillion cubic feet in 2014 (EIA – Shale gas production, 2016). According to the Energy Information Administration (EIA), Pennsylvania possesses 56.2 trillion cubic feet shale gas proved reserves in 2014 (EIA – Shale gas proved reserves, 2016). So, continued exploitation is expected.

However, shale gas exploration activities can influence local air quality. While vertical drilling is usually enough to get to the conventional gas reservoirs, shale gas development requires a combination of vertical and horizontal drilling that adds up to the length considerably longer than a conventional wellbore. Also shale oil and gas development needs for hydraulic fracturing by means of high pressure fluids to create fractures down the wellbore and into the target rock so that the oil or gas flows out (Ogoke et al., 2014; Vidic et al., 2013). Thus, shale gas development causes larger number of engines to run over longer period of time. Application of large diesel-powered equipment or gas turbines during exploring (i.e. drilling and hydraulic fracturing) stages and also the use of diesel trucks for transportation can affect the air quality within the vicinity of the well site and even farther downwind. Even though the emissions from shale gas production can be offset by the decrease in the emissions due to replacing fuels like coal by natural gas at the end use (Pacsi et al., 2013), these emissions can cause severe health issues within local areas around shale gas development sites.

Emissions from shale gas activities are mainly characterized to be volatile organic compounds (VOCs), nitrogen dioxide, sulfur dioxide, and particulate matter (Zielinska et al., 2011; Shonkoff et al., 2014). These pollutants can cause acute diseases, such as respiratory symptoms, lung and heart diseases, and chronic health impacts, such as cancer (Kelly et al., 2012; Adgate et al., 2014). Therefore, public concern exists regarding hazardous air pollutants (HAPs) associated with unconventional gas development activities (Olaguer, 2012). The United States Environmental Protection Agency (EPA) has set National Ambient Air Quality Standards (NAAQS) which regulate standards on concentration of criteria pollutants, namely carbon monoxide (CO), lead (Pb), ozone (O_3), particulate matter (PM), nitrogen dioxide (NO_2), and sulfur dioxide (SO_2). While development of each gas well might require a relatively short period of time, and the environmental health effect would be expected to be small, the unprecedented expansion of activity in regions such as the Marcellus shale, with thousands of new wells drilled each year, could mean that the impact is more significant than would be accounted for with a single-well analysis.

On the other hand, different states have set setback policies in order to reduce the corresponding health risks to people due to emission concentrations higher than standard within the vicinity of shale gas wellsites. Setback policy regulates the minimum distance required between occupied buildings or occupied outdoor areas and the site of the gas well. Nevertheless, Fry (2013) finds that there was no technical basis in the designation of setback distances in 26 municipalities in the Dallas–Fort Worth Metroplex, Texas. Most of these setback distances are set through a compromise among governments, the regulated community, environmental and citizen interest groups, and landowners (Haley et al., 2016). According to the section 3215 of 2015 Pennsylvania Consolidated Statutes (58 PA Cons Stat § 3215), the existing setback limit from residential buildings is 152.4 m (500 ft.) in case of an unconventional gas well. Haley et al. (2016) investigates the sufficiency of current setback distances in Texas, Pennsylvania, and Colorado using VOCs emission measurements taken by others. Based on these evaluations, the authors suggest that the current setback requirement in the Marcellus Shale of Pennsylvania is not sufficient to maintain human exposure below the established limits for benzene and hydrogen sulfide (Haley et al., 2016).

A few extant studies are dedicated to modeling the dispersion of hazardous pollutants originated from oil and gas activities (Rodriguez et al., 2009; Olaguer, 2012). Olaguer (2012) simulated ozone concentration using an average wind speed (4.8 m/sec) and direction (southwest) at 1 pm CST at Fort Worth, Texas in June 2011 by means of an Eulerian air quality model. However, as such results correspond to specific wind speed and direction from the source, they are not qualified to be generalized to all cases (i.e., different wellsite patterns and different locations within the same distance as the evaluated ones). Therefore, this serves as a limitation in evaluating the current setback policies.

Other relevant studies conducted for shale gas areas are mainly focused on modeling ozone, VOCs, and NO_x dispersion, and very few are aimed at modeling PM concentration (Rodriguez et al., 2009; Olaguer, 2012). Rodriguez et al. (2009) evaluated changes in concentration of ozone originated due to oil and gas development in the western U.S. within a 36-km grid using Eulerian dispersion model CAMx. It used CAMx as a chemistry transport model to simulate ozone formed through chemical reaction of NO_x and VOCs. Rodriquez et al. (2009) results indicate that based on background level of ozone concentration in the western United States, reported between 40 to 70 ppb, ozone concentration level caused from oil and gas activities might lead to exceedance of EPA ozone standard. However, to the best of our knowledge, current literature lacks a robust modeling of PM emission distribution associated with shale gas activities.

Different modeling tools have been used for dispersion simulation at different scale. Touma et al. (2006) introduced Eulerian dispersion models as a grid-based regional scale tool which is capable of treating transport and chemical transformation of air toxics. These models are suitable for modeling the formation and transport of ozone, acid rain, and PM. However, the article argues that these models are not appropriate for simulating the air toxics with local impact when finer spatial resolutions are required. Air toxics modeling of pollutant emissions can be demonstrated at four spatial scales: national, regional, urban, and local. National scale estimates mainly aim to characterize the average risk across the country that general population might face and to give a better picture of toxic air problem. On the other hand, local scale models, such as the approach this paper presents, can help demonstrate concentration level and exposure risks very close to specific sources or within their neighborhood. Also some studies investigate emission level changes at regional scale such as Roy et al. (2014) which simulates regional $PM_{2.5}$, NO_x and VOCs emission rates from Marcellus region under 2009 conditions and for the case of emission control technologies application.

One main and critical input to such dispersion modeling tools is known to be the emission rate. Emissions during the shale gas development process mainly originate from diesel engines (Roy et al., 2014) and therefore, evaluation methods are designed based on analysis of these engines. In 1972, EPA published a list of emission factors, required for developing air pollutants emission inventories, in an online document titled AP-42 (Compilation of Air Pollutant Emissions Factors, 1972). Efforts have been made to amend the listed emission factors in AP-42. Shah et al. (2004) did several on-road measurements and laboratory analysis of samples from diesel engines to make an estimate of PM, elemental carbon (EC) and organic carbon (OC) emissions from these engines. Using the factors provided by AP-42, Roy et al. (2014) develops an emission inventory of NOx, VOCs, and $PM_{2.5}$ from major activities in Marcellus shale gas regions specifically located in Pennsylvania, and portions of West Virginia and New York.

The goal of this study is to evaluate the minimum necessary distance from a PA shale gas wellsite to avoid local exceedance of the air quality standards for particulate matter considering the variety of the numbers of wells per site in addition to variable emissions rates during drilling and hydraulic fracturing. By employing an emissions dispersion model across the range of meteorological conditions expected in Pennsylvania for any future Marcellus shale gas well, this study will calculate the probability of exceeding EPA NAAQS for $PM_{2.5}$ at various distances and directions from a generic well site, and compare these results to the current setback policy.

Methodology

Data Sources

Wind data comprising of wind direction, wind speed and relative humidity, measured at ten weather monitoring stations in Pennsylvania all through the year 2015, served as an input to the emissions dispersion model. These stations are Altoona–Blair County Airport, Allegheny County Airport, Bedford Regional Airport, DuBois Regional Airport, Erie International Airport, Port Meadville Airport, Johnstown–Cambria County Airport, Pocono Mountains Municipal Airport, Penn Valley Airport, and Pittsburgh International Airport. These stations are located in the areas where Marcellus shale gas development activities occurred since year 2000. We used measured wind data at these monitoring stations to model the emission dispersion from development of a generic wellsite that could be located at anywhere in the Marcellus shale region of Pennsylvania. These measurements were accessed through Iowa Environmental Mesonet (IEM, 2016). IEM reports wind data for every 20 minutes at specific locations. For the purpose of this study, we used only one wind speed and direction measurement per hour, based on the mean values if multiple measurements were available or based on the only existing measurement for each hour, if measurements were missing.

EPA's latest NAAQS (National Ambient Air Quality Standards, 2012) sets the annual primary and secondary standard levels for $PM_{2.5}$ as $12(\mu g/m^3)$ and $15(\mu g/m^3)$, respectively, and the daily standard for both of them to be equal to $35(\mu g/m^3)$. According to EPA, primary standards provide public health protection while secondary standards provide public welfare protection.

For the purpose of this analysis, we base our estimation of the $PM_{2.5}$ emission rate at well sites on estimated $PM_{2.5}$ emission rate by Roy et al. (2014) over one year per each well. It estimated the mean and 95% confidence interval for $PM_{2.5}$ emission rate from drilling and hydraulic fracturing of one shale gas well to be equal to 0.3 (0.03 – 1) (tons/yr. well drilled) and 0.16 (0.03– 0.4) (tons/yr. well drilled), respectively. They estimated emission rates based on emission factors reported by EPA's inventory models (AP-42) and other literatures for diesel engines with similar size of Marcellus drill rig engines and fracking-pumps. Also they performed Monte Carlo approach to quantify the emission factor and other variables of the emission equations using each variable specific distribution.

We estimated the hourly rate of $PM_{2.5}$ emission from one single well using the reported 95% confidence interval by Roy et al. (2014). First, according to interviews with unconventional gas development experts and also the discussion by Ogoke et al. (2014), we set the time frame of 14 days for drilling and 9 days for hydraulic fracturing of one shale gas well. Then, based on these time periods and annual emission rates by Roy et al. (2014), we calculate the 95% interval for hourly rate of $PM_{2.5}$ emission during drilling and hydraulic fracturing of one well to be 0.81 (0.09 – 2.7) (kg/hr) and 0.67 (0.14 – 1.68) (kg/hr), respectively. Last, we applied the values corresponding to mean and high (97.5th percentile value) emission rate levels in order to generate an overview of the concentrations and also to give an estimate of a likely and conservative considerations regarding limitation of health risks. Use of median value for emission rate could probably be a better choice to estimate the most likely emissions as mean is influenced more by extremes and outliers. However, there is limited data on emission rate measurement and estimation and Monte Carlo results by Roy et al. (2014) does not provide the median.

Generally, particulate matter is known to be made up of a number of components, including acids (such as nitrates and sulfates), organic chemicals, metals, and soil or dust particles (World Health Organization, 2003). To estimate the composition of emissions associated with shale gas activities, many reports on local emission analysis and also on composition of emission from different types of sources were reviewed (Corbett et al., 2014; EPA National Emissions Inventory (NEI); Zielinska et al., 2011). This study considers particulate matter composition to be 45% elemental carbon (EC), 35% nitric acids, and 20% ammonium nitrates. Sensitivity analysis on the effect of $PM_{2.5}$ composition on necessary minimum distances to meet the standards is discussed in the supplemental file to this paper.

Gaussian plume model assumes that no chemical reaction occurs with the dispersed particles involved. However, the increase in relative humidity causes the particle size to increase by the factor that depends on the dry particle size, particle type, and also level of humidity (Gopoch et al., 1980; Martin and Finlay, 2005; Sinclair et al., 1974; Winkler, 1988). For example, Popovicheva et al. (2008a) shows that based on the hydrophobic or hydrophilic nature of soot particles, one particle can uptake 1 to 8 monolayers of water on its surface. For particles in form of aqueous droplets, studies took advantage of Kohler theory to estimate the changes to particles diameter as a result of interaction with water (Akpootu and Gana, 2013; Petters and Kreidenweis, 2007). As a result of change in the particle size, relative humidity affects aerosol concentration (Gopoch et al., 1980). Since elemental carbon has smaller molecular weight than the other types of $PM_{2.5}$ particles, the influence of water uptake through adsorption and absorption (Popovicheva et al., 2008b) on the particle concentration can be more significant.

Model

Air pollution models are powerful tools to quantify the relationship between emission rate and changes in ambient concentration. As it is not feasible to measure pollutant concentration at every single location, these models are becoming more indispensable for regulatory and research applications. Touma et al. (2006) discussed two major types of air quality models, namely local-scale (source-based) dispersion models and regional-scale (grid-based) chemical transport model. For the purpose of this research, the simulation method is Gaussian plume model, the basic method used to estimate concentration in local-scale models. Our model treats the shale gas wellsite as a point source of emission and simulates the dispersion of emissions from development activities per every hour. Thus, it allows for probabilistic evaluation of concentration exceedance of EPA NAAQS through consideration of all possible time periods and multiple locations. The output of this model is a probability map of concentrations, rather than a concentration map. Also it makes it easier to track the trend of changes and perform the sensitivity analysis on different variables and inputs.

Gaussian plume model is a governing advection-diffusion equation, mainly used over short range (within 50 km), describing the movement of pollutants in the atmosphere. This model uses the average wind characteristic data (speed and direction) over a specific period of time and its output is an average estimation of the pollutants concentration at specific location(s).

Gaussian plume equation is as shown in eq 1:

$$C(x, y, z, t) = \frac{Q}{2\pi u \sigma_y \sigma_z} exp\left(-\frac{y^2}{2\sigma_y^2}\right)\left[exp\left(-\frac{(z - H_{eff})^2}{2\sigma_z^2}\right) + exp\left(-\frac{(z + H_{eff})^2}{2\sigma_z^2}\right)\right] \quad (1)$$

where C is the substance concentration as a function of x, y, z and time (t), x is the distance downwind from the stack, y is the crosswind distance from the plume centerline, z is the vertical distance from the ground level, Q is the source emission rate, u is the average wind speed at stack height, σ_y is dispersion coefficient in the crosswind direction, σ_z is dispersion coefficient in the vertical direction, and H_{eff} is the effective stack height.

To calculate σ_y and σ_z values, the Briggs' formula tabulated by Arystanbekova (2004) is used. Stability is a function of wind velocity and sky cloudiness (Arystanbekova, 2004). We defined the stability based on distribution of monitored wind velocity values at the mentioned weather stations during day and night hours. Roughly, stability class of moderately unstable is defined for simulations associated to weather data measured each day between 5 am to 8 pm. Stability class of slightly stable considered in generating simulation result based on weather data measured between 8 pm to 5 am daily. Also as emissions from shale gas development mainly originate from diesel engines (Roy et al., 2014) which are technically located at the ground level and do not have any kind of stack on them, in this study H_{eff} is set to zero.

Presence of any structures around the emission source could affect the concentrations in the near-field. Some modeling tools try to treat the downwash due to presence of buildings and other structures, but there seems to be over-predictions and under-predictions involved (Peterson et al., 2017; Peterson and Beyer-Lout, 2012). However, shale gas development activities typically occur in the rural areas where the probability of existence of such structures within very close vicinity of a wellsite is low. Thus, as the goal of this work is to provide a generic evaluation of shale gas development effect on the local air quality, we assume that there is no such a structure within the vicinity of the generic wellsite.

In this study, the Gaussian plume model was implemented with MATLAB to simulate PM concentrations. The original model code, developed by Dr. Paul Connolly from the University of Manchester (Connolly, 2014), was used which was basically the coded eq 1 with consideration of one constant value for wind speed and direction. This code was modified in order to consider the role of time in emission dispersion procedure by taking hourly wind speed and direction measurements as an input for any period of time, instead of an annual average value. The modified code considers the emission characterization (aerosols size, molecular mass, density, etc.), the effect of humidity on aerosols concentration, and the change in atmosphere stability at different hour of the day. The code simulates all possible cases and provides the probabilistic evaluation of cases wherein exceedance from concentration standards occur.

Analysis

In this study, we assess emission concentrations to determine the minimum distance from the source which is required for an occupied area to be located in order to not experience any exceedance from $PM_{2.5}$ concentration standards. To ensure that conditions across the Marcellus region were represented, wind data from ten selected monitoring stations in the Pennsylvania State are used. These stations are selected as to be located close to Marcellus shale gas development areas in Pennsylvania. Bootstrapping was used to complete the wind data for missing hourly measurements.

Even though Gaussian plume models may be an appropriate modeling tool for long distances (typically within 50 km from the source) (Touma et al., 2006), wind profiles might change over this distance. However, this analysis did not extend the calculated dispersion beyond 5 km. In this steady state model, it is assumed that wind speed and direction is constant within the vicinity of wellsite where concentrations are modeled on an hourly basis. Moreover, we set the goal of this work to demonstrate just the role of shale gas development on the quality of the ambient air within vicinity of the wellsites. Thus, the calculated concentrations in the model only originate from drilling and hydraulic fracturing activities at the wellsite and background concentrations are not considered. This assumption also implies that no accumulation of emissions is presumed from hour to hour.

Background emission concentrations are those generated from other natural and anthropogenic sources such as motor vehicles on the road, factories, and other distant emission sources. EPA provides daily air quality index (AQI) values for the specified year and location in the Air Quality Index Daily Values Report. However, these values are not available at the locations within the vicinity of most of the developed shale gas wellsites. Even though the background concentration has an important impact on defining the setback distance in more polluted areas, consideration of an average value introduces more uncertainty into the results due to underestimation or overestimation at different locations. Therefore, the model output becomes a less comprehensive representative of the changes in the air quality due to shale gas activities.

The model produces hourly $PM_{2.5}$ concentrations at all locations within the vicinity of a representative shale gas wellsite over the drilling time period. The appropriate timeframe is defined based on the number of wells on the wellpad. Using the wind data from ten stations available for every hour during January 1st, 2015 to December 31st, 2015, the code generates arrays of PM concentrations indicating the locations where exceedance of EPA NAAQS occurs on a probabilistic basis.

Exceedance plots are generated based on two time-averaging approaches; annual and daily concentration averages. To calculate the percentage of exceedance occurrence based on annual average concentration, first, all the possible drilling time periods during a year are identified based on number of wells per wellsite. Then, using every set of wind data (from the ten weather monitoring stations), the annual average concentration is modeled for all the plausible time periods during a year. Thus, the percentage of exceedance is defined to be equal to the percentage of the times that annual average concentration at each direction exceeds the annual standard, e.g., 12 μg/m^3 for $PM_{2.5}$.

To plot the safe area boundary based on daily average approach, first the average aerosol concentration is calculated using the wind data for every 24 hours. Then, the percentage of exceedance is defined to be equal to the percentage of days that daily average concentration at each direction exceeds the daily standard, e.g., 35 μg/m^3 for $PM_{2.5}$.

Compliance with EPA's $PM_{2.5}$ annual standard of 12 μg/m^3 is calculated by averaging the annual mean concentrations over three consecutive years. Also compliance with EPA's $PM_{2.5}$ daily standard of 35 μg/m^3 is determined by calculating the 98th percentile of all 365 daily averages each year, and then averaging together three successive years' 98th percentiles. However, shale gas development wellsites are temporary point sources of emissions that usually exist less than a three-year period of time. Besides, the purpose of this work is to provide recommendations, instead of regulation, to avoid any exceedance experience of annual and daily standards of $PM_{2.5}$ which is favorable from public health point of view. For the rest of this paper, we investigate any case wherein one year average concentration exceeds the annual standard and any case wherein one day average concentration exceeds the daily standard.

Results

Annual average concentration of $PM_{2.5}$ emissions was modeled at radial distances from the representative wellsite using the wind data records in 2015. Figure-1 depicts boundaries of areas where concentrations exceed the annual standard 5% and 0% of the times based on annual averaging for two cases of wellpad comprising of one well and six wells. Results are demonstrated for the two emission rate levels, mean (0.81 kg/hr for drilling and 0.67 for hydro fracking) and high (2.7 kg/hr for drilling and 1.68 for hydro fracking). The current Pennsylvania's residential setback distance (500 ft. or 152.4 m) from the shale gas well is displayed by the red-dashed circle. To calculate the annual average concentrations, one to six wells per wellsite were considered based on the permit records from Marcellus shale gas development in Pennsylvania (Department of Oil and Gas Reporting website, 2016). Figure-2 depicts the histogram of number of permitted wells per wellpad in Marcellus shale region of Pennsylvania in 2015.

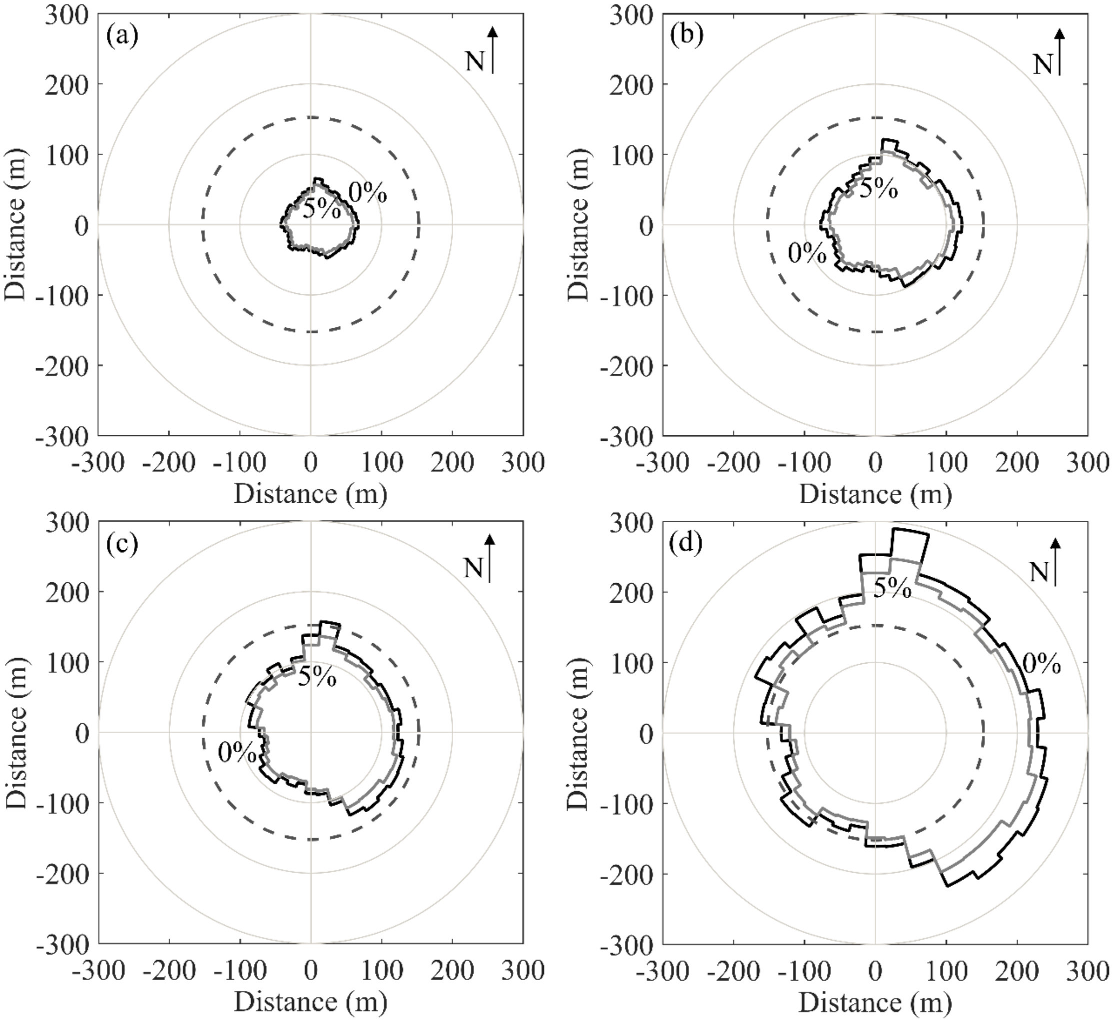

Figure 1. Distance from wellpad to maintain safe level of concentration based on EPA's $PM_{2.5}$ annual concentration standard, for the cases: (a) 1 well at mean emission rate, (b) 1 well at high emission rate, (c) 6 wells at mean emission rate, and (d) 6 wells at high emission rate. The emission source is assumed to be located at the origin. The dashed circle indicates the locations at the current PA's setback limit (500 ft. or 152.4 m) from the source.

While exceedance of the annual standard is unlikely to occur at the current setback distance in case of a wellpad with a single well, the probability of exceeding this standard increases with a greater number of wells. For example, a typical wellpad comprising of six wells can cause exceedance occurrence at specific location with respect to the wellsite even at mean expected emission rate. Figure-1c shows that for a typical wellpad consisting of six wells, a residential area must be located at least 67 – 158 meters away from the center of the wellpad depending on the compass direction to be certain of no exceedance of annual standard at mean emission rate. This distance range increases to 121–291 meters at the high emission rate (Figure-1d). The 95% confidence intervals for the minimum safe distance range from a wellpad with six wells are 62–137 meters (Figure-1c) and 113–248 meters (Figure-1d) at mean and high emission rates, respectively.

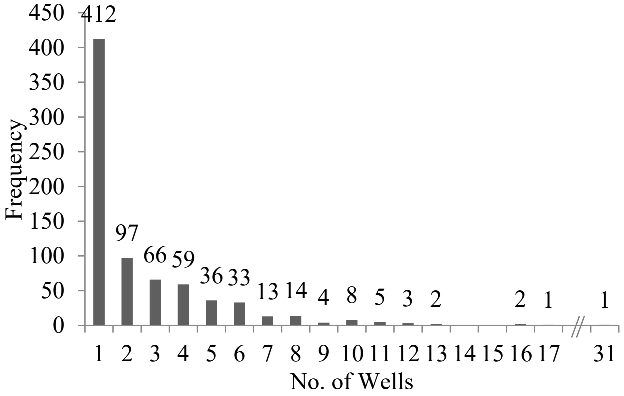

Figure 2. Histogram of number of permitted wells per wellpad in Marcellus shale region of Pennsylvania in 2015. 93% of the wellpads contain 6 wells or fewer.

As a clarification, for instance, to generate the plot presented in Figure-1a, the time period to develop one well is equal to 23 days; 14 days for drilling and 9 days for hydraulic fracturing. For all possible 23-day contiguous time periods during the year 2015, we collected wind data from each of the ten available measurement sites. For each time period, we modeled concentrations within the vicinity of generic wellsite and set concentrations on remaining days to zero in 2015, and calculated the annual average concentration for that specific case. We repeated these calculations for all the plausible time periods. At the last step, we identified the locations where exceedance of EPA’s annual concentration standard occurs in 5% of the sets of results.

These results indicate the effect of changes in number of wells and emission rates on the minimum residential distance required for no exceedance with the probability of higher than 5%. According to Figure-1, the South and South East wind directions are the ones which implies the farthest safe distances from the source. Figure-3 presents the trend of change in safe distance values versus number of wells corresponding to South wind direction for two levels of emission rate.

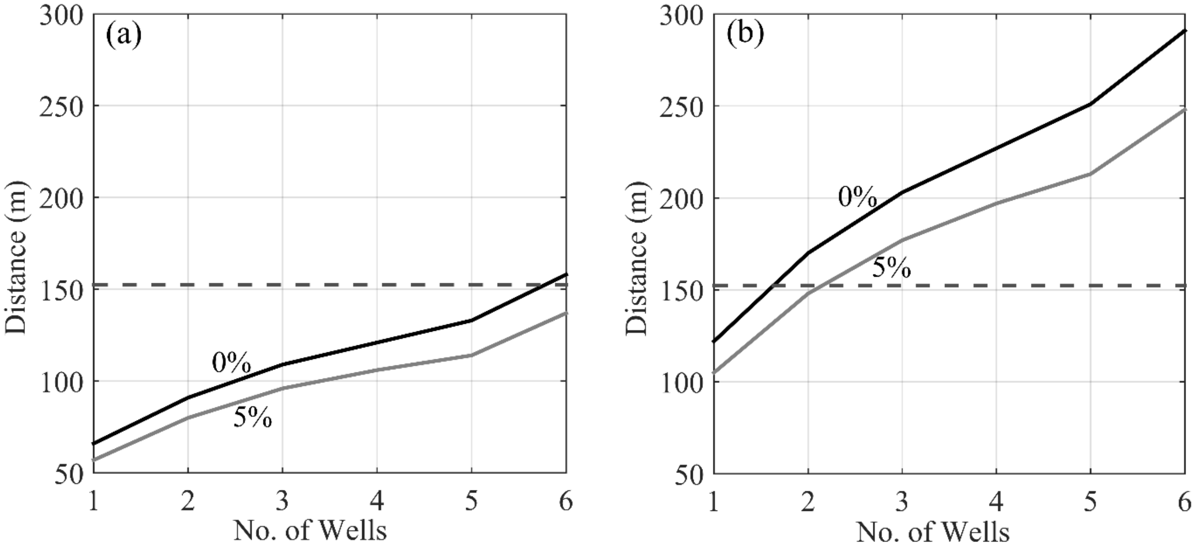

Figure 3. Minimum distance vs. No. of wells to meet annual concentration standard at the north of the source (south wind direction) for the cases: (a) mean emission rate, and (b) high emission rate. The dashed line indicates the current PA's setback limit (500 ft. or 152.4 m).

Results indicate that in case of one well per wellsite, occupied areas should be located no closer than about 67 meters away at mean emission rate and about 122 meters away at the high emission rate in order to not experience any concentration above EPA's annual standard. Thus, PA's setback distance seems to be effective for these cases. However, these distances are a function of the number of wells per site (more wells means longer drilling and fracturing periods) and the necessary distances are found to be equal to at least 158 meters at mean emission rate and about 291 meters at high emission rate in case of six wells per wellsite.

Figure-4 demonstrates boundaries of areas where exceedance of daily standard on $PM_{2.5}$ occurs 5% and 0% of the times. Results are demonstrated for the two emission rate levels, mean and high. Again, the current Pennsylvania's residential setback distance (500 ft. or 152.4 m) from the source is presented by the red-dashed circle. Figure-4 demonstrates that in order to meet the daily standard the corresponding distance ranges from a wellpad with six wells, residences must be at least 272–371 meters away, depending on the compass direction, for the mean emission rate.

This distance range increases to 530–736 meters for the high emission rate. In order to not experience any concentration exceedance more than 5% of the time, the corresponding minimum distance requirements from a wellpad with six wells are 101–208 meters and 189–407 meters for mean and high emission rates, respectively.

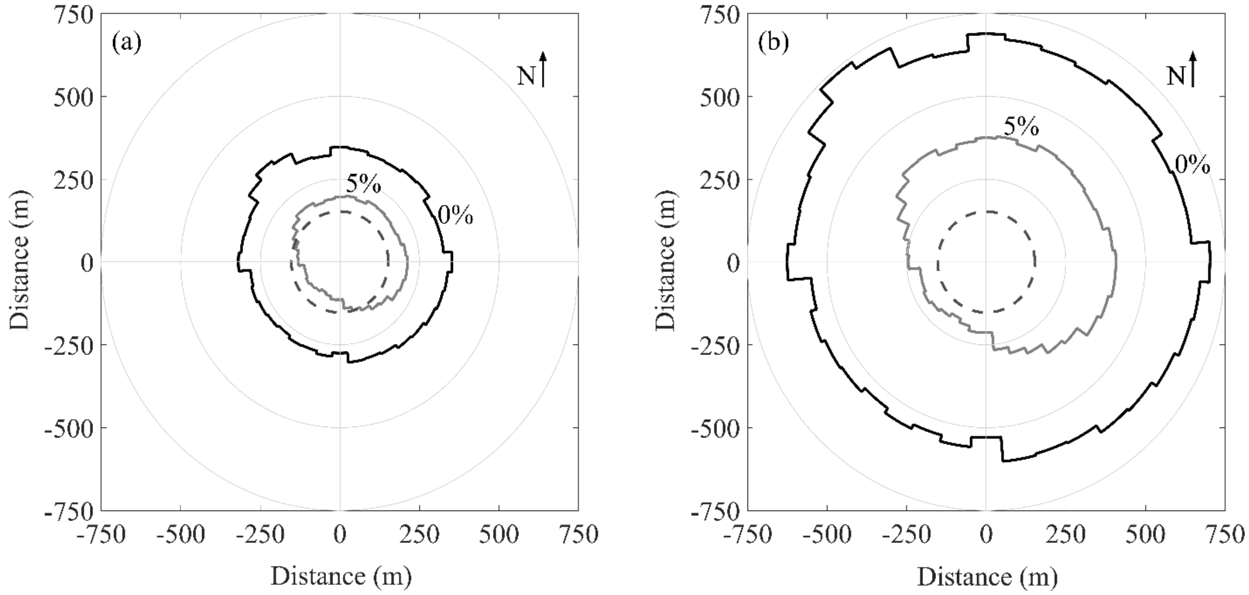

Figure 4. Distance from wellpad to maintain safe level of concentration based on EPA's $PM_{2.5}$ daily concentration standard, for the cases: (a) mean emission rate, and (b) high emission rate. The emission source is assumed to be located at the origin. The dashed circle indicates the locations at the current PA's setback limit (500 ft. or 152.4 m) distance from the source.

The simulations indicate that the minimum distance of at least 371 meters in case of mean emission rate and the minimum distance of at least 736 meters in case of high emission rate is required in order to be certain of no exceedance occurrence of the daily standard.

Results from this simulation indicate that at mean emission rate, the highest percentage of concentration exceedance at 152.4 m (500 ft.) from annual limit is 3% for the case of a wellpad with six wells. This value increases to 87% at high emission rate for the same number of wells. The location that these percentage values represent are reported in Table-1.

Table 1. Probability of concentration exceedance of annual concentration standard at 152.4 m (500 ft.) in case of wellpad with six wells.

Probability Levels of Concentration Exceedance	Mean Emission Rate		High Emission Rate	
	Percentage (%)	Wind Direction	Percentage (%)	Wind Direction
Lowest	0	All except for South – South South West	0	North – North North East East North East – East
Highest	3	South – South South West	87	South – South South West

Note: Values indicate the direction and the percentage of the time that concentrations exceed the annual standard at that direction for mean and high emission rate, at the current setback limit of 152.4 m (500 ft.); e.g., there is a residential located on the "S–SSW" wind direction path which experiences the annual standard exceedance 87% of the times.

Discussion

While Roy et al. (2014) discusses the regional contribution of $PM_{2.5}$ emissions alongside NOx and VOCs originated from Marcellus development in Pennsylvania, they indicate a relatively moderate $PM_{2.5}$ contribution when averaged across the region. These results, however, help to shed light on the more significant, though heterogeneous, local effects which occur at specific locations in the vicinity of wellsites.

Arguments by Haley et al. (2016), based on their evaluation of current setbacks efficiency, support the fact that at the current setback distance in Pennsylvania, people are not protected from potential health effects of VOC emissions. Similarly to Haley et al. (2016), the results from this analysis imply that the current PA setback limit for natural gas wells is not sufficient to ensure inhabited areas meet the EPA's $PM_{2.5}$ daily standard and it is not sufficient to guarantee no exceedance of annual standard for sites with multiple wells per pad. A minimum distance of at least 736 meters (about 2400 ft.) is required in order to ensure concentrations less than EPA's daily average $PM_{2.5}$ standard. Even at this distance, there is still a slight chance that exceedance of daily standard occurs. The emission rates used in this simulation process are the ones reported by Roy et al. (2014) as the 95% confidence interval for $PM_{2.5}$ emission rate. Therefore, even at the suggested setback distance, there is still a probability of 2.5% of experiencing emission rates that would cause exceedance of concentration standards.

Roohani et al. (2017) predicts the regional ozone and $PM_{2.5}$ concentration using the modeling tool CAMx over a 36 km × 36 km grid resolution under three different scenarios that are defined based on three levels of shale gas development activities in 2020. Results by Roohani et al. (2017) demonstrate a relatively small change in the mean annual $PM_{2.5}$ concentration due to shale gas activities under the three scenarios at regional scale (0.1 to 0.4 $\mu g/m^3$). However, our results find these changes to be more significant at local scale as a result of different densities of shale gas activities. For instance, we find the increase in the mean annual $PM_{2.5}$ concentration of a residential located at 152.4 m distance to the north of a wellsite comprising of 6 wells to get up to about 20 and 60 $\mu g/m^3$ at mean and high emission rates, respectively.

The current PA setback limit is in fact sufficient to protect occupied areas from exceedance of the annual standard assuming mean emission rates. However, the required distance in this case is a function of the number of wells located at the site. Setback distances from natural gas development should take the density of that development into account, as currently known regulations use the same distance regardless of the number of wells—the number of wells being a proxy for the length of time that high intensity activities will be occurring at the site. Given the main risks from $PM_{2.5}$ exposure are chronic diseases such as cancer and heart disease (Lepeule et al., 2012), it would be prudent to treat the concentrations above the average annual concentration standard as a higher priority. Even assuming average emission rates, the current setback policy is insufficient for sites with more than 5 wells, and for high emission rates, the current setback distance is only sufficient for a single well per pad.

A limit of no more than 1 well per wellpad would serve to ensure no exceedances of the annual average $PM_{2.5}$ standard occurred assuming 95th percentile emissions of $PM_{2.5}$. Review of permit datasets through 2001–2015 (Department of Oil and Gas Reporting website, 2016) shows that significant percentage of developed wellpads have had more than one well per pad (e.g. 7% of sites in 2015 had more than 6 wells, see Figure 2). A limit on the number of wells per pad should be accompanied by study on the economic and environmental tradeoffs required, but such information is not currently available.

The increase of setback distances for natural gas drilling would likely make some parts of the Marcellus shale inaccessible to gas recovery, at least temporarily. However, as technology continues to stretch the maximum lateral lengths possible, this may not remain a restriction. As drilling costs related to increasing lateral lengths are proprietary, it is not possible to evaluate the impact of increasing setback distance on them. In Pennsylvania, most new drilling activities occur in sparsely populated areas of the commonwealth, so it may be possible to adopt increased setback distances without significant impact, especially considering the fact that they would be temporary restrictions. However, this is unlikely to be the case in more densely populated areas like Allegheny County, which contains the city of Pittsburgh and related suburban communities. The economic effects of such a change are not expected to be exclusively negative however, as increasing distance from a well has been associated with increasing property values (Boxall et al., 2005).

Application of increased setback distance standards may not be quite sufficient by itself to provide human health protection (Haley et al., 2016). There are alternative policies to consider in lieu of increasing setback distances. It would be possible to maintain the current setback distance of 152.4 m (500 ft.) in Pennsylvania, if policy makers set a cap on the $PM_{2.5}$ emissions rate from these sites at 0.165 kg/hr. This value represents an emission rate of only 20% and 25% of the mean emission rate used in this analysis for drilling and hydraulic fracturing, respectively. Such a standard might seem stringent, but it would negate the need for a 480% increase in the setback distance to prevent exceedance of the daily average $PM_{2.5}$ standard. As some well services companies are increasing their use of gas turbines to provide power rather than diesel engines, such a reduction in PM emissions may be possible.

This analysis addresses possible exceedances of the concentration standards for $PM_{2.5}$, though several other pollutants of interest are emitted during gas exploration and production such as nitrogen oxides, ozone, VOCs, sulfur oxides, and PM_{10}. $PM_{2.5}$ is one of the most significant quantities emitted during these activities, and the concentration standards have been established relatively recently based on current health risk research. Continuing study should examine setback policy in light of each of these pollutants.

While the simplifying assumptions for this analysis including a constant emissions rate are reasonable for prediction of a generic future gas well, these assumptions would not necessarily be applicable for the determination of health risks accepted by current policy for past wells. In reality emission rates likely differ based on depth and length of the well, so it may be possible to estimate in advance whether or not the emission rate at a particular site would be high, average, or low, and evaluate the risk and the necessary setback distance on that basis.

These results are based on the assumption that future distributions of wind speed and direction will remain consistent with those recorded in 2015. The wind speed and direction around specific well sites is dependent not just on the overall distribution of weather patterns, but also on the specific geography of the site including hills, trees, ridges, etc. Some modeling tools apply some modifications in order to consider the influence of these complexities on the model output. For example, AERMOD takes the base elevation and hill height scale data as input and consider their influence in modeling the dispersion of a plume (EPA, 2016). However, each of these features can increase or decrease the concentrations near the wells depending on the specifics and setback policy as a useful heuristic in place of doing extensive modeling of each well site, should be based on a generic or flat terrain in order to be applicable to different cases and locations. Also precipitation is not included in this model, and would be expected to increase the settling rate of fine particulate matter, thus reducing the concentrations on those days with rain or snow. However, these results provide expected $PM_{2.5}$ concentrations on dry days, and while the overall probability of an exceedance might change with the inclusion of precipitation, the 0% exceedance distance presented here would not change.

The main limitation of this work is probably the validation of modeling outputs with field measurement data. The modeled concentrations generated by our model at the location of EPA's monitoring stations are below the measurements at these locations, but these stations are located far from most of the shale gas wellsites. Thus, justification of the model's output requires more robust concentration measurements implemented within the vicinity of these wellsites which literature currently lacks, but it can be the subject of a valuable study.

Conclusion

Results from this research indicate that current PA setback policy of 152.4 m (500 ft.) is inadequate to protect residents from exceedances of the EPA's daily concentration standard for $PM_{2.5}$, and it is inadequate to protect against exceedances of the annual concentration standard for sites with 6 or more wells. To protect occupied buildings and outdoor areas against exceedances of the daily average standard, this analysis suggests that setback distances need to be up to 736 meters. To protect against exceedances of the annual average $PM_{2.5}$ standard, setback distances should be a function of the number of wells drilled at the site. Further refinements to this analysis are needed to account for multiple pollutants. Alternative policy options include limits on the number of wells per site (a choice that may have negative environmental implications as it would increase the number of constructed well pads) and limiting the maximum $PM_{2.5}$ emission rate at each site to 0.165 kg/hr.

The results provided here are associated with a generic wellsite in Pennsylvania with no specific structure within its vicinity. If there is such a structure close to a wellsite of interest or for an unusual case like a hospital or a school, it might be more prudent not to generalize these results to the case. For such a case, there might be need for more investigation or even a specific analysis of the site and its vicinity. Also it is worth repeating that the emission rate corresponding to the conservative case in this work is the 97.5th percentile. Simulation of the most conservative case requires the necessary update of this value.

Acknowledgements

This study was supported by John and Willie Leone Family Department of Energy and Mineral Engineering, College of Earth and Mineral Sciences, Pennsylvania State University. We are also grateful to Dr. Sanjay Srinivasan and Dr. John Y. Wang for their insights into unconventional shale gas development processes and procedures.

References

Adgate, J.L., B.D. Goldstein, L.M. McKenzie. 2014. Potential Public Health Hazards, Exposures and Health Effects from Unconventional Natural Gas Development. *Environ. Sci. Technol*. 48: 8307–8320.

Akpootu, D.O. and N.N. Gana, 2013. The Effect of Relative Humidity on the Hygroscopic Growth Factor and Bulk Hygroscopicity of water Soluble Aerosols. *Int. J. Eng. Sci.* 2: 48–57.

Arystanbekova, N.K. 2004. Application of Gaussian plume models for air pollution simulation at instantaneous emissions. *Math. Comput. Simulat*. 67: 451–458.

Boxall, P.C., W.H. Chan, M.L. McMillan. 2005. The impact of oil and natural gas facilities on rural residential property values: a spatial hedonic analysis. *Resour. Energy Econ*. 27: 248–269.

Compilation of Air Pollutant Emissions Factors, 1972. http://www.epa.gov/ttn/chief/ap42/index.html (last accessed on November 22, 2016)

Connolly, P., 2014. http://personalpages.manchester.ac.uk/staff/paul.connolly/teaching/practicals/gaussian_plume_modelling.html (last accessed on October 10, 2016)

Corbett, T., E.C. Abruzzo. 2014. Commonwealth of Pennsylvania Department of Environmental Protection 2014 Annual Ambient Air Monitoring Network Plan. Pennsylvania Department of Environmental Protection

Department of Oil and Gas Reporting website, 2016. http://www.depreportingservices.state.pa.us/ReportServer/Pages/ReportViewer.aspx?/Oil_Gas/Permits_Issued_Detail (last accessed on December 24, 2016)

EIA – Shale gas production, 2016. http://www.eia.gov/dnav/ng/ng_prod_shalegas_s1_a.htm (last accessed on November 22, 2016)

EIA – Shale gas proved reserves, 2016. http://www.eia.gov/dnav/ng/ng_enr_shalegas_a_epg0_r5301_bcf_a.htm (last accessed on November 22, 2016)

EPA, 2016. Office of Air Quality Planning and Standards, Air Quality Assessment Division, Air Quality Modeling Group. User's Guide for the AERMOD Terrain Preprocessor (AERMAP).

EPA 2014 National Emissions Inventory (NEI). https://www.epa.gov/air-emissions-inventories/2014-national-emissions-inventory-nei-data (accessed March 10, 2017).

Fry, M. 2013. Urban gas drilling and distance ordinances in the Texas Barnett Shale. *Energy Policy*. 62: 79–89.

Gopoch, A., S. Burk, K.L. Davidson, 1980. Stability effects on aerosol size and height distributions. *Tellus*. 32(3): 245–250.

Haley, M., M. McCawley, A.C. Epstein, B. Arrington, E.F. Bjerke. 2016. Adequacy of Current State Setbacks for Directional High-Volume Hydraulic Fracturing in the Marcellus, Barnett, and Niobrara Shale Plays. *Environ. Health Perspect*. 124(9): 1323–1333.

IEM: Iowa Environmental Mesonet, 2016. http://mesonet.agron.iastate.edu/request/download.phtml?network=PA_ASOS (last accessed on November 22, 2016)

Jacoby, H.D., F.M. O'Sullivan, S. Paltsev. 2011. The Influence of Shale Gas on U.S. Energy and Environmental Policy. *Economics Energy Environ. Policy*. 1(1): 37−51.

Jenner, S., A.J. Lamadrid. 2013. Shale gas vs. coal: Policy implications from environmental impact comparisons of shale gas, conventional gas, and coal on air, water, and land in the United States. *Energy Policy*. 53: 442–453.

Kelly, F.J., J.C. Fussell. 2012. Size, source and chemical composition as determinants of toxicity attributable to ambient particulate matter. *Atmos. Environ*. 60: 504–526.

Lepeule, J., F. Laden, D. Dockery, J. Schwartz. (2012). Chronic exposure to fine particles and mortality: An extended follow-up of the Harvard six cities study from 1974 to 2009. *Environ. Health Perspect*. 120(7): 965–70.

Martin, A.R. and W.H. Finlay, 2005. The Effect of Humidity on the Size of Particles Delivered from Metered-Dose Inhalers. *Aerosol Sci. Technol.* 39(4): 283–289.

National Ambient Air Quality Standards (NAAQS); 40 CFR part 50; Washington, DC, 2012.

Ogoke, V., L. Schauerte, G. Bouchard, S.C. Inglehart. Simultaneous Operations in Multi-Well Pad: a Cost Effective way of Drilling Multi Wells Pad and Deliver 8 Fracs a Day. Proceeding of the Society of Petroleum Engineers Annual Technical Conference and Exhibition, Amsterdam, The Netherlands, 27–29 October, 2014.

Olaguer, E.P. 2012. The potential near-source ozone impacts of upstream oil and gas industry emissions. *J. Air Waste Manage*. 62(8): 966–977.

Pacsi, A.P., N.S. Alhajeri, D. Zavala-Araiza, M.D. Webster, D.T. Allen. 2013. Regional Air Quality Impacts of Increased Natural Gas Production and Use in Texas. *Environ. Sci. Technol*. 47: 3521–3527.

Peterson, R.L., S.A. Guerra, A.S. Bova. 2017. Critical review of the building downwash algorithms in AERMOD. *J. Air Waste Manage*. 67(8): 826–835.

Peterson, Ronald L., Anke Beyer-Lout. Aermod Building Downwash Theoretical Limitations and Possible Solutions. Paper presented at 105th Annual Conference and Exhibition of the Air & Waste Management Association, San Antonio, Texas, June 2012.

Petters, M.D. and S.M. Kreidenweis, 2007. A single parameter representation of hygroscopic growth and cloud condensation nucleus activity. *Atmos. Chem. Phys.* 7: 1961–1971.

Popovicheva O.B., N.M. Persiantseva1, V. Tishkova, N.K. Shonija, N.A. Zubareva, 2008a. Quantification of water uptake by soot particles. *Environ. Res. Lett.* 3: 025009.

Popovicheva O.B., N.M. Persiantseva1, N.K. Shonija, P. DeMott, K. Koehler, M. Petters, S. Kreidenweis, B. Demirdjian, J. Suzanne, V. Tishkova, 2008b. Water interaction with hydrophobic and hydrophilic soot particles. *Phys. Chem. Chem. Phys.* 10: 2332–2344.

Rodriguez, M.A., M.G. Barna, T. Moore. 2009. Regional Impacts of Oil and Gas Development on Ozone Formation in the Western United States. *J. Air Waste Manage*. 59(9): 1111–1118.

Roohani, Y.H., A.A. Roy, J. Heo, A.L. Robinson, P.J. Adams. 2017. Impacts of natural gas development in the Marcellus and Utica shales on regional ozone and fine particulate matter levels. *Atmos. Environ*. 155: 11–20.

Roy, A.A., P.J. Adams, A.L. Robinson. 2014. Air pollutant emissions from the development, production, and processing of Marcellus Shale natural gas. *J. Air Waste Manage*. 64(1): 19–37.

Shah, S.D., D.R. Cocker, J.W. Miller, J.M. Norbeck. 2004. Emission Rates of Particulate Matter and Elemental and Organic Carbon from In-Use Diesel Engines. *Environ. Sci. Technol*. 38(9): 2544–2550.

Shonkoff, S., J. Hays, M.L. Finkel. 2014. Environmental Public Health Dimensions of Shale and Tight Gas Development. *Environ. Health Perspect*. 122(8): 787–795.

Sinclair, D., R.J. Countess, G.S. Hoopes, 1974. Effect of Relative Humidity On The Size Of Atmospheric Aerosol Particles. *Atmos. Environ.* 8: 1111–1117.

Touma, J.S., V. Isakov, J. Ching, C. Seigneur. 2006. Air Quality Modeling of Hazardous Pollutants: Current Status and Future Directions. *J. Air Waste Manage*. 56(5): 547–558.

Vidic, R.D., S. L. Brantley, J.M. Vandenbossche, D. Yoxtheimer, J. D. Abad. 2013. Impact of Shale Gas Development on Regional Water Quality. *Science*. 340(6134): 1235009.

Winkler, P., 1988. The growth of atmospheric aerosol particles with relative humidity. *Phys. Scr.* 37: 223–230.

World Health Organization (WHO). 2003. Health Aspects of Air Pollution with Particulate Matter, Ozone and Nitrogen Dioxide. Bonn, Germany.

Zielinska, B., E. Fujita, D. Campbell. 2011. Monitoring of Emissions from Barnett Shale Natural Gas Production Facilities for Population Exposure Assessment. Desert Research Institute, Houston TX