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Modeling the Health Effects and Economic Costs of Particulate Matter Emissions from High Volume Hydraulic Fracturing

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Rochester Institute of Technology

**Modeling the Health Effects and Economic Costs of Particulate Matter
Emissions from High Volume Hydraulic Fracturing**

by

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A Thesis Submitted in Partial Fulfillment of the
Master of Science in Environmental Science

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Abstract

With natural gas drilling on the rise (Penn State, 2012), there is a general lack of data on the emissions from the entire lifecycle of hydraulic fracturing. This research project is designed to study the health impacts of emissions from high volume hydraulic fracturing (HVHF) production and at HVHF well sites. Using data from previous research (Korfmacher et al., 2015 and Korfmacher et al., 2016) and the Environmental Protection Agency's Environmental Benefits Mapping and Analysis Program - Community Edition (BenMAP-CE), estimated health impacts and economic costs of emissions are analyzed. This study models the health impacts and economic costs of particulate matter (PM), an inhalable pollutant known to cause adverse health effects (OAR US EPA 2016a). Specifically, the study focuses on emissions at unconventional wells associated with HVHF in Pennsylvania. Based on modeling results, 2,000-5,000 people throughout Pennsylvania are being impacted by PM emissions released during HVHF activities, with higher percentages of the population per grid cell (0.01%-0.25%) impacted near well site locations, as compared to other parts of the state (0.0001%-0.006%). This study found that emissions from PM generated during HVHF activities in Pennsylvania during the years 2011-2015 would result in an estimated 2,100-5,300 premature deaths with 95% confidence intervals of 600-3,500 deaths and 2,400-8,000 deaths respectively. The cost of these premature mortalities are estimated to be \$14 billion-\$37 billion with 95% confidence intervals of \$1 billion-\$34 billion and \$4 billion-\$79 billion respectively. This study shows that there is an increased risk of mortality from PM released during HVHF activities near well sites that appears to be currently underreported due to a lack of EPA monitors in rural parts of the country. This study acts as a guide to highlight problem areas in rural parts of the country, where monitoring stations are lacking and emissions from wells are relatively high.

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Introduction

Particulate Matter

Particulate matter (PM) is a type of pollution composed of a large assortment of diverse chemicals, including nitrogen oxides, ammonia, sulfur dioxide, and other gases, in solid or liquid form that originate from both natural and human activities (EPA 2011; OAR US EPA 2016d). Common sources of PM emissions are fossil fuel combustion, industrial processes, and on-road and non-road vehicles (EPA 2011). Pertinent to this study, unconventional natural gas production and the hydraulic fracturing process are known sources of fine PM emissions (Alvarez 2009). Other known sources are agriculture, forestry, areas under construction, or wildfires (OAR US EPA 2016a; EPA 2011). PM is divided into three groups based on the diameter (less than 10 micrometers, less than 2.5 micrometers, and less than 1 micrometer) and the effect on human airways (OAR US EPA 2016d). Figure 1 shows the relative size of PM_{2.5} and PM₁₀ compared to a human hair and beach sand.

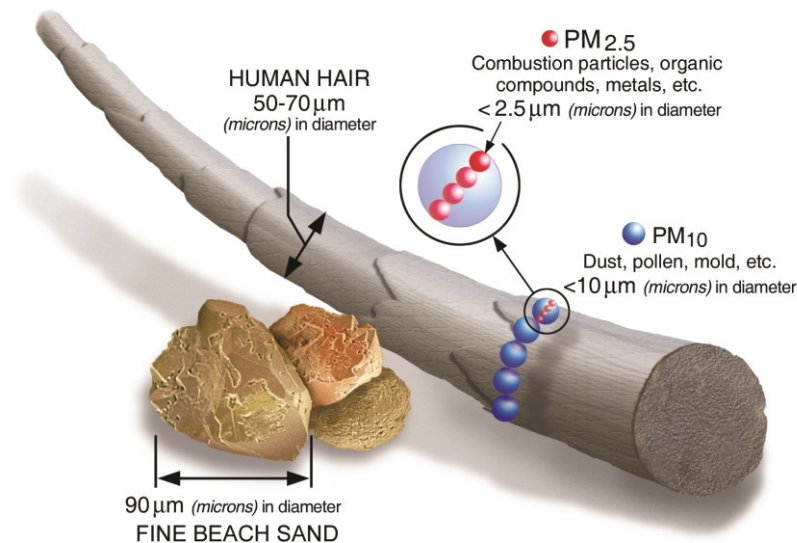


Figure 1. The relative size of PM_{2.5} and PM₁₀ compared to a human hair and beach sand (OAR US EPA 2016d).

PM₁₀ is commonly removed from the human airway through the nasal passage, but PM_{2.5} or less deposits in the lungs. These deposits then cause oxidative stress and can lead to chronic inflammation (Anderson, Thundiyil, and Stolbach, 2012). A groundbreaking study done in 1993, known as the Harvard Six Cities Study, demonstrated a strong correlation between elevated mortality rates and exposure to PM (Dockery et al. 1993). Since 1993, there have been many studies linking PM to adverse health effects, concluding that PM pollution poses a threat to human health and increases the risk of mortality (Kim, Kabir, and Kabir 2015). Another study found that reductions in PM_{2.5} over a seven year period considerably reduced premature mortalities (Fann and Rislely 2011). Reducing PM mortality is a significant health goal, as the World Health Organization (WHO) found that in 2002 there were 0.8 million premature deaths associated with PM_{2.5} worldwide (World Health Organization 2002).

The 1970 Clean Air Act established air quality standards for six pollutants, including PM_{2.5}, which was revised in a 1990 amendment to an annual average daily limit of 12 micrograms per meter cubed for primary pollutant standards and an annual average daily limit of 15 micrograms per meter cubed for secondary pollutant standards (OAR US EPA 2016c; OAR US EPA 2016e). This level is determined by the EPA to be the amount of fine PM at which there are minimal negative health impacts. However, many studies have noted there to be no precise evidence on deciphering a level of PM exposure that no longer causes health issues (Dockery et al. 1993).

Particulate Matter and High Volume Hydraulic Fracturing

Unconventional natural gas development is currently on the rise due to hydraulic fracturing and horizontal drilling. Figure 2 shows the increase in natural gas production from hydraulic fracturing in the United States between 2003 and 2017, with a large portion coming

from the Marcellus Shale Formation (EIA 2017). Hydraulic fracturing is a method used to extract natural gas that involves horizontal drilling through shale rock up to 9,000 feet underground, then uses explosives, high-pressure water, sand, and miscellaneous chemicals to fracture the rock and send gas flowing back up to the well (Penn State 2016). The fracturing process requires 2.5 to 8 million gallons of water per well site, where 60-90% of this water is left underground in the shale formation and the rest of the water arrives back at the surface and then must be treated either onsite or transported to a treatment or disposal facility (Penn State 2016).

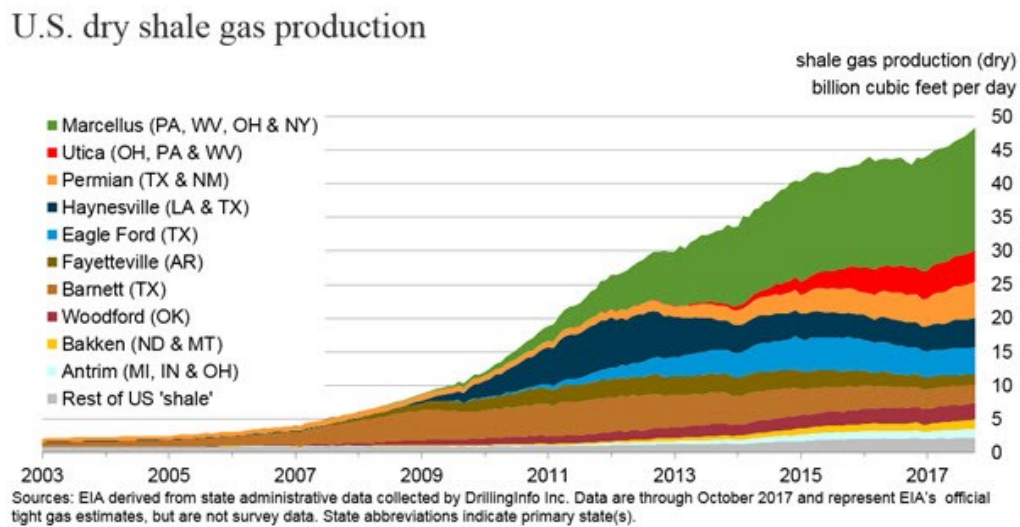


Figure 2. The increase in natural gas production from hydraulic fracturing in the United States and, in particular, the Marcellus shale up to the year 2017 (EIA 2017).

The Marcellus Shale formation in particular has become an active location for HVHF, especially around Pittsburg and rural areas of Pennsylvania (Figure 3). Beginning in 2007, rapid development in this region resulted in 4,200 well sites in Pennsylvania by the year 2011 (Penn State 2016). Emissions from well sites are a recent additional source of PM to the region, particularly in rural areas unaccustomed to high levels of PM pollution. The Pennsylvania Department of Environmental Protection (DEP) reported on emissions from unconventional

natural gas operations in the Marcellus Shale Basin, PA, stating that from 2013 to 2014, there was a 25% increase in fine PM (DEP 2016).

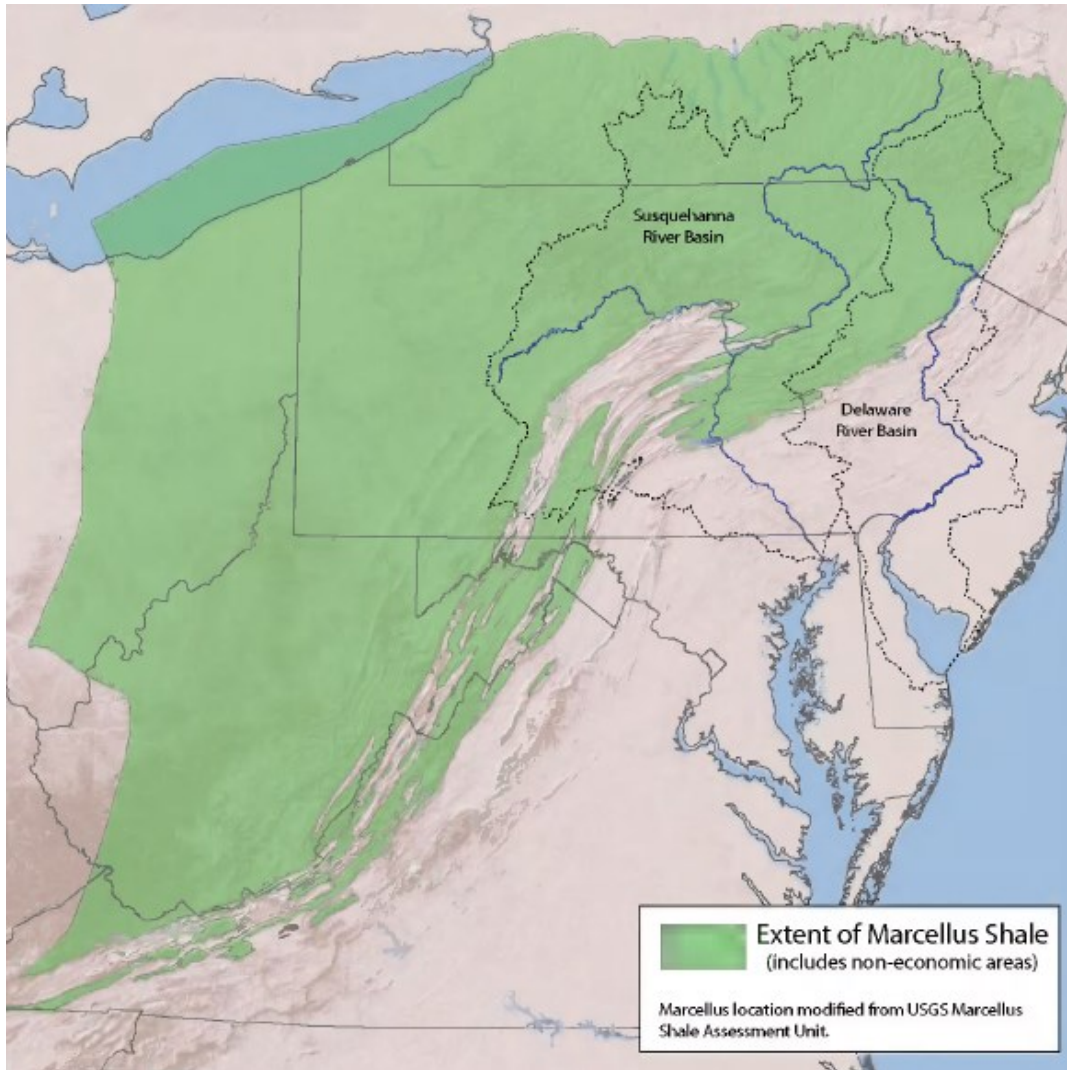


Figure 3 shows area of the Marcellus shale across the United State (Penn State 2016).

The U.S. Energy Information Administration (EIA) stated in the International Energy Outlook 2016 that consumption of natural gas is projected to increase from 120 trillion cubic feet in 2012 to 203 trillion cubic feet by 2040 (EIA 2016a). This increase is largely due to switching from coal to natural gas, because natural gas produces fewer greenhouse gas emissions at a

competitive price. The EIA reported that coal produces 210 pounds of carbon dioxide per million Btu of energy, while natural gas produces 117 pounds of carbon dioxide per million Btu of energy (EIA 2016b). However, this rise in natural gas production may cause an increase in PM pollution near well sites and roads used to transport water and waste, resulting in the potential exposure to people living near these areas.

Particulate Matter and Heavy Duty Diesel Trucks

Transportation is a large part of the HVHF process, using heavy duty diesel trucks to bring in water and sand for drilling. Additionally, trucks are used to transport flow-back wastewater from the well site to wastewater treatment facilities. Figure 4 represents the water use and transportation portion of hydraulic fracturing. A calculation of 4.4 million one-way heavy duty diesel trucks trips was found for transporting materials to and from well sites in the Marcellus Shale region of Pennsylvania between 2011 and 2013 (Korfmacher, Hawker, and Winebrake 2015). A majority of these diesel trucks are likely to have engines dating from before the 2007 model year, when cleaner emission controls technologies were introduced (Goldstein et al. 2014).

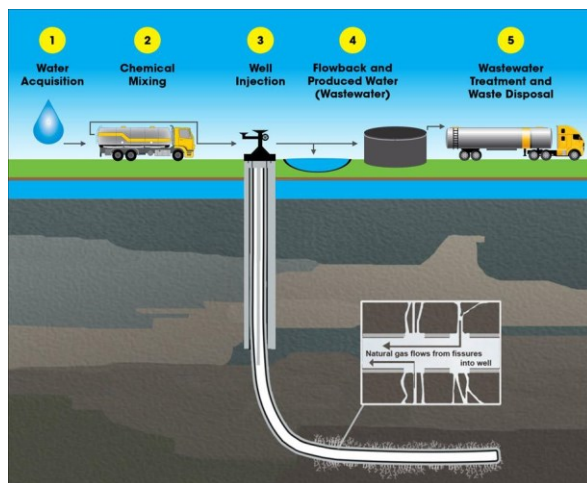


Figure 4. The water and transportation portion of hydraulic fracturing (ORD US EPA 2016).

Heavy duty diesel trucks produce emissions of PM, carbon dioxide, nitrogen oxides, sulfur oxides, and volatile organic compounds (US EPA 2008). From 2011-2013, an estimate for PM (PM₁₀) pollution from transporting materials to and from well sites in the Marcellus Shale region of Pennsylvania was 18.9 to 40.7 Mg for old trucks and 3.1 to 6.6 Mg for new trucks (Korfmacher, Hawker, and Winebrake 2015). Research is lacking on the health impacts from exposure to this additional release of PM produced from diesel trucks used for the hydraulic fracturing process (Goldstein et al. 2014).

Localized well emissions are in addition to the transport emissions and are a more permanent, stationary source of PM pollution. A previous phase of this project (VanMunster 2018) used a similar methodology, modeling the emissions from heavy duty diesel trucks associated with HVHF activities. VanMunster generated dispersion plumes from truck counts by road section using the atmospheric dispersion modeling system AERMOD (US EPA 2017), but was unable to capture the intense trucking and emission activity in the 2-3 week period when wells were drilled, due to a lack of temporal detail. Her emission results were averaged out annually, which diluted the impact and generated very small estimates of premature mortality in Pennsylvania (VanMunster 2018). However, well sites emit PM pollution all year, not just during the couple of weeks during well development. For this reason, well data alone were used and kept at an annual time step for use in BenMAP-CE to model health impacts, producing a potentially more accurate representation of the health impacts from PM pollution linked to hydraulic fracturing.

Modeling Health Impacts of Particulate Matter

The EPA's Environmental Benefits Mapping and Analysis Program - Community Edition (BenMAP-CE) is a useful tool to estimate and model health impacts. A previous study used BenMAP to evaluate the amount of mortalities avoided and economic benefits of the national air quality standards set in 2014 in China. The study compares PM levels from monitoring stations in China with the PM level set by the national air quality standard. The study models the PM_{2.5} concentrations and estimates that 0.35 million deaths were avoided by the national air quality standard in 2014. They also use BenMAP to find the economic benefit of the avoided deaths to be about \$65 billion (Chen et al. 2017).

The US EPA used a similar methodology to assess the health impact of increasing temperatures from climate change. The study uses BenMAP with heat mortality health impact functions to estimate premature mortalities from different temperature scenarios. They use BenMAP to find values for all cause mortality, cardiovascular disease, and non-accidental death along with subsequent economic costs, highlighting the ability to include these assessments in the economics of climate change (Voorhees et al. 2011).

The Harvard Six Cities study provides an example for a health modeling approach. The study design focuses on a population and defines variables such as age, race, and gender. They then compare the recorded ambient air quality with an observed change in air quality across six cities. A regression is run on each city for each of the defined variables and pollution sources to calculate mortality ratios. After controlling for differences in the population, the study found an association between increased mortality and higher levels of fine PM (Dockery et al. 1993). A more recent study conducted by the EPA, titled "Estimating the National Public Health Burden

Associated with Exposure to Ambient PM_{2.5} and Ozone", uses BenMAP-CE software to automate the health impact analysis to conduct an analysis of the effects of PM_{2.5} on mortality. This study combines the photochemical Community Multiscale Air Quality (CMAQ) model along with monitored ambient air quality into a 12x12 km grid. The study then uses population demographics with the air quality data to assess mortality rates across the United States during the summer of 2005. They use mortality risk coefficients derived from epidemiology literature, using sources such as the American Cancer Society and the Harvard Six Cities Study, to find mortality rates from a change in PM emissions. They also calculate the lives saved if there were more stringent air quality standards. The study found that for 2005 air quality levels, there were a total of 130,000 mortalities from PM_{2.5} exposure, concluding that PM_{2.5} emissions are a threat to public health (Fann et al., 2012).

Purpose

This study will use BenMAP-CE to develop a model of the health effects and economic costs of PM_{2.5} emissions at HVHF well sites in Pennsylvania. This model can then be used to identify potentially high PM_{2.5} concentrations in parts of Pennsylvania near well sites and estimate health impacts and economic costs on a larger scale, especially for currently underrepresented rural parts of the country, where there are many well sites but few EPA monitoring stations.

Methods

With the EPA's Environmental Benefits Mapping and Analysis Program - Community Edition (BenMAP-CE), health impacts and economic costs of increased PM emissions from hydraulic fracturing activities can be analyzed. This health impacts analysis approach involves three key mechanisms: (1) the monitored changes in ambient air quality are input into BenMAP-CE; (2) using a specified health equation drawn from epidemiology literature, a relationship is found between pollution and health effects; (3) economic values associated with these health effects are calculated (OAR US EPA 2016b). Figures 5 and 6 illustrate this approach.

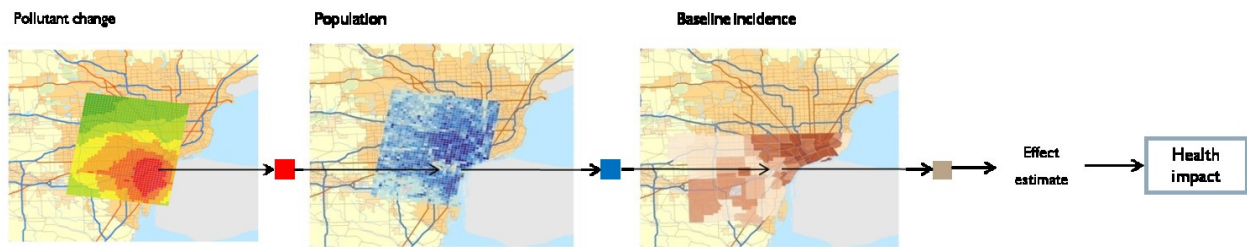


Figure 5. BenMAP-CE incorporates each of the above steps to estimate health impacts (OAR US EPA 2016b).

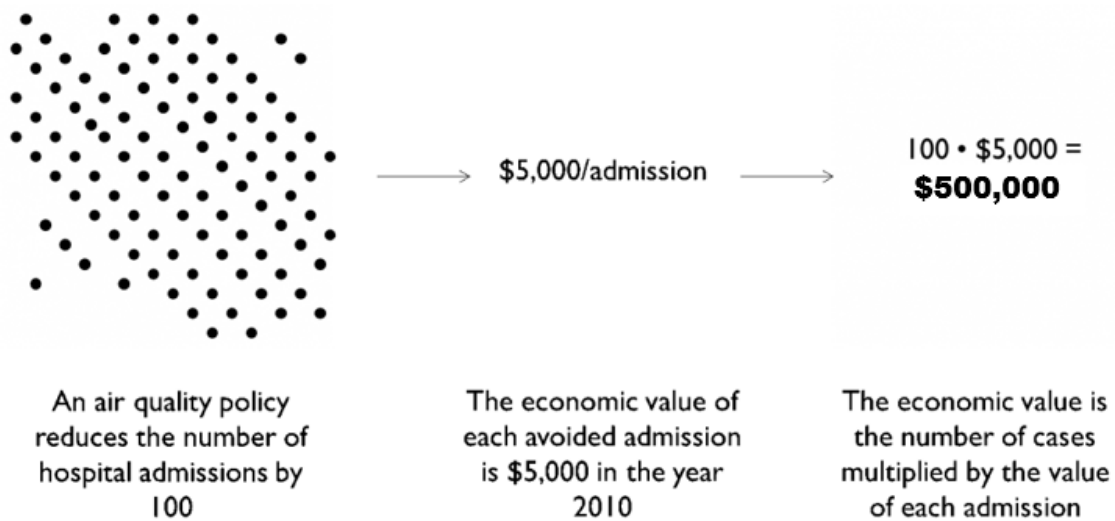


Figure 6. Above is an example of how BenMAP-CE calculates economic values associated with changes in air pollution (OAR US EPA 2016b).

Modeled and monitored air quality data were input into BenMAP-CE. Monitored ambient air quality data provided by EPA monitoring stations, along with reported monitored well site emissions, were used for this analysis (DEP 2016; US EPA 2018). Because the EPA monitoring stations are reported as daily average concentrations, monitored well emissions were converted to match this dataset by dividing annual reported emissions by the total days in a year.

A previous phase of this study used AERMOD to model PM emissions dispersal and concentrations from heavy duty diesel trucks used for HVHF activities in PA (Korfmacher et al. 2016; VanMunster 2018). The raw data from AERMOD results were clipped and merged to the CMAQ grid in ArcGIS, a geographic information system equipped with tools to manipulate and analyze data, and the total amount of emissions were found for each 12x12 km square area to ensure matching resolution across each data set (Korfmacher et al., 2016). Average emission concentrations were then calculated for each 12x12 km square so the resolution of the grid matched that of the monitored ambient air pollution provided in BenMAP-CE.

A similar approach was used for this study to convert reported well site emissions to a 12x12 km CMAQ grid for the use in BenMAP. However, because the reported well site dataset contains almost 6,000 entries per year, AERMOD could not be used to generate a model (DEP 2016). Therefore, the reported emissions were aggregated to a 12x12km CMAQ grid for use in BenMAP without the use of AERMOD.

Monitored changes in ambient air quality from the years 2011-2016 were calculated for the state of Pennsylvania using the US EPA's (USEPA) monitoring stations as well as data the Pennsylvania Department of Environmental Protection (PADEP) releases on annual emissions from hydraulic fracturing activities, including fine PM emissions (DEP 2016). The PADEP

dataset displays reported PM emissions at well sites. The combined USEPA and PADEP monitoring stations together display a truer representation of PM concentrations than the EPA monitoring stations alone. EPA monitoring stations tend to be clustered around urban areas with known air quality issues, with few monitoring stations set up in rural areas (Figure 7).

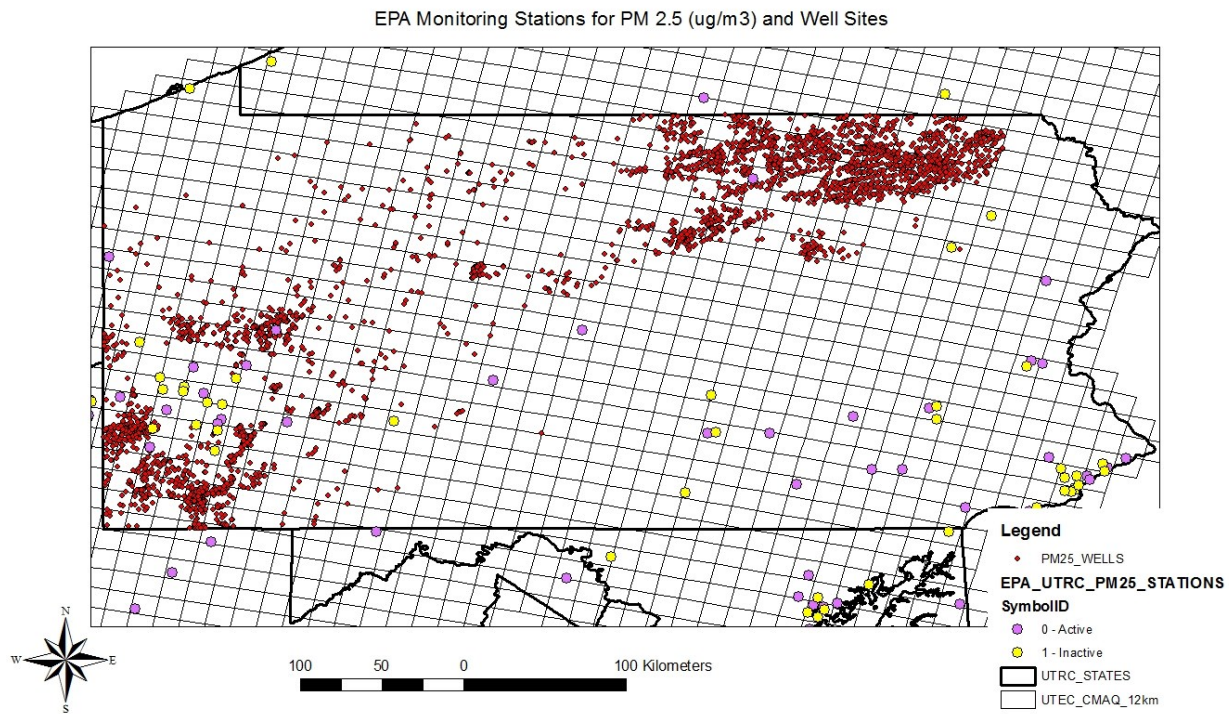


Figure 7. The distribution of active and inactive monitoring stations in Pennsylvania as well as well site locations.

Because of the distance between rural sites, these monitoring stations may not accurately pick up localized emissions from well sites or other pollution sources. The voluntarily reported PADEP well emissions play the part of filling in these large gaps between EPA stations. Using ArcGIS, the well sites were selected by location and the total emissions per well site within each 12x12 km area were found. Because the well sites are reported annually, the average daily concentration was calculated by dividing the total annual amount by the number of days in a year in order match the EPA monitoring emissions format for the use of BenMAP-CE. Changes in

emissions were calculated by comparing the baseline ambient air quality of just the USEPA monitoring stations, provided as part of BenMAP CE, with the combined data set of the PADEP reported emissions and the USEPA monitoring stations.

With BenMAP, one or more Health Impact Functions (HIFs) can be used to determine the effect on health that a change in PM emissions has on the designated population. A HIF involves four key mechanisms designed from epidemiology literature: (1) the monitored changes in ambient air quality; (2) the population exposure density; (3) the baseline occurrence rate; (4) an effect estimate drawn from previous studies (OAR US EPA 2016b).

BenMAP-CE is equipped with HIFs that can be used to analyze several respiratory illnesses and mortality. Figure 8 illustrates how a HIF works. Beta (β) is the percent change that the chosen health effect has per each unit of population (USEPA 2015). Baseline incidence (Y_0) represents the average number of people who suffer from a given health impact occurring from any cause together with air pollution over a set period of time (USEPA 2015). Delta PM (δPM) is the variation between the initial amount of air pollution and the amount after a change in air quality occurs (USEPA 2015). Exposed population (Pop) shows the value of people impacted by a change or reduction in air pollution (USEPA 2015). Basically, the equation is:

$$\text{Health Effect} = \text{Air Quality Change} \times \text{Health Effect Estimate} \times \text{Exposed Population} \\ \times \text{Health Baseline Incidence}$$

(USEPA 2015)

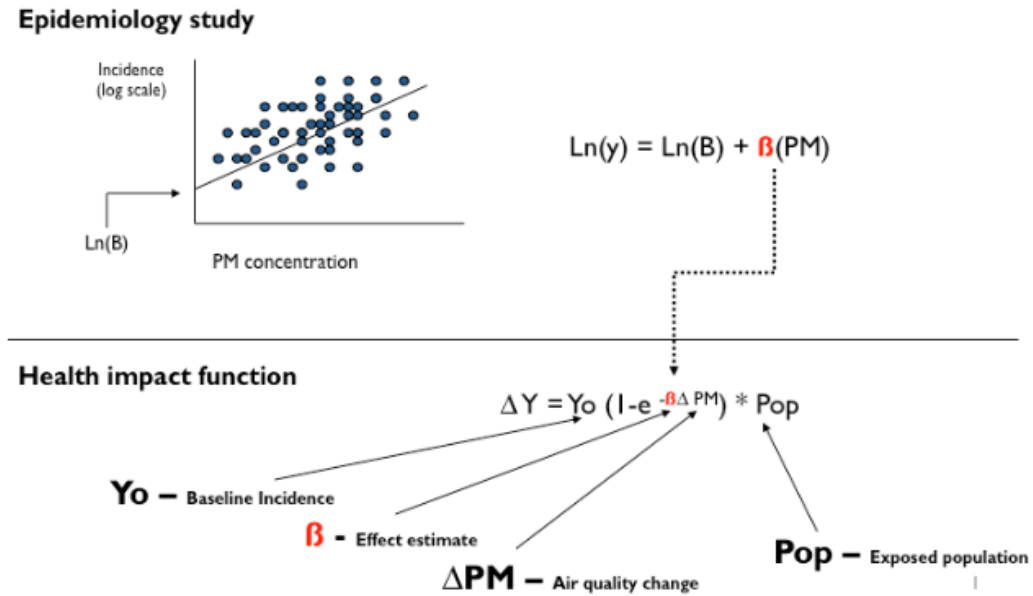


Figure 8. Above is an example of a HIF derived from an epidemiology study (OAR US EPA 2016b).

The focus area of this study will be the state of Pennsylvania. In the rural, northeastern part of Pennsylvania, there are many well sites but a small population density. While the results may show small health effects or low mortality rates because there are fewer people living in this area, this is an underrepresented area regarding air quality monitoring and the methods derived may potentially be used to estimate impacts to rural parts of the country on a larger scale. Figure 9 below shows two maps of Pennsylvania displaying the population density and well site locations.

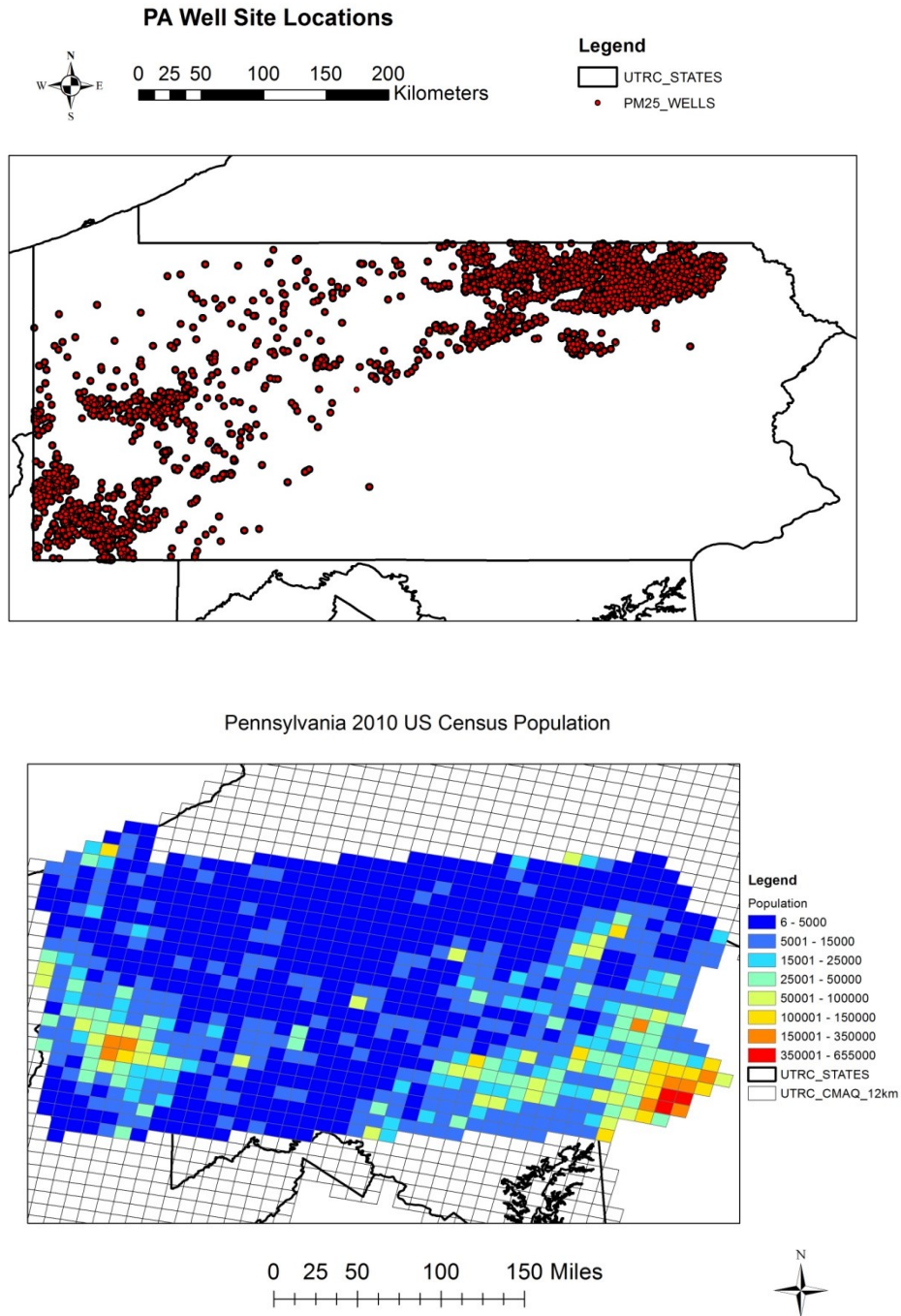


Figure 9 shows the well sites and population density of the study area in 2010.

Fann et al. (2012) suggests using health endpoints related to premature mortality and hospital visits for respiratory and cardiovascular issues, ensuring no two issues get counted

twice. This study also suggests using mortality as an endpoint due to its influence over the EPA regulatory process. Additionally, when selecting a HIF for PM_{2.5} emissions, premature mortality is a good assessor for PM_{2.5} because epidemiological studies generally account for urban areas with large populations as well as single cities with smaller populations, such as the population of Northeastern Pennsylvania (Fann and Risley 2011). When using multiple HIFs it is also important to ensure that each epidemiological study characterized the same population demographics, such as age, race, sex and ethnicity (Fann and Risley 2011). For this study, HIFs were drawn from study areas geographically similar to Pennsylvania, such as Eastern US cities, and assessed all cause mortality.

Using the calculated health impacts, economic costs can be associated with these lives lost or impacted. BenMAP-CE includes the Cost of Illness metric, which represents the cost of hospital admissions, emergency room visits, work loss days, and medical bills related to poor air quality (OAR US EPA 2016b). Furthermore, BenMAP-CE estimates economic values from pollution with a Willingness to Pay metric, which incorporates the Cost of Illness metrics as well as the economic value of pain and dissatisfaction (OAR US EPA 2016b). A Value of Statistical Life (VSL) can also be used to calculate the cost of avoided premature loss of life. VSL is the dollar value associated with the amount a population is willing to pay to slightly decrease the risk of death (OAR US EPA 2016b). From these values, future policy can be assessed relative to this issue or a benefit cost analysis can be derived from this study related to the cost of natural gas to better incorporate the cost environmental externalities.

BenMAP-CE produces results in the form of tables, maps, and raw data (US EPA 2015). These maps can be imported into ArcGIS for comparison and visualization. The results will

potentially fill in missing air quality data and underscore areas of high PM emissions, where health impacts are the greatest.

The first step of BenMAP-CE is to create an air quality surface. A dataset was created for this study. A 12x12km CMAQ grid for the state of Pennsylvania was extracted from the US CMAQ data set provided with BenMAP and then uploaded to use as the grid definition. PM 2.5 was chosen for pollutant. The EPA Standard Monitor dataset was used for the control. For the baseline, a monitor dataset was created using the well site data. In ArcGIS, a monitor dataset was created by first importing the air quality surface shapefile of Pennsylvania produced in BenMAP using just the EPA Standard Monitor dataset for each year 2011-2015. This shapefile is a model of the interpolated air quality using just the EPA stations in Pennsylvania (Figure 10).

Because there are few EPA stations in PA and very few near well site locations, reported well site emissions will be combined in each 12x12km grid cell and added to the amount produced from BenMAP for each grid cell except where there is an EPA station in the grid cell. For grid cells containing an EPA monitor station, only the EPA station data were used. This method is used because it is likely the grid cells containing an EPA station contain an accurate PM_{2.5} report, while grid cells not containing an EPA station, especially ones far away from an EPA station, are not reflecting PM emissions from well sites and, therefore, do not contain an accurate PM_{2.5} report. Figure 11 shows the BenMAP generated air quality surfaces using just the reported well site emissions. Figure 12 displays the maps for the combined EPA plus well site air quality surfaces using ArcGIS.

PM 2.5 Air Quality Surface
Produced by EPA Monitors
(Micrograms per Cubic Meter)

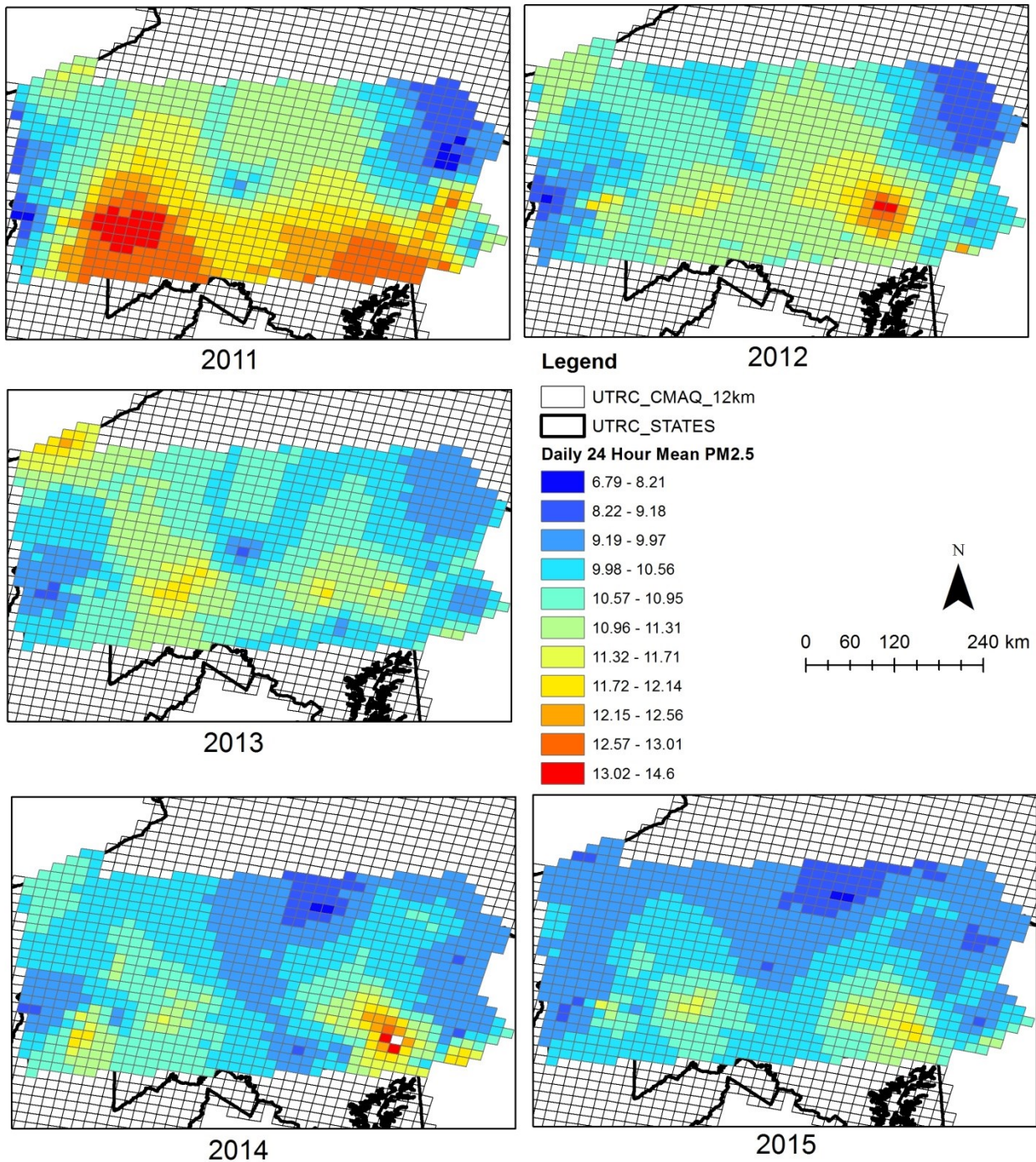


Figure 10 Shows the BenMAP generated air quality surfaces using only the EPA monitor stations for the years 2011-2015.

PM 2.5 Air Quality Surface
Produced by Well Sites
(Micrograms per Cubic Meter)

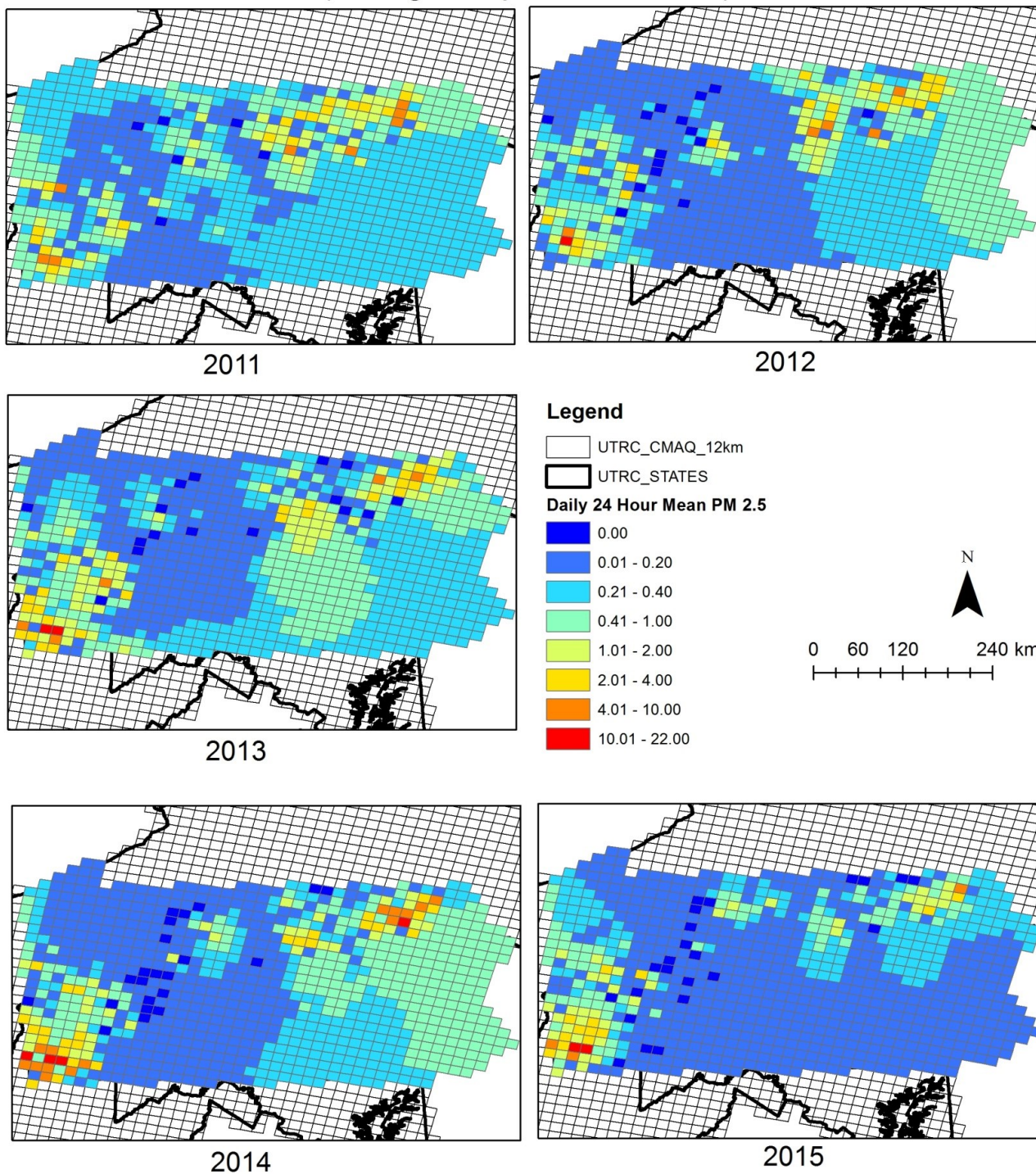


Figure 11 Shows the BenMAP generated air quality surfaces using only the reported well site emissions for the years 2011-2015.

PM 2.5 Air Quality Surface
 Produced by EPA Monitors Plus Well Sites
 (Micrograms per Cubic Meter)

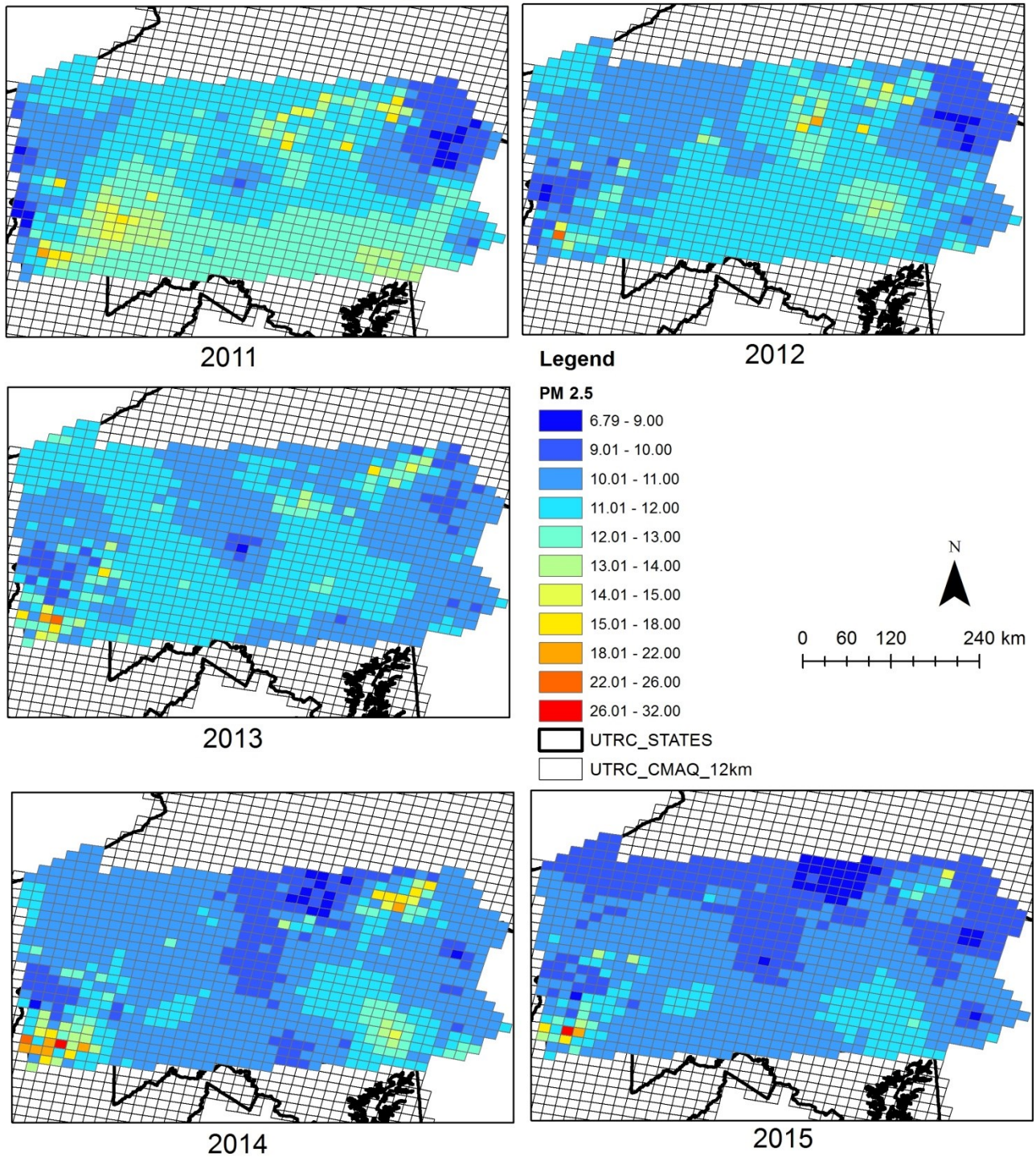


Figure 12 Shows the combined air quality surfaces using the EPA monitor stations and the reported well site emissions for the years 2011-2015.

For the baseline, this combined EPA and well site dataset is used. The delta is then calculated as baseline minus control or **(EPA Stations + Well Sites) - EPA Stations**, resulting in a report of the health impacts of just the well site emissions. BenMAP is equipped with a population dataset for 2010 for the entire United States. This 2010 United States Census population dataset was clipped down to just the area of Pennsylvania for smoother processing. The included EPA Standard Health Impact Functions were used for this project. The HIF's were filtered to select the all cause mortality functions from the authors Krewski 2009, Pope 2002, Lepeule 2012, and Laden 2006 (Krewski et al. 2009; Pope et al. 2002; Lepeule et al. 2012; Laden et al. 2006; US EPA 2014; US EPA 2015).

The incidence aggregation and valuation aggregation were both chosen to use the PA 12x12 km CMAQ grid. No pooling was selected for this project to show the variability of mortality rates across PA. For the valuation method, a Value of Statistical life metric was used "based on a range from \$1-10 million with a normal distribution" (USEPA 2015). An audit trail was produced from BenMAP, displaying the input used for each step in BenMAP to produce the models for individual years (Appendix B).

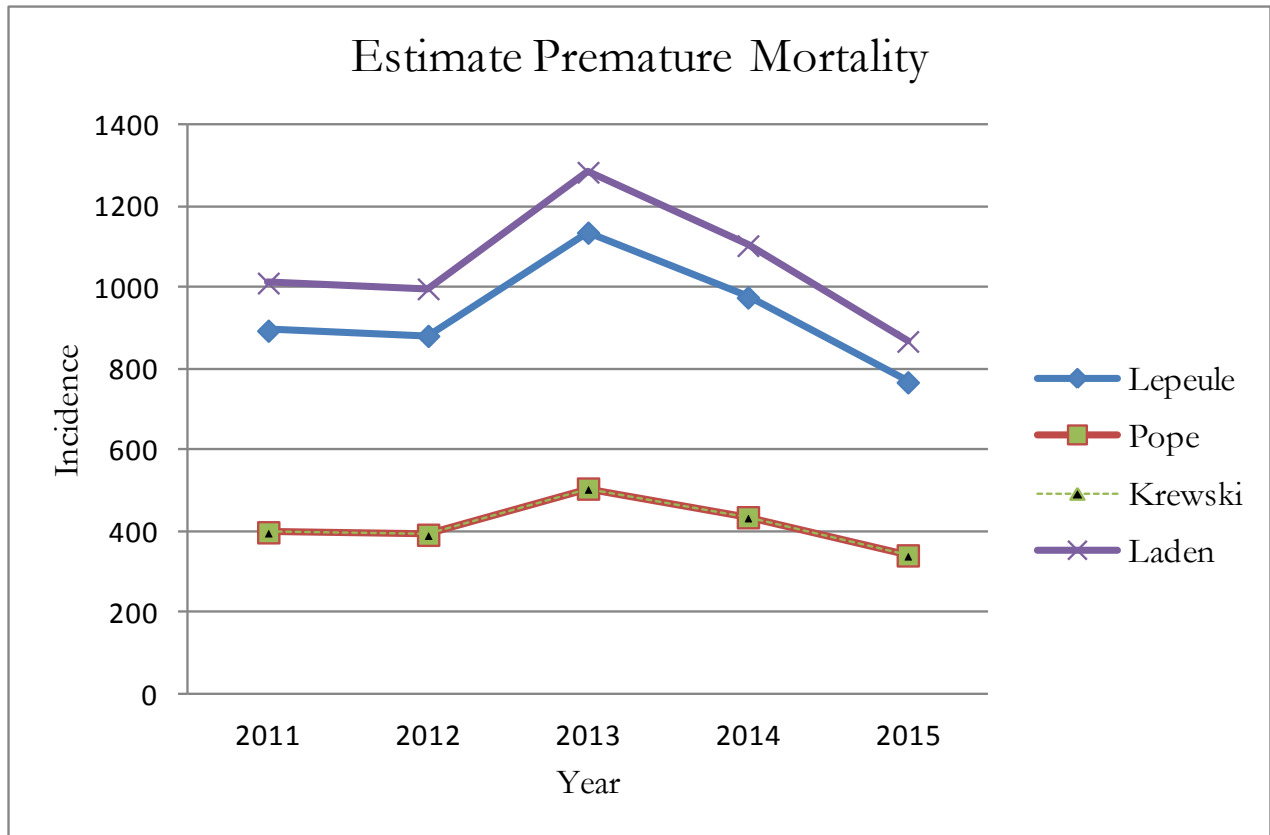
Results

Table 1 shows HIFs and the annual estimated premature deaths and corresponding 95% confidence intervals for each year for emissions from the wells from 2011-2015. Figure 13 graphically displays the estimated premature deaths found for each health equation for each year. For each equation, there was a large increase in premature deaths in 2013, but an overall decrease from 2011 to 2015. The total death toll over the five year period ranged from 2,100 - 5,300 deaths with 95% confidence intervals of 600 - 3,500 deaths and 2,400 - 8,000 deaths respectively. The total estimated economic costs of these deaths for the five year period ranged from \$14 - \$37 billion with 95% confidence intervals of \$1- \$34 billion and \$4 - \$79 billion respectively. Table 2 shows the economic costs of the estimated premature deaths found for each health equation for each year as well as the 95% confidence intervals.

Figure 14 is a map of the estimated mortality using the Laden health equation without converting to a population percentage per grid cell. Without considering the population per grid cell, the map shows hot spots around largely populated cities from emissions captured from the EPA monitors from multiple pollution sources, not just well emissions, as seen around Pittsburg. Additionally, this percentage represents the percent risk for each grid cell. The rural areas represent interpolations with well site emissions added, so they may not be capturing all rural sources. More monitoring stations should be placed in rural areas to capture emissions from all pollution sources. Figures 15 - 17 are maps for each year for each health equation.

The Pope and the Krewski health equations used the same Beta, producing the same incidence and maps (Krewski et al. 2009; Pope et al. 2002). For this reason, only the Krewski health equations maps are displayed below. These maps show the percentage of the population

impacted within each 12 x 12 km grid cell. These maps indicate hot spots are located around well sites. These maps suggest that while the number of premature deaths may be small in rural areas because the population is small, the percentage of premature deaths per grid cell population is higher near well sites than in areas distant from well sites.



Laden Equation: $\left(1 - \left[\frac{1}{e^{\beta \times \Delta PM}}\right]\right) \times \text{Baseline Incidence} \times POP \quad \beta = 0.0148$

Krewski Equation: $\left(1 - \left[\frac{1}{e^{\beta \times \Delta PM}}\right]\right) \times \text{Baseline Incidence} \times POP \quad \beta = 0.0058$

Pope Equation: $\left(1 - \left[\frac{1}{e^{\beta \times \Delta PM}}\right]\right) \times \text{Baseline Incidence} \times POP \quad \beta = 0.0058$

Lepeule Equation: $\left(1 - e^{-\beta \times \Delta PM}\right) \times \text{Baseline Incidence} \times POP \quad \beta = 0.0131$

Figure 13 graphically displays the estimate premature deaths found for each health equation for each year throughout PA and the formula with corresponding Beta values for each health equation (Krewski et al. 2009; Pope et al. 2002; Lepeule et al. 2012; Laden et al. 2006).

Table 1 Estimates of premature deaths and corresponding 95% confidence intervals for each health impact function for each year.

2011	Beta	Age Range	Population	Baseline Mortality	Estimate Premature Deaths	Incidence 95% Confidence Interval
Lepeule	0.013102826	25-99	9,714,123	139,398	894	(448, 1335)
Pope	0.005826891	30-99	8,834,707	138,461	398	(109, 683)
Krewski	0.005826891	30-99	8,834,707	138,461	398	(269, 525)
Laden	0.014842001	25-99	9,714,123	139,398	1012	(456, 1559)
2012						
Lepeule	0.013102826	25-99	9,714,123	139,398	882	(441, 1317)
Pope	0.005826891	30-99	8,834,707	138,461	391	(107, 673)
Krewski	0.005826891	30-99	8,834,707	138,461	391	(265, 517)
Laden	0.014842001	25-99	9,714,123	139,398	998	(449, 1539)
2013						
Lepeule	0.013102826	25-99	9,714,123	139,398	1136	(569, 1695)
Pope	0.005826891	30-99	8,834,707	138,461	505	(138, 868)
Krewski	0.005826891	30-99	8,834,707	138,461	505	(342, 668)
Laden	0.014842001	25-99	9,714,123	139,398	1285	(580, 1979)
2014						
Lepeule	0.013102826	25-99	9,714,123	139,398	976	(490, 1455)
Pope	0.005826891	30-99	8,834,707	138,461	435	(119, 746)
Krewski	0.005826891	30-99	8,834,707	138,461	435	(294, 574)
Laden	0.014842001	25-99	9,714,123	139,398	1104	(499, 1698)
2015						
Lepeule	0.013102826	25-99	9,714,123	139,398	767	(384, 1146)
Pope	0.005826891	30-99	8,834,707	138,461	341	(93.2, 585.6)
Krewski	0.005826891	30-99	8,834,707	138,461	341	(230, 450)
Laden	0.014842001	25-99	9,714,123	139,398	868	(391, 1338)

Table 2 The economic costs of the estimated premature deaths found for each health equation for each year as well as the 95% confidence interval using a normal distribution.

2011	Estimate Premature Deaths	Values (Billions)	Values 95% Confidence Interval	
Lepeule	894.4	\$6.2	\$470,000,000	\$14,000,000,000
Pope	397.5	\$2.8	\$92,000,000	\$6,600,000,000
Krewski	397.5	\$2.8	\$270,000,000	\$5,600,000,000
Laden	1011.9	\$7.0	\$460,000,000	\$16,000,000,000
2012				
Lepeule	881.6	\$6.1	\$880,000,000	\$13,000,000,000
Pope	391.4	\$2.7	\$290,000,000	\$6,300,000,000
Krewski	391.4	\$2.7	\$430,000,000	\$5,400,000,000
Laden	997.6	\$6.9	\$930,000,000	\$15,000,000,000
2013				
Lepeule	1136.1	\$7.9	\$1,200,000,000	\$17,000,000,000
Pope	505.3	\$3.5	\$420,000,000	\$8,100,000,000
Krewski	505.3	\$3.5	\$590,000,000	\$6,900,000,000
Laden	1285.1	\$9.0	\$1,300,000,000	\$19,000,000,000
2014				
Lepeule	976.3	\$6.8	\$810,000,000	\$14,000,000,000
Pope	434.6	\$3.0	\$250,000,000	\$7,100,000,000
Krewski	434.6	\$3.0	\$410,000,000	\$6,000,000,000
Laden	1104	\$7.7	\$840,000,000	\$17,000,000,000
2015				
Lepeule	767.2	\$5.3	\$760,000,000	\$11,000,000,000
Pope	340.6	\$2.4	\$250,000,000	\$5,500,000,000
Krewski	340.6	\$2.4	\$370,000,000	\$4,700,000,000
Laden	868	\$6.0	\$800,000,000	\$13,000,000,000

Laden Estimate Premature Mortality

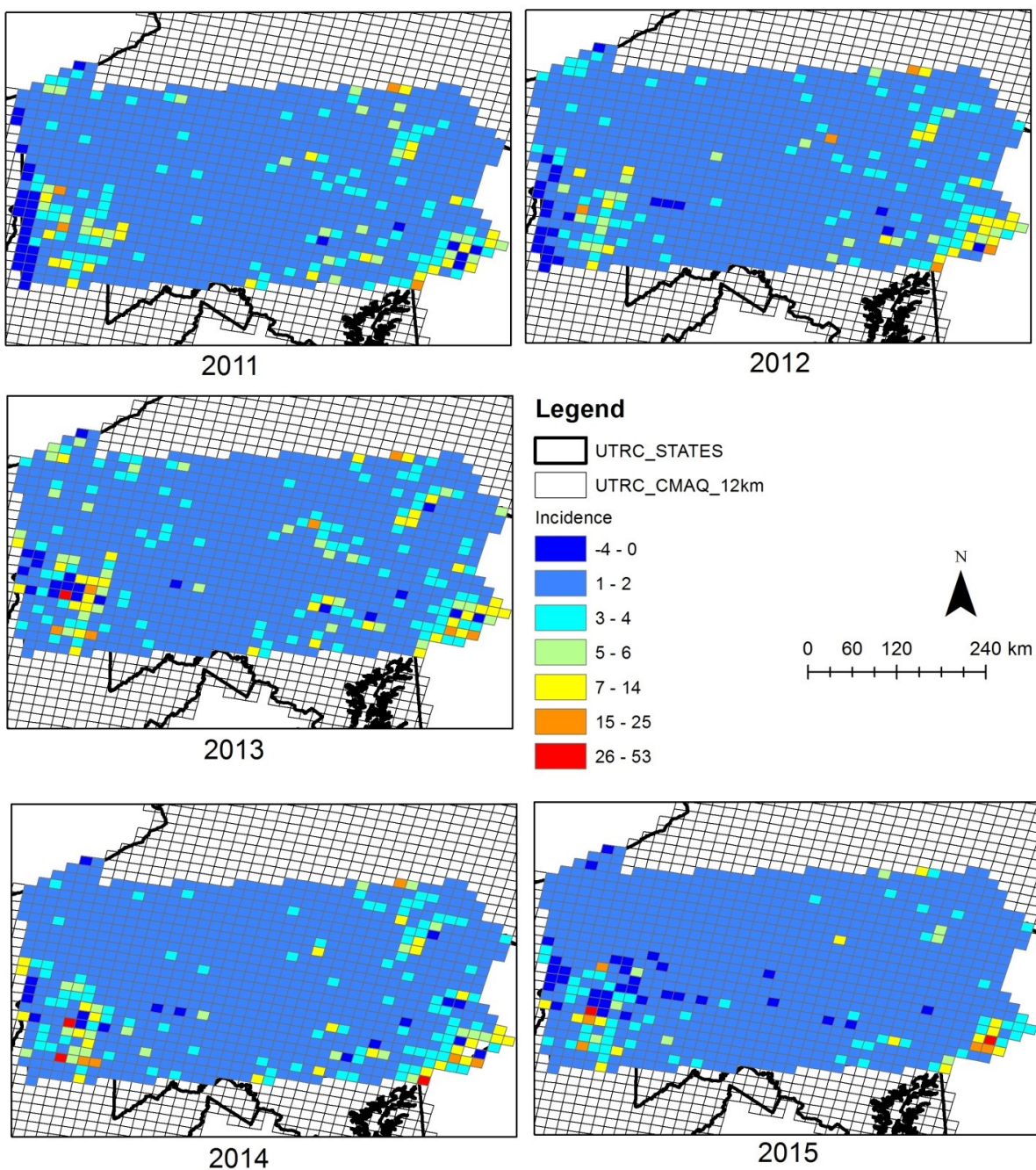


Figure 14 Map of the estimated mortality using the Laden health equation without converting to a population percentage per grid cell distribution.

Laden Estimate Premature Mortality (Population Percentage)

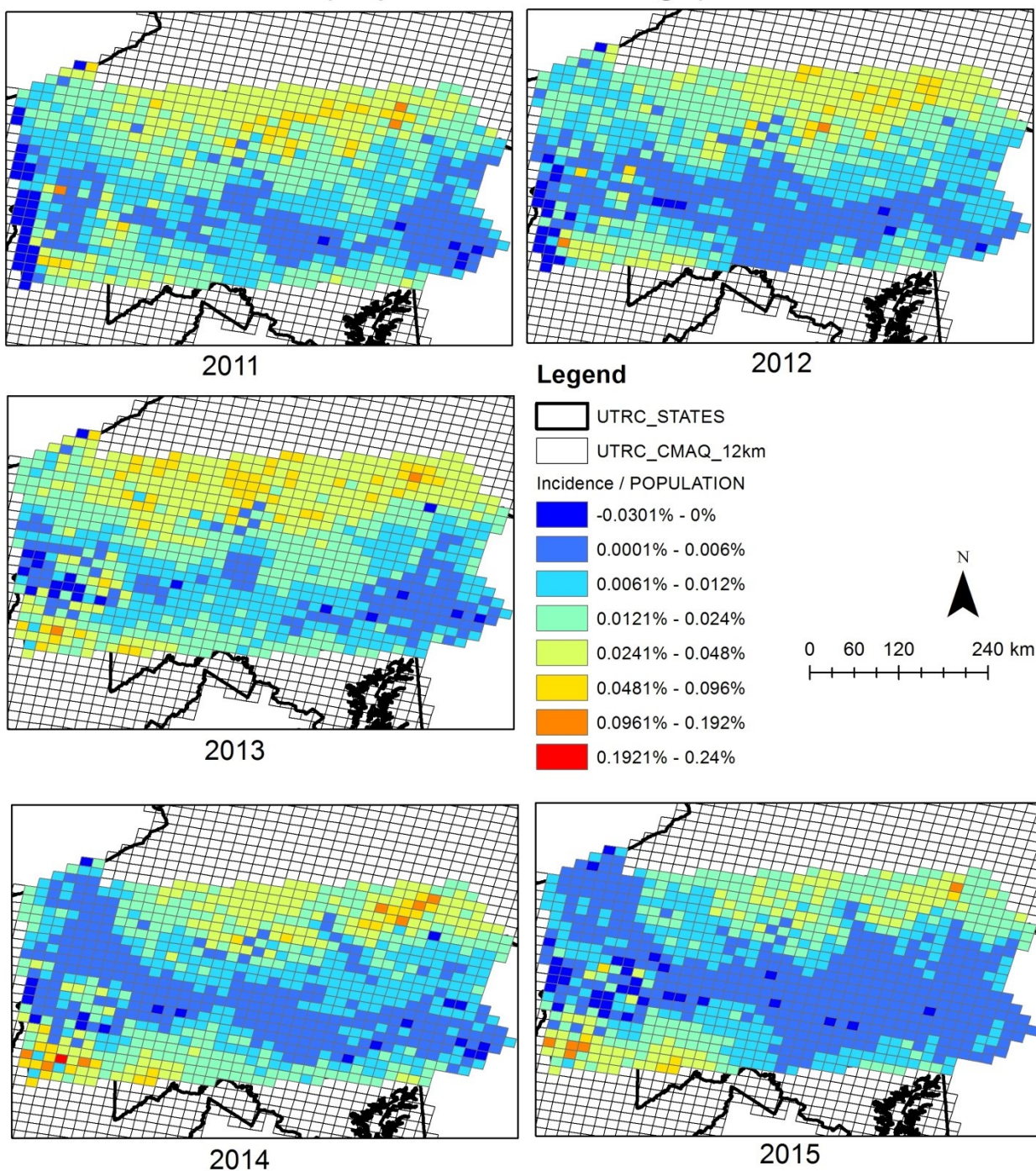


Figure 15 Maps of the estimated mortality using the Laden health equation as a percentage of the population impacted, or the percent risk, within each 12 x 12 km grid cell for each year.

Krewski Estimate Premature Mortality (Population Percentage)

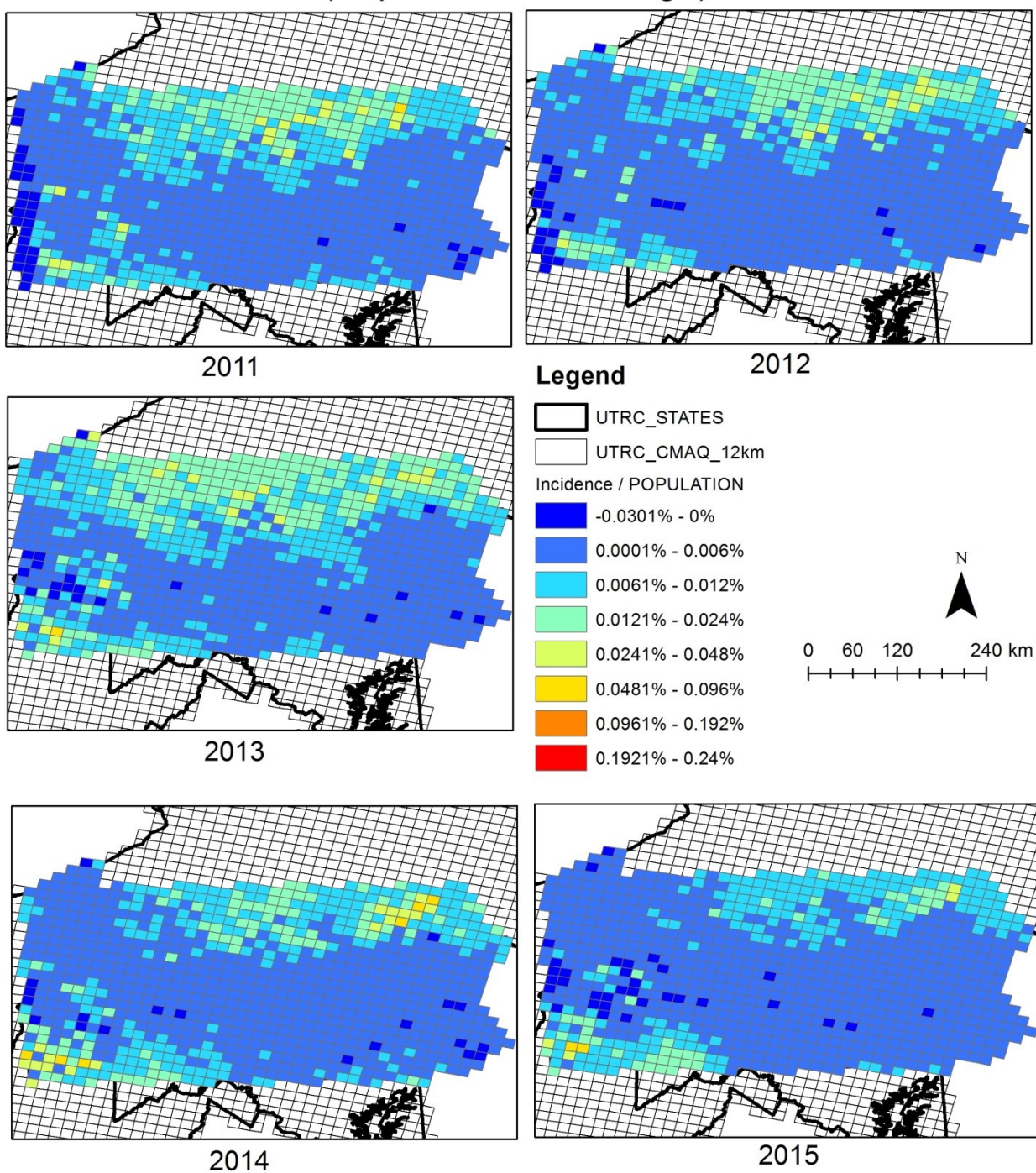


Figure 16 Maps of the estimated mortality using the Krewski health equation as a percentage of the population impacted, or the percent risk, within each 12 x 12 km grid cell for each year.

Lepeule Estimate Premature Mortality (Population Percentage)

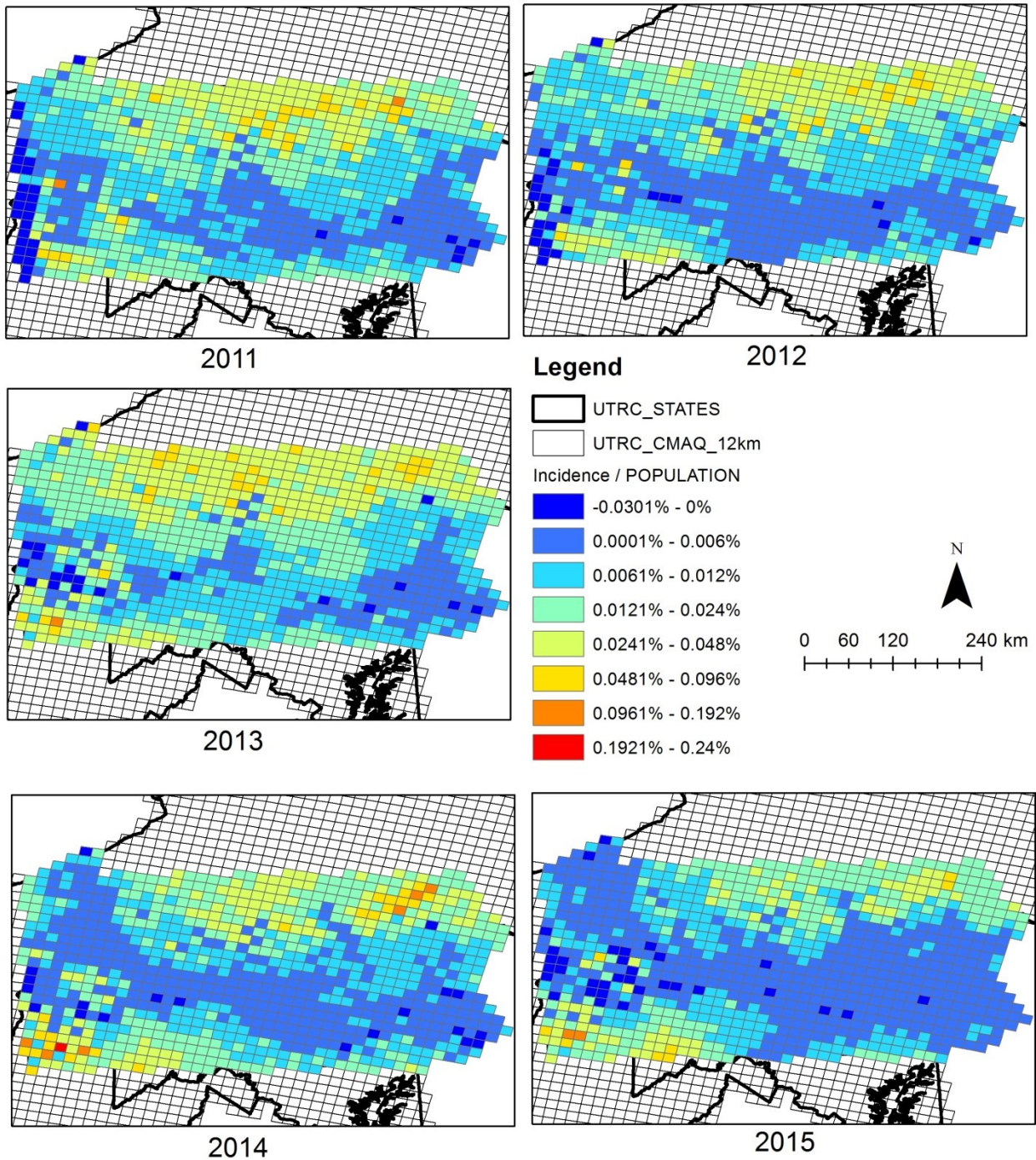


Figure 17 Maps of the estimated mortality using the Lepeule health equation as a percentage of the population impacted, or the percent risk, within each 12 x 12 km grid cell for each year.

Discussion

PM_{2.5} released at HVHF well sites from hydraulic fracturing activities are causing an increased risk of premature mortality to populations living near well sites, based on model results using the well emissions data. The results indicate that as a product of well emissions from 2011-2015, an estimated 2,100-5,300 premature deaths occurred annually, with 95% confidence intervals of 600-3,500 deaths and 2,400-8,000 deaths respectively. EPA monitoring stations are located far from well site locations (Figure 7) and are likely not picking up significant PM_{2.5} emissions from area wells, generating an air quality surface that is underreporting the amount of PM_{2.5} in rural parts of PA near well sites. Looking at the well site emissions map (Figure 11), there are hot spots in rural Northeastern PA where PM_{2.5} emissions reached 10-22 micrograms per cubic meter, but the EPA monitor map (Figure 10) shows a smooth gradient in that area of PM_{2.5} emissions under 10 micrograms per cubic meter. This suggests that EPA monitor stations are not picking up the additional well emissions and that the extrapolations of just the EPA monitors are based off of predominately urban monitor stations, underestimating the PM_{2.5} concentrations in some rural areas. This study is a guide to problem areas, such as rural parts of Northeastern PA (Figures 15-17), where EPA stations are lacking and emissions from wells are relatively high, based on self-reported data.

Referring to Figures 10-12, comparing the air quality surface generated by only the EPA monitoring stations versus the air quality surface generated by only the well site locations, the EPA stations do not appear to represent the reported well site emissions. Fine PM has a travel range of less than one kilometer to hundreds of kilometers, depending on atmospheric conditions and the surrounding land (WHO 2006). For this reason, it is important to monitor ambient air

quality conditions at a smaller scale, especially near industrial activities (WHO 2006). Rural areas are currently underrepresented concerning air quality monitoring in the United States. Within the study area, there was an increase in EPA stations from the year 2011-2015 (Appendix A), however the increase was small (1 station was added for the rural northeastern part of Pennsylvania) and there remains a large gap in monitoring stations in rural areas of Pennsylvania. This study suggests the EPA should consider placing more monitor stations in rural parts of the county near industrial activities, such as concentrated well sites.

There are several limitations to this analysis. The well site emissions are based off a voluntary report of emissions at well sites. These reports come from a calculation based off of emission factors that the hydraulic fracturing companies deem most appropriate, rather than actual emissions monitoring (PADEP 2016). Furthermore, some well sites opt out of reporting emissions, potentially causing the results of this project to be an underestimation of emission impacts. Future projects should work toward gaining a more accurate inventory of well site emissions by placing monitors near well sites.

Additionally, this study assumes PM stays within a 12x12 km range after being released at a well site (so no additions or mixing between 12x12 boxes). The dispersal of PM may be impacted by the land features and weather patterns, potentially shifting the location of the high PM concentration areas. Future studies with the capability to run large data sets through AERMOD should input the reported well site emissions into AERMOD to create a more accurate model of the dispersal pattern and travel distance of fine PM emissions released at well sites.

While the results indicate relatively low mortality rates across PA, as seen in Figure 14, when considering the population distribution across PA, a larger percentage of risk of 0.01% - 0.24% is seen near well sites than in other parts of PA where risk of 0.0001% - 0.006% is measured (Figures 15-17). This correlation suggests that living near well sites increases a population's risk of premature mortality, because the ratio is disproportionate across PA. This also suggests that there is a necessity for further EPA monitors to be placed near HVHF activities to better assess PM_{2.5} emissions on a finer scale and more accurately represent the air quality.

Table 1 shows a large range of 400-1000 incidence in the estimate premature mortality from different health equations derived from epidemiological studies from different authors. This difference is caused from the use of different hazard ratios in each equation, resulting in different beta coefficients. The range of incidence, as recommended by the EPA, shows that while there are scientific differences on the amount of impacts from PM on premature mortality, there still exists an impact from PM on premature mortality (USEPA 2012). The results of this study, even at the lower bound as seen in the estimate premature deaths found by using the Pope or Krewski health equations, still suggest 2,070 premature deaths in Pennsylvania over the five year period due to emissions near well sites (Table 1).

There is also a monetary benefit from improved air quality. The Value of a Statistical Life for premature mortality per incidence was \$8 million for a 1990 income level and \$9.6 million for a 2020 income level (USEPA 2012). Tables 2 shows the differences in values associated with the estimate incidences found from the chosen health equations. Essentially, there is value of \$8-9 million per estimate incidence as seen in Table 2. There are many uncertainties when considering economic effects, such as inflation, discount rates, income level, etc., which contributes to the large range in confidence for each value. Additionally, the age

range of 25-99 will also impact the value of life, as the population varies per age group, causing more uncertainty in the economic value for each health equation. Figure 18 is a graph of the age distribution in Pennsylvania from the 2010 United States Census. There appears to be a decreasing number of people above the age of 65, with increased populations aged 15-24 and 45-54. The VSL for a younger person will be a higher value than that of an older person. Because of this, large confidence intervals can be seen in Table 2 for the values associated with premature mortality.

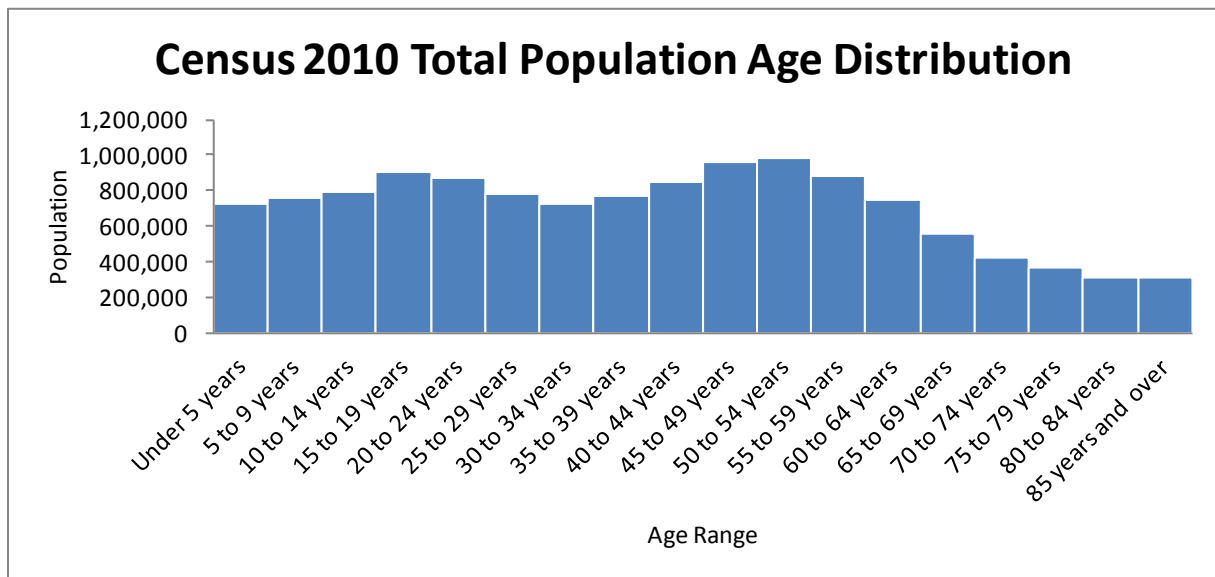


Figure 18 displays a graph of the age distribution in Pennsylvania in 2010 (US Census Bureau 2018).

Conclusions

This study highlights areas of increased risk of mortality from PM generated by hydraulic fracturing activities. There is an increased risk of mortality from PM released during hydraulic fracturing activities near well sites that appears to be currently underreported due to a lack of EPA monitors in rural parts of the country. As seen in Figures 15-17 and Table 1, there are an estimated 2,070-5,267 premature deaths in Pennsylvania as a result of PM emissions released during hydraulic fracturing activities from 2011-2015, with higher percentages of the population per grid cell (0.01%-0.25%) being impacted near well site locations as compared to other parts of the state (0.0001%-0.006%). The cost of these premature mortalities, as seen in Table 2, are estimated to be \$14 billion-\$37 billion and a 95% confidence interval of \$1 billion-\$34 billion and \$4 billion-\$79 billion respectively.

These estimated values should be considered when determining the cost to produce natural gas using hydraulic fracturing. It is important to assess environmental externalities when addressing policy related to energy production. While natural gas production produces fewer particulate emissions than other fossil fuels, such as coal, increased natural gas production may shift the focus away from growth in renewable energy generation (Feng, Davis, Sun, & Hubacek, 2016). Additionally, because well sites are typically considered individual sources of emissions rather than as collective unit of many well sites, emissions from wells are effectively unregulated by the Clean Air Act (Kosnik 2007; Brady 2011). This underscores the need for EPA monitoring stations near hydraulic fracturing well sites. This study acts as a guide to hot spot emission locations, where EPA stations are needed. A similar study using BenMAP to assess air quality in

China stated one of the biggest limitations of their study was an inadequate number of monitoring sites (Chen et al. 2017).

This study can also be used to predict the outcome in regards to fine PM and premature mortality of future hydraulic fracturing activities in other parts of the country as well as current, underrepresented areas near hydraulic fracturing activities. Policymakers should consult these impacts when considering the use of hydraulic fracturing over other sources to meet energy consumption needs and how the data limitations suggest a more regulatory approach to reporting emissions.

Previous stages of this project studying the emissions from heavy duty diesel trucks associated with HVHF can be combined with the findings of this study to fine-tune hot spot locations of PM emissions. These combined emissions should be run through AERMOD to better account for the dispersal of emissions and then through BenMAP to model the health impacts and economic costs. This study did not account for the increase in emissions from heavy duty diesel truck used for hydraulic fracturing activities, potentially underreporting the full health impacts of hydraulic fracturing activities. The combined studies will provide a more complete evaluation of the emissions and health impacts from HVHF activities.

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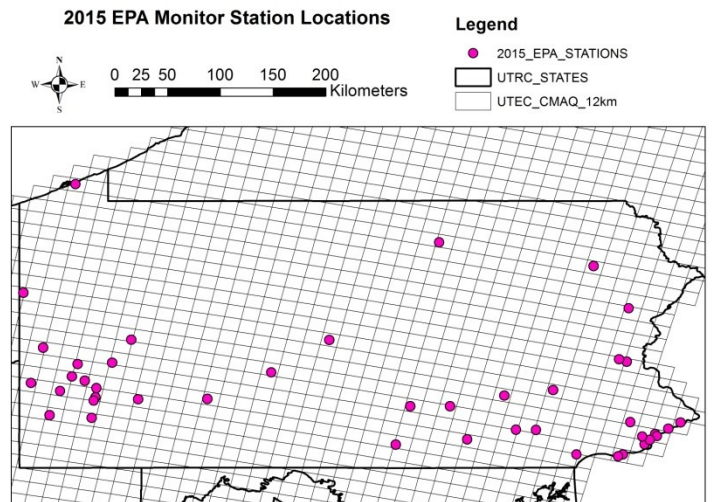
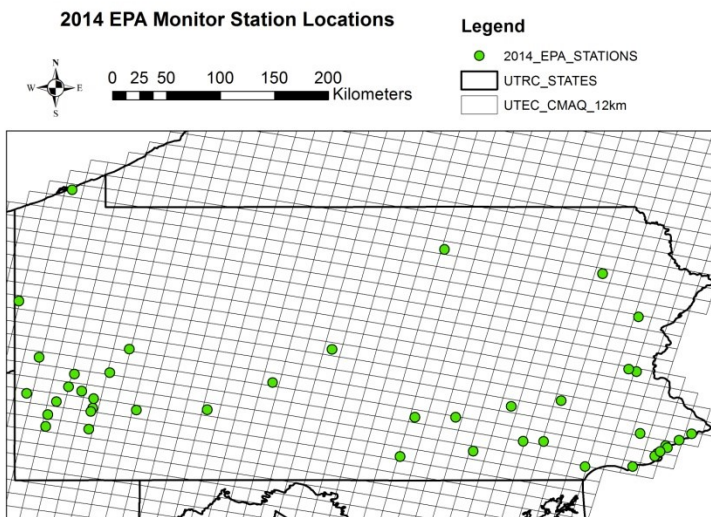
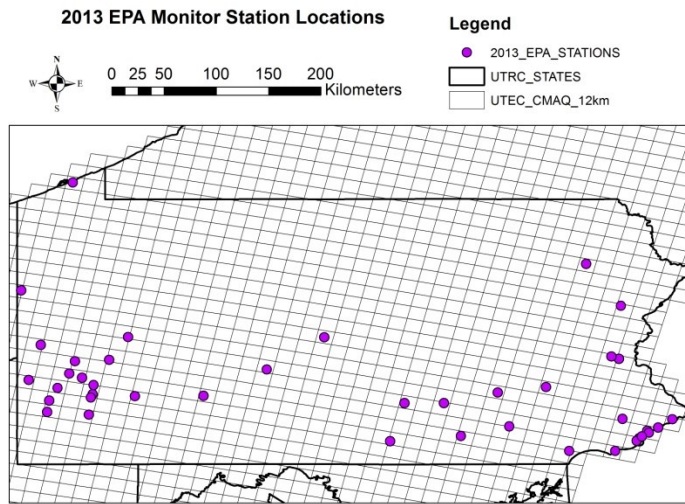
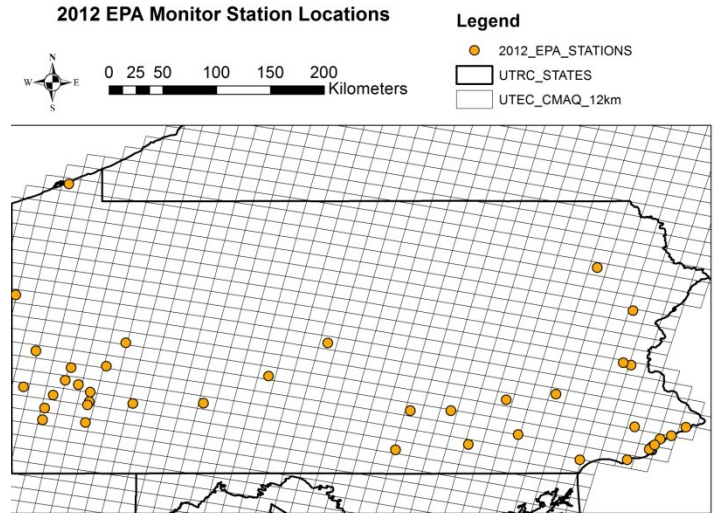
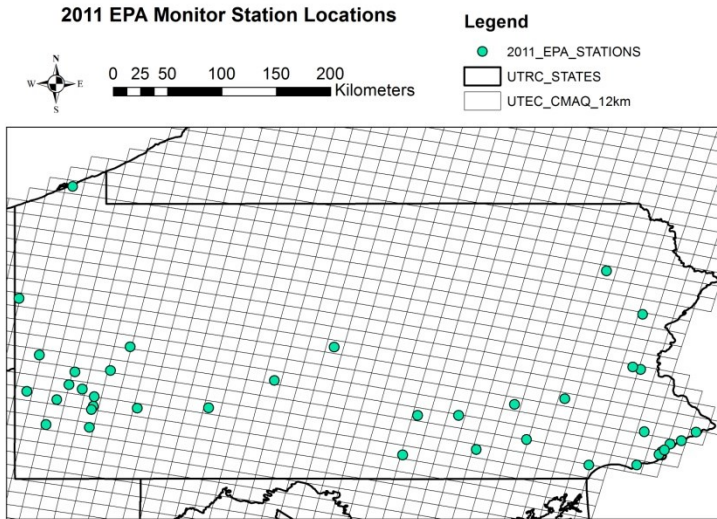
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Appendix A

EPA monitor station locations for the years 2011 to 2015.



Appendix B

BenMAP Audit Trail for 2011

BenMAP-CE 1.1.0

<Aggregate, Pool & Value>

Create Datetime:2018-04-17 12:23:12

IsRunInPointMode:False

Latin Hypercube Points:20

Population Dataset:PA-PA_CMAQ_12KM

Year:2010

Threshold:0

<Baseline.And.Control.Group0>

<Pollutant>

Name:PM2.5

Observation Type:Daily

Season0:January 01-March 31

Season1:April 01-June 30

Season2:July 01-September 30

Season3:October 01-December 31

Metric0:D24HourMean

Seasonal Metric0:QuarterlyMean

</Pollutant>

<Baseline.Air.Quality.Surfaces>

Create Datetime:2018-03-21 10:26:40

Pollutant:PM2.5

Interpolation Method:VoronoiNeighborhoodAveragin

Library Monitors:True

Monitor Dataset Name:EPA plus Wells Updated

Monitor Year:2011

<Grid.Definition>

Name:PA_CMAQ_12KM

ID:40

Columns:357

Rows:172

Grid Type:Shapefile

Shapefile Name:PA_CMAQ_12KM_WGS1984

</Grid.Definition>

<Pollutant>

Name:PM2.5

Observation Type:Daily

Season0:January 01-March 31

Season1:April 01-June 30

Season2:July 01-September 30

Season3:October 01-December 31

Metric0:D24HourMean

Seasonal Metric0:QuarterlyMean

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Create Datetime:2018-03-21 10:27:02
Pollutant:PM2.5
Interpolation Method:VoronoiNeighborhoodAveragin
Library Monitors:True
Monitor Dataset Name:EPA Standard Monitors PM2.5
Monitor Year:2011
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Name:PA_CMAQ_12KM
ID:40
Columns:357
Rows:172
Grid Type:Shapefile
Shapefile Name:PA_CMAQ_12KM_WGS1984
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Name:PM2.5
Observation Type:Daily
Season0:January 01-March 31
Season1:April 01-June 30
Season2:July 01-September 30
Season3:October 01-December 31
Metric0:D24HourMean
Seasonal Metric0:QuarterlyMean
</Pollutant>
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</Baseline.And.Control.Group0>
<Selected.health.impact.functions>
<Health.impact.function.0>
Health impact function dataset:EPA Standard Health Functions
Endpoint group:Mortality
Endpoint:Mortality, All Cause
Start age:30
End age:99
Race:
Ethnicity:
Gender:
Pollutant:PM2.5
Metric:D24HourMean
Metric statistic:Mean
Seasonal metric:QuarterlyMean
Author:Krewski et al.
Qualifier:Random effects cox; 44 individual and 7 ecologic co-variates; 1999--2000 follow-up
(Commentary table 4)

Function:(1-(1/EXP(Beta*DELTAQ)))*Incidence*POP

Year:2009

Location:

Other pollutants:TSP, O3, SO4, SO2

Reference:Krewski D, Jerrett M, Burnett R, et al. 2009. Extended Follow-Up and Spatial analysis of the American Cancer Society Linking Particulate Air Pollution and Mortality. Health Effects Institute, Cambridge MA

Baseline functional form:Incidence*POP

Incidence dataset:Mortality Incidence (2010)

Prevalence dataset:

Variable dataset:

Beta:0.005826891

Beta distribution:Normal

P1Beta:0.000962763

P2Beta:0

A:0

NameA:

B:0

NameB:

C:0

NameC:

Percentile:0

</Health.impact.function.0>

<Health.impact.function.1>

Health impact function dataset:EPA Standard Health Functions

Endpoint group:Mortality

Endpoint:Mortality, All Cause

Start age:25

End age:99

Race:

Ethnicity:

Gender:

Pollutant:PM2.5

Metric:D24HourMean

Metric statistic:Mean

Seasonal metric:QuarterlyMean

Author:Laden et al.

Qualifier:

Function:(1-(1/EXP(Beta*DELTAQ)))*Incidence*POP

Year:2006

Location:

Other pollutants:

Reference:Laden, F., J. Schwartz, F. E. Speizer and D. W. Dockery. 2006. Reduction in Fine Particulate Air Pollution and Mortality: Extended follow-up of the Harvard Six Cities Study. Am J Respir Crit Care Med.

Baseline functional form:Incidence*POP

Incidence dataset:Mortality Incidence (2010)
Prevalence dataset:
Variable dataset:
Beta:0.014842001
Beta distribution:Normal
P1Beta:0.004169721
P2Beta:0
A:0
NameA:
B:0
NameB:
C:0
NameC:
Percentile:0
</Health.impact.function.1>
<Health.impact.function.2>
Health impact function dataset:EPA Standard Health Functions
Endpoint group:Mortality
Endpoint:Mortality, All Cause
Start age:25
End age:99
Race:
Ethnicity:
Gender:
Pollutant:PM2.5
Metric:D24HourMean
Metric statistic:Mean
Seasonal metric:QuarterlyMean
Author:Lepeule et al.
Qualifier:
Function:(1-EXP(-Beta*DELTAQ))*Incidence*POP
Year:2012
Location:
Other pollutants:
Reference:Lepeule J, Laden F, Dockery D, Schwartz J. Chronic exposure to fine particles and mortality: an extended follow-up of the Harvard Six Cities study from 1974 to 2009. Vol 120(7). 965-970
Baseline functional form:Incidence*POP
Incidence dataset:Mortality Incidence (2010)
Prevalence dataset:
Variable dataset:
Beta:0.013102826
Beta distribution:Normal
P1Beta:0.00334674
P2Beta:0
A:0

NameA:
B:0
NameB:
C:0
NameC:
Percentile:0
</Health.impact.function.2>
<Health.impact.function.3>
Health impact function dataset:EPA Standard Health Functions
Endpoint group:Mortality
Endpoint:Mortality, All Cause
Start age:30
End age:99
Race:
Ethnicity:
Gender:
Pollutant:PM2.5
Metric:D24HourMean
Metric statistic:Mean
Seasonal metric:QuarterlyMean
Author:Pope et al.
Qualifier:
Function: $(1-(1/\text{EXP}(\text{Beta}*\text{DELTAQ}))) * \text{Incidence} * \text{POP}$
Year:2002
Location:
Other pollutants:
Reference:Pope, C.A., 3rd, R.T. Burnett, M.J. Thun, E.E. Calle, D. Krewski, K. Ito and G.D. Thurston. 2002. Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution. *Jama*. Vol. 287 (9): 1132-41.
Baseline functional form:Incidence*POP
Incidence dataset:Mortality Incidence (2010)
Prevalence dataset:
Variable dataset:
Beta:0.005826891
Beta distribution:Normal
P1Beta:0.002157076
P2Beta:0
A:0
NameA:
B:0
NameB:
C:0
NameC:
Percentile:0
</Health.impact.function.3>
<Health.impact.function.4>

Health impact function dataset:EPA Standard Health Functions
Endpoint group:Mortality
Endpoint:Mortality, All Cause
Start age:0
End age:0
Race:
Ethnicity:
Gender:
Pollutant:PM2.5
Metric:D24HourMean
Metric statistic:Mean
Seasonal metric:QuarterlyMean
Author:Woodruff et al.
Qualifier:
Function: $(1 - (1 / ((1 - \text{Incidence}) * \text{EXP}(\text{Beta} * \text{DeltaQ}) + \text{Incidence}))) * \text{Incidence} * \text{POP}$
Year:2006
Location:
Other pollutants:
Reference:Woodruff, T. J., J. D. Parker and K. C. Schoendorf. 2006. Fine particulate matter (PM2.5) air pollution and selected causes of postneonatal infant mortality in California. Environmental Health Perspectives. Vol. 114: 786-790.
Baseline functional form:Incidence*POP
Incidence dataset:Mortality Incidence (2010)
Prevalence dataset:
Variable dataset:
Beta:0.006765865
Beta distribution:Normal
P1Beta:0.007338828
P2Beta:0
A:0
NameA:
B:0
NameB:
C:0
NameC:
Percentile:0
</Health.impact.function.4>
</Selected.health.impact.functions>
<Log.And.Message>
Processing complete. HIF processing time: 0 hours 0 minutes 58 seconds.
</Log.And.Message>
Sort Incidence LHPs:False
Default Advanced Pooling Method:Roundweightstotwodigits
Default Monte Carlo Iterations:5000
Random Seed:1
<Inflation.Adjustment>

Dataset:
Year:2010
</Inflation.Adjustment>
<Income.Growth.Adjustment>
Dataset:
Year : -1
<Adjust.Income.Growth.EndpointGroups>
Upper Respiratory Symptoms:1
Mortality:1
Lower Respiratory Symptoms:1
Chronic Bronchitis:1
Chronic Asthma:1
Asthma Exacerbation:1
Acute Respiratory Symptoms:1
Acute Bronchitis:1
</Adjust.Income.Growth.EndpointGroups>
</Income.Growth.Adjustment>
<Incidence.Aggregation>
Name:PA_CMAQ_12KM
ID:40
Columns:357
Rows:172
Grid Type:Shapefile
Shapefile Name:PA_CMAQ_12KM_WGS1984
</Incidence.Aggregation>
<Valuation.Aggregation>
Name:PA_CMAQ_12KM
ID:40
Columns:357
Rows:172
Grid Type:Shapefile
Shapefile Name:PA_CMAQ_12KM_WGS1984
</Valuation.Aggregation>
<Incidence.Pooling.And.Aggregation.>
<MortalityPooling.Method.TypeNone>
<Health.impact.function>
Health impact function dataset:EPA Standard Health Functions
Endpoint group:Mortality
Endpoint:Mortality, All Cause
Pollutant:PM2.5
Metric:D24HourMean
Metric statistic:Mean
Author:Krewski et al.
Year:2009
Location:116 U.S. cities
Other pollutants:TSP, O3, SO4, SO2

Reference:Krewski D, Jerrett M, Burnett R, et al. 2009. Extended Follow-Up and Spatial analysis of the American Cancer Society Linking Particulate Air Pollution and Mortality. Health Effects Institute, Cambridge MA

Start age:30

End age:99

Baseline functional form:TSP, O3, SO4, SO2

Incidence dataset:Mortality Incidence (2010)

Beta:0.005826891

Beta distribution:Normal

P1Beta:0.000962763

P2Beta:0

A:0

NameA:

B:0

NameB:

C:0

NameC:

Percentile:0

Weight:0

</Health.impact.function>

<Health.impact.function>

Health impact function dataset:EPA Standard Health Functions

Endpoint group:Mortality

Endpoint:Mortality, All Cause

Pollutant:PM2.5

Metric:D24HourMean

Metric statistic:Mean

Author:Laden et al.

Year:2006

Location:6 cities

Other pollutants:

Reference:Laden, F., J. Schwartz, F. E. Speizer and D. W. Dockery. 2006. Reduction in Fine Particulate Air Pollution and Mortality: Extended follow-up of the Harvard Six Cities Study. Am J Respir Crit Care Med.

Start age:25

End age:99

Baseline functional form:

Incidence dataset:Mortality Incidence (2010)

Beta:0.014842001

Beta distribution:Normal

P1Beta:0.004169721

P2Beta:0

A:0

NameA:

B:0

NameB:

C:0
NameC:
Percentile:0
Weight:0
</Health.impact.function>
<Health.impact.function>
Health impact function dataset:EPA Standard Health Functions
Endpoint group:Mortality
Endpoint:Mortality, All Cause
Pollutant:PM2.5
Metric:D24HourMean
Metric statistic:Mean
Author:Lepeule et al.
Year:2012
Location:6 Eastern Cities
Other pollutants:
Reference:Lepeule J, Laden F, Dockery D, Schwartz J. Chronic exposure to fine particles and mortality: an extended follow-up of the Harvard Six Cities study from 1974 to 2009. Vol 120(7). 965-970
Start age:25
End age:99
Baseline functional form:
Incidence dataset:Mortality Incidence (2010)
Beta:0.013102826
Beta distribution:Normal
P1Beta:0.00334674
P2Beta:0
A:0
NameA:
B:0
NameB:
C:0
NameC:
Percentile:0
Weight:0
</Health.impact.function>
<Health.impact.function>
Health impact function dataset:EPA Standard Health Functions
Endpoint group:Mortality
Endpoint:Mortality, All Cause
Pollutant:PM2.5
Metric:D24HourMean
Metric statistic:Mean
Author:Pope et al.
Year:2002
Location:51 cities

Other pollutants:

Reference:Pope, C.A., 3rd, R.T. Burnett, M.J. Thun, E.E. Calle, D. Krewski, K. Ito and G.D. Thurston. 2002. Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution. *Jama*. Vol. 287 (9): 1132-41.

Start age:30

End age:99

Baseline functional form:

Incidence dataset:Mortality Incidence (2010)

Beta:0.005826891

Beta distribution:Normal

P1Beta:0.002157076

P2Beta:0

A:0

NameA:

B:0

NameB:

C:0

NameC:

Percentile:0

Weight:0

</Health.impact.function>

</MortalityPooling.Method.TypeNone>

<Health.impact.function>

Health impact function dataset:EPA Standard Health Functions

Endpoint group:Mortality

Endpoint:Mortality, All Cause

Pollutant:PM2.5

Metric:D24HourMean

Metric statistic:Mean

Seasonal metric:QuarterlyMean

Author:Krewski et al.

Qualifier:Random effects cox; 44 individual and 7 ecologic co-variates; 1999--2000 follow-up (Commentary table 4)

Function:(1-(1/EXP(Beta*DELTAQ)))*Incidence*POP

Year:2009

Location:

Other pollutants:TSP, O3, SO4, SO2

Reference:Krewski D, Jerrett M, Burnett R, et al. 2009. Extended Follow-Up and Spatial analysis of the American Cancer Society Linking Particulate Air Pollution and Mortality. Health Effects Institute, Cambridge MA

Start age:30

End age:99

Baseline functional form:Incidence*POP

Incidence dataset:Mortality Incidence (2010)

Beta:0.005826891

Beta distribution:Normal

P1Beta:0.000962763
P2Beta:0
A:0
NameA:
B:0
NameB:
C:0
NameC:
Percentile:0
Weight:0
</Health.impact.function>
<Health.impact.function>
Health impact function dataset:EPA Standard Health Functions
Endpoint group:Mortality
Endpoint:Mortality, All Cause
Pollutant:PM2.5
Metric:D24HourMean
Metric statistic:Mean
Seasonal metric:QuarterlyMean
Author:Laden et al.
Qualifier:
Function: $(1-(1/\text{EXP}(\text{Beta}*\text{DELTAQ}))) * \text{Incidence} * \text{POP}$
Year:2006
Location:
Other pollutants:
Reference:Laden, F., J. Schwartz, F. E. Speizer and D. W. Dockery. 2006. Reduction in Fine Particulate Air Pollution and Mortality: Extended follow-up of the Harvard Six Cities Study. Am J Respir Crit Care Med.
Start age:25
End age:99
Baseline functional form:Incidence*POP
Incidence dataset:Mortality Incidence (2010)
Beta:0.014842001
Beta distribution:Normal
P1Beta:0.004169721
P2Beta:0
A:0
NameA:
B:0
NameB:
C:0
NameC:
Percentile:0
Weight:0
</Health.impact.function>
<Health.impact.function>

Health impact function dataset:EPA Standard Health Functions
 Endpoint group:Mortality
 Endpoint:Mortality, All Cause
 Pollutant:PM2.5
 Metric:D24HourMean
 Metric statistic:Mean
 Seasonal metric:QuarterlyMean
 Author:Lepeule et al.
 Qualifier:
 Function: $(1 - \exp(-\beta \cdot \Delta Q)) \cdot \text{Incidence} \cdot \text{POP}$
 Year:2012
 Location:
 Other pollutants:
 Reference:Lepeule J, Laden F, Dockery D, Schwartz J. Chronic exposure to fine particles and mortality: an extended follow-up of the Harvard Six Cities study from 1974 to 2009. Vol 120(7). 965-970
 Start age:25
 End age:99
 Baseline functional form: $\text{Incidence} \cdot \text{POP}$
 Incidence dataset:Mortality Incidence (2010)
 Beta:0.013102826
 Beta distribution:Normal
 P1Beta:0.00334674
 P2Beta:0
 A:0
 NameA:
 B:0
 NameB:
 C:0
 NameC:
 Percentile:0
 Weight:0
 </Health.impact.function>
 <Health.impact.function>
 Health impact function dataset:EPA Standard Health Functions
 Endpoint group:Mortality
 Endpoint:Mortality, All Cause
 Pollutant:PM2.5
 Metric:D24HourMean
 Metric statistic:Mean
 Seasonal metric:QuarterlyMean
 Author:Pope et al.
 Qualifier:
 Function: $(1 - (1 / \exp(\beta \cdot \Delta Q))) \cdot \text{Incidence} \cdot \text{POP}$
 Year:2002
 Location:

Other pollutants:

Reference:Pope, C.A., 3rd, R.T. Burnett, M.J. Thun, E.E. Calle, D. Krewski, K. Ito and G.D. Thurston. 2002. Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution. *Jama*. Vol. 287 (9): 1132-41.

Start age:30

End age:99

Baseline functional form:Incidence*POP

Incidence dataset:Mortality Incidence (2010)

Beta:0.005826891

Beta distribution:Normal

P1Beta:0.002157076

P2Beta:0

A:0

NameA:

B:0

NameB:

C:0

NameC:

Percentile:0

Weight:0

</Health.impact.function>

</Incidence.Pooling.And.Aggregation.>

<Valuation.Pooling.Window.Name.2011>

Mortality

<KrewskiPooling.Method.TypeNone>

<Valuation.Function>

ID:332

Dataset:EPA Standard Valuation Functions

EndPointGroupID:12

Endpoint group:Mortality

EndPointID:50

Endpoint:Mortality, All Cause

Start age:0

End age:99

Qualifier:VSL, based on 26 value-of-life studies.

Reference:

Function:A*B*AllGoodsIndex

NameA:mean VSL in 1990\$

DistA:Weibull

A:4800000

P1A:5320000

P2A:1.50958800315857

NameB:CPI-U "all items" conversion factor

B:1.31752109527588

NameC:

C:0

NamedD:
D:0
Weight:0
</Valuation.Function>
</KrewskiPooling.Method.TypeNone>
<LadenPooling.Method.TypeNone>
<Valuation.Function>
ID:332
Dataset:EPA Standard Valuation Functions
EndPointGroupID:12
Endpoint group:Mortality
EndPointID:50
Endpoint:Mortality, All Cause
Start age:0
End age:99
Qualifier:VSL, based on 26 value-of-life studies.
Reference:
Function: $A*B*AllGoodsIndex$
NameA:mean VSL in 1990\$
DistA:Weibull
A:4800000
P1A:5320000
P2A:1.50958800315857
NameB:CPI-U "all items" conversion factor
B:1.31752109527588
NameC:
C:0
NamedD:
D:0
Weight:0
</Valuation.Function>
</LadenPooling.Method.TypeNone>
<LepeulePooling.Method.TypeNone>
<Valuation.Function>
ID:332
Dataset:EPA Standard Valuation Functions
EndPointGroupID:12
Endpoint group:Mortality
EndPointID:50
Endpoint:Mortality, All Cause
Start age:0
End age:99
Qualifier:VSL, based on 26 value-of-life studies.
Reference:
Function: $A*B*AllGoodsIndex$
NameA:mean VSL in 1990\$

DistA:Weibull
A:4800000
P1A:5320000
P2A:1.50958800315857
NameB:CPI-U "all items" conversion factor
B:1.31752109527588
NameC:
C:0
NameD:
D:0
Weight:0
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</LepeulePooling.Method.TypeNone>
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<Valuation.Function>
ID:332
Dataset:EPA Standard Valuation Functions
EndPointGroupID:12
Endpoint group:Mortality
EndPointID:50
Endpoint:Mortality, All Cause
Start age:0
End age:99
Qualifier:VSL, based on 26 value-of-life studies.
Reference:
Function:A*B*AllGoodsIndex
NameA:mean VSL in 1990\$
DistA:Weibull
A:4800000
P1A:5320000
P2A:1.50958800315857
NameB:CPI-U "all items" conversion factor
B:1.31752109527588
NameC:
C:0
NameD:
D:0
Weight:0
</Valuation.Function>
</PopePooling.Method.TypeNone>
</Valuation.Pooling.Window.Name.2011>
Processing complete. Valuation processing time: 0 hours 0 minutes 2 seconds.
</Aggregate, Pool & Value>