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Spatial distribution of unconventional gas wells and human populations in the Marcellus Shale in the United States: Vulnerability analysis

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ABSTRACT

Modern forms of drilling and extraction have recently led to a boom in oil and gas production in the U.S. and stimulated a controversy around its economic benefits and environmental and human health impacts. Using an environmental justice paradigm this study applies Geographic Information Systems (GIS) and spatial analysis to determine whether certain vulnerable human populations are unequally exposed to pollution from unconventional gas wells in Pennsylvania, West Virginia, and Ohio. Several GIS-based approaches were used to identify exposed areas, and a t-test was used to find statistically significant differences between rural populations living close to wells and rural populations living farther away. Sociodemographic indicators include age (children and the elderly), poverty level, education level, and race at the census tract level. Local Indicators of Spatial Autocorrelation (LISA) technique was applied to find spatial clusters where both high well density and high proportions of vulnerable populations occur. The results demonstrate that the environmental injustice occurs in areas with unconventional wells in Pennsylvania with respect to the poor population. There are also localized clusters of vulnerable populations in exposed areas in all three states: Pennsylvania (for poverty and elderly population), West Virginia (for poverty, elderly population, and education level) and Ohio (for children).

Introduction

Background

Worldwide, oil and natural gas are principle sources of energy. Advances in drilling and extraction technology, a supportive domestic energy policy, and economic developments have recently stimulated an increase in oil and gas production in the United States. Hydraulic fracturing, introduced in the late 1940s, is one of these advanced technologies (Kolb, 2013). It is a process of drilling and injecting fluids (water mixed with sand and other components) into the ground at a high pressure in order to fracture rocks to release oil or natural gas trapped inside (Mooney, 2011). Hydraulic fracturing technology enables the extraction of oil and natural gas from "unconventional reservoirs" such as shale rock and is currently used in 17 states in areas with shale deposits, often referred to as "plays". The most well-known are the Barnett, Marcellus, Utica and Bakken (Kolb, 2013). Another recent technology called directional or horizontal drilling turns a downward drill bit 90° and enables it to continue drilling within a shale layer. Combinations of these two technologies with other technologies (multi-well pads and cluster drilling) have led to a boom in natural gas production in the United States. Natural gas production has been steadily increasing in the country since 2005; in 2013, the US generated 20.6% of the world's gas, making it the top natural gas producer (BP, 2014).

Water is the key ingredient in the fracturing fluid, but there are other ingredients that have very specific purposes in the process. For example, hydrochloric acid is used to initiate cracks in shale, glutaraldehyde and ammonium bisulfite to reduce or inhibit corrosion, polyacrilamide to minimize friction between water and pipe, silica to hold fractures open and allow gas to escape, and isopropanol to increase viscosity of the fluid (Kolb, 2013). The complete chemical makeup of the hydraulic fracturing fluid has long been legally understood as a trade secret by the companies, but some chemicals were recently disclosed due to increasing pressure from federal and state regulations and the public (Waxman, Markey, & Degette, 2011).

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While proponents of this new technology argue that it brings new employment opportunities and stimulates local economic activity, its numerous opponents are voicing strong concerns about ground and surface water contamination, risks to air quality from the liquid waste lagoons, and serious health effects (CCFE, 2010; CEH, 2013). The controversy between the economic effects and the environmental and health impacts of hydraulic fracturing has generated a constant stream of research publications and reports from public health organizations and advocacy groups (Nolon & Polidoro, 2012).

Several studies have explored the potential impacts of hydraulic fracturing on public health (Colborn, Kwiatkowski, Schultz, & Bachran, 2011; Ferrar et al., 2013; Howarth, Ingraffea, & Engelder, 2011; Finkel & Hays, 2013; Goldstein, Kriesky, & Pavliakova, 2012; McKenzie et al., 2014; Witter et al., 2013) and concluded that there is evidence of potential health risks resulting from harmful levels of pollutants in air and water. Air pollution resulting from drilling, processing, gas leaks, and diesel emissions from transportation includes nitrogen oxides, particulate matter (Litovitz, Curtright, Abramzon, Burger, & Samaras, 2013), and ozone (Kemball-Cook et al., 2010; Olaguer, 2012).

One of the main sources of pollution is water that returns to the surface. It may be contaminated with radiation that naturally occurs in the rock (Radium-226 and radon) and salts of barium, which can then enter streams and rivers (Warner, Christie, Jackson, & Vengosh, 2013). Three studies also found systematic evidence for methane contamination of drinking water associated with shale-gas extraction (Darrah, Vengosh, Jackson, Warner, & Poreda, 2014; Jackson et al., 2013; Osborn, Vengosh, Warner, & Jackson, 2011). Hydraulic fracturing process and injection of used water back into the ground, can also lead to increased seismic activity in areas that have never had earthquakes (Kolb, 2013).

Clearing of land for well pads and construction of access roads lead to heavy traffic and noise pollution and substantially changes traditional life styles of residents in rural areas (EA, 2013; Kolb, 2013). Noise pollution can lead to hypertension, sleep disturbance, and cardiovascular disease (Babisch, Beule, Schust, Kersten, & Ising, 2005; Van Kempen et al., 2002). These communities also experience an influx of temporary workers, which often leads to social disruption, increase in crime, and a change in social norms and behaviors (CEH, 2013). A recent study documented self-reported health impacts and mental and physical health stressors perceived to result from natural gas development (Ferrar et al., 2013). Stress was the most commonly reported health effect, with sources of stress listed as "denied or provided false information", "corruption", "concerns/complaints ignored" and "being taken advantage of"; the lack of transparency between the hydraulic fracturing industry and the local communities is one of the root causes of stress (Ferrar et al., 2013).

Theoretical framework

While multiple studies analyzed potential health effects of hydraulic fracturing, few investigated socio-demographic characteristics of population disproportionately exposed to its effects. Our study attempts to add to this body of literature and analyzes this issue using an environmental justice framework. "Environmental justice" is defined by U.S. EPA as "the fair treatment and meaningful involvement of all people regardless of race, color, national origin, or income with respect to the development, implementation and enforcement of environmental laws, regulations, and policies" (http://www.epa.gov/environmentaljustice/basics/index.html) and refers to the fair distribution of environmental benefits and burdens. It argues for equal access to a clean environment and equal protection from possible environmental harm, irrespective of race, income, class, or any other differentiating feature of socioeconomic status (Cutter, 1995). In 1987, the Unites Church of Christ published a report analyzing the relationship between waste site locations and race in the Unites States (Commission for Racial Justice, 1987). This report, along with U.S. Government Accounting Office report (GAO, 1983), helped mobilize the environmental justice movement and shaped a new research framework within geography, sociology, and other disciplines. Environmental justice research focuses on examining a hazardous facility in relationship to demographic characteristics such as percent poor or percent minority, and many studies have found evidence of significant positive correlation between race, educational attainment or poverty and emissions from hazardous facilities (Boone, Fragkias, Buckley, & Grove, 2014; Osiecki, Kim, Chukwudozie, & Calhoun, 2013; Sicotte & Swanson, 2007). U.S. Environmental Protection Agency recently attempted to conduct an environmental justice screening in the context of studying the potential impacts of hydraulic fracturing on drinking water resources, but found that data available at the time of the study was insufficient (EPA, 2012).

For more than a decade, Geographic Information Systems (GIS) and associated spatial analytical techniques have been used to examine environmental injustice issues (Fisher, Kelly, & Romm, 2006; Maantay, 2007; Mennis, 2002). Spatial coincidence and proximity analysis are two commonly used methods to determine exposure potential in environmental justice research (Chakraborty & Maantay, 2011; Maantay, 2007). The spatial coincidence method simply treats populations within a certain geographic unit containing a polluting facility as potentially exposed to environmental burdens, while the proximity analysis assumes populations living within a certain specified distance of the polluting facility are impacted, and those outside the buffer are not impacted. The proximity analysis method more adequately captures the potential for exposure than the spatial coincidence method (Chakraborty & Maantay, 2011), and many GIS-based environmental justice studies use it to determine the exposure potential (Maranville, Ting, & Zhang, 2009; Miranda, Keating, & Edwards, 2008).

Our study aims to contribute to the environmental justice literature and determine whether certain vulnerable groups are unequally exposed to pollution from unconventional gas wells. Traditionally, environmental justice studies analyze unequal exposure based on race, poverty and educational attainment of the population. One recent study concluded that more epidemiological studies are needed on vulnerable populations that live, work and play in shale gas development areas (Shonkoff, Hays, & Finkel, 2014). The study included children and the elderly, along with pregnant women and those with compromised immune systems. Children are more susceptible to health effect of pollution because they take in 20–50% more air than adults (Kleinman, 2000), have faster metabolic rates and immature and developing body systems (Lauver, 2012). Elderly people are more susceptible to air pollution due to ageing (Bentayeb et al., 2012) and because air pollution can aggravate existing health conditions (EPA, 2009).

Our study objective is to use GIS and spatial statistics to analyze relationships between the proximity and the density of unconventional gas wells and the characteristics of potentially affected populations at the Census tract level in the Marcellus Shale area. More specifically, our research question is: are unconventioanl gas wells disproportionately located in the communities with higher proportions of vulnerable populations.

Study area

The Marcellus Shale is a rock formation that underlies the Southern Tier and Finger Lakes regions of New York, northern and western Pennsylvania, eastern Ohio, and most of West Virginia. It stretches across nearly 95,000 square miles, ranges in depth from 2000 to 9000 feet below the surface, and is believed to hold trillions of cubic feet of natural gas (Kargbo, Wilhelm, & Campbell, 2010; Kolb, 2013). By 2008, the Marcellus Shale Play had become the focus of natural gas development. With the help of hydraulic fracturing technology, the surge of drilling has generated significant economic benefits (Kolb, 2013). A few thousand feet under the Marcellus Shale, the Utica Shale supplies rich natural gas as well. Larger than the Marcellus Shale, it underlies much of the northeastern United States and adjacent parts of Canada. Since it is rapidly becoming another major source of oil and shale gas, unconventional gas wells within the Marcellus Shale extent but drilling on the Utica Shale are also included in our study. As shown in Fig. 1, the study area contains portions of Ohio, Pennsylvania, and West Virginia.

Data

Collecting locations of unconventional gas wells was the most challenging part of this study because there are no standards for documenting these wells, and each state collect, classifies, and reports drilling permits and wells differently. For example, Pennsylvania's Department of Environmental Protection uses the term “unconventional”, and Ohio's Department of Natural Resources, Division of Oil and Gas Resource Management uses the term “horizontal”. Using Kolb's explanation of the key differences between conventional and unconventional drilling (Kolb, 2013, p.59), we excluded vertical and conventional wells, and included unconventional, fracture, and horizontal wells when we searched state databases. We included only active gas wells, and excluded inactive wells where drilling was completed, cancelled, plugged, or temporarily abandoned. We provide wells data as a supplement to the article, and data collection process is described below.

For Pennsylvania, we obtained data from the Department of Environmental Protection (PADEP, 2013), selecting only “unconventional” wells. The table contained 6916 records with three different well statuses: active, regulatory inactive status, and plugged well. Selecting “active” status yielded 6522 wells. For West Virginia, we used three-step process to obtain data from the Office of Oil and Gas within West Virginia Department of Environmental Protection. First, we selected active gas wells from the wells database (https://apps.dep.wv.gov/oog/wellsearch_new.cfm). Unfortunately, this database did not contain any attributes distinguishing conventional and unconventional wells, so as the second step, we used well permits database, which contained more than thirty permit types (WVDEP, 2013). We selected eight permit types that had “horizontal” or “fracture” in their name because these two processes - horizontal drilling and hydraulic fracturing – are associated with unconventional gas production. The search returned 5279 permits (2228 horizontal, 2075 fracture, 801 horizontal 6A, 159 coalbed methane/horizontal, 9 fracture/horizontal wells, 4 fracture/coalbed methane, 3 fracture/drill deeper, and zero horizontal deep types). Finally, we joined two tables together using unique permit number (API field) and then selected only active gas wells within the permit search results. The final dataset for West Virginia included 2729 unconventional gas wells. For Ohio, at the time of the data collection, it was available online from the Department of Natural Resources, Division of Oil and Gas Resource Management (ODNR, 2013) as two spreadsheet tables – one for Utica (887 records) and one for Marcellus shale (27 records) horizontal wells. The status field in the tables listed four types of wells: drilled, drilling, permitted and producing. We selected only “producing” wells for our analysis (160 total) since the other three types of wells were not in operation. All tables contained wells' coordinates in latitude/longitude (Pennsylvania and Ohio) or UTM zone 17 North NAD1983 (West Virginia), so we mapped them in GIS.

The analysis of different human populations was conducted at the Census tract level. The original 2010 Census tracts data were downloaded from U.S. Census Bureau (http://www.census.gov/cgi-

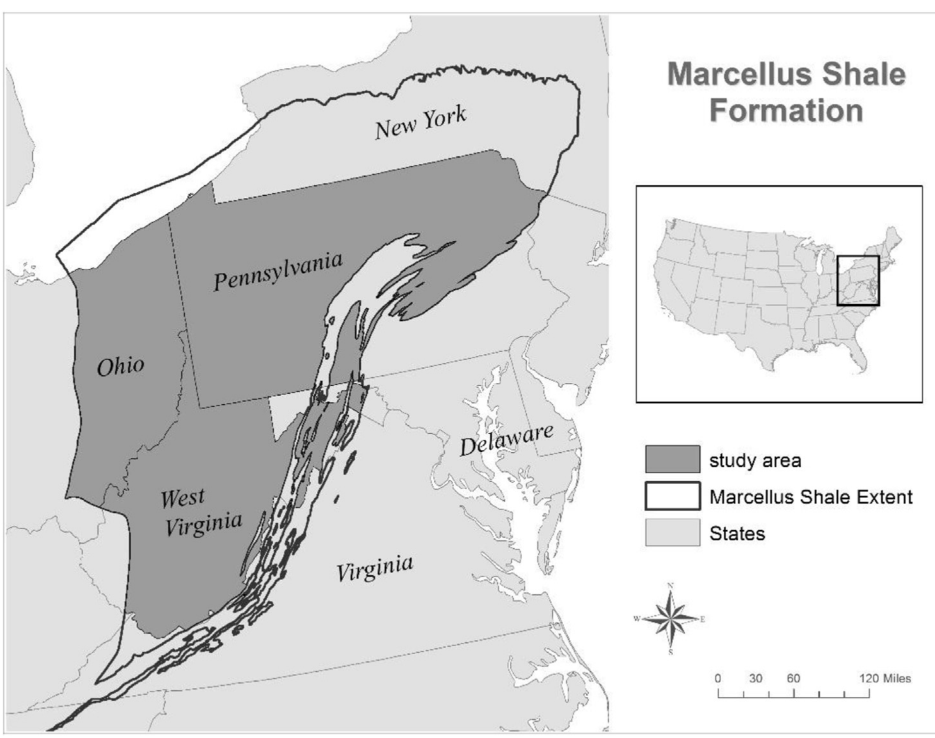


Fig. 1. Marcellus Shale formation.

bin/geo/shapefiles2011/main), and all Census tracts located within or intersecting with the Marcellus Shale extent were extracted for the analysis.

Demographic characteristics downloaded from the 2010 U.S. Census include percent population age 65 and older, percent population age 15 and younger, and percent minority. Percent population below the poverty level and percent adults without high school degree data were collected from the 2007–2011 American Community Survey (ACS) 5-year estimates. We used 5-year estimates (versus 1- or 3-year estimates) and we chose census tract as the unit of analysis (versus census block group, a smaller geographical unit) because they both provide larger number of survey respondents, a smaller margin of error, and thus a more reliable estimate (Census, 2008). Following the ACS data reliability guidelines (ESRI, 2013), census tracts with low reliability (coefficient of variation > 40) were excluded from each state. Data preprocessing also included urban areas removal. Due to the large amount of land required for unconventional drilling, hydraulic fracturing mainly exists in rural rather than in urban areas. By using the urban areas data layer from the U.S. Census Bureau, all census tracts with centroids in urban areas were removed. Table 1 shows the number of tracts excluded from and included in the analysis.

The final dataset included 280 census tracts in Ohio, 579 census tracts in Pennsylvania, and 269 census tracts in West Virginia. The summary statistics of the socioeconomic data included in the analysis are shown in Table 2, and their spatial distribution is shown in Fig. 2.

To better represent potential exposure of the population in each Census tract, land-cover data was downloaded from the U.S. Geological Survey (http://www.mrlc.gov/nlcd2006.php) and residential areas were extracted. Three residential categories were used: low intensity, indicating areas with impervious surfaces accounting for 20%–49% percent of total cover; medium intensity, indicating areas with impervious surfaces accounting for 50%–79% of the total cover; and high intensity, where people reside or work in high numbers, and impervious surfaces account for 80–100 % of the total cover (Homer, Huang, Yang, Wylie, & Coan, 2004).

For each census tract, we calculated the density of hydraulically fractured wells (Fig. 3). The highest density value was 2.89 wells/sq.km. We used it in spatial analysis as a proxy for the magnitude of potential pollution exposure.

Methods

In this study, we used five demographic and socioeconomic variables - percent elderly population, percent children, percent minority, percent population below the poverty level, and percent adults without high school diploma - in the analysis. We used non-spatial (t-test) and a spatial clustering technique (Local Indicators of Spatial Autocorrelation, or LISA) to analyze potential exposure to pollution from unconventional gas wells. LISA identifies statistically significant spatial clusters of similarly high or similarly low values for one or two variables (Anselin, 1995).

Table 1
2010 Census tracts excluded from and included in the analysis, by state.

Census 2010 tracts	Ohio	Pennsylvania	West Virginia
Total number of census tracts in the state	2952	3218	484
Number of census tracts in Marcellus shale	1263	1486	384
Number of census tracts in Marcellus shale and inside an urbanized area (excluded from analysis)	940	878	115
Number of census tracts in Marcellus shale and outside an urbanized area with low ACS data reliability (excluded from analysis)	43	29	0
Final number of census tracts included in the analysis	280	579	269

Table 2
Socioeconomic Data for 2010 census tracts included in the in the analysis.

Statistics	State (# of tracts)											
	Ohio (280)				Pennsylvania (579)				West Virginia (269)			
	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD
% Below poverty-level	1.9	55.2	**14.4**	8	1.8	48.3	**11.2**	5	5.3	47.3	**18.1**	6.7
% no high school diploma	2.4	68.2	**15.1**	8.9	2.2	29.4	**12.6**	4.3	3.9	53.2	**19.8**	7.9
% Non-white population	0.2	65.7	**3.2**	7	0.2	39	**2.6**	4.9	0.2	36.2	**2.8**	4.5
% Under 15 years of age	9.1	40	**20.5**	3.9	5.6	31	**18.1**	2.7	11.9	24.7	**18.4**	2
% Over 65 years of age	6.9	30.8	**15.5**	3.5	7.8	32.5	**17.6**	3.4	8.8	25.3	**16.7**	2.8

Environmental justice analysis — T-test

To define the exposed population, both the spatial coincidence and the proximity methods were applied (Chakraborty & Maantay, 2011). For the spatial coincidence method, census tracts containing unconventional gas wells were considered as tracts at risk of pollution exposure.

For the proximity analysis we used two buffer distances (3 and 5 km from the wells) and then applied four different methods to select Census tracts exposed to pollution within each buffer. We chose these buffer distances because they proved to be an effective representation of variation in human exposure to industrial pollution in previous studies (Burwell-Naney et al., 2013; Maranville et al., 2009; Mohai & Saha, 2006; Perlin, Wong, & Sexton, 2001). A combination of two buffers and four selection methods produced eight possible outcomes from the proximity method. Results of these eight outcomes, along with spatial coincidence method results, were then compared.

The first selection method assumed Census tracts with at least 50% of the area within the buffer to be tracts at risk (Fig. 4(a)). Although populations are not evenly distributed within each Census tract, it may be reasonable to consider most of the population as within the buffer zone if most of the unit's area is contained by the buffer (Miranda et al., 2008). The other three approaches took the spatial distribution of the residential areas into account. Specifically, in the second approach, all residential areas (low, medium, and high intensity) were included in the analysis. If any of these residential areas within a Census tract intersected or were contained within a buffer, that Census tract was selected as tract at risk (Fig. 4(b)). Since roads and streets were included in the low and medium intensity residential categories, the third approach only used high intensity residential areas to make the selection stricter. So, high intensity residential areas which intersected with or were contained within the buffer were selected, and census tracts containing these areas were considered to be at risk (Fig. 4(c)). As a combination of the previous approaches, the fourth approach treated Census tracts with at least 50% of the total residential area (containing low, median, and high intensity types together) within the buffer zones as tracts at risk (Fig. 4(d)).

Using these selection methods, all Census tracts were classified into two categories: Census tracts that are at risk of pollution

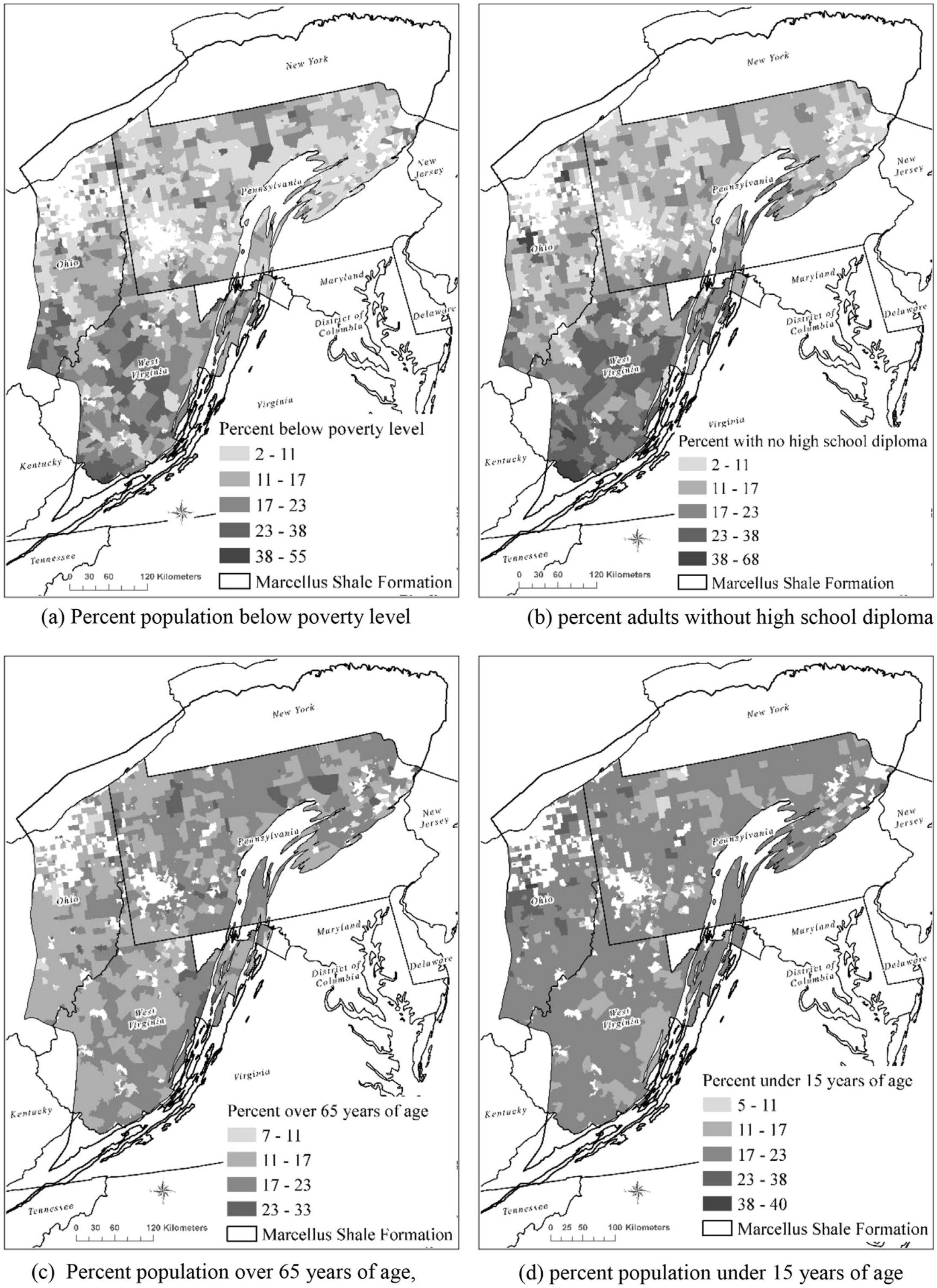
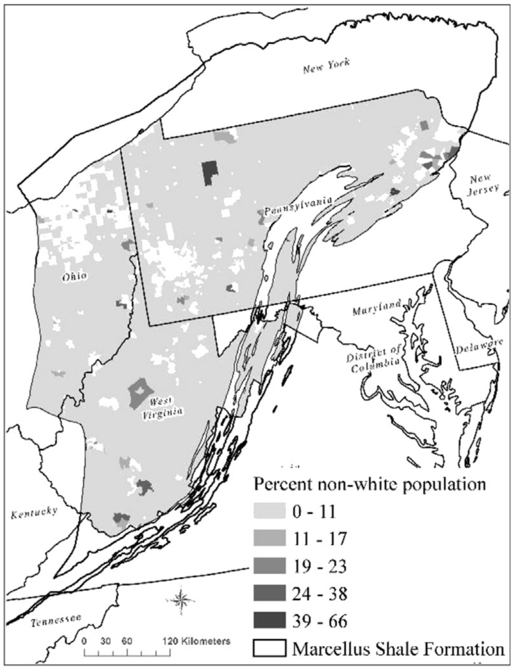


Fig. 2. Socioeconomic characteristics of population. White areas within the study area are urban areas removed from the analysis.

exposure and tracts that are not. To determine whether the populations living in tracts at risk of pollution exposure are significantly different from populations in other Census tracts, for each socioeconomic variable, a two-sampled Welch's t-test was calculated using SPSS software. This test is an adaption of Student's t-test and is used to compare means of two samples with unequal variances (Welch, 1947).

Environmental justice analysis — bivariate LISA

In order to examine the relationship between unconventional well density and socioeconomic variables spatially, a bivariate local indicator of spatial autocorrelation analysis was performed using GeoDa software (Anselin, Syabri, & Kho, 2010). Developed by Luc Anselin (Anselin, 1995), a local indicator of spatial association, also



(e) Percent non-white population

Fig. 2. (*continued*).

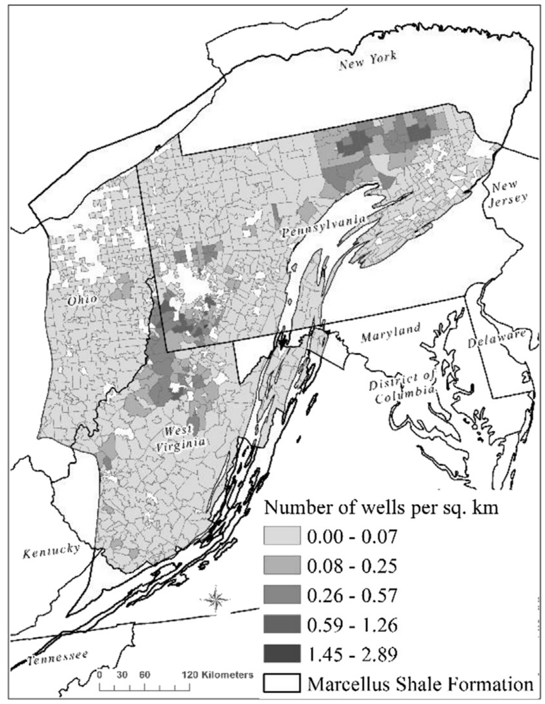


Fig. 3. Density of hydraulically fractured wells per Census tract.

known as a univariate LISA, tests whether local correlations between values of a feature and values of its neighbors are significantly different from what would be expected from a complete spatial randomization. It identifies significant spatial clusters by involving the cross product between the standardized value of a variable for feature *i* and that of the average of the neighboring values. To determine the standardized value of a variable for a given feature the mean value of the variable for the entire study area is calculated first. As a simple extension of the univariate LISA, the bivariate LISA identifies the extent of spatial clusters by involving the cross product of the standardized values of one variable at location *i* with that of the average neighboring values of the other variable. Statistical significance of these spatial clusters is evaluated using Monte-Carlo spatial randomization (Anselin, 1995). We defined spatial neighborhood for LISA analysis as the eight nearest neighboring tracts.

Bivariate LISA produces four clusters: High-High, High-Low, Low-High, and Low-Low. In the context of our study, a High-High cluster indicates areas with significantly higher than average density of wells surrounded by neighbors with significantly higher than the average values of a given socioeconomic variable. High-Low cluster indicates areas with higher than average density of wells surrounded by neighbors with lower than the average values of a given socioeconomic variable. Low-High cluster indicates areas with lower than average density of wells surrounded by neighbors with higher than the average values of a given socioeconomic variable, and Low-Low cluster indicates areas with lower than average density of wells surrounded by neighbors with lower than the average values of a given socioeconomic variable.

Results

Environmental justice analysis — T-test

As all Census tracts of each state were classified into two categories (Census tracts that are at risk and Census tracts that are not), the t-values associated with the mean differences between the two categories are calculated and summarized in Tables 3a through 3c. T-test values significant at the 95% confidence level (i.e., corresponding p-values ≤ 0.05) are marked as follows: * means that census tracts at risk have significantly higher mean value than

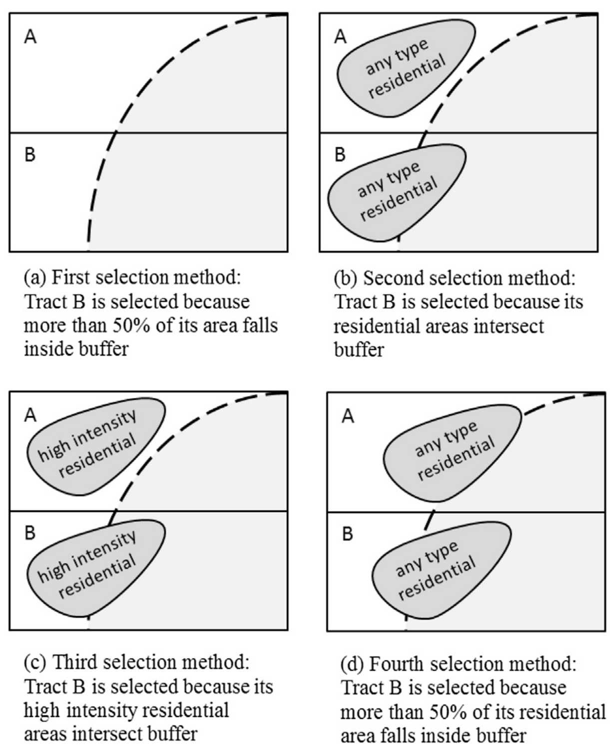


Fig. 4. Schematic illustration of four selection methods. Two tracts of equal size, A and B, are intersected by a circular buffer (dashed line). In all four cases tract A is not selected, tract B is selected.

Table 3a
T-test results (Ohio).

Variables	Spatial coins	Method 1		Method 2		Method 3		Method 4	
		3 km	5 km	3 km	5 km	3 km	5 km	3 km	5 km
poverty	1.007	−0.063	0.919	1.433	1.733	0.897	1.755	−0.063	−1.032
education	0.324	−0.958	−0.485	−0.793	−0.582	0.173	−0.479	−0.958	−0.476
race	4.776#	5.338#	3.940#	3.120#	3.330#	2.400#	2.936#	5.338#	4.946#
children	0.166	−0.287	0.136	0.370	0.863	0.202	0.67	−1.339	−0.52
elderly	−0.970	−1.339	−1.523	−1.323	−1.899	−0.539	−1.764	−0.287	−0.501

Table 3b
T-test results (Pennsylvania).

Variables	Spatial coins	Method 1		Method 2		Method 3		Method 4	
		3 km	5 km	3 km	5 km	3 km	5 km	3 km	5 km
poverty	−3.923*	−1.012	−2.697*	−4.152*	−3.185*	−3.217*	−2.831*	−1.667	−2.777*
education	−1.844	0.529	0.905	0.045	1.225	1.476	1.732	−0.549	0.849
race	3.346#	2.850#	1.975#	4.228#	3.751#	3.654#	3.499#	1.784	3.157#
children	0.914	−0.499	1.002	1.034	1.724	1.24	1.648	0.89	0.452
elderly	−1.084	−0.568	−1.292	−1.583	−2.032*	−1.065	−1.542	−0.96	−1.004

Table 3c
T-test results (West Virginia).

Variables	Spatial coins	Method 1		Method 2		Method 3		Method 4	
		3 km	5 km	3 km	5 km	3 km	5 km	3 km	5 km
poverty	−1.159	−0.280	0.277	−1.394	−1.069	−0.318	−0.217	0.527	−0.333
education	−1.680	−2.414#	−1.063	−0.859	−0.634	−1.075	−0.555	2.078#	0.24
race	1.983#	−0.409	−0.824	1.700	1.647	0.753	0.446	1.497	1.392
children	0.808	−2.443#	−0.671	0.142	−0.049	0.35	0.009	2.122#	0.413
elderly	0.830	−0.038	−1.897	1.547	1.899	2.004#	2.701#	−0.437	2.219#

Note: Spatial Coins.(Spatial coincidence) – Census tracts which contain hydraulically fractured wells are considered “exposed”.
Method 1 – Census tracts with at least 50% of the area within buffer zones are considered “exposed”.
Method 2 – Census tracts with any residential areas within buffer zones are considered “exposed”.
Method 3 – Census tracts with only high-intensity residential areas within buffer zones are considered “exposed”.
Method 4 – Census tracts with at least 50% of all residential areas within buffer zones are considered “exposed”.

tracts that are not at risk (this result represents environmental injustice); # means that census tracts at risk have significantly lower mean value than tracts that are not at risk (this result represents the opposite of environmental injustice). In order to get a more complete understanding of the population vulnerability we discuss both types of findings – presence and absence of environmental injustice.

Our analysis shows that environmental injustice was observed only in Pennsylvania, particularly with respect to poverty: in seven out of nine analyses, potentially exposed tracts had significantly higher percent of people below poverty level than non-exposed tracts (Table 3b). With respect to percent elderly population, only one time (out of nine) it showed significantly higher percent in potentially exposed areas in Pennsylvania. Results for West Virginia and Ohio did not show any evidence of environmental injustice with respect to the five socio-demographic characteristics of population (Tables 3a and 3c). In fact, in several instances, potentially exposed tracts have significantly lower percent of vulnerable populations than non-exposed tracts. For example, in Ohio and Pennsylvania, 9 out of 9 and 8 out of 9 analyses (respectively) showed significantly lower percent of minorities in census tracts at risk and in West Virginia 3 out of 9 analyses showed significantly lower percent elderly in census tracts at risk.

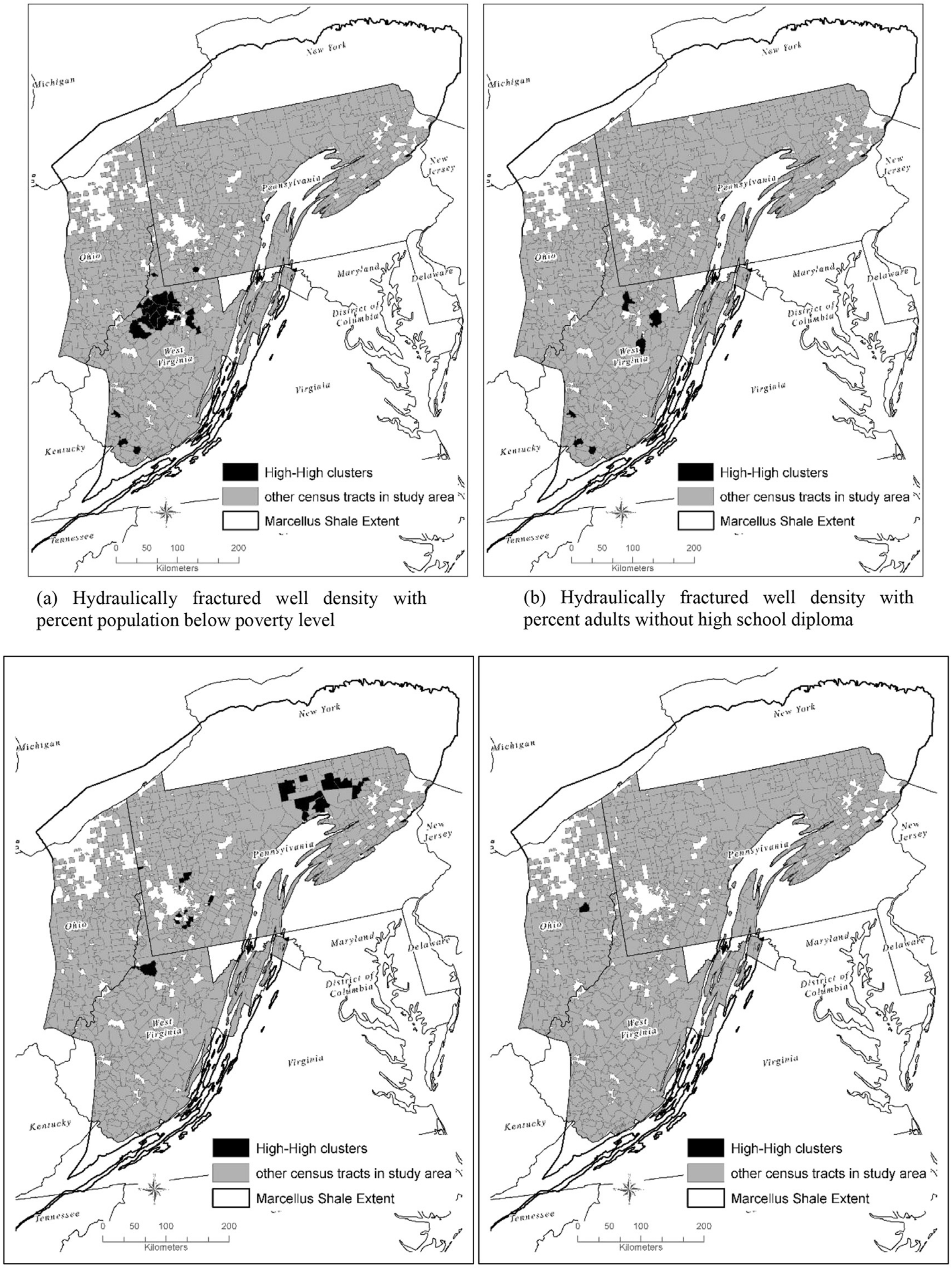
Environmental justice analysis – multivariate LISA

Bivariate LISA analysis was conducted between each socioeconomic variable and unconventional well density at a 0.05 significance level. For the purpose of this study, High–High clusters are the focus of attention, because they correspond to areas where high well density and high percent of vulnerable populations occur near each other.

A large cluster of high well density and high percent population below poverty level (Fig. 5, map (a)) is located in West Virginia, close to the Ohio and Pennsylvania border. Several much smaller clusters can be also found in southern West Virginia, and Pennsylvania. Fewer and smaller clusters are observed for percent adults without high school degree (Fig. 5, map (b)) in northern and southern West Virginia. Areas of densely located unconventional wells and high percent of population over 65 are primarily found in three places (Fig. 5, map (c)) – in the northeastern and southwestern Pennsylvania, and a small cluster in northern West Virginia. For percent children under 15 years of age and unconventional well density there is only one cluster in Ohio (Fig. 5, map (d)). Small clusters where tracts with high densities of unconventional wells are surrounded by tracts with high percentage of minority are located in southwestern Pennsylvania and southern West Virginia (Fig. 5, map (e)). When these maps are visually compared to the well density map (Fig. 3) it becomes clear that all high-high clusters are located in areas with high well density, but not all areas of high well density are areas of unequal exposure to potential pollution.

Discussion

Our study addresses the potential impact of unconventional gas production from the environmental justice perspective. This



(a) Hydraulically fractured well density with percent population below poverty level

(b) Hydraulically fractured well density with percent adults without high school diploma

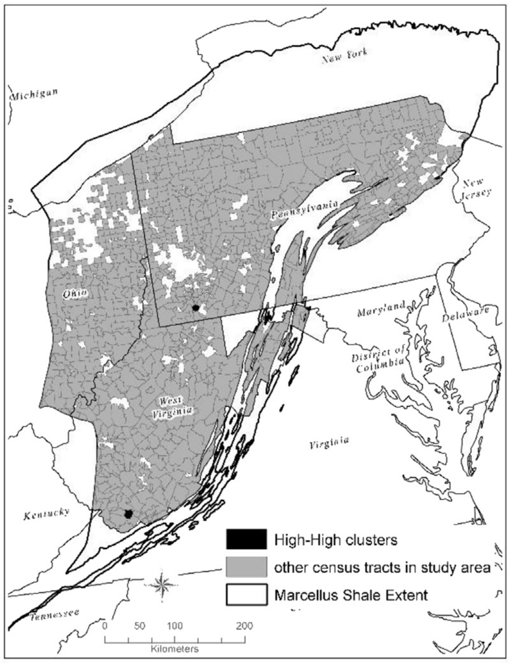
(c) Hydraulically fractured well density with percent elderly over 65

(d) Hydraulically fractured well density with percent children under 15

Fig. 5. Bivariate LISA results. High-high clusters show areas where both high well density and high proportions of vulnerable populations occur.

perspective focuses on vulnerable populations and their exposure to sources of potential environmental harm. Our objective was to analyze relationships between the unconventional wells and the characteristics of potentially affected populations at the Census tract level in the Marcellus Shale in three states. We used a t-test to find out if there are statistically significant differences between populations living close to and exposed to pollution from unconventional wells and populations living outside those areas. We also used spatial clustering technique (LISA) to map areas where both high well density and high proportions of vulnerable populations occur.

Our study contributes to a broader literature on population vulnerability and environmental justice in two ways. First, its broad geographical nature emphasizes the importance of regional-level



(e) Hydraulically fractured well density with percent non-whites

Fig. 5. (*continued*).

analysis. We showed that analyzing potential exposure to pollution for a large geographical region allows for comparison of population vulnerability and environmental justice between several states. Second, our study emphasizes the importance of including not only socio-economically disadvantaged, but also age-based groups in future research on pollution exposure and vulnerable population. Both children and elderly have been rarely included in these studies, and we suggest that future research consider them as equally important as race and poverty-based groups.

A major limitation of our study is quality, availability and consistency of unconventional well data across three states. Each state reports unconventional gas wells data differently, so we had to apply our own criteria when selecting wells for the analysis. These difficulties in data acquisition had potentially biased results of the study. Our experience with data collection clearly demonstrates an urgent need for a new data policy that defines data collection standards and access policies that cross state boundaries. If common data collection and reporting standards are established, it would be possible to perform vulnerability analyses that produce more robust and defensible results.

Another limitation of this study is that its findings are only valid at the Census tract level, because relationships between hazardous facilities and socioeconomic variables may change or become more or less significant when changing the scale of the study (Fisher et al., 2006; Sheppard, Leitner, McMaster, & Tian, 1999). For future research, analysis of relationships at both finer and coarser scales (i.e., census block group, town, or county) should be conducted.

Conclusion

The main finding of our research is that unconventional gas wells are disproportionately located in the communities with environmental justice concerns in one state. Results consistently indicated that census tracts with potential exposure to pollution from unconventional wells have significantly higher percent of poor population in Pennsylvania. Our results confirm previous environmental justice studies and indicate that the poor are the most affected population group.

There were no instances of environmental injustice in three other variables (race, education, and children) between populations potentially exposed to pollution and non-exposed populations in all three states. We found only one instance of unequal exposure of the elderly population in Pennsylvania. These results – equal exposure for children and the elderly – can be explained, at least partially, by the statistical characteristics of these two variables. Both percent of children and percent elderly have the smallest range of values and standard deviations in all three states (Table 2) and are distributed more evenly in the study area than the other variables (compare Fig. 4(c) and (d) to Fig. 4(a), (b) and (e)). Therefore, it is not surprising that there is no significant difference between these populations within the exposed and non-exposed areas. Our results are specific to the three states, and it would be important for the future studies to compare our findings to other states, where unconventional gas drilling is expanding and the distribution of children and the elderly is more varied.

When analyzed spatially, the relationships between well density and the characteristics of potentially affected populations showed High-High clusters in all states, with the highest number of clusters in West Virginia. In this state, local clusters of environmental injustice were found with respect to percent population below poverty level, percent adults without high school diploma, and percent elderly. In Pennsylvania High-High clusters are located in Census tracts with a high percentage of population over 65 years of age, and a high percent below poverty. In Ohio, only one Census tract shows as the center of a High-High cluster where higher density of unconventional wells and higher percent of children are present.

This study advances our understanding of the socio-economic characteristics of populations living in the hydraulically fractured areas in Marcellus Shale and underscores the importance of environmental justice perspective in the analysis. We hope that our findings can be useful to policy makers, environmental health advocacy groups and public health agencies to help them focus their efforts on specific geographic areas where we identified high-high clusters. We also hope that our conclusions about disproportionate potential exposure of the poor in Pennsylvania to high density of unconventional gas wells can catalyze the discussions between the public, local advocacy groups, and legislators to contribute to the regulatory decision-making process regarding unconventional gas development.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.apgeog.2015.03.011.

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