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Health Survey Of Households Near Shale Gas Extraction Sites

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HEALTH SURVEY OF HOUSEHOLDS NEAR SHALE GAS EXTRACTION SITES

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Running Head— *Animals Used to Assess Human Health Near Shale Gas Wells*

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Abstract— The Marcellus formation supports an advanced rate of extraction of shale-based natura**l** gas, particularly as a result of the rapid development of directional drilling and hydraulic fracturing technologies. The confluence of these trends has spurred public concern about potential health impacts on residents that live in proximity to the putative environmental exposures related to the extraction activities, in largely rural communities of the Marcellus region.

A cross-sectional survey of 492 persons and 580 companion / backyard animals from 180 randomly selected households in an area of active unconventional natural gas drilling was conducted. Cluster analyses were performed to identify significant human and animal-sentinel health events of *a priori* interest. Frequency of reported dermal, respiratory, gastrointestinal, cardiovascular, and / or neurological symptoms amongst household humans and animals were further assessed to determine if they differed according to gas well proximity and density, by constructing two hierarchical logistic regression models, each based on either Euclidean distance or integrated dispersion density functions.

Spatial scanning revealed clusters of respiratory and dermal events for humans, overlaying regions of the study area with highest density of gas wells. Animal-sentinel events significantly overlapped with similar dermal and respiratory event clusters. While increased prevalence of dermal complaints among residents were observed in a dose-response fashion with increasing proximity, and dermal symptoms also correlated with gas well density, such associations where not evident for other symptom outcomes. Moreover, frequency of concordant symptom outcomes amongst dogs and large animal livestock (i.e. beef and dairy cattle) was not significantly associated with distance and density of gas wells.

Proximity and density of natural gas wells may be related to increased odds of experiencing skin symptoms. Companion and livestock animals may serve as useful sentinel species for early detection of potential irritant effects, related to nearby natural gas extraction activity. However, further investigation regarding sources and routes of exposure is warranted.

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CONTENTS

1. Introduction

1.1. Modern natural gas extraction (NGE) activity

Over the past two decades, the United States has gauged its efforts to deal with waning reserves of natural gas, its inextricable dependence on fossil fuels, and concerns of greenhouse gas emissions, by supporting exploration and development of unconventional sources of fuel [1]. Natural gas, particularly originating from shale beds, has emerged as a principally promising source of alternative energy [2].

Spurred advancement in modern shale-based natural gas exploration and production are an outcome of the implementation of two novel extractive techniques. First, the use of a drilling technology known as *directional drilling*, is implemented by guiding a drill bit downhole at a 90º angle to extend along the internal seam of existing gas-rich shale bedrock. Second, fissures and gaps are created in the rock via *hydraulic fracturing* at varying intervals [3]. Hydraulic fracturing ('hydrofracing') as a process entails the pumping and injection of fluids and a propping agent through a drilled and encased hole under significant pressure, gradually creating fissures and cracks within the target shale bed. The propent structurally support the fissures and newly produced pores within the hydrocarbon-containing shale, thus allowing for rich gaseous hydrocarbons to flow into, and subsequently be recovered from the wellbore. On average, the hydraulic fracturing process may last 2–5 days, may be repeated multiple times on the same well, and is typically performed for the greatest duration possible given the profitability over the lifetime of a well [3,4].

1.2. Potential health related exposures

While hydrofracing fluids are composed of approximately 98% water and sand/ mud propent (v/v), all phases of hydrocarbon gas production involve added complex mixtures of chemical substances. During conventional hydraulic fracturing, up to 2% (v/v) involves use of chemical additives in very large volumes. These compounds vary in range of toxicity and public health concern [5], and the precise formulations of chemicals are generally unknown [6].

While additives and coadjuvants present in hydraulic fracturing fluids are of particular concern, further consideration needs to be given to the innate toxicants (e.g. heavy metals, naturally occurring radioactive compounds (NORMs), volatile organic compounds (VOCs), etc.) of natural origin, which could be mobilized above ground from geomatrices of varying depth during gas extraction [7]. The mixture of gas, fracturing fluid, as well as any subterranean labile chemical compounds, once mobilized above ground; also pose a significant source of concern within the dimensions of water, soil, and air exposure. Of the five million gallons of water, on average, used to hydraulically fracture a shale gas well once, 30–70% can remain underground and potentially become a source of significant exposure through groundwater hydrodynamics [5]. Despite the vast separation between the zone of natural gas extraction, and the various sites of potential exposure, a number of recent geochemical studies demonstrated the potential migration of shale-based materials, documenting movements from extensively deep Marcellus shale formations into shallow drinking-water aquifers [8]. A recent pilot analysis of the VOC patterns over all major phases of NGE in a rural western Colorado area demonstrated that well pads can be potential sources of non-methane hydrocarbon release into the air, particularly during the initial drilling stages [9].

1.3. Public health concerns

Appalachian communities sitting atop the Marcellus shale formation, among them notably in the southwestern Pennsylvanian (USA) region, reside in proximity to natural gas drilling and hydraulic fracturing operations, and seem to be identified as targets to potential toxicological consequences of NGE, with public health outcomes that remain largely unknown. Initial case reports have been published on disease events as a function of extraction activity in human populations, citing health effects such as subchronic and short-term dermal irritation, neurological effects, and upper respiratory conditions [7].Very few peer-reviewed studies have attempted to produce some human impact assessments recently [10,11]. While large-scale drilling operations in southwestern regions of Pennsylvania and elsewhere are currently expanding, and are expected to increase in the future, little to no action has been taken thus far to accrue data from systematic epidemiologic studies.

1.4. Animals as sentinels

Since the publication of the National Research Council's 1991 *Animals as Sentinels of Environmental Health Hazards* [12], numerous studies have suggested that efficient and valid epidemiological approaches to study novel and complex environmental exposures to humans, should include the implementation of animal sentinel surveillance, whereby diseases in naturally occurring animal receptors may be used to signal potential human health threats [12]. Sentinel surveillance offers a comparative epidemiological approach based on "shared risks", and has a number of experimental advantages which have been documented elsewhere [13]. Generally, animal species may serve as more rapid detection systems of environmental hazards due to their closer and direct interaction with the environment, increased susceptibility, shorter latency for development of disease, and freedom from co-occurring socioeconomic, demographic, and cultural confounders [14]. Animal mortality and morbidity has been previously documented in proximity to NGE [7]. Ecosystem changes attributed to NGE have also been reported [15–17]. However, it is notable that studies implementing animal sentinel approaches are often encumbered by gaps in information on animal health history, disease diagnosis, interspecies variation, and the inextricable difficulty with extrapolations to human health.

1.5. Research approach

To elucidate the health burden of human populations near natural gas extraction activity in southwestern Pennsylvania, an interviewer-administered environmental health survey of households was conducted to assess the extent of companion and back-yard animal health signs in relation to human symptom prevalence, in geographic proximity to NGE activities. This paper details the results of the first known systematic cross-sectional study of human and animal populations in this setting and presents a number of conclusions derived from statistical and geographic information systems (GIS) analyses.

2. Methods

2.1. Description of study area

The Marcellus formation is a Middle Devonian-age black, low density, organically rich shale which has been predominantly horizontally drilled for gas extraction in the southwestern portion of the State of Pennsylvania (USA) [18]. As a result, the study design described herein focused on the southwestern Pennsylvanian county, Washington County (40° 11′ 24″ N, 80° 15′ 0″ W) chosen as a representative region where horizontal drilling and hydraulic fracturing activities are most dense (one gas well per ~3.7 Km^2) with a total of 604 active Marcellus Shale gas wells based on 2012 data [19].

Washington County comprises 66 municipalities, including 32 spatially large townships and 34 spatially minor regions with a greater population density, urbanization, and provision of treated municipal water supplies and other major utilities (32 boroughs and 2 cities). Since the primary focus of the study is on innate human and animal populations in rural areas where NGE activity is present, we chose to systematically exclude regions of Washington County from the study that are highly urbanized areas unlikely to support natural gas activity, and areas serviced by exogenous water supplies not endemic to the study area. Moreover, we excluded municipalities of the county that border West Virginia, to eliminate confounding effects of nearby NGE activity in West Virginia that operates under different policies and regulations. Degree of urbanization, and other relevant exclusion criteria for townships, was developed based on Topologically Integrated Geographic Encoding and Referencing (TIGER) data provided by the Pennsylvania Department of Transportation (PennDOT), found on the geospatial data clearinghouse, PASDA (Pennsylvania Spatial Data Access; http://www.pasda.psu.edu/). ***Figure 1*** demonstrates the chosen study site, consisting of the 38 chosen contiguous townships in Washington County, Pennsylvania.

2.2. Selection of households

A spatially-stratified random sampling method using Geographic Information Systems was implemented using ArcGIS Desktop 10.0 software (ESRI, Inc., Redlands, CA, USA), for target households. Systematic household selection was based on randomly generating sampling points within the boundary of the study area using the following chosen geospatial parameters: 1000 randomly generated points (using the 'Create_Random_Points' function in the Data Management Tool), spaced at 100 m apart, where eligible municipalities were selected as the constraining feature class such that point generation was constrained for each municipality to receive 20 random points. This procedure yielded 760 geospatially randomly generated sampling points in the 38 townships throughout the entire study area within Washington County. Lastly, each random point was reverse-geocoded in order to locate the nearest household. ***Figure 2*** illustrates the end result of the spatial randomization for the selection of participants from the study base. Sampling points were geomasked by systematically off-setting each point by a pre-determined level, to protect security and privacy.

2.3. Household eligibility

Households were deemed eligible if the residence had infrastructural access to well water, spring water, or untreated community (multi-household) well water. In a systematic approach, the survey team visited each eligible home nearest to the randomly generated sampling point (within an ~805 m radius) up to three times to determine eligibility and establish contact, documenting the result of each visit on a tracking form. Visits were coordinated to ensure that multiple attempts were made at different times of a given day, and at different periods throughout the week.

2.4. Questionnaire

A confidential community environmental health questionnaire was developed to collect data on the general health of humans, as well as companion animals and backyard livestock at each study household. Questions were drawn from previously validated survey questionnaires from the Centers for Disease Control and Prevention (CDC) National Health and Nutrition Examination Study (NHANES) [20] as well as First Nations Food, Nutrition and Environment Study (FNFNES) [21], CDC's National Health Interview Survey (NHIS) [22], Agency for Toxic Substances and Disease Registry (ATSDR) [23], World Health Organization (WHO) [24], and the SF-12v2® standardized (4-week recall) survey of health status [25,26]. Development of the questionnaire was guided by focus group meetings with community leaders and health organizations having knowledge of long-term health concerns of local residents. The questionnaire was pilot tested in early May, 2012 on a sample of 15 individuals outside of the study area to ensure that questions were comprehensible, and that the survey could be completed within 15–20 minutes.

The survey was designed so that at each household, one adult representative could provide information on age, gender, residence time, as well as educational attainment, and occupation for each household member. The survey asked the respondents if they or members of their households ever had any of 55 health symptoms "*in the past year*", the date that symptoms started, as well as when (if any) conditions were diagnosed by a health professional. We focused on health symptoms of *a priori* interest, including several conditions that characterize irritant symptoms (skin, and respiratory conditions) as well as cardiac, gastrointestinal, and neurological health events). Health data were also collected regarding ethnicity, income, tobacco smoke exposure, and BMI (Kg / m^2, calculated based on self-reported body height and weight).

Separate questionnaire items were created to assess the health status of all companion and backyard animals in each household. This included information on the approximate age of each animal, the number of animals for a given species, whether they are housed or are allowed to roam outdoors, the main source of available water (municipal, well, spring, surface, tank, etc…), and any health problems, changes in production, or deaths that have been sustained within one year from the date of the survey. The survey asked about veterinary diagnoses and treatment approaches (if any) whenever health problems were documented. Prior to data analysis, a Yale University-affiliated public health veterinarian classified reported health conditions for all animals in each household into composite health outcomes (e.g. dermal, respiratory, neurological, gastrointestinal, etc…).

Additional questions were designed to ascertain respondent's level of satisfaction and perceived concern, based on a 6-level Likert scale rating, within specific domains of environmental quality, including air, water, and land quality, as well as neighborhood level of noise, environmental (non-farm) odors, and neighborhood road use and traffic. Additionally, there were questions (yes/no) to recall any observed changes in land or terrain, surface water, vegetation or plant growth, and wildlife density patterns near or around their residence in the past year from the date of the administered questionnaire. To evaluate the extent to which possible awareness bias may affect the validity of self-reported health information the questionnaire included a question (yes / no) regarding awareness of any environmental health risks near their residence.

Information on environmental exposures was collected, including: 1) Main source of drinking water as well as main source of water used for other purposes in the household other than for drinking (municipal, drilled well, dug well, uprotected dug well, spring water, bottled water, tank / cistern, water buffalo); 2) Water well characteristics (depth and casing type); 3) Water treatment or filtration systems used in the household (heat sterilization, chlorination, solar / UV disinfection, filtration, settling, water softening, deionization); 4) Household environmental characteristics (presence/absence: air purifier, gas stove, actively used fireplace, and an actively used woodstove).

2.5. Administration of questionnaire

Yale University School of Medicine Institutional Review Board of the Human Research Protection Program (HRPP) determined the study protocols posed minimal risk to human subjects, and all participants gave verbal informed consent prior to enrollment in the study.

At each eligible household, one English speaking adult at least 18 years of age with no serious language or mental impairment, who formally lived in the given residence for a minimum of one year, was invited to respond to the household questionnaire. Interviews were conducted Monday–Friday (10:00–20:00) and Saturday–Sunday (12:00–18:00). Starting in June 2012, two trained interviewers were accompanied by a community consultant; a local resident recruited from the membership of the community who aided the interviewers in explaining the purpose of the survey, and answered any questions or concerns. The survey was presented as a general environmental health questionnaire. Interviewers were trained to administer the survey instrument in a uniform and consistent fashion, such that questionnaires could be completed in less than 15–20 min. Eligible respondents were offered a small cash stipend for participation. A study team member recorded the Global Positioning System (GPS) coordinates of the household using a Garmin GPSMAP® 62S Series handheld GPS device (Garmin International, Inc., Olathe, KS). Survey personnel were not aware of the mapping results for gas well proximity to the households being surveyed.

2.6. Exposure Assessment

2.6.1 Household proximity to nearest active gas well

A map of active unconventional gas wells in the county was designed by utilizing gas well permit data publically available at the Pennsylvania Department of Environmental Protection [27]. Using ArcGIS, we calculated the distance between the household location (as defined by the GPS reading taken during the site visit) and each gas well appearing on the map. We then classified households by distance from the nearest well, as <1 Km, 1-2 Km or > 2 Km.

2.6.2 Gas well density

Gas well density in the vicinity of each household was used as a secondary metric of exposure. The effect of more than one well on human health symptoms was quantified using an integrated exposure modeling approach previously described by Holford *et al.* [28]. This method assumed that putative pollutant dispersion from a gas well can be approximated by an unknown step function (0–1 Km, 1–2 Km, and > 2 Km, a referent category) which is estimated. The multiple point sources of putative pollutants were cumulated such that each well contributed to the exposure within a given distance buffer, used as a regressor in a hierarchical linear logistic model. Parameters associated with these regressor variables estimated the odds ratio associated with exposure to one additional well in the specified range.

2.7. Statistical analysis

Simple prevalence rates and frequencies were calculated for individual human and animal participants at different distances from the nearest gas well. Non-parametric tests of comparison were used to analyze covariates between distance groups. Human and animal health outcomes were initially analyzed to assess geospatial clustering using a purely spatial scan statistic first described by Kulldorff and Nagarwalla [29]. A Bernoulli-based model scanning for areas with high symptom density was used for analysis of cases located < 1 Km to the nearest natural gas well, in comparison to those > 2 Km from the nearest natural gas well. Relative risk, log-likelihood and overall cluster significance was inferred by 999 Monte Carlo simulated iterations using a pre-defined circular-shaped scanning window. Given the sparse nature of the animal case data and the lack of an *a priori* hypothesis about symptomatology, spatial clusters in animals were defined by including all animals and by compositing dermal, respiratory, and gastrointestinal outcomes.

The association between household distance from a well (< 1 Km, 1-2 Km, or > 2 Km) and presence or absence of each of five types of composite health conditions mentioned in published case reports [30] (dermal, respiratory, gastro-intestinal, neurological and cardiovascular) for humans and major physical ailments for animals were tested in a generalized linear mixed model (GLMM) logistic regression with a random effect to account for the clustering within a household. Adjustment was performed for individual demographic covariates (gender, age, education, and occupation) and potential household-level confounders (reported awareness of a nearby environmental hazard, groundfed water usage, and presence of smokers in the household). Responses from the SF-12v2® were scored using SF-12v2® software (QualityMetric, Lincoln, RI). The mental and physical component scores were reported after normalizing for gender, age, and BMI. Spatial syndromic clusters were analyzed using SaTScan software (available online: http://www.satscan.org/). Statistical analyses were conducted using SAS 9.2 (SAS Institute, Cary, NC).

3. Results

3.1. Individual and household-level demographics

Of the eligible households (n= 255), (n=183) (% 72.3) questionnaires were completed (refusal rate= % 18.6), documenting a total of 492 humans participants, and 580 companion / backyard farm animals. Reference the CONSORT diagram in ***Figure 3*** for the summary of the experimental design. **Table 1** describes individual and household characteristics according to stratum of a given household's proximity to the nearest active Marcellus gas well. Overall, gender, mean age, and occupational status did not significantly differ across distance categories, though individuals living between 1-2 Km from the nearest gas well were slightly older compared to individuals in the reference group (p= 0.03) Further analysis (not shown in Table 1) indicated that households in the reference group (> 2 Km from the nearest gas well) tended to have a higher proportion of children ($p = 0.001$). While reported smoking was less common in households near gas wells, smoking prevalence and other household level variables including BMI, water quality—reported taste and odor— and awareness of proximate environmental risks were distributed relatively homogenously across distance categories ($p > 0.05$). ***Table 2*** also demonstrates the distribution of animal species identified during the surveillance, where dogs and large animal livestock (beef and dairy cattle) in particular tended to be the most prevalent companion and backyard animal in the study population, respectively.

3.2. Symptom spatial cluster analysis

Figure 4 summarizes results of the Bernoulli cluster analysis using SaTScan, indicating the relative risk (RR) and the associated p-value for log-likelihood as part of an initial exploratory spatial data survey. In all cases of human reported health effects, only one spatial cluster was statistically significantly identified for each major reported symptom. The only symptom distributions that yielded results that met the significance level necessary to reject the 'complete spatial randomness' (CSR) null hypothesis, were the dermal and respiratory conditions. The mean centroids that identify the geographic center for each symptom cluster, demonstrate a substantial degree of overlap, consistent with the fact that 58 % of persons in the study sample with skin symptoms also reported respiratory complaints during 2011‒2012. When cluster analysis was conducted for composite dermal and respiratory conditions for any companion or backyard animal health event, a cluster of similar geographic disposition was identified (**Figure 5.**), though this cluster was only marginally significant ($p= 0.04$) beyond the level of random variation. In all analyses, significant human and animal clusters were found in the region of Washington County that is superimposed by the greatest density of active unconventional natural gas well.

3.3. Reported symptoms and health-related quality of life

Human household members living in households either less than 1 Km or 1-2 Km from natural gas wells were more likely to complain about any type of skin problem over the past year compared to those in households greater than 2 Km (**Table 3.**). In a hierarchical model that adjusted for age, education, gender, occupation, smokers in household, and awareness of environmental risk (**Table 4.**), this risk (OR= 3.7; CI 1.4–9.9) was highest among persons living less than 1 Km from the nearest gas well compared to the reference (persons living > 2 Km). Risk of dermal symptoms was second highest among persons living 1-2 Km away (OR= 1.96; CI 0.7-5.9) compared to the reference. Households reporting skin problems were significantly more likely to report that the well water had an unnatural appearance compared to households without skin complaints (36 vs. 13%: Fisher's Exact p = 0.001). For the other symptom complexes, there was a less consistent relationship between the prevalence of symptom reports and proximity to nearest gas well.

The risk of dermal complaints also increased with increasing density of gas wells in the vicinity (**Table 4.**). Density of gas wells, especially for houses located 1–2 Km from the nearest well, yielded the largest explanatory effect in the model, such that prevalent skin symptom risk increases by 13.6% for each additional gas well found near a house. In some households, there was a 20 fold increase in risk associated with well density (data not shown). For the SF-12 responses of the principal household respondent, physical health component scores were lower in households less than 1 km from the nearest well (p=0.03), but there was no clear dose response relationship across distance categories (Table 3).

Results of hierarchical regression applied to relevant symptoms acquired during the surveillance of health status of different companion and livestock animals are demonstrated in **Table 5**. For all animal species, after adjusting models for a number of covariates including animal age, type of water source, and housing type, symptom risks were not differentially explained by proximity to the nearest natural gas well, nor where they explained by additive effects of gas wells for a given distance from their housing ($p > 0.05$).

4. Discussion

This spatially random household survey of health of humans and animals in a region with a large number of active natural gas wells, is the largest study to date concerning the human and animal health impacts of natural gas extraction activities. The survey findings indicate that persons were more likely to experience prevalent dermal and respiratory symptoms when residing in households located in close proximity to dense distributions of active wells. This association of well proximity and frequency of reported skin problems demonstrated a dose response relationship. Additionally, reports of skin problems were often associated with respiratory symptoms. Proximity to wells was also associated with a decrease in perceived health status, but not with the prevalence of neurological or gastrointestinal symptoms.

One explanation for the observed epidemiologic findings in relation to the activity amidst the nearby natural gas wells, could be the fact that well water quality changes, owed to well development imperfections or inadvertent underground communication between endemic water supplies and fracturing activities, could serve as a source of potential exposure. On the other hand, the fact that the geographic area studied has experienced petroleum and coal exploration and extraction activities in the past century [31], could confound this particular notion and cannot be ruled out. It is important to note that our study did not have the necessary capacity to explore the specific nature of causation in the NGE exposure-health outcomes axis.

In the possible event of groundwater contamination, a number of naturally occurring chemicals as well as chemical adjuvants associated with the hydraulic fracturing process have irritant properties and could potentially cause a multitude of skin conditions. Published reports of associations between the prevalence of eczema and other skin conditions with exposure to drinking water polluted with chemicals including volatile organic compounds [32–34], as well as changes in water hardness [35,36] have been documented. A second possible explanation for the skin complaints could be exposure to air pollutants including volatile organic compounds from upwind sources, such as flaring of gas wells [11].

An interesting finding in this study is that surveyed animal health did not corroborate the findings of the human surveillance data in modeling prevalent conditions with respect to putative exposures from gas wells, defined by geospatial distance and density. Companion and backyard animals live in close association to their human counterparts, and share similar domestic exposures. In light of these significant figures of merit, the sentinel data reported herein may suggest that the human health risk estimates should be interpreted with great caution, and the possibility of artifactual chance outcomes cannot be ruled out. Conversely, the validity of the sentinel health outcomes should also be interpreted with extreme caution. For example, the fact that only 13% of the animals enrolled in the survey experienced at least one irritant symptom in 2011–2012, may point to the fact that the sample size of recruited animals was insufficient to overcome the β-error, given the low frequency of health outcomes. On the other hand, the fact that geospatial cluster analysis points to a marginally significant cluster of positive symptoms amongst the surveyed animal species, and that this cluster was congruent with the same portion of the study area where significant clusters of human irritant cases where observed may suggest the importance of continued examination of animal health events in future epidemiologic studies of human health outcomes in relation to proximate NGE.

A limitation of the study was the reliance on self-report of health symptoms, though the extent to which the associated biases may impose a threat to the validity of the risk estimates is not clear. For example, the presence of symptoms amongst other household members may have been under-reported by the household respondent. Conversely, awareness in individuals concerned about the presence of an environmental health hazard, and a consequently increased likelihood of reporting of illness symptoms, may be a significant competing bias. Measurement bias was minimized by training interviewers, with particular attention paid to preventing any suggestion of a link between natural gas extraction and clinical risk. However, the respondents already may have been aware of such a possibility. Though a number of participants expressed their concern regarding environmental health hazards near the household, in our adjusted model that considered perceived environmental risk, the elevated risk of dermal symptoms with well proximity, remained.

While hypothesis generating studies often run the risk of being hampered by high rates of type-I error due to issues of multiple analyses, we tried to limit the extent to this potential threat to study validity by compositing symptom outcomes, as well as designing surveys that asked questions on *a priori* symptoms of interest, refraining from conducting any *a posteriori* subgroup analyses, and we report on results of all analyses that were undertaken. Defining more conservative α-levels using methods such as Bonferroni correction, are a common approach to deal with multiplicity; however we felt that this potentially overly stringent criterion was not warranted in the current study. While it is uncertain to what degree human and animal study samples described in this study are representative of the population bases as well as residents of other communities experiencing similar rates of NGE activity, secondary analyses of non-enrolled members of the population indicated that selection bias due to heterogeneous participation among the varying distances from a gas well, was not statistically significant ($p > 0.05$).

Our study supports the need for further research into health effects of natural gas extraction activities. Such research could include biomonitoring of individuals for particular chemical exposures.

5. References

1. Joint Institute for Strategic Energy Analysis (JISEA). 2012. Natural Gas and the Transformation of the U.S. Energy Sector: Electricity. Logan J, Heath G, Paranhos E, Boyd W, Carlson K, Macknick J. NREL/TP-6A50-55538. Golden, Colorado, USA: National Renewable Energy Laboratory, U.S. Department of Energy.
2. Kargbo DM, Wilhelm RG, Campbell DJ. 2010. Natural gas plays in the Marcellus shale: Challenges and potential opportunities. Environ. Sci. Technol. 44:5679–5684.
3. Argonne National Laboratory (ANL). 2012. Hydraulic Fracturing: Technology, Impacts, and Policy. Clark CE, Burnham AJ, Harto CB, Horner RM. 2012. (No. ANL/EVS/R-12/5). Argonne National Laboratory (ANL): Argonne, Illinois, USA: U.S. Department of Energy.
4. House of Commons Energy and Climate Change Committee. 2011. Shale Gas: Fifth Report of Session 2010–2012, Volume I. The Stationary Office Limited (HC 795). London, United Kingdom: House of Commons.
5. Office of Fossil Energy. 2009. Modern Shale Gas Development in the United States: A Primer. National Energy Technology Laboratory, U.S. Department of Energy. Available: http://www.netl.doe.gov/technologies/oil-gas/publications/epreports/shale_gas_primer_2009.pdf [accessed 5 December 2012].
6. Waxman HA, Markey EJ, DeGette D. 2011. Chemicals used in hydraulic fracturing. United States House of Representatives Committee on Energy and Commerce Minority Staff. Available: http://democrats.energycommerce.house.gov/sites/default/files/documents/Hydraulic%20Fracturing%20Report%204.18.11.pdf [accessed 5 December 2012].

7. Bamberger M, Oswald RE. 2012. Impacts of gas drilling on human and animal health. New Solutions. 22: 51–77.
8. Warner NR, Jackson RB, Darrah TH, Osborn SG, Down A, Zhao K, White A, Vengosh A. 2012. Geochemical evidence for possible natural migration of Marcellus formation brine to shallow aquifers in Pensylvania. PNAS. 109: 11961–11966 .
9. Witter R, Stinson K, Sackett H, Putter S, Kinney G, Teitelbaum D, Newman L. 2008. Potential exposure-related human health effects of oil and gas development: A White Paper. Colorado School of Public Health.
10. Colborn T, Kwiatkowski C, Schulz K, Bachran M. 2011. Natural gas operations from a public health perspective. Hum. Ecol. Risk Assess. 17:1039–1056.
11. McKenzie LM, Witter RZ, Newman LS, Adgate JL. 2012. Human health risk assessment of air emissions from development of unconventional natural gas resources. Sci. Tot. Environ. 424: 79–87.
12. National Research Council (US). Committee on Animals as Monitors of Environmental Hazards. (1991). Animals as sentinels of environmental health hazards. National Academies Press.
13. Rabinowitz PM, Gordon Z, Holmes R, Taylor B, Wilcox M, Chudnov D, Nadkarni P, Dein JF. 2005. Animals as sentinels of human environmental health hazards: An evidence-based analysis. EcoHealth. 2: 26–37.
14. Van der Schalie WH, Gardner HS, Bantle JA, DeRosa CT, Finch RA, Reif JS, Reuter RH, Backer LC, Burger J, Folmar LC, Stokes WS. 1999. Animals as sentinels of human health hazards of environmental chemicals. Environ. Health Perspect. 107: 309–315.

15. Waldner CL. 2008. Western Canada study of animal health effects associated with exposure to emissions from oil and natural gas field facilities. Study design and data collection I. Herd performance records and management. Arch. Environ. Occup. Health. 63: 167–184.

16. Waldner CL. 2009. Risk of abortion and stillbirth in cow-calf herds exposed to the oil and gas industry in Western Canada. Arch. Environ. Occup. Health. 64:29–45.

17. Waldner CL, Ribble CS, Janzen ED, Campbell JR. 2001. Associations between oil- and gas-well sites, processing facilities, flaring, and beef cattle reproduction and calf mortality in western Canada. Prev. Vet. Med. 50:1–17.

18. Slonecker ET, Milheim LE, Roig-Silva CM, Malizia AR, Marr DA, Fisher GB. 2012. Landscape consequences of natural gas extraction in Bradford and Washington counties, 2004–2010. *U.S. Geological Survey Open-File Report*, 1154, 36. Available: http://pubs.usgs.gov/of/2012/1154/of2012-1154.pdf [accessed 25 April 2013].

19. PA Department of Environmental Protection. Oil and Gas Reporting Website. Pennsylvania Department of Environmental Protection, 2012. Available: https://www.paoilandgasreporting.state.pa.us/publicreports/Modules/Welcome/Welcome.aspx [accessed 12 January 2012].

20. National Center for Health Statistics. 1994. Plan and operation of the Third National Health and Nutrition Examination Survey, 1988–94. Series 1: programs and collection procedures. Vital Health Stat 1: 1–407.

21. Chan L, Receveur O, Sharp D, Schwartz H, Ing A, Tikhonov C. 2011. First Nations Food, Nutrition and Environment Study (FNFNES): Results from British Columbia (2008/2009). Prince George: University of Northern British Columbia.

22. National Center for Health Statistics. Centers for Disease Control and Prevention (CDC). National Health Interview Survey Website. Questionnaires, Datasets, and Related Documentation. 2013. Available: http://www.cdc.gov/nchs/nhis/nhis_questionnaires.htm [accessed 29 April 2013].

23. Agency for Toxic Substances and Disease Registry. *Exposure Investigation:* Biological and Environmental Monitoring for Exposure to Benzene and Related Petroleum Chemicals. Cost Recovery #: A835. U.S. Department of Health and Human Services, Public Health Services. 2011. Atlanta, Georgia. Available: http://www.atsdr.cdc.gov/hac/pha/CorpusEI/ExposuretoBenzeneinTXHCEI01052011.pdf [accessed 29 April 2013].

24. World Health Organization / United Nations Children's Fund (WHO/UNICEF). 2006. Core Questions on Drinking Water and Sanitation for Household Surveys. Geneva, Switzerland. Available: http://whqlibdoc.who.int/publications/2006/9789241563260_eng.pdf [accessed 29 April 2013.]

25. Ware JE, Kosinski M, Keller SD. 1996. A 12-item short-form health survey: Construction of scales and preliminary tests of reliability and validity. Medical Care. 34: 220–233.

26. Ware JE, Kosinski M, Turner-Bowker DM, Grandek B. 2005. How to score version 2 of the SF-12 health survey (with a supplement documenting version 1). Lincoln, RI: QualityMetric Incorporated.

27. Pennsylvania Department of Environmental Protection (PA DEP). 2012. Oil & Gas Reporting Website. Pennsylvania Department of Environmental Protection. Available:

https://www.paoilandgasreporting.state.pa.us/publicreports/Modules/Welcome/Welcome.aspx [accessed 12 Jan 2013].

28. Holford TR, Ebisu K, McKay LA, Gent JF, Triche EW, Bracken MB, Leaderer BP. 2010. Integrated exposure modeling: A model using GIS and GLM. Statistics in Medicine. 29: 116–129.
29. Kulldorff M, Nagarwalla N. 1995. Spatial disease clusters: Detection and inference. Statistics in medicine. 95: 799–810.
30. Steinzor N, Subra W, Sumi L. 2013. Investigating links between shale gas development and health impacts through a community survey project in Pennsylvania. New Solutions. 23: 55–83.
31. Munn MJ. 1912. Description of the Claysville quadrangle [Pennsylvania]: US Geol. Survey Geol Atlas, Folio, 180.
32. Lybarger JA, Lee R, Vogt DP, Perhac RM, Spengler RF, Brown DR. 1998. Medical costs and lost productivity from health conditions at volatile organic compound-contaminated superfund sites. Environmental research. 79:9–19.
33. Lampi P, Vohlonen I, Tuomisto J, Heinonen OP. 2000. Increase of specific symptoms after long-term use of chlorophenol polluted drinking water in a community. European Journal of Epidemiology. 16:245–51.
34. Yorifuji T, Noguchi M, Tsuda T, Suzuki E, Takao S, Kashima S, Yanagisawa Y. 2012. Does open-air exposure to volatile organic compounds near a plastic recycling factory cause health effects? Journal of Occupational Health. 54:79-87.

35. Chaumont A, Voisin C, Sardella A, Bernard A. 2012. Interactions between domestic water hardness, infant swimming and atopy in the development of childhood eczema. Environmental Research. 116:52–57.

36. McNally NJ, Williams HC, Phillips DR, Smallman-Raynor M, Lewis S, Venn A, Britton J. 1998. Atopic eczema and domestic water hardness. Lancet. 352: 527–531.

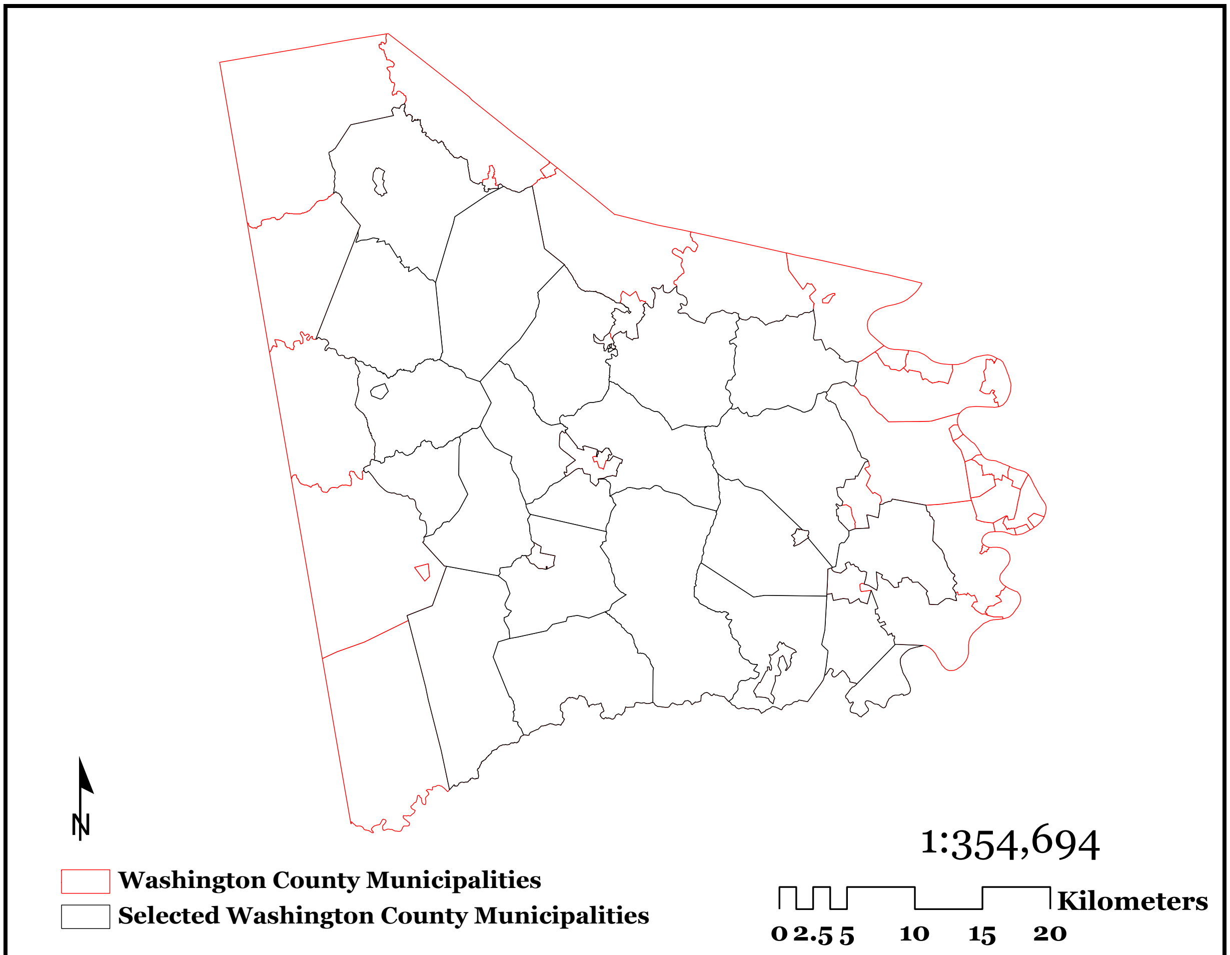

Figure 1. Selection of relevant study municipalities of Washington County, Pennsylvania, USA

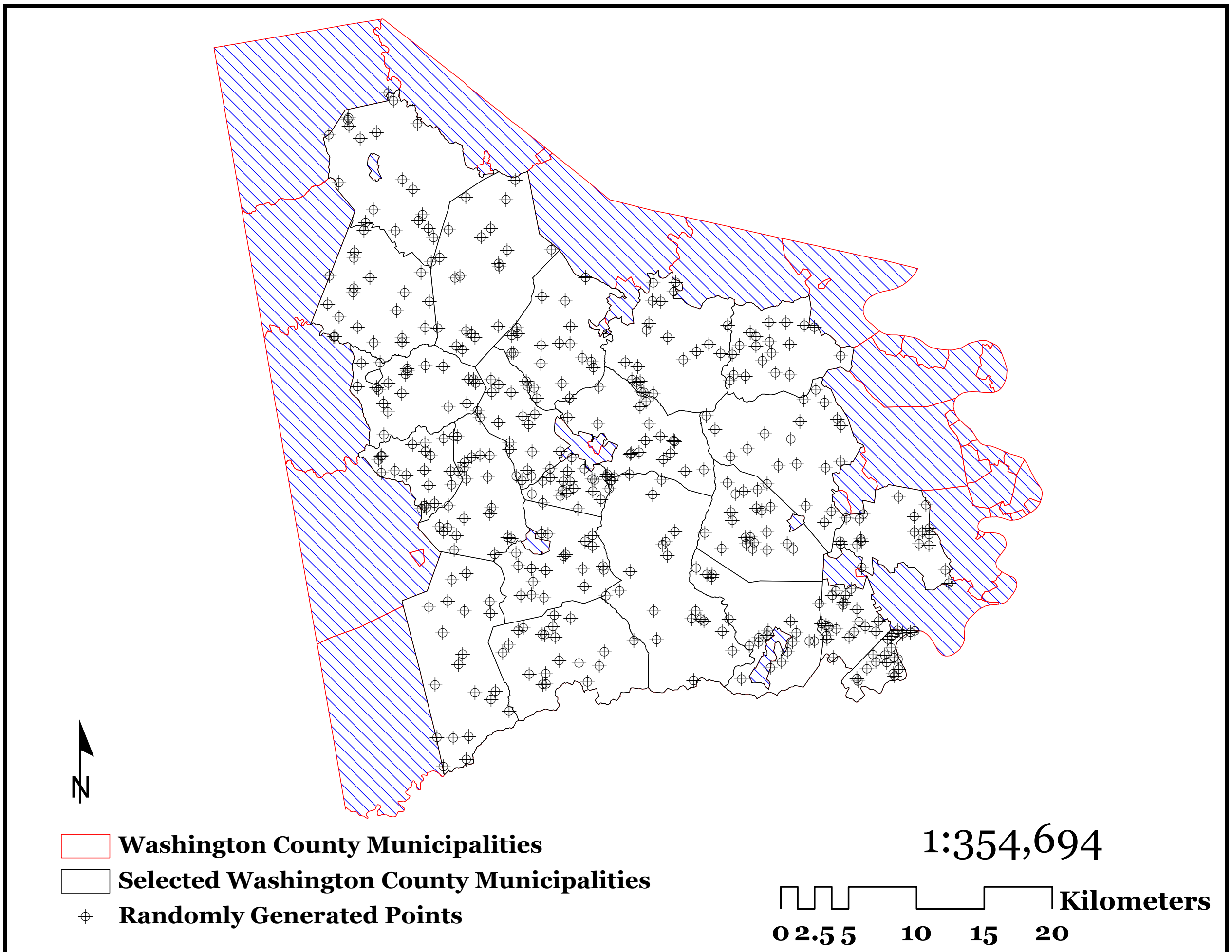

Figure 2. Distribution of randomly generated sampling points for eligible municipalities of Washington County, Pennsylvania, USA.

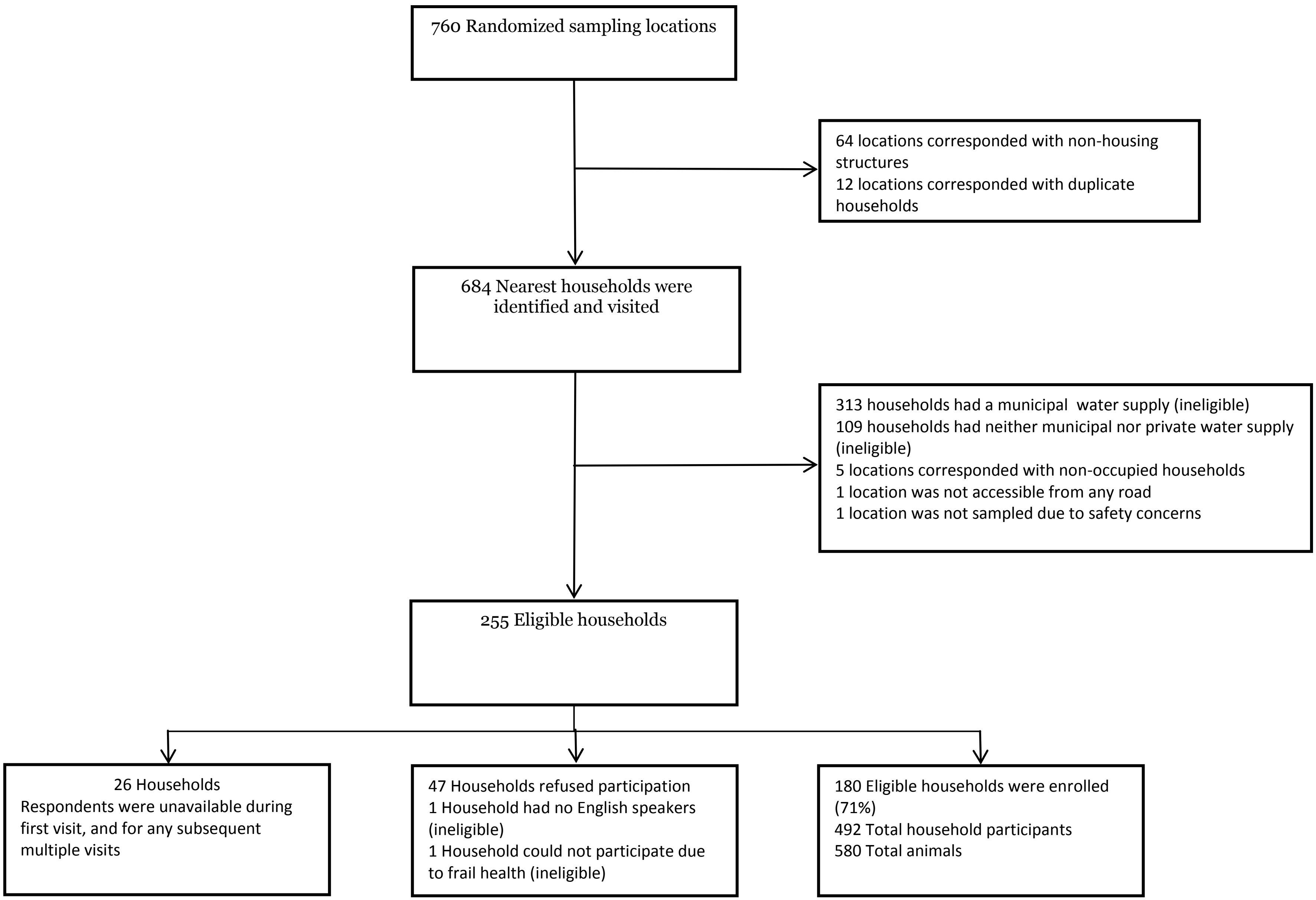

Figure 3. Screening, enrollment, and survey.

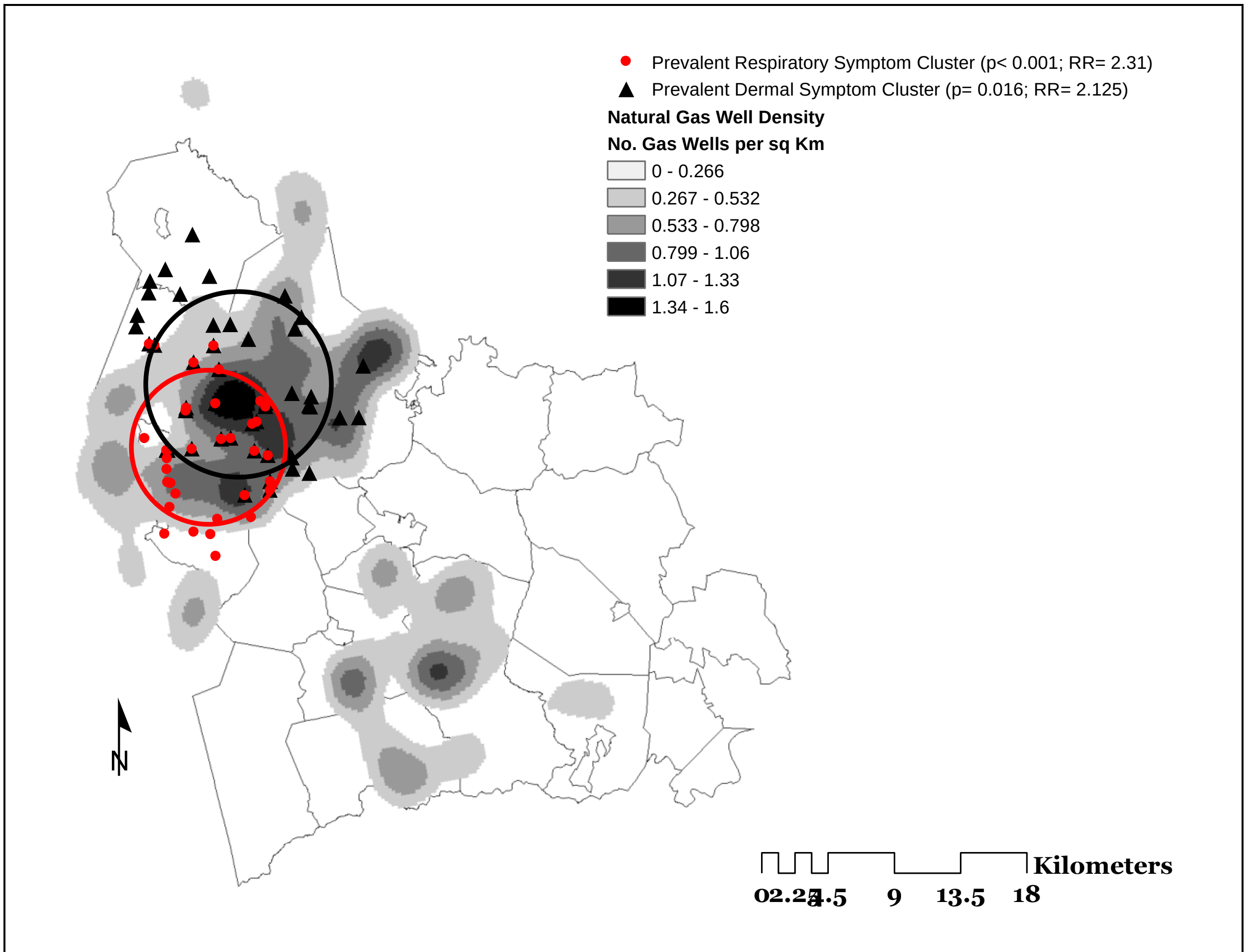

Figure 4. Summary of spatial cluster analysis via a Bernoulli model distribution to assess significant prevalent respiratory and dermatologic symptoms reported by members of households in proximity to natural gas wells in Washington County, Pennsylvania, USA.

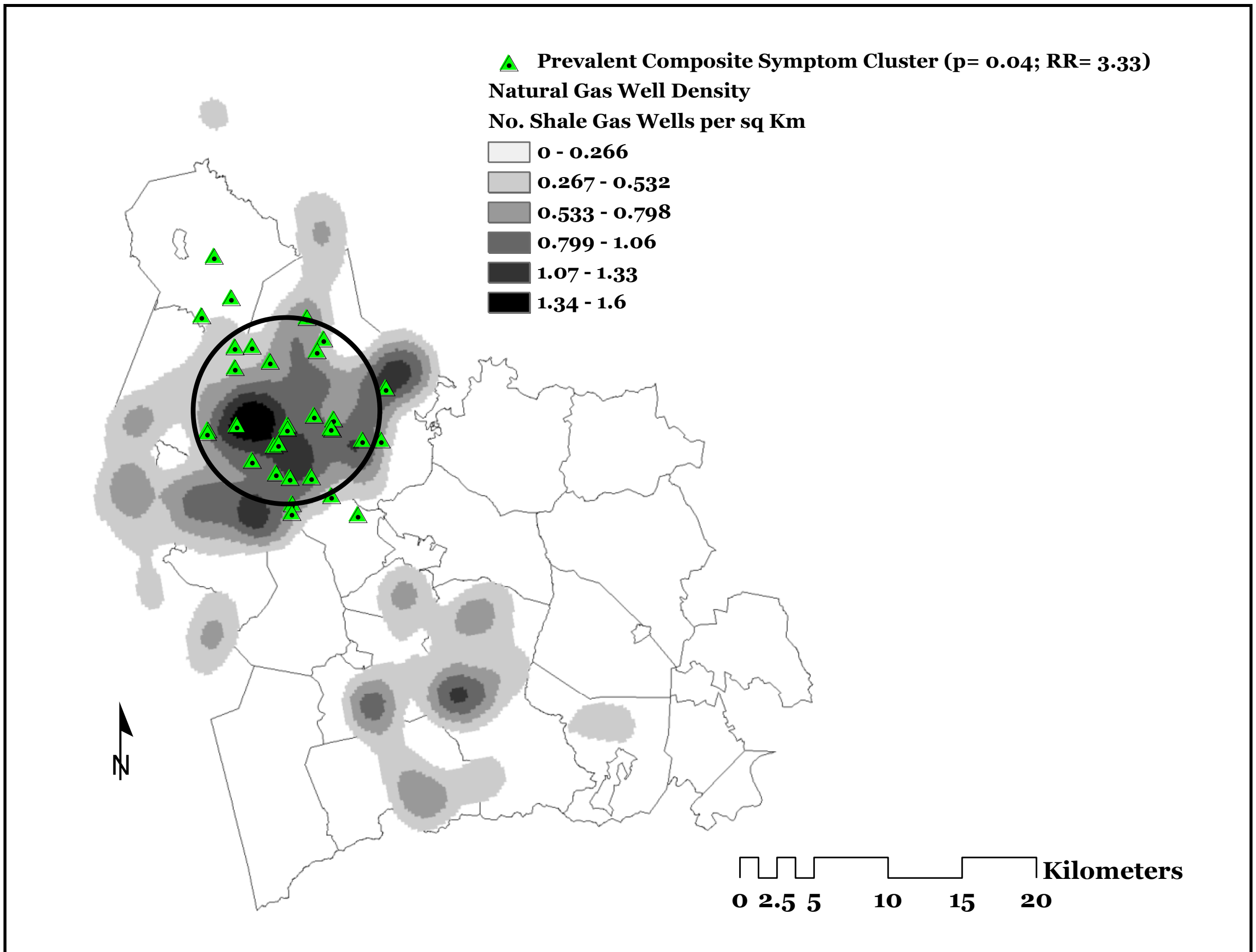

Figure 5. Summary of spatial cluster analysis via a Bernoulli model distribution to assess significant prevalent composite respiratory and dermal symptoms of household companion and backyard animals, residing in proximity to natural gas wells in Washington County, Pennsylvania, USA.

Table 1. Demographics of 492 Enrolled Study Participants by Proximity to the Nearest Natural Gas Well.*

Characteristic		*< 1 Km*	*1-2 Km*	*> 2 Km*	*All*
All household individuals					
Individuals—no.		117	110	265	492
Sex—no. (%)					
	Male	65 (56)	58 (53)	128 (48)	251 (51)
	Female	52 (44)	52 (47)	137 (52)	241 (49)
Education—yr					
	Mean ± SD	13.3 ± 1.96	13.6 ± 2.0	13.3 ± 1.9	13.4 ± 1.9
Age—yr					
	Mean ± SD	45.4 ± 21.8	48.3 ± 20.8	41.2 ± 24.1	43.8 ± 23.0
Occupation—no. (%)†					
	M/P	25 (21)	23 (21)	48 (18)	96 (19)
	O/S	14 (12)	9 (8)	19 (7)	42(9)
	BC	42 (36)	44 (40)	81 (31)	167 (34)
	NW	36 (31)	34 (31)	117 (44)	187 (38)
Household respondents					
Households—no.		48	45	87	180
Smoking—no. (%)‡		6 (12)	7 (21)	20 (33)	33 (18)
Body Mass Index—Kg / m²					
	Mean ± SD	27.4 ± 4.9	28.3 ± 4.8	27.6 ± 6.2	27.7 ± 5.5
Use groundfed water—no. (%)					
	Drinking	29 (60)	32 (71)	57 (65)	118 (66)
	Other	39 (81)	41 (91)	70 (80)	150 (83)
Water has unnatural appearance—no. (%)		8 (17)	7 (16)	5 (6)	20 (11)
Taste / odor prevents water use—no. (%)		11 (23)	10 (22)	22 (25)	43 (24)
Dissatisfied w/ Odor in environment —no. (%)		6 (13)	1 (2)	2 (2)	9 (5)
Environmental risk awareness—no. (%)¶		15 (31)	12 (27)	14 (16)	41 (23)

*Values may not sum to 100% due to rounding error.

†Participant occupation was categorized into six main industries according to the U.S. Census system, and presented here in four main groups: M/P—management or professional; O/S—office, sales, or service; BC—blue collar (fishing, farming, and forestry; construction, extraction, maintenance, production, transportation, and material moving); NW—no worker (student, disabled, retired, or unemployed).

‡Household smoking was determined when respondents were asked if they or at least one member of their household smoked cigarettes at the time of the survey.

¶ Household respondents were asked if they were aware of any environmental health risks near their residence (yes / no), to approximate potential sources of expectation or awareness bias.
Where appropriate, individual level data was compared while accounting for household clustering using a GLMM.

Table 2. Distribution of 580 Domestic Animals Enrolled into the Household Survey by Proximity to the Nearest Natural Gas Well.*

Species Type	***< 1 Km***	***1-2 Km***	***> 2 Km***	***All***
All companion animal individuals				
Individuals—no. (%)	153	170	257	580
Cats	56 (37)	63 (37)	68 (26)	187 (32)
Dogs	58 (38)	72 (42)	109 (42)	239 (41)
Large livestock	23 (15)	25 (15)	39 (15)	87 (15)
Poultry	5 (3)	7 (4)	19 (7)	31 (5)
Other	11 (7)	3 (2)	22 (9)	36 (6)

*Values may not sum to 100% due to rounding error.

Table 3. Prevalence of Selected Health Conditions Reported by Individuals by Proximity to the Nearest Gas Well*

Symptoms	***< 1 Km† (N= 117)***	***1-2 Km (N= 110)***	***> 2 Km (N= 265)***
Dermal—no. (%)	16 (14)	8 (7)	8 (3)
Rashes / skin problems	8 (7)	7 (6)	7 (3)
Dermatitis	4 (4)	5 (4)	4 (1)
Irritation	4 (4)	3 (3)	2 (1)
Burning	6 (5)	5 (4)	2 (1)
Itching	7 (6)	6 (5)	3 (1)
Hair loss	1 (1)	1 (1)	1 (0.4)
Respiratory—no. (%)	32 (27)	45 (41)	63 (24)
Asthma / COPD	11 (9)	15 (14)	26 (10)
Allergies / sinus problems	21 (18)	31 (28)	37 (14)
Chronic bronchitis	7 (6)	3 (3)	2 (1)
Chest wheeze / whistling	5 (4)	5 (4)	12 (4)
Shortness of breath	7 (6)	6 (5)	10 (4)
Chest tightness	4 (3)	6 (5)	5 (2)
Cardiac—no. (%)	32 (27)	36 (33)	54 (20)
High blood pressure	26 (22)	32 (29)	42 (16)
Chest pain	7 (6)	4 (4)	8 (3)
Heart palpitations	7 (6)	5 (4)	9 (3)
Ankle swelling	6 (5)	6 (5)	9 (3)
Gastrointestinal—no. (%)	11 (9)	14 (13)	14 (5)
Ulcers / stomach problems	9 (8)	7 (6)	10 (4)
Liver problems	4 (3)	0 (0)	1 (0.4)
Nausea / vomiting	1 (1)	3 (3)	1 (0.4)
Abdominal pain	3 (3)	3 (3)	2 (1)
Diarrhea	4 (3)	3 (3)	2 (1)
Bleeding	2 (2)	5 (4)	1 (0.4)
Neurologic—no. (%)	36 (31)	34 (31)	54 (20)
Neurologic problems	1 (1)	3 (3)	2 (1)
Severe headache / migraine	17 (10)	16 (14)	23 (9)
Dizziness/ balance problems	8 (7)	8 (7)	18 (7)
Depression	3 (3)	4 (4)	2 (1)
Difficulty concentrating / remembering	6 (5)	9 (8)	9 (3)
Difficulty sleeping / insomnia	14 (12)	15 (14)	18 (7)
Anxiety/ nervousness	7 (6)	6 (5)	13 (5)
Seizures	1 (1)	2 (2)	2 (1)

*Five categories representing major health conditions of *a priori* interest chosen to ascertain symptom prevalence amongst individuals living in proximity to the nearest gas well in 2011-2012.

†Values may not sum to 100% due to rounding error.

Table 4. The effects of Nearest Gas Well Proximity and Total Gas Well Density on Human Symptom Risk and Reported Health Status.

Model Outcome†	***< 1 Km***			***1–2 Km***			***> 2 Km***
Distance—OR (95% CI, P-value)							
Dermal	3.70	(1.4–9.9)	0.008	1.96	(0.7–5.9)	0.229	Ref
Respiratory	1.00	(0.6–1.9)	0.902	1.93	(1.1–3.5)	0.031	Ref
Cardiac	1.40	(0.7–2.6)	0.295	1.70	(0.9–3.2)	0.094	Ref
Gastrointestinal	1.50	(0.5–4.2)	0.422	2.03	(0.7–5.5)	0.164	Ref
Neurological	1.60	(1.0–2.8)	0.067	1.62	(0.9–2.8)	0.083	Ref
Gas Well Density—OR (95% CI, P-value)							
Dermal	1.08	(0.9–1.2)	0.140	1.14	(1.04–1.2)	0.006	Ref
Respiratory	1.10	(0.6–1.9)	0.600	1.10	(1.1–3.5)	0.700	Ref
Cardiac	0.90	(0.9–1.1)	0.500	1.00	(0.9–1.2)	0.200	Ref
Gastrointestinal	0.93	(0.8–1.1)	0.300	1.01	(0.9–1.1)	0.800	Ref
Neurological	1.65	(0.9–1.1)	0.080	1.03	(0.9–1.1)	0.300	Ref
SF-12 Health status—Mean ± SD							
Physical component score	48.2 ± 12.4			44.2 ± 14.0			50.9 ± 10.4*
Mental component score	51.8 ± 10.6			53.6 ± 9.1			53.1 ± 8.4

* p=0.03

†Hierarchical logistic regression models in all cases adjusted for age, education, gender, occupation, household smoking status, and awareness of environmental risk.

Table 5. Effects of Nearest Gas Well Proximity and Total Gas Well Density on Symptom Risk Amongst Companion and Backyard Animals*

Outcome	***< 1 Km***			***1–2 Km***			***> 2 Km***
Distance—OR (95% CI, P-value)							
Dermal / respiratory	1.3	(0.4–4.1)	0.65	0.8	(0.3–2.9)	0.84	Ref
Gastrointestinal	1.4	(0.2–10.1)	0.75	0.87	(0.1–7.5)	0.89	Ref
Any ailment	1.3	(0.4–3.5)	0.70	0.88	(0.3–2.6)	0.82	
Gas Well Density—OR (95% CI, P-value)							
Dermal / respiratory	1.03	(0.9–1.2)	0.73	1.05	(0.9–1.2)	0.53	Ref
Gastrointestinal	0.99	(0.7–1.3)	0.99	1.04	(0.8–1.3)	0.78	Ref
Any ailment	1.03	(0.9–1.2)	0.71	1.03	(0.9–1.2)	0.61	Ref

* Hierarchical logistic regression models in all cases adjusted for animal age, water source (well, spring, surface, cistern), and housing type.