Categorical Review of Health Reports on Unconventional Oil and Gas Development; Impacts in Pennsylvania

2019 | FracTracker Alliance Issue Paper

Kyle Ferrar, Western Program Coordinator

Erica Jackson, Community Outreach and Communications Specialist

Samantha Malone

Picture from Southwest Pennsylvania Environmental Health Project, Drilling rig behind house in Pennsylvania, 2013, Provided by FracTracker Alliance, fractracker.org/photos

Introduction

The “fracking boom”, brought about by advancements in directional drilling and hydraulic fracturing, has increased access to shale deposits of natural gas and oil across the United States. According to the Energy Information Administration (EIA), production of oil and gas in the U.S. has increased by nearly 60% since 2008, and in 2018, the U.S. became the world’s largest crude oil producer [1]. That year the U.S. produced an average of 10.88 million barrels of crude oil per day (Mb/d) and 83.26 billion cubic feet of dry natural gas per day (Bcf/d). The EIA predicts that these values will continue to rise in the coming years, reaching 13.2 Mb/d of crude oil and 92.1 Bcf/d of natural gas in 2020 [2].

These advancements including high volume, hydraulic fracturing, horizontal drilling, and massive multi-well well pads have allowed operators to access massive “unconventional” reserves deep within tight shale and other source rock. These same geological layers were once the source for conventional oil pools that are now largely drained. Production wells accessing these “unconventional” reserves can be grouped under the term unconventional oil and gas development (UOGD), which this report will use to address all forms of unconventional extraction, whether for oil, wet gas, or dry gas.

The federal government’s recent rollbacks on environmental policies, including pulling the U.S. out of The Paris Agreement, have aided the industry’s growth. In September of 2018, the Bureau of Land Management weakened methane controls for oil and gas production on public lands [2]. The following month, the Environmental Protection Agency proposed a rollback on its New Source Performance Standards rule, reducing the frequency of methane leak inspections (https://www.epa.gov/controlling-air-pollution-oil-and-natural-gas-industry/proposed-improvements-2016-new-source). Methane, a potent greenhouse gas, is emitted during oil and gas production through both leaks and intentional venting and flaring. Alvarez, Ramón A., et al. (2018) estimated that 2.3% of natural gas produced in the U.S. escapes as methane during production, an amount that has been significantly underestimated in the past and contributes substantially to climate change [3]. A currently pending publication by Dr. Robert Howarth’s laboratory at the Cornell University puts the full-cycle methane estimate at 4.1%, and concludes that the global increase in methane over the last 10 years has been driven by the oil and gas industry [4].

The Marcellus and Utica shale plays in the Appalachian Basin are major drivers behind the country’s increase in natural gas production. Spanning across parts of New York, Pennsylvania, Ohio, West Virginia, and eastern Kentucky, these shale plays accounted for 29% of the country’s total natural gas production in July, 2018 [5]. In addition to dry natural gas, the Appalachian Basin contains natural gas liquids (NGLs) such as ethane, propane, butane, isobutane and pentane. These NGLs, which are most abundant in the western portion of the Marcellus Shale, serve as feedstocks for petrochemical products, such as plastics and resins.

UOGD continues to grow in the U.S. despite falling natural gas prices. New markets, such as plastics manufacturing have helped to increase the demand for the glut. The shale gas boom and subsequent availability of NGLs in Appalachia has attracted the attention of plastic producers (which are often owned by oil and gas companies). The industry is rapidly building infrastructure in the region to support a major hub for petrochemical production, storage, and trading. In 2017, Royal Dutch Shell began construction on an ethane cracker in Potter Township of Beaver County, Pennsylvania to convert ethane to polyethylene plastics, the first plant of its kind built outside of the Gulf Coast in 20 years. Another ethane cracker is in the planning stages down the Ohio River in Belmont County, Ohio, and ethane storage opportunities are being explored in underground salt caverns and gas fields throughout Appalachia. The buildout also depends on a vast network of unconventional wells to extract NGLs, pipelines to transport them,

and natural gas processing and fractionation plants to separate components of the natural gas stream.

This infrastructure is increasingly encroaching on communities and residential areas. The Oil and Gas Threat Map, a joint project of FracTracker Alliance, Clean Air Task Force, and Earthworks, estimated that 12.6 million people live within the half-mile threat radius of active oil and gas wells, compressor stations, and/or processing stations [6]. The proximity of homes to development has raised significant public health concerns and community resistance since communities started raising concerns of exposure to groundwater and air contamination, beginning in 2007 and 2008. In Pennsylvania, a growing number of organizations and community groups have formed to address these concerns. The Southwest Pennsylvania Environmental Health Project assists residents who believe their health has been impacted by unconventional oil and gas development (UOGD). This nonprofit also conducts research into the health effects of UOGD, contributing to a growing body of academic literature on this topic.

The breadth of literature focused on the community and environmental health effects of living in proximity to extraction activities (exploration and production) has been growing, largely since 2009.

A previous, very thorough review by Hays and Shonkoff (2016) categorically analyzed primary health literature spanning 2009-2015 [7]. That specific time frame focuses on ramping development of unconventional shale and “tight-gas” throughout the world. During that period 685 papers were published in peer-reviewed scientific journals, 226 of those (33%) were health-focused. Major findings in the Hays and Shonkoff report found that 85% of public health studies were positively correlated with adverse health outcomes. Additionally 69% of water quality studies contained findings that indicated potential or actual incidence of water contamination and 87% of air quality studies showed elevated air pollutant emissions or atmospheric concentrations. Since 2016, the body of literature has expanded to the point where the topics covered in Hays and Shonkoff (2016), (air quality, groundwater impacts, and health impacts) would each benefit from independent reviews.

In this report, we conduct a thorough review of health impacts research spanning 2016-2018. This assessment includes all literature associated with the public health impacts of unconventional oil and gas development. We screened the entire body of literature published between January 1, 2016 and December 31, 2018. Study results were extracted from research in 24 shale plays. Study methods and results were categorized in order to analyze the growth of literature in this field, and to provide an overview of the current understandings of risks resulting from UOGD. We then apply what is relevant and can be considered consistent across geologies to the current state of UOGD in Pennsylvania.

Methods

This paper reviews the recent health impacts literature published since January 1, 2016. We focus our analysis on public health studies published following the Hays and Shonkoff (2016) review. We screened the entire body of literature using a categorical method, and extracted results from research in all shale plays. The literature was limited to health impacts studies and toxicological assessments of drilling and production related chemicals. Risk summaries that simply provided toxicological profiles using remote-sourced literature such as material safety datasheets were not included. Using this breadth of primary public health literature we summarized trends in findings and categorize potential health outcomes. We applied what is relevant and known to be consistent across geologies to a risk assessment of Pennsylvanian communities living proximal to Marcellus Shale Play development.

Data Collection

The studies reviewed are not limited to the hydraulic fracturing process, which is one short phase of an entire industrial process that brings hydrocarbons through a bore hole to consumers. The reviewed literature assesses the entire process of exploration and production. Studies on midstream infrastructure are included as well. This timeframe spans from initial grading and construction of the support infrastructure and well-pads, through drilling and completion (hydraulic fracturing or other stimulation techniques) to daily production and well-site maintenance, as well as the infrastructure necessary for transporting raw crude and natural gas off site and products to market.

This review was completed using three near-comprehensive databases that compile literature focused on and related to the environmental and community health impacts of unconventional oil and gas development. They include the following:

- Resources for the Future (RFF) database
- The Endocrine Disruption Exchange (TEDX) FrackHealth database,
- Physicians, Scientists, and Engineers (PSE) ROGER database

Following a review of these databases, we conducted Google Scholar searches to check for additional Pennsylvania-specific research.

Literature searches were limited to a time period beginning January 1, 2016 to December 31, 2018. Search criteria included “Pennsylvania health “oil and gas”” and “Pennsylvania health unconventional oil and gas.” Several manuscripts that were in the process of peer review publication, and then published in early 2019 were also included due to their significance in the field. The review focused on peer reviewed literature, and rigorous gray literature, such as government reports, within PA communities.

Finally, a review of the research listed on the Southwest Pennsylvania Environmental Health Project’s (EHP) website was conducted. This website contains both research that EHP has contributed to and other health studies using Pennsylvania data.

Categorization

In addition to listing the health impacts documented by each study, studies were catalogued with a variety of identifiers, listed below. Some categories were binary, others were organized by key words. Binary indicators were used to break studies into categories, such as according to whether a) a health impact was noted; and b) if water / air resources were impacted.

Study identifiers include:

- Citation
- Year
- Original research or review
- Health impact paper or toxicological assessment
- Evidence of impact or risk detected- yes or no
- Type of health impact or risk detected
- Media impacted – yes or no
- Type of media impacted (air or water)
- Source of concern
- Type of development: unconventional, conventional, and or petrochemical
- Petro type

- State(s) or country(ies)
- Primary publishing institution
- Publication type
- Peer-reviewed - yes or no
- Database

Health impact studies included epidemiologic studies and exposure assessments including those that use proxies for exposure targets, such as those focused on measuring exposures at receptor sites.

The source of concern describes the activity that may cause a health effect, such as living near development or a wastewater spill. The “petro type” category identifies the material studied in the literature, such as oil or gas. The “media impacted” category lists known or discussed exposure pathways such as air or water as well as the known or hypothesized source of risk. Sources of risk included hydraulic fracturing fluid, silica sand, wastewater, drinking water contamination, diesel particulate matter, volatile organic compounds (VOCs), proximity to well sites and drilling, well completions including hydraulic fracturing, radon, flaring, noise, and general degradation of air quality. Environmental justice studies were also included.

Due to the large number of research articles to screen and process, three FracTracker Alliance staff researchers conducted the literature review and subsequent categorization in tandem. Researchers included Erica Jackson, Samantha Malone, and Kyle Ferrar. Techniques were synchronized prior to the start of the categorization, but reviewer bias remains a consideration for these methods. Quality control was conducted by a single researcher, Kyle Ferrar, to alleviate bias and help assure consistent assignment of categories.

Pennsylvania Setbacks

This study also considered implications and risk zones for Pennsylvania communities proximal to the development of the Marcellus Shale Play. Results of the study including exposure distances, hazardous chemicals, and impacted population were assessed in term of the threat to Pennsylvania communities within the Marcellus Shale Play. This play has motivated the most attention on hydraulic fracturing and the rest of the invasive industrial processes involved in unconventional natural gas development (UNGD) in the literature and media.

Using Geographic Information Systems (GIS) techniques and ESRI ArcGIS Pro V2.0.1.8933 software, a spatial analysis of Marcellus wells was conducted. Two mile, one mile and half mile buffers were generated around well-sites, and population counts within these buffer zones were calculated. Buffer distances were determined based on existing epidemiologic and exposure assessment literature [8-11]. Using U.S. Census Bureau 2015 American Community Survey population data at the census tract level, population estimates were calculated based on percentage of landmass located within the buffer zone. Maps showing population counts, as well as well counts by county are shown. Maps of well and compressor station locations were also created.

Results

The constraints of the literature review limited the total count to 156 public health studies which were initially categorized and considered. Upon further inspection, a total of 142 research articles were determined to fit this study’s criteria and were included in this review. Studies that were eliminated included original research that was not published in peer review journals; assessments of public health impacts from coal seam gas rather than tight shale gas; groundwater, surface water, and air analyses; studies focused on geological tracers of contamination sources; analyses of spills etc... Much of it provides detailed insight into the

impacts that result from the less publicized support activities that accompany the continual production of oil and gas, but not specifically related to health impacts. While not included in this review, the exposure assessments conducted by the SWPEHP model with concentration measurements of BTEX chemicals at homes near Marcellus Wells, compressor stations, and during pipeline maintenance activities such as the cleaning process known as PIGGING are of particular note [10, 12, 13]. The full list of studies included in this review are listed in the Appendix.

A longitudinal breakdown of the studies reviewed shows increasing numbers of studies published per year. From 2016 to 2018, the number of studies increased from 41 to 51, an increase of 19.6%. The proportion of health impact studies to toxicological assessments also increased from 48.8% to 52.9%. Figure 1 and 2, below, provide visual break downs of the studies published, by year.

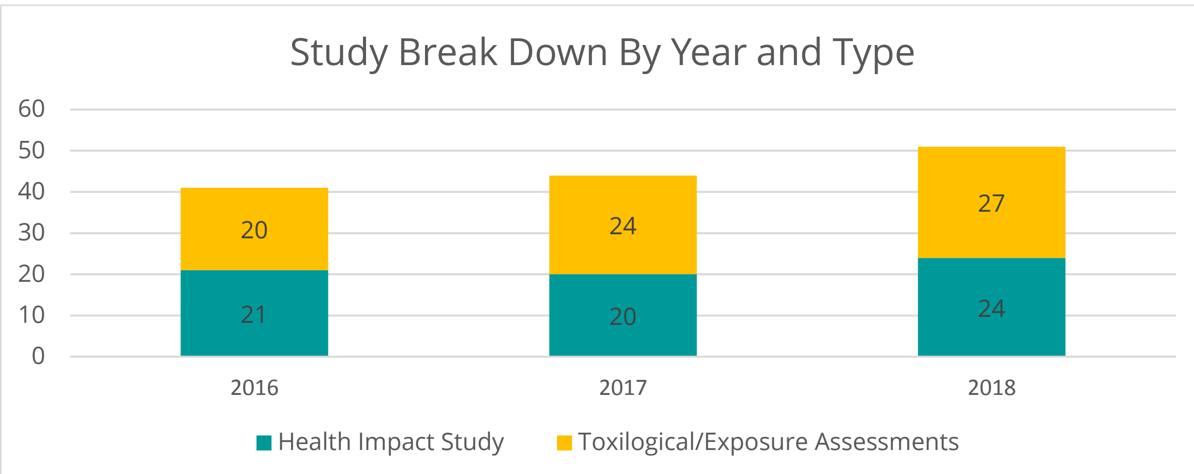


Figure 1. Research articles of health studies focused on UOGD by year. Health studies are separated into those that assessed health impacts using epidemiologic methods or exposure assessments and toxicological assessments. Review articles are also included.

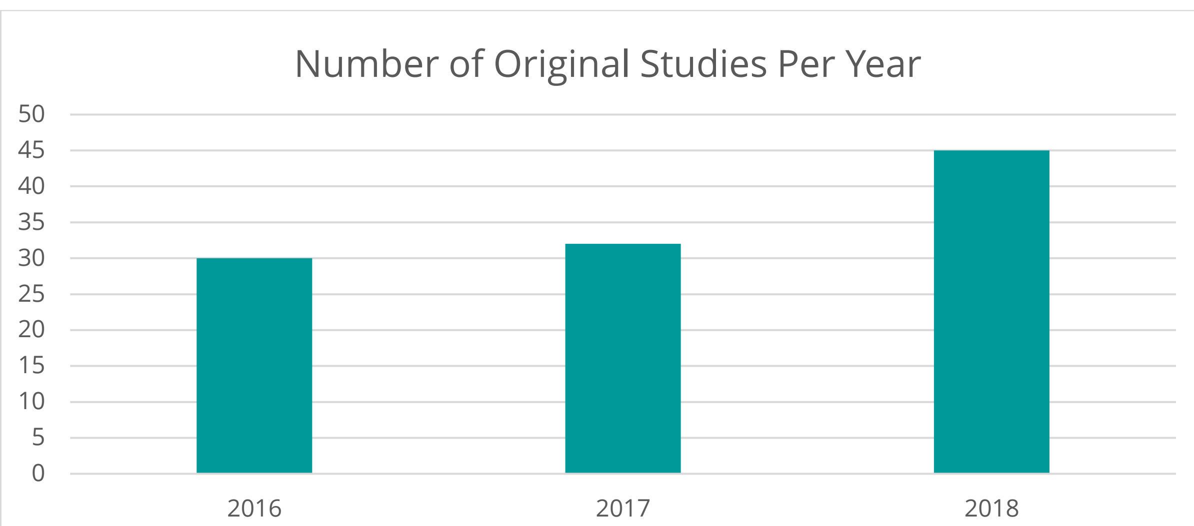


Figure 2. Research articles that reported original research on UOGD by year. Research reporting on original results, as opposed to regulatory reports and summary review articles, were counted.

Of the 142 studies in our sample population (including 5 published in 2019), a total of 127 reports 89.4%) indicated a positive relationship of UOGD with health impacts. There were a total of 106 articles that published new, original research, with 104 focused on health impacts. Of these 104 articles, 94 indicated a positive relationship with health impacts (90.3%). A visual breakdown of these categories is shown in Figure 3, below.

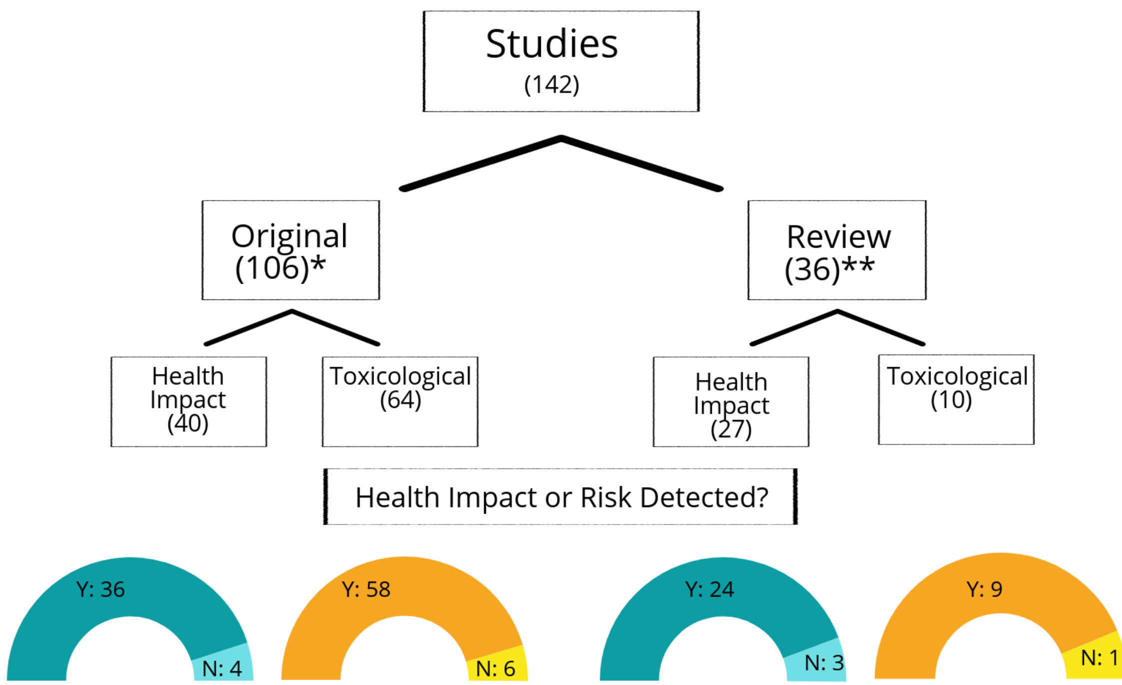


Figure 3. Breakdown of Public Health Studies published 2016-2018. Studies were categorized by study type and whether the journal articles were original research or review articles. The proportion of studies that found positive correlations of UOGD with health impacts is also shown. *Two studies were not categorized as “Health Impact” or “Toxicological”. **One study fell under both “Health Impact and Toxicological” categories.

There were a total over 24 categories of health impacts and symptoms associated with 14 separate bodily systems reported in the health impact studies. Bodily systems impacted by symptoms include impacts to eyes, ears, nose, and throat; brain and nerves; skin, hair, and nails [14-18]; mental health and behavior [19-23]; reproduction and pregnancy [8, 15, 16, 24]; endocrine system [25-27]; respiratory [28]; cardiovascular and pulmonary [29]; blood and immune system; kidneys and urinary system [30]; general health; sexual health; and physical

health. Specific health impacts reported in the studies included mortality, asthma and other respiratory outcomes [31-33], cancer risk including hematologic cancer [34], impacts on pregnancy and birth outcomes [8, 24, 35-38], silicosis [39], impacts on quality of life including self-reported stress [21, 40-43], annoyance and sleep disturbance from noise and light exposures [21, 44], physical injury [45, 46], sexually transmitted infections [47, 48], general health symptoms such as fatigue [40, 48], pneumonia hospitalizations [49], and skin-related hospitalizations [50].

Pennsylvania Analysis

An impressive 70 studies (49.3%) were in some way associated with Pennsylvania (PA) and the Marcellus Shale, and 28 studies were focused exclusively in PA. Criteria for determining association varied based on the type of study. In the case of epidemiology and health impacts studies, sample populations were located solely in PA or in PA and other regions. For toxicology studies, analytes were sampled from sources in PA, and for exposure assessments, monitoring was conducted in PA, or PA was the source of the data. Of the 70 total, 66 were health impact studies and 4 were toxicological assessments; 26 were reviews of existing literature. The annual publication counts of these PA studies are shown below in Figure 4.

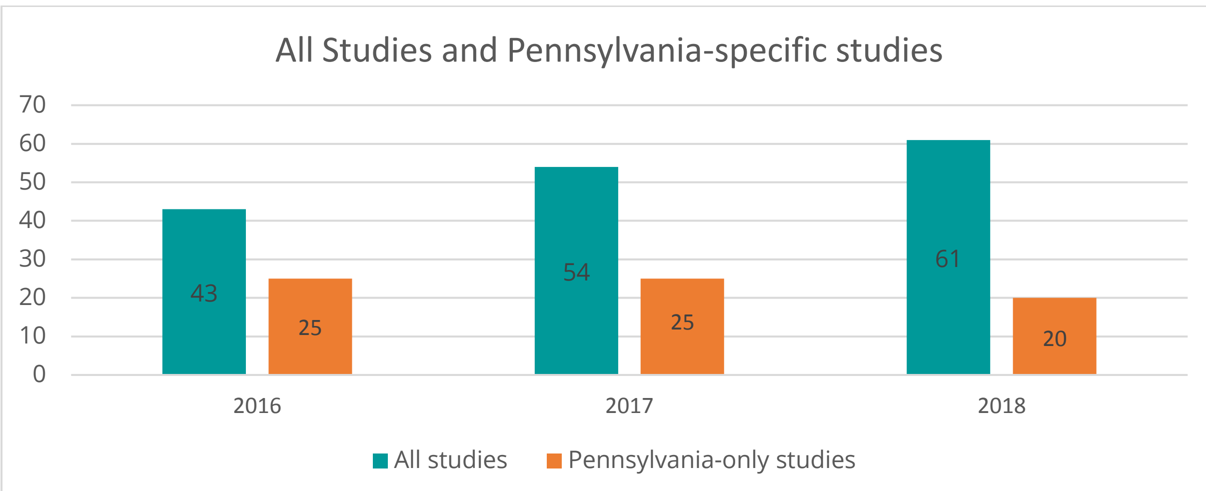


Figure 4. Pennsylvania articles vs all reviewed articles, by year. The counts of PA articles were graphed alongside the total count of articles included in this review. The total count of PA articles is roughly half the total.

Health impacts associated with Marcellus development include respiratory symptoms and illnesses, including increased risk of mild, moderate, and severe asthma exacerbations and pediatric asthma [31, 33, 51-53]; silicosis [39]; pulmonary impairment [54]; self-reported stress [43]; adverse impacts to general quality of life [55]; adverse mental health impacts including depression [20]; impacts from noise disturbances including disrupted sleep and worry about health [44, 51]; cancer [56, 57]; liver damage, immunodeficiency, and neurological symptoms [56]; impacts on pregnancy and reproduction, including increased risk of infant deaths [36, 58]; increased low birth weight and decreased term birth weight [24]; and association with preterm birth [35]; increased rates of sexually transmitted diseases, including gonorrhea and chlamydia [47, 59]; Brain and Nerves [52]; as well as migraines and headaches [51, 60].

Of the 28 studies that focused specifically on PA, there were a total of 19 health impact studies, of which 15 (78%) found evidence of a health impact and 4 of which did not. The review yielded nine Pennsylvania- specific toxicological and exposure assessments of UOGD. A total of seven

studies found evidence of health risks from modeled scenarios, chemical characterization, and/or toxicological testing.

Important Health Impact Findings

- Cancer outcomes, including Non-Hodgkins lymphoma [62], and urinary bladder cancer [61]
- Impacts on pregnancy and development, including association with early infant mortality, pre-term birth, and poor infant health [24, 35, 36, 58]
- Impacts on mental health and well-being, including depression, self-reported stress, worry about health, and sleep disturbances [20, 43, 44]
- Pneumonia hospitalizations rates in elderly populations [49]
- Increased risk of asthma exacerbations [31, 33]
- Skin-related hospitalizations [50]
- General health symptoms, such as headache, fatigue, nasal and sinus impacts, and throat irritation [51, 60]
- Impacts on sexual health, in particular gonorrhea and chlamydia rates, which may be driven by demographic and population changes where unconventional oil and gas development occurs [47, 59]
- A Delphi study to determine adequacy of current current setback distances from unconventional oil and gas development found that current distances do not protect public health [10]
- Radon concentration at wellheads is strongly correlated with production rate, and poses hazard to the public and environment [67]
- Risk assessment of residential exposure to contaminated drinking water from a modeled spill of flowback water poses cancer risk from radiouclide exposure and non-cancer risk from barium and thallium exposure [63]
- Risk assessment of exposure of contaminated drinking water from a spill of flowback water poses excess lifetime cancer risk and exposure to barium and lithium in drinking water pose non-cancer risk [64]
- Exposure to contaminants in unconventional oil and gas wastewater spread on roads, poses a health risk from release of salt, radioactivity and organic contaminants into the environment, at concentrations above drinking water standards. Toxicological studies indicated that the organic micropollutants in watewater caused toxicity to aquatic organisms like Daphnia magna [65]
- Chemical characterization and toxicologic research of fracking fluids and wastewater pose the possibility of “toxicity to human organs, sensitization, irritation, developmental effects, and tumor promotion” [66]
- A modeled scenario of exposure patterns of volatile organic compounds (VOCs), particulate matter (PM) and diesel found periods of extreme exposure which correlate with the documented peaks in reported health complaints [68]

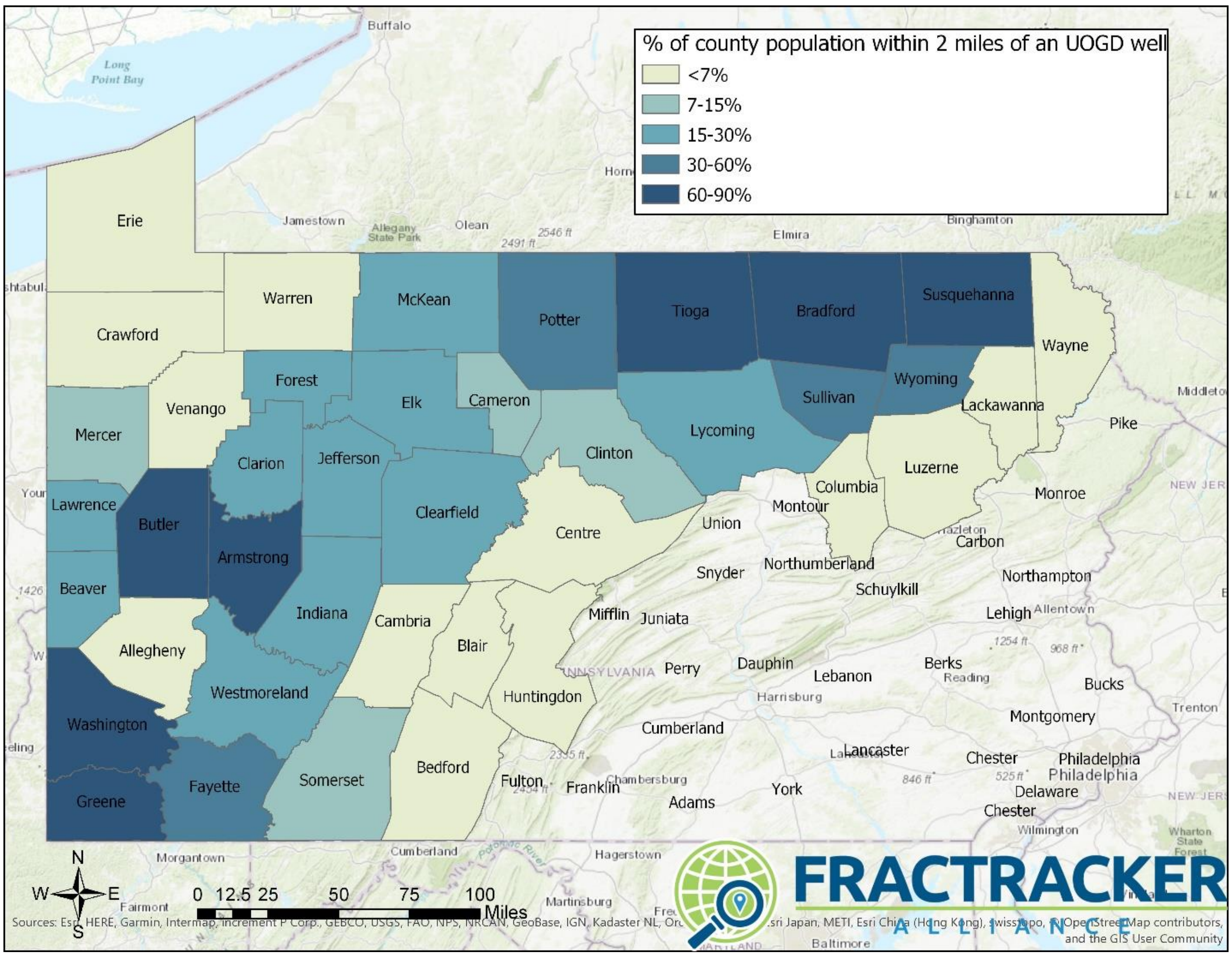
FracTracker Geospatial Assessment

Our own geospatial analysis of well sites and census data showed that an estimated 170,232 individuals (3.4% of the total PA population count) live within a half-mile of an unconventional well in Pennsylvania, and an estimated 226,521 (4.5% of the total population) live within a half-

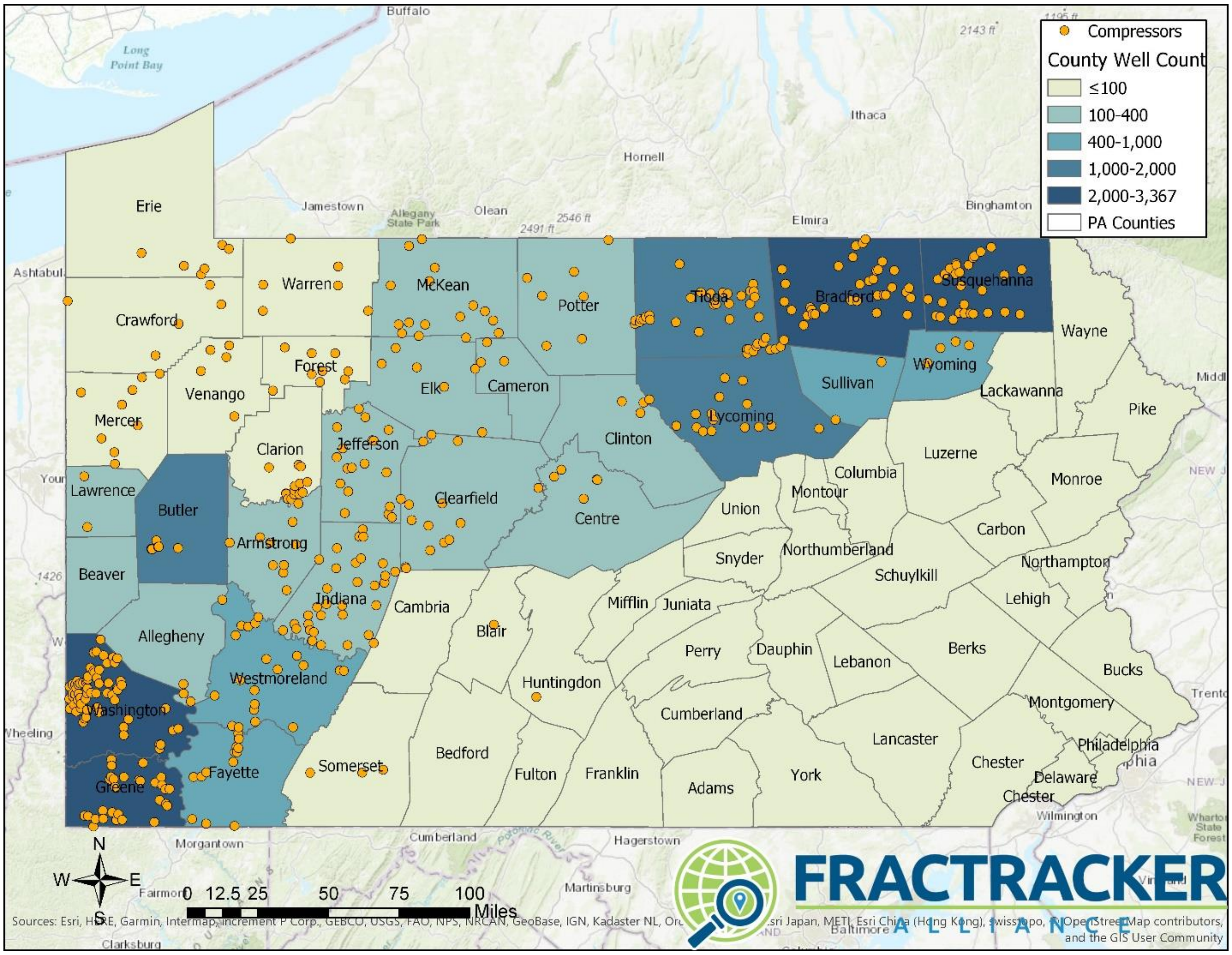
mile of a permitted site. An estimated, 446,891 (8.9% of total state population), live within 1 mile of an unconventional well in Pennsylvania, and a total of 582,395 (11.6%) live within a 1 mile distance of a permit. Population counts for the 2-mile setback distance are 954,728 (19.1%) and 1,229,198 (24.6%) of Pennsylvanians proximal to unconventional wells and permitted sites, respectively. The populations under 18 remain consistent at around 20% of the impacted counts for all studied setback distances. Table 1 shows the results of these analyses for both wells and permits. The analysis used U.S. Census Bureau 2015 American Community Survey Data. Counts were summarized by county, and are shown in Map 2 below. Map 3 shows well counts by county, and also includes locations of compressor stations.

Table 1. Setback analysis population counts for PA. A setback analysis was conducted at 3 distances from well-sites and issued permits in PA, 0.5 mile, 1.0 mile, and 2.0 miles. Using 2015 ACS census data, population counts were estimated within these setback distances.

	Affected Population Near Wells				Affected Population Near Permits			
Study Distance	**Total Pop**	**Pct Total**	**Under 18**	**Under 18 Pct**	**Total Pop**	**Pct Total**	**Under 18**	**Under 18 Pct**
0.5 Mile	170,232	3.4%	33,932	19.9%	226,521	4.5%	45,077	19.9%
1 Mile	446,891	8.9%	89,056	19.9%	582,395	11.6%	116,104	19.9%
2 Mile	954,728	19.1%	190,777	20.0%	1,229,198	24.6%	244,860	19.9%



Map 2. Population percentages of Pennsylvanians living within 2 miles of an UOGD well-site, summarized by county. Estimates were produced using U.S. Census Bureau 2015 ACS data.



Map 3. Unconventional well counts by county. Well counts were summed by county using GIS techniques. Well counts are provided in the map, and are overlaid with the locations of compressor.

Discussion

Comparison with previous reviews

Since 2016, exposure assessment research has grown substantially. By the end of 2015, there were 31 peer reviewed health impacts articles containing original research [7]. Through 2018, the number has grown by 104 research articles. The ratio of articles finding positive relationships between UOGD and elevated health risks or actual health impacts has also increased, from 80.4% to 90.3%.

A consistent conclusion in these reviews remains true. While the number of quantitative epidemiologic studies has grown (40 were published during the study time frame), more high quality epidemiologic studies are necessary to determine the specific causes of health impacts, whether they are attributable to chemical exposures or allostatic load (stress). The ratio of health outcome studies is limited because comprehensive epidemiologic research is expensive, time consuming, and suffers from inaccurate exposure assessments and “drawing conclusions

about the magnitude of health burdens attributable to UNGD remains difficult from an epidemiologic perspective.” An epidemiology review by Stacy (2017) states “additional work using more granular estimates of exposure or personalized monitoring is urgently needed” [69].

That is not to say that the literature does not clearly indicate a multitude of health impacts that have resulted from UOGD near communities. The extent to which the health of individuals and communities has been impacted is what still needs to be determined, as well as the particular risk drivers for each case. More high quality epidemiologic studies are necessary to track impacts and understand the consequences of liberal permitting processes and lack of public health regulations to prevent or reduce exposures. The primary exposure pathways documented by reviewed literature included degraded air quality (26.1%), groundwater contamination (5.6%), surface water contamination (3.5%), or a combination of the three (53.5%). Additional exposure pathways included consumption of exposed livestock and fauna, citrus and other produce.

Several studies identified knowledge gaps surrounding the risks of chemicals used in hydraulic-fracturing fluids and/or wastewater. Specific gaps include lack of toxicity information [70], including chronic oral reference values for non-cancer impacts, and oral slope factors for cancer [71], and lack of evaluation by the International Agency for Research on Cancer [41]. Furthermore, a lack of proposed federal water quality standards for chemicals with known health impacts, and differences in classifying chemicals amongst countries and agencies pose challenges to preventing exposure.[72] The lack of industry transparency surrounding hydraulic-fracturing chemicals exacerbates concerns about the health impacts of exposure. Many states, including Pennsylvania, allow exemptions to rules that require public-disclosure of chemicals used in fracking fluids. A report by Partnership for Policy Integrity (PFPI), with data analysis by FracTracker found that between 2013 and 2017, drilling companies injected at least one chemical with an undisclosed identity into over 2,500 unconventional natural gas wells drilled in Pennsylvania [73]. Additionally, an EPA assessment found that chemicals reviewed and approved by EPA for use in fracking had known toxic effects and some of those approved (with toxic effects) were used in PA in the Marcellus Shale play. These are some of the same chemicals known to have been kept confidential as Trade Secrets [73].

Epidemiologic Assessments

Epidemiologic studies are incredibly important to the advancement of knowledge, because they measure the change experienced by a population as a response to the stimulus, which in the case of this review is UOGD. The list of high quality peer-reviewed epidemiologic assessments has grown increasingly each year but still remains short. The majority of studies have used proximity metrics as a proxy for exposure, and some have included well density metrics as an additional indicator of exposure. Evidence for health impacts were measurable at various distances from UOGD, including half-mile, two mile, 15km, and even 10 mile distances [8, 36]. Evidence of risks to infant health, including low birth weight were found when mothers lived within three kilometers of unconventional oil and gas development [24, 36].

Most studies thus far have been retrospective. Health response data is therefore limited to self-reported symptoms and electronic health databases. These remote-sensing methods allow researchers to obtain high sample counts and generate powerful statistics, but critics state these study models do not have the resources to link human health outcomes directly to a unique source of pollution, such as an unconventional well-pad or a compressor station. On the other hand, frontline communities declare that the causal relationship of UOGD to health impact is clear. Results of epidemiologic studies included in this review (2016-2018) are discussed below:

Early life exposure, including prenatal exposure has been the most studied topic. Researchers have documented relationships between UOGD and is associated with adverse birth outcomes and morbidity in children. A Pennsylvania study showed developmental, structural and functional birth defects were found to result from proximity to UOGD[38]. Pennsylvania studies have also measured preterm birth (<37 weeks) [8, 9, 35]. These studies and others from Pennsylvania populations have also documented low birth weight due to prenatal exposures[36]. Fetal death and early infant mortality have also both been epidemiologically linked to UOGD [8, 58].

Pennsylvania epidemiologic research has also shown that exposure to UOGD is associated with respiratory outcomes including asthma exacerbation in children and adults [31]. A relationship was found between UOGD and oral corticosteroid orders, asthma emergency department (ED) visits, and hospitalization.

Pennsylvania hospitalization rates show relationships of exposure to UOGD and acute myocardial infarction (MI), chronic obstructive pulmonary disease (COPD), pneumonia, and other upper respiratory disorders [49].

More research from Pennsylvania showed impacts including current chronic rhinosinusitis, migraines, fatigue, all related to neurological impacts [60].

The relationship between cancer and proximity to UOGD has also been established in the Pennsylvania literature. Cancer types include all childhood leukemia subtypes, urinary bladder cancer, and thyroid cancer [61], and research in Colorado discovered correlations with acute lymphoblastic leukemia and Non-Hodgkin's lymphoma [62].

Studies on the county level, comparing counties where unconventional oil and gas development has occurred with those where it has not, found elevated hospitalization rates for pneumonia among older populations in Pennsylvania, consistent with higher levels of air pollution and reports of stress and feelings of powerlessness in Pennsylvania.[43, 49] An analysis by the Clean Air Task Force found that 238 counties in 21 states face cancer risk from oil and gas air toxins that above the Environmental Protection Agency's one-in-a-million threshold level, with the greatest concerns in Texas, Louisiana, Oklahoma, North Dakota, Pennsylvania, and Colorado [74].

Exposure Assessments

Exposure assessment studies have mostly focused on air pollution and emissions from UOGD. This pathway is considered the primary pathway of exposure for frontline communities. Groundwater contamination is possible and has occurred from hydraulic fracturing and wastewater injection. More thorough analyses of pathways will illuminate the determinants of fate and transport. The PA Department of Environmental Protection officially acknowledges 335 cases of groundwater contamination caused by Marcellus Shale development. An important finding is that there is a lack of groundwater studies focused on health impacts. This is due to the difficulty of tracking the transport of pollution through groundwater. Movement through the subsurface environment takes time and evaluating groundwater contamination requires monitoring as well as the presence of a population of groundwater wells to sample, each of which are not as available or obvious as data and effects of air pollution (air being more observable and acutely experienced).

In the existing literature the contribution of UOGD to local and regional air pollution is the most widely acknowledged as well as the most geographically widespread risk driver, affecting the greatest number of communities. Below we summarize results of some of the exposure

assessments reviewed. We discuss the cocktail of pollutants that have been assessed as transported through air and water. These are known risk drivers with documented human health impacts. The specific pollutants were found to pose exposure risks and should be prioritized by regulators.

Exposure to volatile organic compounds (VOCs) are a particular concern for unconventional oil and gas development. Modeling of exposure patterns found that greatest exposure to VOCs occurred during the drilling, flaring, finishing, and gas production stages in the development and production of a well pad [68]. An analysis of VOC exposure found no elevated levels 500 feet or greater from a well in Colorado [75], and monitoring of VOC levels 900 meters from wells during fracturing and flaring found no elevated levels in Pennsylvania [76]. However, acute and chronic non-cancer risk and acute cancer risk was detected from occupational inhalation exposure of VOCs found in certain chemical storage tanks and flow back pits in the United States [77].

Exposure to particulate matter from unconventional oil and gas development was associated with silica-induced lung injury, inflammation and onset/incidence of fibrosis [78], chronic neurological diseases in young children [79], cardiovascular and respiratory symptoms [80], hospitalizations of pneumonia [53].

Exposure to noise pollution found levels above health and annoyance thresholds in Colorado, and West Virginia [81-83]. Evidence of disrupted sleep from noise pollution was found in Pennsylvania and caused reported psychological stress in Ohio [21].

Exposure to silica from quartz sand used as “proppants” to open fissures in shale formations was the focus of six studies. A retrospective assessment of silica exposure amongst workers in industrial sand facilities found that the cumulative exposure in workers with silicosis was more than twice the exposure of the control group [39]. While the study included workers from before the onset of unconventional oil and gas extraction, exposure to silica is a likely contributor to future cases of silicosis in the oil and gas workforce in the United States if safety measure are not taken [28, 78, 84]. Community exposures to particulate matter from sand mining activities were found to be unlikely to cause chronic adverse health conditions at a study site in Wisconsin [85]. Rats exposed to silica dust and diesel PM had the capacity to increase silica-induced lung injury, inflammation and onset/incidence of fibrosis [78].

Assessments of occupational risk to the oil and gas work force found risks including exposure to air toxins and flowback fluid from inadequate safety practices, equipment failure, and illegal practices [63], sudden cardiac death from exposure to high concentrations toxins during manual tank gauging [86], and risk of cancer from exposure to benzo(a)pyrene in flowback water and other increased risk of adverse health effects from exposure to benzene [63, 87, 88].

Pennsylvania GIS Analysis

Our GIS analysis of Pennsylvania leases and Marcellus wells shows that UOGD has the greatest impact in the northeast and southwest parts of the state, with Washington, Greene, Bradford, and Susquehanna Counties containing the highest well counts (between 2,000 and 3,367). In these five counties, in addition to Butler and Armstrong Counties, the majority of the population (>60%) is within two miles of an UOG well. In total, well over one million Pennsylvanian residents live within two miles of a permitted unconventional well site; 25% of them are children. An estimated 446,891 people live within one mile of a well (9% of which are under the age of 18), which is within distances associated with greater incidence of low–birth weight and declines in measures of infant health [58] [36]. Epidemiologic studies on PA frontline communities have shown increased asthma exacerbation [31], pre-term birth,[8] infant Mortality [58], Depression symptoms [89], pneumonia hospitalization [90], and STIs [48, 91]. Communities affected by UOGD have also reported stress [40] and sleep disturbances [7, 92].

Policy

The energy extraction industry's hold on state economies and other mid-level governments, particularly at the county level, has restricted local control of permitting restrictions and setback regulations. These governmental tiers appear to be the most influence-able by strong lobbying for business interests, particularly extractive industries. This trend clearly resulted in the development of Pennsylvania's Act 13, which removed the ability for communities to retain any bit of local control over zoning or setback regulations. Act 13 was so restrictive of local sovereignty that major portions of Act 13 having to do with zoning and MLUL were overturned by the Supreme Court (Robinson, Delaware Riverkeeper Network v. PA).

The geographical distribution shows that development has largely followed ease of accessibility, both of the shale formation (where the play is shallower and thicker) and the costs of surface mineral rights. Claims of economic prosperity accompanying leasing and development are enticing for many property owners who actively sought out operators to lease their mineral rights, and those who are in more vulnerable economic shape are more likely to lease their minerals [7]. Researchers Clough and Bell (2016) found that local and regional economic prosperity, often promised by the UOGD industry to accompany leasing and development, never transpired on a community level. The economic prosperity promised to offset the damages to infrastructure and alleviate concerns for health effects does not exist [93]. Communities are instead left to their own resources to recover from unsustainable boom-bust cycles, further elevating allostatic loads.

A major talking point promoting expansion of natural gas has been the position that natural gas is a bridge fuel, specifically from coal to renewables such as solar, wind and geothermal. Coal fired power plants continue to be a large source of air pollution. Their contribution to climate change and respiratory health impacts, as well as their high cost of operation have vastly reduced the coal industry and it will continue to shrink as more power stations are taken off the grid. Meanwhile reports from fossil-fuel industry sources state that natural gas power stations are the only affordable replacement to ensure consistent uninterrupted service to consumers. On the other hand recent investments in major energy storage projects by private utilities shows that if this talking point was accurate at one time, that time has since passed [94].

While major point source emissions from CFPP's have been reduced by the consistent closing of power stations, this displacement of coal by natural gas has led to a more diffuse source of public health threats. The sources of pollution are now more distributed, and the contribution of methane to the atmosphere has also largely increased as a result. Methane is a potent green-

house gas 86 times more potent in heating the atmosphere than carbon dioxide on a 20 year timeframe. At the estimated full life-cycle leakage rate the climate-changing impact of methane from UOGD is actually worse than burning coal and will make it harder to avert a 1.5°C increase in global warming [95]. Well pads and infrastructure degrade air quality, surface water quality, have the potential and have already contaminated groundwater sources as well. From the primary research conducted in the Marcellus Shale and specifically in Pennsylvania, we find that impacts are not just anecdotal or segregated to a particular region. Wherever there is a dense concentration of UOGD in the shale play, public health assessments are documenting community and environmental health impacts.

Infrastructure and the Shell Ethane Cracker

The sources of pollution are not limited to just oil and gas well pads either. Expansive infrastructure is necessary to support the transmission, processing and even petrochemical manufacturing that constitute the fossil fuel extraction economy. In addition to natural gas liquids (NGL) pipelines, cryogenic plants, and fractionation facilities in shale plays, plans for ethylene cracker projects are also in the works.

The international shale boom has depressed both oil and gas prices, but the decrease in natural gas prices has been most substantial domestically. As the price of natural gas continues to fall operators are looking for ways to balance profits. What materials were once considered production by-products – the longer chain hydrocarbon condensates, have become valuable raw materials for ethane production. Major operators such as Shell, Exxon, and BP have the capacity to make use of these byproducts. The Ohio River Valley is becoming a hot bed for new ethane "cracker" facilities, starting in Pennsylvania, leading to the development of a new major industrial corridor on the Ohio River [96].

The Shell ethane cracker is the first of its kind to be built outside of the Gulf Coast in 20 years, and is described as Royal Dutch Shell's "world-class" petrochemical facility. It is currently under construction in Southwestern Pennsylvania's Potter County. An analysis of existing, similar, ethane cracker emissions show that the facility will result in a marked increase in VOC's, particularly benzene and acrolein. These chemicals are drivers of ozone production and risk drivers of respiratory disorders such as asthma, as well as being carcinogens [97].

Applicability

While previous studies and reviews have differentiated between unconventional natural gas development (UNGD) and unconventional development for oil, the authors recommend that unconventional development for all types of hydrocarbon production be considered similar enough that future research addresses the entire field as UOGD. A common language when addressing the process of unconventional hydrocarbon extraction will motivate future research to consider each activity as a component of the singular larger system that is UOGD.

In addition to the U.S. EPA grouping unconventional oil and natural gas under the same regulatory umbrella, a major conclusion of this review is that there is a clear scientific rational for aggregating all unconventional hydrocarbon extraction activities under a single term, UOGD. First, primary exposure pathways are conserved across different shale plays regardless of whether the play favors oil or gas. Air pollution results from all forms of unconventional extraction, whether the stimulation is aimed at light crude, heavy crude, or natural gas. Concentrations of certain air pollutants such as hydrogen sulfide may vary from region to region and even within a single play, but emissions of VOC's and methane are consistent whether the shale play is targeted for oil production or dry gas. These chemicals are the same regional drivers of local and regional air pollution and international impacts of climate change no matter which play is studied. Second, while each shale play has its own nuances that need to be

considered when developing research plans, we find from reviewing these articles an entire inventory of health outcomes. And there does not exist any geographical diversity in the health impacts. Each health endpoint could be attributed to multiple if not all shale plays studied. The same health impacts measured in these various regions will be experienced by frontline communities in other states, countries and regions of the world. Therefore results from health research documenting impacts from any hydrocarbon producing shale play can be considered largely ubiquitous.

It is also important to move beyond the distinction of conventional from unconventional oil and gas development. UOGD is unique because of the scaling of the extractive operations. A single unconventional well pad is much larger than a conventional well pad, the well bores are deeper and longer, entailing the use of more resources and therefore they are a larger source of pollution and natural resource depletion. Otherwise, research shows that the toxicological profile of major risk drivers in emissions and spills are the same, and communities living near conventional oil and gas fields document the same exposures and health impacts as communities proximal to unconventional development [98-100].

Conclusions

The results of this study indicate that a variety of health impacts in every major organ system are being experienced by individuals living near UOGD. Furthermore, these impacted communities clearly attribute declines in health to the presence of the oil and gas industry. Additionally, the epidemiologic studies with a longitudinal aspect that tracked the inclement growth of the industry show a response to increased development and additional drilling. It is recommended that state regulatory agencies take a precautionary approach before allowing further growth of shale development. As shown in the Pennsylvania analysis and maps above, approximately 12,000 UOGD wells have been drilled in Pennsylvania in just over a decade, and as a result Pennsylvania has been the primary target for epidemiologic studies to address community concerns for the current state of risk. Additional high quality epidemiologic studies are needed to identify the exact exposure mechanisms degrading health. Regardless of chemical exposure mechanisms, it is clear that stress and allostatic load for frontline communities is in itself causing a public health emergency. This can only be addressed by assuring communities a sense of environmental justice; that they and their children will not be subjected to living in an environment contaminated by UOGD operations.

References

1. Doman, L., Kahan, A. *United States remains the world's top producer of petroleum and natural gas hydrocarbons*. 2018.
2. *Waste Prevention, Production Subject to Royalties, and Resource Conservation; Rescission or Revision of Certain Requirements*, B.o.L. Management, Editor. 2018. p. 49184-49214.
3. Alvarez, R.A., Zavala-Araiza, D., Lyon, D. R., Allen, D. T., Barkley, Z. R., Brandt, A. R., ... & Kort, E. A., *Assessment of methane emissions from the US oil and gas supply chain.* Science, 2018. **361**(6398): p. 186-188.
4. Howarth, R., *Talk titled "The Role of Shale Gas Development in the Methane Cycle: New Insights from 13C and 14C Data"*. 2018.
5. Kopalek, M., Mueller K. *Appalachia, Permian, Haynesville drive U.S. natural gas production growth*. 2018.
6. *Oil and Gas Threat Map*. FracTracker Alliance, Clean Air Task Force, Earthworks.
7. Hays, J. and S.B. Shonkoff, *Toward an Understanding of the Environmental and Public Health Impacts of Unconventional Natural Gas Development: A Categorical Assessment of the Peer-Reviewed Scientific Literature, 2009-2015.* PLoS One, 2016. **11**(4): p. e0154164.
8. Whitworth, K.W., A.K. Marshall, and E. Symanski, *Maternal residential proximity to unconventional gas development and perinatal outcomes among a diverse urban population in Texas.* PLOS ONE, 2017. **12**(7): p. e0180966.
9. Walker Whitworth, K., A. Kaye Marshall, and E. Symanski, *Drilling and Production Activity Related to Unconventional Gas Development and Severity of Preterm Birth.* (1552-9924 (Electronic)).
10. Lewis, C.A.-O., L.H. Greiner, and D.R. Brown, *Setback distances for unconventional oil and gas development: Delphi study results.* (1932-6203 (Electronic)).
11. Haley, M., et al., *Adequacy of Current State Setbacks for Directional High-Volume Hydraulic Fracturing in the Marcellus, Barnett, and Niobrara Shale Plays.* Environmental health perspectives, 2016. **124**(9): p. 1323-1333.
12. Greiner, L., Brown, D., Lewis, C. , *Health and Unconventional Oil & Gas Development: Delphi Study Results*.
13. Straw, E., *An Environmental	Exposure Assessment of Particulate Matter and Volatile Organic	Compounds Using On-Sight Monitoring and	Modeling to Predict Exposures.*
14. Claudio, F., K. Rijke, and A. Page, *The CSG arena: a critical review of unconventional gas developments and best-practice health impact assessment in Queensland, Australia*. Vol. 36. 2018. 105-114.
15. Epstein, A.C., *Chapter Five - The Human Health Implications of Oil and Natural Gas Development*, in *Advances in Chemical Pollution, Environmental Management and Protection*, K.A. Schug and Z.L. Hildenbrand, Editors. 2017, Elsevier. p. 113-145.
16. Stigler Granados, P., *Chapter Six - Public Health Concerns and Unconventional Oil and Gas Development*, in *Advances in Chemical Pollution, Environmental Management and Protection*, K.A. Schug and Z.L. Hildenbrand, Editors. 2017, Elsevier. p. 147-166.
17. Haynes, E.N., et al., *A Historical Perspective of Unconventional Oil and Gas Extraction and Public Health*. 2017, Oxford University Press.
18. Saunders, P.J., et al., *A review of the public health impacts of unconventional natural gas development.* (1573-2983 (Electronic)).
19. Casey, J.A., S. Goldman-Mellor, and R. Catalano, *Association between Oklahoma earthquakes and anxiety-related Google search episodes.* Environmental Epidemiology, 2018. **2**(2): p. e016.

20. Casey, J.A., et al., *Associations of unconventional natural gas development with depression symptoms and disordered sleep in Pennsylvania.* Scientific Reports, 2018. **8**(1): p. 11375.
21. Fisher, M.P., et al., *Psychosocial implications of unconventional natural gas development: Quality of life in Ohio's Guernsey and Noble Counties.* Journal of Environmental Psychology, 2018. **55**: p. 90-98.
22. Haswell, M.R. and A. Bethmont, *Health concerns associated with unconventional gas mining in rural Australia.* (1445-6354 (Electronic)).
23. Maguire, K. and J.V. Winters, *Energy Boom and Gloom? Local Effects of Oil and Natural Gas Drilling on Subjective Well-Being.* Growth and Change, 2017. **48**(4): p. 590-610.
24. Hill, E.L., *Shale gas development and infant health: Evidence from Pennsylvania.* Journal of Health Economics, 2018. **61**: p. 134-150.
25. Cozzarelli, I.M., et al., *Environmental signatures and effects of an oil and gas wastewater spill in the Williston Basin, North Dakota.* (1879-1026 (Electronic)).
26. Kassotis, C.D.A.-O.h.o.o., et al., *Endocrine-Disrupting Activities and Organic Contaminants Associated with Oil and Gas Operations in Wyoming Groundwater.* (1432-0703 (Electronic)).
27. Kassotis, C.D., et al., *Endocrine-Disrupting Chemicals and Oil and Natural Gas Operations: Potential Environmental Contamination and Recommendations to Assess Complex Environmental Mixtures.* Environmental health perspectives, 2016. **124**(3): p. 256-264.
28. Rahman, H., G. Johnson, and R. D. Harbison, *Occupational Health Surveillance: Pulmonary Function Test in Proppant Exposures*. Vol. 04. 2016. 37-45.
29. McKenzie, L.M., et al., *Relationships between indicators of cardiovascular disease and intensity of oil and natural gas activity in Northeastern Colorado.* Environmental Research, 2019. **170**: p. 56-64.
30. Finkel, M.L., *Shale gas development and cancer incidence in southwest Pennsylvania.* (1476-5616 (Electronic)).
31. Rasmussen, S.G., et al., *Association Between Unconventional Natural Gas Development in the Marcellus Shale and Asthma ExacerbationsUnconventional Natural Gas Development and Asthma ExacerbationsUnconventional Natural Gas Development and Asthma Exacerbations.* JAMA Internal Medicine, 2016. **176**(9): p. 1334-1343.
32. Shamasunder, B., et al., *Community-Based Health and Exposure Study around Urban Oil Developments in South Los Angeles.* International Journal of Environmental Research and Public Health, 2018. **15**(1): p. 138.
33. Willis, M.D., et al., *Unconventional natural gas development and pediatric asthma hospitalizations in Pennsylvania.* Environmental Research, 2018. **166**: p. 402-408.
34. Finkel, M.L. and J. Hays, *Environmental and health impacts of 'fracking': why epidemiological studies are necessary.* (1470-2738 (Electronic)).
35. Casey, J.A., et al., *Unconventional Natural Gas Development and Birth Outcomes in Pennsylvania, USA.* Epidemiology (Cambridge, Mass.), 2016. **27**(2): p. 163-172.
36. Currie, J., M. Greenstone, and K. Meckel, *Hydraulic fracturing and infant health: New evidence from Pennsylvania.* Science Advances, 2017. **3**(12): p. e1603021.
37. Caron-Beaudoin, E., et al., *Gestational exposure to volatile organic compounds (VOCs) in Northeastern British Columbia, Canada: A pilot study.* (1873-6750 (Electronic)).
38. Ma, Z.-Q., *Time Series Evaluation of Birth Defects in Areas with and without Unconventional Natural Gas Development*. Vol. 1. 2016.
39. Rando R.J., P.M.V., Robert E Glenn, Cheol Woong Kwon, John E Parker, *Retrospective Assessment of Respirable Quartz Exposure for a Silicosis Study of the Industrial Sand Industry.* Annals of Work Exposures and Health, 2018. **62**(8): p. 1021-1032.

40. Elliott, E.G., et al., *A community-based evaluation of proximity to unconventional oil and gas wells, drinking water contaminants, and health symptoms in Ohio.* Environmental Research, 2018. **167**: p. 550-557.
41. Elliott, E.G., et al., *Unconventional oil and gas development and risk of childhood leukemia: Assessing the evidence.* Science of The Total Environment, 2017. **576**: p. 138-147.
42. Lai, P.-H., et al., *Coping with change in rural landscapes: The psychological stress of rural residents experiencing unconventional gas developments.* Land Use Policy, 2017. **67**: p. 487-497.
43. McDermott-Levy, R. and V. Garcia, *Health Concerns of Northeastern Pennsylvania Residents Living in an Unconventional Oil and Gas Development County.* Public Health Nursing, 2016. **33**(6): p. 502-510.
44. Richburg, C.M. and J. Slagley, *Noise concerns of residents living in close proximity to hydraulic fracturing sites in Southwest Pennsylvania.* Public Health Nursing, 2019. **36**(1): p. 3-10.
45. Blair, B.D., et al., *Is reporting "significant damage" transparent? Assessing fire and explosion risk at oil and gas operations in the United States.* Energy Research & Social Science, 2017. **29**: p. 36-43.
46. Blair, B., et al., *Truck and multivehicle truck accidents with injuries observed near Colorado oil and gas operations*. Vol. 15. 2018.
47. Beleche, T. and I. Cintina, *Fracking and risky behaviors: Evidence from Pennsylvania.* (1873-6130 (Electronic)).
48. Deziel, N.C., et al., *Shale gas activity and increased rates of sexually transmitted infections in Ohio, 2000–2016.* PLOS ONE, 2018. **13**(3): p. e0194203.
49. Peng, L., C. Meyerhoefer, and S.-Y. Chou, *The health implications of unconventional natural gas development in Pennsylvania.* Health Economics, 2018. **27**(6): p. 956-983.
50. Denham, A., et al., *Unconventional natural gas development and hospitalizations: evidence from Pennsylvania, United States, 2003–2014.* Public Health, 2019. **168**: p. 17-25.
51. Weinberger, B., et al., *Health symptoms in residents living near shale gas activity: A retrospective record review from the Environmental Health Project.* Preventive Medicine Reports, 2017. **8**: p. 112-115.
52. Wilke, R.A. and J.W. Freeman, *Potential Health Implications Related to FrackingPotential Health Implications Related to FrackingPotential Health Implications Related to Fracking.* JAMA, 2017. **318**(17): p. 1645-1646.
53. McCawley, M.A., *Does increased traffic flow around unconventional resource development activities represent the major respiratory hazard to neighboring communities?: knowns and unknowns.* (1531-6971 (Electronic)).
54. Rahman, H.H., G.T. Johnson, and R.D. Harbison, *Occupational Health Surveillance: Pulmonary Function Test in Proppant Exposures.* Occupational Diseases and Environmental Medicine, 2016. **Vol.04No.02**: p. 9.
55. Mayer, A., *Quality of life and unconventional oil and gas development: Towards a comprehensive impact model for host communities.* The Extractive Industries and Society, 2017. **4**(4): p. 923-930.
56. Johnston, J.E., E. Lim, and H. Roh, *Impact of upstream oil extraction and environmental public health: A review of the evidence.* Science of The Total Environment, 2019. **657**: p. 187-199.
57. Yao, Y., Chen, T., Shen, S. S., Niu, Y., DesMarais, T. L., Linn, R., ... & Chen, L. C., *Malignant human cell transformation of Marcellus Shale gas drilling flowback water.* Toxicology and Applied Pharmacology, 2015. **288**(1): p. 121-130.
58. Busby, C. and J. Mangano, *There's a World Going on Underground —Infant Mortality and Fracking in Pennsylvania Open Access*. Vol. 8. 2017. 381-393.

59. Komarek, T. and A. Cseh, *Fracking and public health: Evidence from gonorrhea incidence in the Marcellus Shale region.* Journal of Public Health Policy, 2017. **38**(4): p. 464-481.
60. Tustin, A.W., et al., *Associations between Unconventional Natural Gas Development and Nasal and Sinus, Migraine Headache, and Fatigue Symptoms in Pennsylvania.* Environmental Health Perspectives, 2017. **125**(2): p. 189-197.
61. Finkel, M.L., *Shale gas development and cancer incidence in southwest Pennsylvania.* 2016(1476-5616 (Electronic)).
62. McKenzie, L.M., et al., *Childhood hematologic cancer and residential proximity to oil and gas development.* PLOS ONE, 2017. **12**(2): p. e0170423.
63. Abualfaraj, N., P.L. Gurian, and M.S. Olson, *Frequency Analysis of Failure Scenarios from Shale Gas Development.* International journal of environmental research and public health, 2018. **15**(5): p. 885.
64. Rish, W.R. and E.J. Pfau, *Bounding Analysis of Drinking Water Health Risks from a Spill of Hydraulic Fracturing Flowback Water.* Risk Analysis, 2018. **38**(4): p. 724-754.
65. Tasker, T.L., et al., *Environmental and Human Health Impacts of Spreading Oil and Gas Wastewater on Roads.* Environmental Science & Technology, 2018. **52**(12): p. 7081-7091.
66. Crosby, L.M., et al., *Toxicological and chemical studies of wastewater from hydraulic fracture and conventional shale gas wells.* Environmental Toxicology and Chemistry, 2018. **37**(8): p. 2098-2111.
67. Tian, W., et al., *Quantitative Prediction of Radon Concentration at Wellhead in Shale Gas Development*. 2016.
68. Brown, D.R., Lewis, C. & Weinberger, B. I., *Human exposure to unconventional natural gas development: A public health demonstration of periodic high exposure to chemical mixtures in ambient air.* Journal of Environmental Science and Health, 2016. **50**(5): p. 460-472.
69. Stacy, S.L., *A Review of the Human Health Impacts of Unconventional Natural Gas Development.* Current Epidemiology Reports, 2017. **4**(1): p. 38-45.
70. Elliott, E.G., et al., *A systematic evaluation of chemicals in hydraulic-fracturing fluids and wastewater for reproductive and developmental toxicity.* (1559-064X (Electronic)).
71. Yost, E.E., et al., *Overview of Chronic Oral Toxicity Values for Chemicals Present in Hydraulic Fracturing Fluids, Flowback, and Produced Waters.* Environmental Science & Technology, 2016. **50**(9): p. 4788-4797.
72. Inayat-Hussain, S.H., et al., *Prioritization of reproductive toxicants in unconventional oil and gas operations using a multi-country regulatory data-driven hazard assessment.* Environment International, 2018. **117**: p. 348-358.
73. Horwitt, D., *Keystone Secrets*. 2018, Partnership for Policy Integrity.
74. Fleischman, L. and J. Banks, & Graham, J., *Fossil Fumes: A public health analysis of toxic air pollution from the oil and gas industry. Clean Air Task Force and Alliance of Nurses for Healthy Environments, Report*. 2016, Clean Air Task Force.
75. McMullin, T.S., et al., *Exposures and Health Risks from Volatile Organic Compounds in Communities Located near Oil and Gas Exploration and Production Activities in Colorado (U.S.A.).* International journal of environmental research and public health, 2018. **15**(7): p. 1500.
76. Maskrey, J.R., et al., *Air monitoring of volatile organic compounds at relevant receptors during hydraulic fracturing operations in Washington County, Pennsylvania.* Environmental Monitoring and Assessment, 2016. **188**(7): p. 410.
77. Chen, H. and K.E. Carter, *Modeling potential occupational inhalation exposures and associated risks of toxic organics from chemical storage tanks used in hydraulic fracturing using AERMOD.* Environmental Pollution, 2017. **224**: p. 300-309.

78. Farris, B.Y., et al., *Pulmonary toxicity following acute coexposures to diesel particulate matter and α-quartz crystalline silica in the Sprague-Dawley rat.* Inhalation Toxicology, 2017. **29**(7): p. 322-339.
79. Webb, E., et al., *Neurodevelopmental and neurological effects of chemicals associated with unconventional oil and natural gas operations and their potential effects on infants and children*, in *Reviews on Environmental Health*. 2018. p. 3.
80. Fann, N., et al., *Assessing Human Health PM2.5 and Ozone Impacts from U.S. Oil and Natural Gas Sector Emissions in 2025.* Environmental Science & Technology, 2018. **52**(15): p. 8095-8103.
81. Radtke, C., et al., *Noise characterization of oil and gas operations.* Journal of Occupational and Environmental Hygiene, 2017. **14**(8): p. 659-667.
82. Boyle, M.D., et al., *A pilot study to assess residential noise exposure near natural gas compressor stations.* PLOS ONE, 2017. **12**(4): p. e0174310.
83. Blair, B.D., et al., *Residential noise from nearby oil and gas well construction and drilling.* Journal of Exposure Science & Environmental Epidemiology, 2018. **28**(6): p. 538-547.
84. Quail, M.T., *Overview of Silica-Related Clusters in the United States: Will Fracking Operations Become the Next Cluster?* (0022-0892 (Print)).
85. Peters, T.M., et al., *Community airborne particulate matter from mining for sand used as hydraulic fracturing proppant.* (1879-1026 (Electronic)).
86. Harrison, R.J., Retzer, K., Kosnett, M.J., et al, *Sudden deaths among oil and gas extraction workers resulting from oxygen deficiency and inhalation of hydrocarbon gases and vapors—United States, January 2010–March 2015*, in *Morbidity and Mortality Weekly Report*. 2016, Centers for Disease Control and Prevention. p. 6-9.
87. Rich, A.L. and H.T. Orimoloye, *Elevated Atmospheric Levels of Benzene and Benzene-Related Compounds from Unconventional Shale Extraction and Processing: Human Health Concern for Residential Communities.* Environmental Health Insights, 2016. **10**: p. EHI.S33314.
88. Carpenter, D.O., *Hydraulic fracturing for natural gas: impact on health and environment.* (2191-0308 (Electronic)).
89. Hirsch, J.K., et al., *Psychosocial Impact of Fracking: a Review of the Literature on the Mental Health Consequences of Hydraulic Fracturing.* International Journal of Mental Health and Addiction, 2018. **16**(1): p. 1-15.
90. Peng, L., Meyerhoefer, C., Chou, S.Y., *The health implications of unconventional natural gas development in Pennsylvania.* Health Economics, 2018. **27**(6): p. 956-983.
91. Beleche, T. and I. Cintina, *Fracking and risky behaviors: Evidence from Pennsylvania.* 2018(1873-6130 (Electronic)).
92. Hays, J., M. McCawley, and S.B.C. Shonkoff, *Public health implications of environmental noise associated with unconventional oil and gas development.* 2016
93. Clough, E., & Bell, D, *Just fracking: a distributive environmental justice analysis of unconventional gas development in Pennsylvania, USA.* Environmental Research Letters, 2016. **11**(2): p. 020001.
94. Guess, M. *Arizona utility reveals battery deals that give California a run for its money*. 2019 2/20/19].
95. Howarth, R.W., R. Santoro, and A. Ingraffea, *Methane and the greenhouse-gas footprint of natural gas from shale formations.* Climatic Change, 2011. **106**(4): p. 679.
96. Jackson, E., *Ethane Cracker Project: Risks of Bringing Plastic Manufacturing to Ohio.* 2018: FracTracker Alliance. https://www.fractracker.org/2013/09/swpa-preta/.
97. Michanowicz, D.F., K. Malone, S Kelso, M. Kriesky, J. Fabisiak, J., *Ethane Cracker Discussion in Regional Air Pollution Report*. 2013 FracTracker Alliance. https://www.fractracker.org/2013/09/swpa-preta/.

98. Werner, A.K., et al., *Is Increasing Coal Seam Gas Well Development Activity Associated with Increasing Hospitalisation Rates in Queensland, Australia? An Exploratory Analysis 1995-2011. LID - E540 [pii] LID - 10.3390/ijerph14050540 [doi].* (1660-4601 (Electronic)).
99. Werner, A.K., et al., *All-age hospitalization rates in coal seam gas areas in Queensland, Australia, 1995-2011.* BMC public health, 2016. **16**: p. 125-125.
100. Werner, A.K., et al., *Examination of Child and Adolescent Hospital Admission Rates in Queensland, Australia, 1995–2011: A Comparison of Coal Seam Gas, Coal Mining, and Rural Areas.* Maternal and Child Health Journal, 2018. **22**(9): p. 1306-1318.

FracTracker Alliance
1845 Market St, Ste. 204,
Camp Hill, PA 17011
(717) 303-0403
info@fractracker.org
www.fractracker.org
@FracTracker

Appendix: List of Studies

Abdullah, K., Malloy, T., Stenstrom, M.K., Suffet, I.H. (2017). Toxicity of acidization fluids used in California oil exploration. Toxicological & Environmental Chemistry, 99 (1), 78-94
Abualfaraj, N., Gurian, P. L., & Olson, M. S. (2018). Frequency Analysis of Failure Scenarios from Shale Gas Development. International journal of environmental research and public health, 15(5).
Abualfaraj, N., Gurian, P.L., Olson, M. S. (2018) Assessing Residential Exposure Risk from Spills of Flowback Water from Marcellus Shale Hydraulic Fracturing Activity. International Journal of Environmental Research and Public Health, 15(4), 727.
Allshouse, W.B., Adgate, J.L., Blair, B.D., McKenzie, L.M.. 2017. Spatiotemporal Industrial Activity Model for Estimating the Intensity of Oil and Gas Operations in Colorado. Environmental Science & Technology 51 (17), 10243-10250. DOI: 10.1021/acs.est.7b02084.
Archibald, A.T., Ordóñez, C., Brent, E., Williams, M.L., (2018). Potential impacts of emissions associated with unconventional hydrocarbon extraction on UK air quality and human health. Air Quality, Atmosphere & Health 11(6), 627-637
Bain, P. A., & Kumar, A. (2018). In vitro nuclear receptor inhibition and cytotoxicity of hydraulic fracturing chemicals and their binary mixtures. Chemosphere, 198, 565-573.
Balise V.D., Meng C., Cornelius-Green J.N., Kassotis C.D., Kennedy R. Nagel R.C.. (2016). Systematic review of the association between oil and natural gas extraction processes and human reproduction. Fertility and Sterility. Volume 106, Issue 4. Pages 795-819.
Bean, J. K., Bhandari, S., Bilotto, A., & Hildebrandt Ruiz, L. (2018). Formation of Particulate Matter from the Oxidation of Evaporated Hydraulic Fracturing Wastewater. Environmental science & technology, 52(8), 4960-4968.
Beleche, T., & Cintina, I. (2018). Fracking and risky behaviors: Evidence from Pennsylvania. Economics & Human Biology, 31, 69-82.
Blair, B. D., McKenzie, L. M., Allshouse, W. B., & Adgate, J. L. (2017). Is reporting “significant damage” transparent? Assessing fire and explosion risk at oil and gas operations in the United States. Energy research & social science, 29, 36-43.
Blair, B., Hughes, J., Allshouse, W., McKenzie, L., & Adgate, J. (2018). Truck and multivehicle truck accidents with injuries near Colorado oil and gas operations. International journal of environmental research and public health, 15(9), 1861.
Blair, B.D., Brindley, S., Dinkeloo, E., McKenzie, L.M., Adgate, J.L.. 2018. Residential noise from nearby oil and gas well construction and drilling. Journal of Exposure Science & Environmental Epidemiologyvolume 28, pages538–547 (2018)
Blewett, T.A., Delompre, P.L., He, Y., Folkerts, E.J., Flynn, S.L., Alessi, D.S., Goss, G.G. (2017). The sub-lethal and reproductive effects of acute and chronic exposure to flowback and produced water from hydraulic fracturing on the water flea Daphnia magna. Environmental Science & Technology 51(5), 3032-3039
Blewett, T.A., Delompré, P.L.M., Glover, C.N., Goss, G.G. (2018). Physical immobility as a sensitive indicator of hydraulic fracturing fluid toxicity towards Daphnia magna. Science of the Total Environment. 635, 639-643
Bolden, A.L., Schultz, K., Pelch, K.E., Kwiatkowski, C.F. (2018). Exploring the endocrine activity of air pollutants associated with unconventional oil and gas extraction. Environmental Health 17(1),26
Boulé, L. A., Chapman, T. J., Hillman, S. E., Kassotis, C. D., O’dell, C., Robert, J., & Lawrence, B. P. (2018). Developmental exposure to a mixture of 23 chemicals associated with unconventional oil and gas operations alters the immune system of mice. Toxicological Sciences, 163(2), 639-654.
Boyle MD, Payne-Sturges DC, Sangaramoorthy T, Wilson S, Nachman KE, Babik K, Jenkins CC, Trowell J, Milton DK, Sapkota A. 2016. Hazard ranking methodology for assessing health impacts of

unconventional natural gas development and production: the Maryland Case Study. PLoS One 11(1), e0145368
Boyle MD, Soneja S, Quirós-Alcalá L, Dalemarre L, Sapkota AR, et al. (2017) A pilot study to assess residential noise exposure near natural gas compressor stations. PLOS ONE 12(4): e0174310. https://doi.org/10.1371/journal.pone.0174310
Brown et al. 2016. Human exposure to unconventional natural gas development: A public health demonstration of periodic high exposure to chemical mixtures in ambient air. Journal of Environmental Science and Health, PartA. 2016; 50(5):460-472.
Busby, C. and Mangano, J. (2017) There's a World Going on Underground—Infant Mortality and Fracking in Pennsylvania. Journal of Environmental Protection, 8, 381-393. doi: 10.4236/jep.2017.84028.
Butler, K. Tayour, C, Batkikian, C. Contreras, C. Bane, M. Rhoades, E. Masis, Evenor. Rangan, C. Williams, T. 2018. Public Health and Safety Risks of Oil and GAs FAcilities in Los Angeles. Los Angeles County Department of Health
Caron-Beaudoin, É., Valter, N., Chevrier, J., Ayotte, P., Frohlich, K., & Verner, M. A. (2018). Gestational exposure to volatile organic compounds (VOCs) in Northeastern British Columbia, Canada: A pilot study. Environment international, 110, 131-138.
Carpenter, D.O. (2016). Hydraulic fracturing for natural gas: impact on health and environment. Reviews on Environmental Health 31(1), 47-51
Casey, J. A., Goldman-Mellor, S., & Catalano, R. (2018). Association between Oklahoma earthquakes and anxiety-related Google search episodes. Environmental Epidemiology, 2(2), e016.
Casey, J. A., Savitz, D. A., Rasmussen, S. G., Ogburn, E. L., Pollak, J., Mercer, D. G., & Schwartz, B. S. (2016). Unconventional Natural Gas Development and Birth Outcomes in Pennsylvania, USA. Epidemiology (Cambridge, Mass.), 27(2), 163-72.
Casey, J. A., Wilcox, H. C., Hirsch, A. G., Pollak, J., & Schwartz, B. S. (2018). Associations of unconventional natural gas development with depression symptoms and disordered sleep in Pennsylvania. Scientific reports, 8(1), 11375.
Centner, T. J., & Eberhart, N. S. (2016). The use of best management practices to respond to externalities from developing shale gas resources. Journal of Environmental Planning and Management, 59(4), 746-768.
Chen, H., Carter, K.E., (2017). Modeling potential occupational inhalation exposures and associated risks of toxic organics from chemical storage tanks used in hydraulic fracturing using AERMOD. Environmental Pollution, 224, 300-309
Chen, L., Miller, S. A., & Ellis, B. R. (2017). Comparative Human Toxicity Impact of Electricity Produced from Shale Gas and Coal. Environmental science & technology, 51(21), 13018-13027.
Chen, L., Miller, S.A., Ellis, B.R., (2017). Comparative human toxicity impact of electricity produced from shale gas and coal. Environmental Science & Technology, 51(21), 3820–3830
Clough, E., & Bell, D. (2016). Just fracking: a distributive environmental justice analysis of unconventional gas development in Pennsylvania, USA. Environmental Research Letters, 11(2), 025001.
Cozzarelli, I.M., Skalak, K.J., Kent, D.B., Engle, M.A., Benthem, A., Mumford, A.C., Haase, K., Farag, A., Harper, D., Nagel, S.C., et al. Environmental signatures and effects of an oil and gas wastewater spill in the Williston Basin, North Dakota. Science of the Total Environment, 579, 1781-1793
Crosby, L.M, Tatu, C.A., Varonka, M., Charles, K.M., Orem, W.H., (2018). Toxicological and chemical studies of wastewater from hydraulic fracture and conventional shale gas wells. Environmental Toxicology and Chemistry 37(8), 2098-2111.

Currie, J., Greenstone, M., & Meckel, K. (2017). Hydraulic fracturing and infant health: New evidence from Pennsylvania. Science advances, 3(12), e1603021.
Cushing L, Johnston J, Franklin M, et al. 2018. OP III – 3 Using satellite observations to estimate exposure to flaring: implications for future studies of the health impacts of unconventional oil and gas operations. Occup Environ Med 2018;75:A5-A6.
DeDonder, Keith & Gehring, Ronette & Riviere, Jim & Baynes, Ronald & Tell, Lisa & W. Vickroy, Thomas. (2016). Residue concerns following exposure of livestock to oil and petroleum products. Journal of the American Veterinary Medical Association. 248. 144-146.
Denham, A., Willis, M., Zavez, A., Hill, E.. 2019. Unconventional natural gas development and hospitalizations: evidence from Pennsylvania, United States, 2003–2014. Public Health. Volume 168. Pages 17-25.ISSN 0033-3506. https://doi.org/10.1016/j.puhe.2018.11.020.
Deziel, N.C., Humeau, Z., Elliott, E.G., Warren, J.L., Niccolai, L.M., (2018). Shale gas activity and increased rates of sexually transmitted infections in Ohio, 2000–2016. PloS One 13(3) e0194203
Durant, B., Abualfaraj, N., Olson, M.S., Gurian, P.L. (2016). Assessing dermal exposure risk to workers from flowback water during shale gas hydraulic fracturing activity. Journal of Natural Gas Science and Engineering 34, 969-978
Elliott, E.G., Ettinger, A.S., Leaderer, B.P., Bracken, M.B., Deziel, N.C., (2017). A systematic evaluation of chemicals in hydraulic-fracturing fluids and wastewater for reproductive and developmental toxicity. Journal of Exposure Science and Environmental Epidemiology 27(1),90-99,
Elliott, E.G., Ma, X., Leaderer, B.P., McKay, L.A., Pedersen, C.J., Wang, C., Gerber, C.J., Wright, T.J., Sumner, A.J., Brennan, M., Silva, G.S., Warren, J.L., Plata, D.L.,Deziel, N.C. (2018). A community-based evaluation of proximity to unconventional oil and gas wells, drinking water contaminants, and health symptoms in Ohio. Environmental Research 167,550-557.
Elliott, E.G., Trinh, P., Ma, X., Leaderer, B.P., Ward, M.H., Deziel, N.C., (2017). Unconventional oil and gas development and risk of childhood leukemia: assessing the evidence. Science of the Total Environment 576,138-147
Elsner, M., & Hoelzer, K. (2016). Quantitative survey and structural classification of hydraulic fracturing chemicals reported in unconventional gas production. Environmental science & technology, 50(7), 3290-3314.
Epstein, A.C., (2017). Chapter Five: The Human Health Implications of Oil and Natural Gas Development. Advances in Chemical Pollution, Environmental Management and Protection, Volume (1), 113-145
Fann, N., Baker, K. R., Chan, E. A., Eyth, A., Macpherson, A., Miller, E., & Snyder, J. (2018). Assessing Human Health PM2. 5 and Ozone Impacts from US Oil and Natural Gas Sector Emissions in 2025. Environmental science & technology, 52(15), 8095-8103.
Farris, B.Y., Antonini, J.M., Fedan, J.S., Mercer, R.R., Roach, K.A., Chen, B.T., Schwegler-Berry, D., Kashon, M.L., Barger, M.W., Roberts, J.R. (2017). Pulmonary toxicity following acute coexposures to diesel particulate matter and alpha-quartz crystalline silica in the Sprague-Dawley rat. Inhalation Toxicology, 29(7), 322-339.
Finkel, M.L. (2016) Shale gas development and cancer incidence in southwest Pennsylvania. Public Health 141, 198-206.
Finkel, M.L., Hays, J. (2016). Environmental and health impacts of ‘fracking’: why epidemiological studies are necessary. Journal Epidemiol Community Health 70, 221-222
Fisher, M.P., Mayer, A., Vollet, K., Hill, E.L., Haynes, E.N. (2018). Psychosocial implications of unconventional natural gas development: Quality of life in Ohio's Guernsey and Noble Counties. J Environ Psychol 55:90-98

Fleischman, L., Banks, J., & Graham, J. (2016). Fossil Fumes: A public health analysis of toxic air pollution from the oil and gas industry. Clean Air Task Force and Alliance of Nurses for Healthy Environments, Report.
Folkerts, E.J., Blewett, T.A., He, Y., Goss, G.G. (2017). Alterations to juvenile zebrafish (danio rerio) swim performance after acute embryonic exposure to sub-lethal exposures of hydraulic fracturing flowback and produced water. Aquat Toxicol 193:50-59
Folkerts, E.J., Blewett, T.A., He, Y., Goss, G.G.. 2017. Cardio-respirometry disruption in zebrafish (Danio rerio) embryos exposed to hydraulic fracturing flowback and produced water. Environmental Pollution. Volume 231, Part 2. Pages 1477-1487. ISSN 0269-7491, Folkerts, E.J., Blewett, T.A., He, Y., Goss, G.G.. 2017. Cardio-respirometry disruption in zebrafish (Danio rerio) embryos exposed to hydraulic fracturing flowback and produced water. Environmental Pollution. Volume 231, Part 2. Pages 1477-1487. ISSN 0269-7491, https://doi.org/10.1016/j.envpol.2017.09.011.
Funk, S.P., Duffin, L., He, Y., McMullen, C., Sun, C., Utting, N., Martin, J.W., Goss, G.G., Alessi, D.S.. 2019. Assessment of impacts of diphenyl phosphate on groundwater and near-surface environments: Sorption and toxicity. Journal of Contaminant Hydrology.
Goldstein, B. D., Renn, O., & Jovanovic, A. S. (2016). Public health, risk perception, and risk communication: unconventional shale gas in the United States and the European Union. In Environmental and Health Issues in Unconventional Oil and Gas Development (pp. 107-127). Elsevier.
Granados, P.S. (2017). Chapter Six: Public Health Concerns and Unconventional Oil and Gas Development., Advances in Chemical Pollution, Environmental Management and Protection, 147-166
Haley, M., McCawley, M., Epstein, A.C., Arrington, B., Bjerke, E.F. (2016). Adequacy of current state setbacks for directional high-volume hydraulic fracturing in the Marcellus, Barnett, and Niobrara Shale plays. Environmental Health Perspectives 124(9),1323-1333
Harrison, R. J. (2016). Sudden deaths among oil and gas extraction workers resulting from oxygen deficiency and inhalation of hydrocarbon gases and vapors—United States, January 2010–March 2015. MMWR. Morbidity and mortality weekly report, 65.
Haswell, M.R., Bethmont, A. (2016). Health concerns associated with unconventional gas mining in rural Australia. Rural Remote Health 16(4), 3825.
Haynes, E.N., McKenzie, L., Malin, S.A., Cherrie, J.W. (2017). A Historical Perspective of Unconventional Oil and Gas Extraction and Public Health. Oxford Research Encyclopedias, Environmental Science, 1-33
Hays, J., McCawley, M., Shonkoff, S.B.C. (2017). Public health implications of environmental noise associated with unconventional oil and gas development. Science of the Total Environment 580, 448-156
Hays, J., Shonkoff, S.B.C. (2016). Toward an understanding of the environmental and public health impacts of unconventional natural gas development: A categorical assessment of the peer-reviewed scientific literature, 2009-2015. PLoS ONE 11(4),e0154164
He, Y., Flynn, S.L., Folkerts, E.J., Zhang, Y., Ruan, D., Alessi, D.S., Martin, J.W., Goss, G.G., Chemical and toxicological characterizations of hydraulic fracturing flowback and produced water. Water Research. Volume 114. Pages 78-87. ISSN 0043-1354. https://doi.org/10.1016/j.watres.2017.02.027.
He, Y., Sun, Y., Zhang, Y., Folkerts, E.J., Martin, J.W., Goss, G.G.. 2018. Developmental Toxicity of the Organic Fraction from Hydraulic Fracturing Flowback and Produced Waters to Early Life Stages of Zebrafish (Danio rerio). Environmental Science & Technology 2018 52 (6), 3820-3830. DOI: 10.1021/acs.est.7b06557
He, Y., Zhang, Y., Martin, J.W., Alessi, D.S., Giesy, J.P., Goss, G.G. (2018). In vitro assessment of endocrine disrupting potential of organic fractions extracted from hydraulic fracturing flowback and produced water (HF-FPW). Environ Int 121, 824-831

Hildenbrand, Z. L., Mach, P. M., McBride, E. M., Dorreyatim, M. N., Taylor, J. T., Carlton Jr, D. D., ... & Verbeck, G. F. (2016). Point source attribution of ambient contamination events near unconventional oil and gas development. Science of the Total Environment, 573, 382-388.
Hill, E.L. (2018). Shale gas development and infant health: Evidence from Pennsylvania. Journal of Health Economics, 61, 134-150.
Hirsch, J.K., Bryant S. K., Selby-Nelson, E. M., Hamel-Lambert, J.M., Rosmann, M.R., Barnes, T.A., Abrahamson, D., Meit, S. S., GreyWolf, I., Beckmann, S., LaFromboise, T.. (2018). Psychosocial Impact of Fracking: a Review of the Literature on the Mental Health Consequences of Hydraulic Fracturing. International Journal of Mental Health and Addiction. 16(1). 1-15.
Hu, G., Kaur, M., Hewage, K., Sadiq, R.. 2019. Fuzzy clustering analysis of hydraulic fracturing additives for environmental and human health risk mitigation. Clean Technologies and Environmental Policy. 21(1). 39-53.
Hull, N.M., Rosenblum, J.S., Robertson, C.E., Harris, J.K., Linden, K.G., (2018). Succession of toxicity and microbiota in hydraulic fracturing flowback and produced water in the Denver–Julesburg Basin. Science of the Total Environment, 644,183-192.
Hurley, T., Chhipi-Shrestha, G., Gheisi, A., Hewage, K., Sadiq, R. (2016). Characterizing hydraulic fracturing fluid greenness: application of a hazard-based index approach. Clean Technologies and Environmental Policy 18(3), 647-668
Inayat-Hussain, S.H., Fukumura, M., Muiz Aziz A., Jin, C.M., Jin, L.W., Garcia-Milian, R., Vasiliou, V., Deziel, N.C. (2018). Prioritization of reproductive toxicants in unconventional oil and gas operations using a multi-country regulatory data-driven hazard assessment. Environment International 117, 348-358
Ishikawa, M., Muraguchi, R., Azuma, A., Nawata, S., Miya, M., Katsuura, T., Naito, T., Oyama, Y.. 2016. Cytotoxic actions of 2{,}2-dibromo-3-nitrilopropionamide{,} a biocide in hydraulic fracturing fluids{,} on rat thymocytes. Toxicol. Res. 5(5). 1329-1334.
Janitz, A. E., Dao, H. D., Campbell, J. E., Stoner, J. A., & Peck, J. D. (2019). The association between natural gas well activity and specific congenital anomalies in Oklahoma, 1997–2009. Environment international, 122, 381-388.
Johnston, J. E., Lim, E., & Roh, H. (2018). Impact of upstream oil extraction and environmental public health: A review of the evidence. Science of The Total Environment.
Kassotis, C. D., Bromfield, J. J., Klemp, K. C., Meng, C. X., Wolfe, A., Zoeller, R. T., ... & Nagel, S. C. (2016). Adverse reproductive and developmental health outcomes following prenatal exposure to a hydraulic fracturing chemical mixture in female C57Bl/6 mice. Endocrinology, 157(9), 3469-3481.
Kassotis, C. D., Nagel, S. C., & Stapleton, H. M. (2018). Unconventional oil and gas chemicals and wastewater-impacted water samples promote adipogenesis via PPARγ-dependent and independent mechanisms in 3T3-L1 cells. Science of The Total Environment.
Kassotis, C. D., Vu, D. C., Vo, P. H., Lin, C. H., Cornelius-Green, J. N., Patton, S., & Nagel, S. C. (2018). Endocrine-Disrupting Activities and Organic Contaminants Associated with Oil and Gas Operations in Wyoming Groundwater. Archives of environmental contamination and toxicology, 1-12.
Kassotis, C., Tillitt, D., Lin, C-H., McElroy, J., Nagel, S. (2016). Endocrine-disrupting chemicals in oil and natural gas operations: potential environmental contamination and recommendations to assess complex environmental mixtures. Environmental Health Perspectives 124(3), 256-264
Kassotis, C.D., Iwanowicz, L.R., Akob, D.M., Cozzarelli, I.M., Mumford, A.C., Orem, W.H., Nagel, S.C. (2016). Endocrine disrupting activities of surface water associated with a West Virginia oil and gas industry wastewater disposal site. Science of the Total Environment 557-558,901-910

Koehler, K., Ellis, J. H., Casey, J. A., Manthos, D., Bandeen-Roche, K., Platt, R., & Schwartz, B. S. (2018). Exposure Assessment Using Secondary Data Sources in Unconventional Natural Gas Development and Health Studies. Environmental science & technology, 52(10), 6061-6069.
Komarek, T., & Cseh, A. (2017). Fracking and public health: Evidence from gonorrhea incidence in the Marcellus Shale region. Journal of public health policy, 38(4), 464-481.
Konkel, L. (2016). Salting the earth: The environmental impact of oil and gas wastewater spills.
Krupnick, A., & Echarte, I. (2017). Health Impacts of Unconventional Oil and Gas Development. Resources for the Future (RFF). June.
Kuwayama, Y., Roeshot, S., Krupnick, A., Richardson, N., & Mares, J. (2017). Risks and mitigation options for on-site storage of wastewater from shale gas and tight oil development. Energy Policy, 101, 582-593.
Lai, P., Kevin D. Lyons, Gerard T. Kyle, Urs P. Kreuter. (2017). Coping with change in rural landscapes: The psychological stress of rural residents experiencing unconventional gas developments. Land Use Policy. Volume 67. Pages 487-497. ISSN 0264-8377.
Lewis, C., Greiner, L. H., & Brown, D. R. (2018). Setback distances for unconventional oil and gas development: Delphi study results. PloS one, 13(8), e0202462.
Liberatore, H.K., Plewa, M.J., Wagner, E.D., VanBriesen, J.M., Burnett, D.B., Cizmas, L.H., Richardson, S.D. (2017). Identification and comparative mammalian cell cytotoxicity of new iodo-phenolic disinfection byproducts in chloraminated oil and gas wastewaters. Environmental Science & Technology Letters, 4(11),475-480
M. Peters, Thomas & O'Shaughnessy, Patrick & Grant, Ryan & Altmaier, Ralph & Swanton, Elizabeth & Falk, Jeffrey & Osterberg, David & Parker, Edith & G. Wyland, Nancy & Sousan, Sinan & Liz Stark, Aimee & Thorne, Peter. (2017). Community airborne particulate matter from mining for sand used as hydraulic fracturing proppant. Science of The Total Environment. 609. 1475-1482. 10.1016/j.scitotenv.2017.08.006.
Ma, Z., Sneeringer, K., Liu, L., Kuller, L. (2016). Time series evaluation of birth defects in areas with and without unconventional natural gas development. Journal of Public Health Epidemiology, 1(2)
Maguire, K. and Winters, J. V. (2017), Energy Boom and Gloom? Local Effects of Oil and Natural Gas Drilling on Subjective Well-Being. Growth and Change, 48: 590-610. doi:10.1111/grow.12204
Maskrey, Joshua R., Insley, Allison L., Hynds, Erin S., Panko, Julie M.. 2016. Air monitoring of volatile organic compounds at relevant receptors during hydraulic fracturing operations in Washington County, Pennsylvania. Environmental Monitoring and Assessment. 188(7). Page 410.
Mayer, A. (2017). Quality of life and unconventional oil and gas development: Towards a comprehensive impact model for host communities. The Extractive Industries and Society. Volume 4, Issue 4. Pages 923-930.
McCawley, M.A. (2017). Does increased traffic flow around unconventional resource development activities represent the major respiratory hazard to neighboring communities?: Knowns and unknowns. Current Opinion in Pulmonary Medicine, 23(2),161-166.
McCoy, D., Sanders, P.. 2018. Fracking and health. BMJ. 361.
McDermott-Levy, R., & Garcia, V. (2016). Health concerns of northeastern Pennsylvania residents living in an unconventional oil and gas development county. Public Health Nursing, 33(6), 502-510.
McKenzie LM, Allshouse WB, Byers TE, Bedrick EJ, Serdar B, Adgate JL (2017) Childhood hematologic cancer and residential proximity to oil and gas development. PLoS ONE 12(2): e0170423.
McKenzie, L. M., Blair, B., Hughes, J., Allshouse, W. B., Blake, N. J., Helmig, D., ... & Adgate, J. L. (2018). Ambient Nonmethane Hydrocarbon Levels Along Colorado's Northern Front Range: Acute and Chronic Health Risks. Environmental science & technology, 52(8), 4514-4525.

McKenzie, L. M., Crooks, J., Peel, J. L., Blair, B. D., Brindley, S., Allshouse, W. B., ... & Adgate, J. L. (2018). Relationships between Indicators of Cardiovascular Disease and Intensity of Oil and Natural Gas Activity in Northeastern Colorado. Environmental Research.
McMullin, T. et al. 2017 Assessment of Potential Public Health Effects from Oil and Gas Operations in Colorado. Colorado Department of Public Health and Environment.
McMullin, T., Bamber, A., Bon, D., Vigil, D., & Van Dyke, M. (2018). Exposures and Health Risks from Volatile Organic Compounds in Communities Located near Oil and Gas Exploration and Production Activities in Colorado (USA). International journal of environmental research and public health, 15(7), 1500.
Mitchell, A. L., Griffin, W. M. and Casman, E. A. (2016), Lung Cancer Risk from Radon in Marcellus Shale Gas in Northeast U.S. Homes. Risk Analysis, 36: 2105-2119. doi:10.1111/risa.12570
Mrdjen, I., & Lee, J. (2016). High volume hydraulic fracturing operations: potential impacts on surface water and human health. International journal of environmental health research, 26(4), 361-380
Orem, W., Varonka, M., Crosby, L., Haase, K., Loftin, K., Hladik, M., Akob, D.M., Tatu, C., Mumford, A., Jaeschke, J, et al. (2017). Organic geochemistry and toxicology of a stream impacted by unconventional oil and gas wastewater disposal operations. Applied Geochemistry, 80,155-167
Paulik, L.B., Donald, C.E., Smith, B.W., Tidwell, L.G., Hobbie, K.A., Kincl, L., Haynes, E.N., Anderson, K.A. (2016). Emissions of polycyclic aromatic hydrocarbons from natural gas extraction into air. Environ Sci Technol 50(14), 7921-7929
Peng, L., Meyerhoefer, C., Chou, S.Y., The health implications of unconventional natural gas development in Pennsylvania. Health Economics, 27 (6), 956-983
Quail, M.T. (2017). Overview of silica-related clusters in the United States: Will fracking operations become the next cluster? Journal of Evironmental Health, 79(6),20-27
Radtke, C., Autenrieth, D.A., Lipsey, T., Brazile, W.J.. (2017) Noise characterization of oil and gas operations, Journal of Occupational and Environmental Hygiene,14:8, 659-667, DOI: 10.1080/15459624.2017.1316386
Rahman, H.H., Johnson, G.T. and Harbison, R.D. (2016) Occupational Health Surveillance: Pulmonary Function Test in Proppant Exposures. Occupational Diseases and Environmental Medicine,04,37-45. doi: 10.4236/odem.2016.42005
Rando R.J., Pamela M Vacek, Robert E Glenn, Cheol Woong Kwon, John E Parker. (2018) Retrospective Assessment of Respirable Quartz Exposure for a Silicosis Study of the Industrial Sand Industry, Annals of Work Exposures and Health, Volume 62, Issue 8, 15 October 2018, Pages 1021–1032, https://doi.org/10.1093/annweh/wxy064
Rasmussen SG, Ogburn EL, McCormack M, et al.(2016). Association Between Unconventional Natural Gas Development in the Marcellus Shale and Asthma Exacerbations. JAMA Intern Med.;176(9):1334–1343. doi:10.1001/jamainternmed.2016.2436
Rich, A. L., & Orimoloye, H. T. (2016). Elevated Atmospheric Levels of Benzene and Benzene-Related Compounds from Unconventional Shale Extraction and Processing: Human Health Concern for Residential Communities. Environmental Health Insights. https://doi.org/10.4137/EHI.S33314
Rich, A. L., Patel, J. T., & Al-Angari, S. S. (2016). Carbon Disulfide (CS2) Interference in Glucose Metabolism from Unconventional Oil and Gas Extraction and Processing Emissions. Environmental health insights, 10, 51-7. doi:10.4137/EHI.S31906
Richburg, C.M., Slagley, J. (2018). Noise concerns of residents living in close proximity to hydraulic fracturing sites in Southwest Pennsylvania. Public Health Nursing
Rish, W.R., Pfau, E.J. (2017). Bounding analysis of drinking water health risks from a spill of hydraulic fracturing flowback water. Risk Anal 38(4), 724-754

Robert, J., McGuire, C.C., Kim, F., Nagel, S.C., Price, S.J., Lawrence, B.P., Andino, F.J.. 2018. Water Contaminants Associated With Unconventional Oil and Gas Extraction Cause Immunotoxicity to Amphibian Tadpoles. Toxicological Sciences. Volume 166, Issue 1. Pages 39–50. https://doi.org/10.1093/toxsci/kfy179.
Sangaramoorthy, T. (2018). Maryland is not for shale: Scientific and public anxieties of predicting health impacts of fracking. The Extractive Industries and Society.
Sapouckey, S.A., Kassotis, C.D., Nagel, S.C., Vandenberg, L.N. (2018). Prenatal exposure to unconventional oil and gas operation chemical mixtures altered mammary gland development in adult female mice. Endocrinology 159(3), 1277-1289
Saunders, P.J., McCoy, D., Goldstein, R., Saunders, A.T., Munroe, A. (2018). A review of the public health impacts of unconventional natural gas development. Environmental Geochemistry and Health, 40 (1), 1-57
Shamasunder, B., Collier-Oxandale, A., Blickley, J., Sadd, J., Chan, M., Navarro, S., ... & Wong, N. J. (2018). Community-based health and exposure study around urban oil developments in south Los Angeles. International journal of environmental research and public health, 15(1), 138.
Stacy, S. L. (2017). A review of the human health impacts of unconventional natural gas development. Current Epidemiology Reports, 4(1), 38-45.
Stringfellow, W.T., Camarillo, M.K., Domen, J.K., Sandelin, W.L,, Varadharajan, C., Jordan, P.D., Reagan, M.T., Cooley, H., Heberger, M.G., Birkholzer, J.T. (2017). Identifying chemicals of concern in hydraulic fracturing fluids used for oil production. Environmental Polluttion 220(),413-420.
Stringfellow, W.T., Camarillo, M.K., Domen, J.K., Shonkoff, S.B.C. (2017). Comparison of chemical-use between hydraulic fracturing, acidizing, and routine oil and gas development. PLoS ONE, 12(4).
Sun, Y., Wang, D., Tsang, D.C.W., Wang, L., Ok, Y.S., Feng, Y.(2019). A critical review of risks, characteristics, and treatment strategies for potentially toxic elements in wastewater from shale gas extraction. Environ Int 125:452-469
Tasker, T. L., Burgos, W. D., Piotrowski, P., Castillo-Meza, L., Blewett, T. A., Ganow, K. B., ... & Vanden Heuvel, J. P. (2018). Environmental and Human Health Impacts of Spreading Oil and Gas Wastewater on Roads. Environmental science & technology.
Tian, Wei & Wu, Xingru & Shen, Tong & Zhang, Zhenyu & Kalra, Sumeer. (2016). Quantitative Prediction of Radon Concentration at Wellhead in Shale Gas Development. 10.2118/180358-MS.
Torres L, Yadav OP, Khan E. 2018. Risk assessment of human exposure to Ra-226 in oil produced water from the Bakken Shale. Sci Total Environ.626 867-874. doi:10.1016/j.scitotenv.2018.01.171. PMID: 29396348.
Torres, L., Yadav, O.P., Khan, E. (2016). A review on risk assessment techniques for hydraulic fracturing water and produced water management implemented in onshore unconventional oil and gas production. Science of Total Environment 539,478-493
Tustin AW, Hirsch AG, Rasmussen SG, Casey JA, Bandeen-Roche K, Schwartz BS. 2017. Associations between unconventional natural gas development and nasal and sinus, migraine headache, and fatigue symptoms in Pennsylvania. Environ Health Perspect 125:189–197; http://dx.doi.org/10.1289/EHP281
Ward, H., Eykelbosh, A., & Nicol, A. M. (2016). Addressing uncertainty in public health risks due to hydraulic fracturing. Environmental Health Review, 59(2), 57-61.
Watterson, A., & Dinan, W. (2018). Public health and unconventional oil and gas extraction including fracking: Global lessons from a Scottish government review. International journal of environmental research and public health, 15(4), 675.
Webb, E., Hays, J., Dyrszka, L., et al. (2016). Potential hazards of air pollutant emissions from unconventional oil and natural gas operations on the respiratory health of children and infants.

Reviews on Environmental Health, 31(2), pp. 225-243. Retrieved 21 Dec. 2018, from doi:10.1515/reveh-2014-0070
Webb, E., Moon, J., Dyrszka, L., Rodriguez, B., Cox, C., Patisaul, H., ... & London, E. (2018). Neurodevelopmental and neurological effects of chemicals associated with unconventional oil and natural gas operations and their potential effects on infants and children. Reviews on environmental health, 33(1), 3-29.
Weinberger B., Greiner L.H., Walleigh L., Brown D.. (2017). Health symptoms in residents living near shale gas activity: A retrospective record review from the Environmental Health Project. Preventive Medicine Reports. Volume 8. Pages 112-115.
Whitworth, K. W., Marshall, A. K., & Symanski, E. (2018). Drilling and production activity related to unconventional gas development and severity of preterm birth. Environmental Health Perspectives, 126(3). https://doi.org/10.1289/EHP2622
Whitworth, K.W., Marshall, A.K., Symanski, E. (2017). Maternal residential proximity to unconventional gas development and perinatal outcomes among a diverse urban population in Texas. PLoS One 12(7)
Wilke RA, Freeman JW. 2017. Potential health implications related to fracking. JAMA 318(17),1645–1646
Willis M.D., Todd A. Jusko, Jill S. Halterman, Elaine L. Hill. (2018). Unconventional natural gas development and pediatric asthma hospitalizations in Pennsylvania. Environmental Research. Volume 16. Pages 402-408. ISSN 0013-9351.,
Wright, R., & Muma, R. D. (2018). High-volume Hydraulic Fracturing and Human Health Outcomes: A Scoping Review. Journal of occupational and environmental medicine, 60(5), 424-429.
Yost, E.E., Stanek, J., Burgoon, L.D. (2017). A decision analysis framework for estimating the potential hazards for drinking water resources of chemicals used in hydraulic fracturing fluids. Sci Total Environ 574:1544-1558
Yost, E.E., Stanek, J., DeWoskin, R.S., Burgoon, L.D. (2016). Estimating the potential toxicity of chemicals associated with hydraulic fracturing operations using quantitative structure–activity relationship modeling. Environ Sci Technol 50(14), 732-7742
Yost, E.E., Stanek, J., DeWoskin, R.S., Burgoon, L.D. (2016). Overview of chronic oral toxicity values for chemicals present in hydraulic fracturing fluids, flowback, and produced waters. Environ Sci Technol 50(9), 4788-4797
Zhang, A., Cortes, V., Phelps, B., Van, R. H., Srebotnjak, T.. 2018. Experimental Analysis of Soil and Mandarin Orange Plants Treated with Heavy Metals Found in Oilfield-Produced Wastewater. Sustainability. 10(5).