WRITTEN STATEMENT OF
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Chairman Whitehouse, Ranking Member Grassley, and distinguished Members of the Senate Budget Committee, it is an honor to have the opportunity to participate in this important hearing.

My name is Nicole Deziel, and I am an Associate Professor at the Yale School of Public Health in the Department of Environmental Health Sciences. My testimony will address the human health impacts of oil and gas development. These remarks are informed by a strong body of evidence including my own 9 years of research and more than 25 publications on the exposures, health, and environmental justice impacts of oil and gas development (OGD) to communities living near oil and gas wells across multiple states.

I have five key points to share.

***1. Living near oil and gas development has been associated with a range of health problems, with the greatest evidence of risks reported for children.***

The growth in the oil and gas development industry has placed millions of United States (US) residents in the path of multiple hazards associated with oil and gas operations. In 2020, nearly 1,000,000 oil and gas wells were in operation (1), and a 2017 analysis estimated that 17.6 million US residents lived within 1600 m (1 mile) of an active oil or gas well (2).

Oil and gas development has been associated with a range of health problems in nearby populations, with the greatest risks reported for children. The weight of the scientific evidence indicates that the risk of various adverse health outcomes (e.g., adverse birth outcomes, respiratory outcomes) increases with a greater proximity and density of oil and gas wells around people's homes.

Approximately 50 peer-reviewed epidemiologic studies, including those from my own research group, provide evidence of a relationship between oil and gas development and human health risks (3-6) (Table 1). These studies report associations between residential proximity to, or density of, oil and gas wells and increased adverse pregnancy outcomes, childhood cancer incidence, hospitalizations, asthma exacerbations, and mental health issues (Table 1).

The strongest evidence is for health problems to newborn babies, such as birth defects, preterm birth, and low birthweight. Such associations have been observed across numerous states including Pennsylvania, Colorado, Texas, Oklahoma, and Ohio (5-7). The fact that there is consistency of results across multiple studies that were conducted using different methodologies, in different locations, during different time periods, and among diverse populations provides additional confidence in the body of research.

Additional studies in pediatric populations demonstrate a higher burden of childhood leukemia in communities exposed to oil and gas extraction (8, 9). For example, in our recent study conducted in Pennsylvania and looking at unconventional oil and gas development (UOGD; also referred to as shale gas development or fracking), we found that children ages 2-7 living near unconventional oil and gas at birth were two to three times more likely to be diagnosed with acute lymphoblastic leukemia than unexposed children, after accounting for other factors that can influence cancer risk.

Respiratory health outcomes are another well-studied health outcome, with at least nine peer-reviewed studies published to date from California, Pennsylvania, and Texas. These studies reported associations between oil and gas development and asthma exacerbations, asthma hospitalizations, and respiratory symptoms (10-17).

The Bradford Hill Criteria is a framework used to evaluate the strength of epidemiological evidence between an exposure and observed outcome. These criteria are widely used in the field of epidemiology and public health practice to guide decision-making. Table 2 shows how the body of evidence on the relationship between OGD and perinatal health outcomes meets the criteria and strongly supports an association between close geographic proximity to OGD and adverse perinatal outcomes.

| Table 1. Health studies of oil and gas development. Adapted from Deziel 2022. | | | | |
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| **Oil and gas exposure assessment method** | **Study endpoints** | | | |
| | Adverse perinatal outcomes (n=25) | Hospitalizations, asthma, or cardiovascular diseases (n=13) | Cancer (n=4) | Other health outcomes (n=9) |
| **Aggregate Proximity-based Metrics and Models** | | | | |
| Presence or number of wells or permits per zip code, county, or other geographic metric | Ma 2016 (18)<br>Tran 2021 (19)<br>Busby 2017 (20)<br>Tang 2021 (21)<br>Tran 2020 (22)<br>Apergis 2019 (23)<br>Hill 2018 (24) | Jemielita (25) 2015<br>Willis 2018 (14)<br>Denham 2019 (26)<br>Denham 2021 (27)<br>Willis 2020 (28)<br>Peng 2018 (11)<br>Johnston 2021 (15)<br>Trickey 2023 (17) | Fryzek 2013 (29)<br>Finkel 2016 (30) | Deziel 2018 (31)<br>Beleche 2018 (32)<br>Komarek 2017 (33)<br>Johnson 2020 (34) |
| Distance to UOG well | Currie 2017 (35)<br>Willis 2021 (36)<br>Hill 2022 (37) | Koehler 2018 (10) | | Weisner 2023 (38) |
| Inverse distance weighted well count | Stacy 2015 (39)<br>McKenzie 2014 (40)<br>Whitworth 2018 (41)<br>Whitworth 2017 (42)<br>Janitz 2019 (43)<br>Caron-Beaudoin 2021 (44)<br>Willis 2023 (45)<br>Gaughan 2023 (7) | Koehler 2018 (10) | McKenzie 2017 (8) | |
| Inverse distance-squared weighted | Gonzalez 2020 (46) | | | |
| Activity-based metric | Casey 2016 (47)<br>Casey 2019 (48)<br>Tran 2020 (22) | McAlexander 2020 (49)<br>Koehler 2018 (10)<br>Rasmussen 2016 (13)<br>Willis 2020 (28) | | Tustin 2016 (50)<br>Casey 2018 (51) |
| **Pathway-Specific and Other Models and Metrics** | | | | |
| Water pathway | Gaughan 2023 (7) | | Clark 2023 (7) | |
| Air pathway | McKenzie 2019 (52) | McKenzie 2019 (53) | | |
| Flaring | Cushing 2020 (54) | | | |
| Manmade earthquakes | Han 2023 (55) | | | Elser 2023 (56) |

| Table 2. Application of the Bradford Hill Criteria for Causation to the peer-reviewed epidemiological literature on oil and gas development and perinatal health outcomes. (Adapted from Shonkoff, Seth BC, et al. "RE: Response to CalGEM Questions for the California Oil and Gas Public Health Rulemaking Scientific Advisory Panel." (57) | | |
|---|---|---|
| **Criteria** | **Description of Criteria** | **Perinatal Health Studies** |
| **Strength of Association** | Environmental studies commonly report modest effects sizes (i.e., relative to active tobacco smoking or alcohol consumption). A small magnitude of association can support a causal relationship, a larger association may be more convincing. | Reported effect sizes are in ranges similar to other well-established environmental reproductive and developmental hazards, such as $PM_{2.5}$. Some studies have found stronger effect estimates for OGD exposures among socially marginalized groups. |
| **Consistency** | Consistent findings observed by different persons in different places with different samples strengthens the likelihood of an effect. | Adverse birth outcomes have been observed in multiple studies using multiple methods in different populations at different times and locations (e.g., California, Pennsylvania, Colorado, Texas). While there is some variation in findings by specific perinatal outcomes, the overall body of evidence is highly consistent in supporting the association between OGD and adverse perinatal outcomes. |
| **Specificity** | Causation is likely if there is no other likely explanation. | All peer-reviewed birth outcome studies included in our review controlled for other potential confounders by (i) accounting or adjusting for other individual-level or area-level factors (e.g., other air pollution sources, neighborhood socioeconomic status) in the analysis. Other studies applied statistical modeling approaches such as difference-in-difference that accounts for temporal and spatial trends that may confound observed effects. |
| **Temporality** | Exposure precedes the disease. | Most birth outcomes studies have proper temporal alignment between exposure and outcome and use a retrospective cohort, case control or other study design that allows retroactive assessment of exposures to OGD occurring before the onset of disease. They do not consider exposure that occurred at the time of disease or oil and gas wells drilled after the disease. |

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| **Biological Gradient (Dose-Response)** | Greater exposure leads to a greater likelihood of the outcome. | Some studies have found dose-response relationships based on oil and gas production volume categories or metrics of inverse distance weighting and/or oil and gas well density in California and elsewhere. |
| **Plausibility** | The exposure pathway and biological mechanism is plausible based on other knowledge. | Individual health-damaging chemical pollutants are well-understood to be emitted from OGD (e.g., $PM_{2.5}$, benzene) and established as contributing to increased risk for the same adverse perinatal outcomes observed in the epidemiology studies. Stressors associated with OGD (e.g., psychosocial stress) can also contribute to increased adverse perinatal outcomes. |
| **Coherence** | Causal inference is possible only if the literature or substantive knowledge supports this conclusion. | In particular, the body of peer-reviewed literature is converging towards singular directions for adverse perinatal outcomes. |
| **Experiment** | Causation is a valid conclusion if researchers have seen observed associations in prior experimental studies. | N/A- Human population-based experimental studies are not available due to ethical issues. |
| **Analogy** | For similar programs operating, similar results can be expected to bolster the causal inference concluded. | Pollutants well known to be emitted during OGD including benzene, toluene and 1,3 butadiene are listed as reproductive or developmental toxicants. EPA's current Integrated Science Assessments of particulate matter and tropospheric ozone conclude that the evidence is suggestive of, but is not sufficient to infer, a causative relationship between birth outcomes, including preterm birth and low birth weight, and $PM_{2.5}$ and long-term ozone exposures. Additionally, increased stress during pregnancy can alter fetal growth and length of gestation. |

***2. A growing number of environmental monitoring studies have concluded that oil and gas development contributes to air pollution, noise, odors, water contamination, radioactive releases, seismic activity, and increased traffic.***

*Chemical Contaminants in Water*

With more than 9 million people in the US relying on drinking-water sources located within 1.6 km (1 mile) from an unconventional oil and gas well (9), water contamination has been a major community concern (15, 16). Hundreds of chemicals have been reportedly used in injection water or detected in wastewater, including known and suspected developmental and reproductive toxicants and carcinogens, such as metals, volatile organic compounds, polycyclic aromatic hydrocarbons, phthalates, and per- and poly-fluoroalkyl substances (PFAS) (58-65). Water contamination may occur due to surface spills of fracturing or wastewater fluids, release of improperly treated wastewater, structural failures, and well leaks (65-72). Groundwater monitoring studies conducted thus far do not support widespread contamination (73-76). However, groundwater and surface water impairments, spills, and violations have been documented across multiple states (66, 68, 77-82).

*Air Pollutants*

UOGD generates air pollutants from various sources, including well and road construction; use of diesel-powered construction, drilling, and transportation equipment and vehicles; dust generation during drilling; intentional flaring of natural gas; and volatilization of wastewater constituents (83-85). Emission sources have different temporal profiles and may be continuous over varying time frames (e.g., diesel equipment, leaks) or be intermittent (e.g., flaring, venting). They may also occur at the well pad or off-site from transportation or associated UOG infrastructure (10). Studies of airborne emissions or concentrations have identified several pollutants associated with UOGD activities, including carcinogens (e.g., diesel particulate matter, polycyclic aromatic hydrocarbons), and reproductive and/or developmental toxicants (e.g., ethylbenzene, toluene) (59, 83, 86-90).

*Radiation, Radioactivity, and Radon*

Technologically enhanced naturally occurring radioactive compounds (TENORMS) have been detected in a variety of wastes generated by unconventional oil and gas development, including produced water (91-93), lateral drill cuttings (93), and impoundment sediments (94), and co-occur with sludges and mineral scales that accumulate inside unconventional oil and gas development equipment (91). TENORMS have also been found in streambed sediments next to facilities managing unconventional oil and gas development wastewaters (95). Additionally, higher indoor radon levels were observed in homes with more or closer oil and gas wells compared to those with fewer or farther oil and gas wells (96, 97). Health effects of radiation exposure include adult and childhood cancers (58), impaired lung function (98), increased blood pressure (99), and oxidative stress (100).

*Sensory Stressors*

Sensory stressors include noise, artificial light at night, and odors (3, 101-103). Noise pollution can activate the sympathetic nervous system; lead to annoyance, stress, and sleep disturbance; and potentially contribute to cardiovascular disease and adverse birth outcomes (3, 104). Odorous compounds can reflect mixtures of volatile organic or sulfuric compounds, which have neurotoxic and respiratory effects, and can also trigger annoyance, concern, and anxiety at levels below established toxicity thresholds (105, 106).

*Greenhouse Gases*

Methane, a potent greenhouse gas, is emitted to the air throughout UOGD from leaks and intentional releases (e.g., venting) (107). Although methane is not directly toxic to nearby communities, except at very high levels in tap water, at which point it poses a flammability danger, it impacts future health risks through its role in climate change.

***3. Exposures and health risks are not distributed equally across nearby communities, with disproportionate impacts observed for some disadvantaged populations.***

Certain subgroups of the population, such as communities of color or lower income, often bear a disproportionate burden of exposure to environmental pollution, can lack adequate access to regulatory and reporting information, and health risks may be exacerbated by the co-occurrence of socioeconomic stressors. In Texas, unconventional oil and gas wastewater disposal wells were more likely to be sited in communities of color (108). In our study in Ohio, we found that oil and gas waste wells were disproportionately sited in areas of lower income (109). In Texas, Hispanic populations were more likely to be exposed to flaring, a practice of burning excess gas yielding light at night, noise, and noxious odors (110). In another study from our group, we found that communities with high proportions of lower-income and elderly people in rural areas are the most vulnerable to groundwater pollution from hydraulic fracturing in the Appalachian Basin (OH, PA, WV) (111). A recent California study found that Black, Hispanic, and socioeconomically marginalized people had disproportionately higher exposure to oil and gas wells over three time periods (112).

***4. The limited monitoring data, particularly in rural areas where substantial drilling occurs, are challenges to fully understanding hazards and risks.***

I will take the example of water contamination from oil and gas. Potential water contamination events include surface spills of fracturing or wastewater fluids, release of improperly treated wastewater, and leaks in well infrastructure (113). The fracturing fluids and wastewater used or produced by oil and gas development may contain toxic, radioactive, endocrine-disrupting, and/or carcinogenic chemicals (58, 59).

An estimated 1-4% of UOG wells have reported spills (77, 78) and approximately 20% have a non-administrative violation (e.g., a pollution indicdent, well construction issue) (66). While unconventional oil and gas studies have not found evidence of widespread water contamination. (9, 75, 76, 114), specific instances of groundwater and surface water impairments have been identified (68, 79, 115).

Water monitoring data near drilling sites are limited, posing a challenge to the assessment of potential water-related impacts. In the US, oil and gas development often occurs in rural areas where homes are served by private domestic drinking water wells, which are not subject to federal regulations and monitoring (116). Water testing can be cost-prohibitive, and in our studies, many residents had never had their drinking water tested.

***5. Multiple, complementary strategies would serve to more adequately address oil and gas hazards and better protect community health.***

One of the most commonly-used policy protections for communities near oil and gas wells are setbacks, the allowable distance between an oil and gas well and a sensitive receptor such as homes, schools, and other places where people live, work, and play. The utility of setbacks is based on the premise that the hazards associated with oil and gas operations attenuate with distance. Because hazards dissipate at different functions of distance, it is challenging to establish a universal setback that optimally addresses all hazards. Furthermore, setbacks also do not prevent the release of methane or other greenhouse gases that contribute to climate change (117). Finally, increasing distance between OGD activities and human residential communities could place OGD infrastructure closer to wildlife communities, thereby shifting the burden to ecological rather than human health impacts (118). To date, 23 states have adopted or are considering setbacks that vary widely and range from 100 ft (e.g., Arkansas and New York) to 3200 ft (California) (119).

From a public health perspective, the most effective strategy for protecting communities from the hazards of OGD would be to reduce development of new oil and gas wells and phase out existing oil and gas activities and infrastructure with proper well plugging and environmental remediation because the local hazards and regional hazards such as greenhouse gases would be completely removed (117). Although most effective at protecting health, complete elimination represents a systemic shift from the status quo with substantial political, socioeconomic, and logistical ramifications. Despite these challenges, examples of elimination are occurring throughout the US. Unconventional oil and gas development has been eliminated in Vermont, Maryland, New York, and Washington, states. The Delaware River Basin (DRB) Commission prohibited hydraulic fracturing in the DRB region, which covers parts of New York, Pennsylvania, New Jersey and Delaware. Some municipalities are moving towards complete OGD elimination, including Los Angeles, which has approved a ban of all new conventional and unconventional oil and gas wells and a phase-out of existing wells.

Figure 1 below illustrates the concept of a Hierarchy of Controls. The concept of hierarchy of controls originated from the fields of occupational health to prioritize mitigation strategies from the most to the least effective at reducing hazards to workers. This figure represents an application of this framework to the nearby communities. At the top is the most health protective strategy: to stop drilling and developing new wells, phase out existing OGD activities and associated infrastructure, and properly plug remediate legacy wells and ancillary infrastructure. Other strategies include setbacks and engineering controls.

***In conclusion, there is clear evidence for health hazards from oil and gas development, which are not adequately addressed by current policies.***

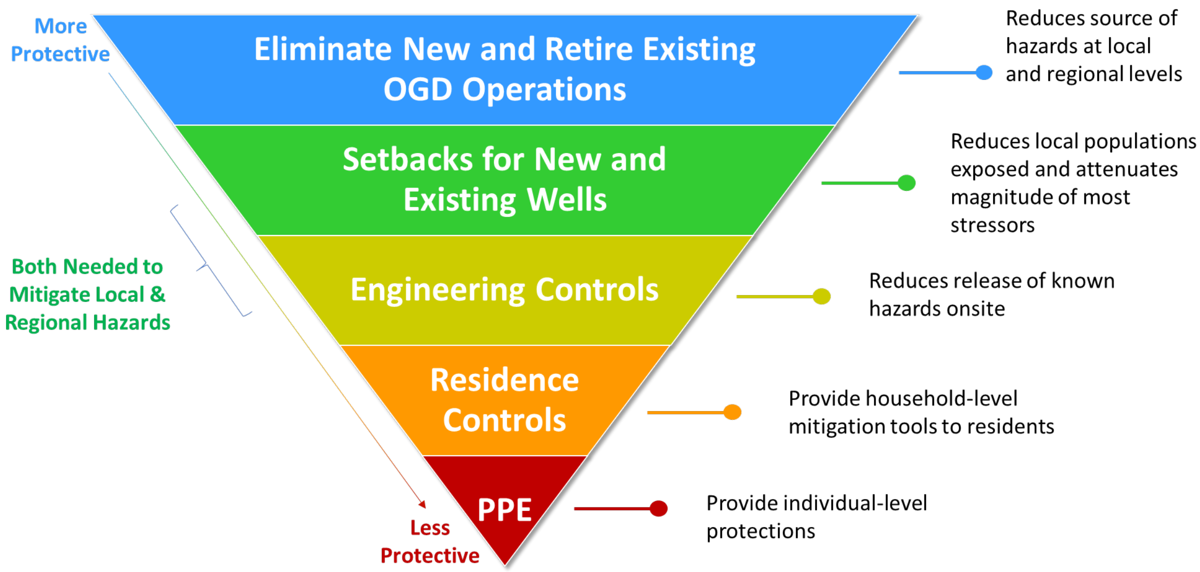


**Figure 1. Hierarchy of controls to reduce public health harms from oil and gas development (OGD) activities. PPE: personal protective equipment (Adapted from Deziel et al. 2022) (117).**

References

1. Administration EI. U.S. Oil and Natural Gas Wells by Production Rate. https://www.eia.gov/petroleum/wells/. 2022,
2. Czolowski ED, Santoro RL, Srebotnjak T, et al. Toward Consistent Methodology to Quantify Populations in Proximity to Oil and Gas Development: A National Spatial Analysis and Review. *Environmental health perspectives* 2017;125(8):086004.
3. Hays J, McCawley M, Shonkoff SBC. Public health implications of environmental noise associated with unconventional oil and gas development. *The Science of the total environment* 2017;580:448-56.
4. Gorski I SB. Environmental Health Concerns From Unconventional Natural Gas Development. *Oxford Research Encyclopedia* 2019;Global Public Health.
5. Deziel NC, Brokovich E, Grotto I, et al. Unconventional oil and gas development and health outcomes: A scoping review of the epidemiological research. *Environmental research* 2020;182:109124.
6. Deziel NC, Clark CJ, Casey JA, et al. Assessing Exposure to Unconventional Oil and Gas Development: Strengths, Challenges, and Implications for Epidemiologic Research. *Current Environmental Health Reports* 2022.
7. Gaughan C, Sorrentino KM, Liew Z, et al. Residential proximity to unconventional oil and gas development and birth defects in Ohio. *Environmental research* 2023;229:115937.
8. McKenzie LM, Allshouse WB, Byers TE, et al. Childhood hematologic cancer and residential proximity to oil and gas development. *PloS one* 2017;12(2):e0170423.
9. Clark CJ, Johnson NP, Soriano Jr M, et al. Unconventional oil and gas development exposure and risk of childhood acute lymphoblastic leukemia: a case–control study in Pennsylvania, 2009–2017. *Environmental Health Perspectives* 2022;130(8):087001.
10. Koehler K, Ellis JH, Casey JA, et al. Exposure Assessment Using Secondary Data Sources in Unconventional Natural Gas Development and Health Studies. *Environmental science & technology* 2018;52(10):6061-9.
11. Peng L, Meyerhoefer C, Chou S-Y. The health implications of unconventional natural gas development in Pennsylvania. *Health Economics* 2018;27(6):956-83.
12. Rabinowitz PM, Slizovskiy IB, Lamers V, et al. Proximity to natural gas wells and reported health status: results of a household survey in Washington County, Pennsylvania. *Environmental health perspectives* 2015;123(1):21-6.
13. Rasmussen SG, Ogburn EL, McCormack M, et al. Association Between Unconventional Natural Gas Development in the Marcellus Shale and Asthma Exacerbations. *JAMA internal medicine* 2016;176(9):1334-43.
14. Willis MD, Jusko TA, Halterman JS, et al. Unconventional natural gas development and pediatric asthma hospitalizations in Pennsylvania. *Environmental research* 2018;166:402-8.
15. Johnston JE, Enebish T, Eckel SP, et al. Respiratory health, pulmonary function and local engagement in urban communities near oil development. *Environmental research* 2021;197:111088.
16. Shamasunder B, Collier-Oxandale A, Blickley J, 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):138.
17. Trickey KS, Chen Z, Sanghavi P. Hospitalisations for cardiovascular and respiratory disease among older adults living near unconventional natural gas development: a difference-in-differences analysis. *The Lancet Planetary Health* 2023;7(3):e187-e96.
18. Ma Z, Sneeringer KC, Liu L, et al. Time series evaluation of birth defects in areas with and without unconventional natural gas development. *J Epidemiol Public Health Rev* 2016;1(4):10.16966.

19. Tran KV, Casey JA, Cushing LJ, et al. Residential proximity to hydraulically fractured oil and gas wells and adverse birth outcomes in urban and rural communities in California (2006-2015). *Environmental epidemiology (Philadelphia, Pa)* 2021;5(6):e172-e.
20. Busby C, Mangano JJ. There'sa world going on underground—infant mortality and fracking in Pennsylvania. *Journal of Environmental Protection* 2017;8(04):381.
21. Tang IW, Langlois PH, Vieira VM. Birth defects and unconventional natural gas developments in Texas, 1999–2011. *Environmental research* 2021;194:110511.
22. Tran KV, Casey JA, Cushing LJ, et al. Residential proximity to oil and gas development and birth outcomes in California: a retrospective cohort study of 2006–2015 births. *Environmental health perspectives* 2020;128(6):067001.
23. Apergis N, Hayat T, Saeed T. Fracking and infant mortality: fresh evidence from Oklahoma. *Environmental Science and Pollution Research* 2019;26(31):32360-7.
24. Hill EL. Shale gas development and infant health: Evidence from Pennsylvania. *Journal of Health Economics* 2018;61:134-50.
25. Jemielita T, Gerton GL, Neidell M, et al. Unconventional gas and oil drilling is associated with increased hospital utilization rates. *PloS one* 2015;10(7):e0131093.
26. Denham A, Willis M, Zavez A, et al. Unconventional natural gas development and hospitalizations: evidence from Pennsylvania, United States, 2003–2014. *Public Health* 2019;168:17-25.
27. Denham A, Willis MD, Croft DP, et al. Acute myocardial infarction associated with unconventional natural gas development: A natural experiment. *Environmental research* 2021;195:110872.
28. Willis M, Hystad P, Denham A, et al. Natural gas development, flaring practices and paediatric asthma hospitalizations in Texas. *International Journal of Epidemiology* 2020;49(6):1883-96.
29. Fryzek J, Pastula S, Jiang X, et al. Childhood cancer incidence in Pennsylvania counties in relation to living in counties with hydraulic fracturing sites. *J Occup Environ Med* 2013;55(7):796-801.
30. Finkel ML. Shale gas development and cancer incidence in southwest Pennsylvania. *Public Health* 2016;141:198-206.
31. Deziel NC, Humeau Z, Elliott EG, et al. Shale gas activity and increased rates of sexually transmitted infections in Ohio, 2000-2016. *PloS one* 2018;13(3):e0194203.
32. Beleche T, Cintina I. Fracking and risky behaviors: Evidence from Pennsylvania. *Economics & Human Biology* 2018;31:69-82.
33. Komarek TM. Crime and natural resource booms: evidence from unconventional natural gas production. *The Annals of Regional Science* 2018;61(1):113-37.
34. Johnson NP, Warren JL, Elliott EG, et al. A Multiregion Analysis of Shale Drilling Activity and Rates of Sexually Transmitted Infections in the United States. *Sexually transmitted diseases* 2020;47(4):254-60.
35. Currie J, Greenstone M, Meckel K. Hydraulic fracturing and infant health: New evidence from Pennsylvania. *Science Advances* 2017;3(12):e1603021.
36. Willis MD, Hill EL, Boslett A, et al. Associations between Residential Proximity to Oil and Gas Drilling and Term Birth Weight and Small-for-Gestational-Age Infants in Texas: A Difference-in-Differences Analysis. *Environmental health perspectives* 2021;129(7):077002.
37. Hill EL, Ma L. Drinking water, fracking, and infant health. *Journal of Health Economics* 2022;82:102595.
38. Weisner ML, Allshouse WB, Erjavac BW, et al. Health Symptoms and Proximity to Active Multi-Well Unconventional Oil and Gas Development Sites in the City and County of Broomfield, Colorado. *International journal of environmental research and public health* 2023;20(3):2634.
39. Stacy SL, Brink LL, Larkin JC, et al. Perinatal outcomes and unconventional natural gas operations in Southwest Pennsylvania. *PloS one* 2015;10(6):e0126425.
40. McKenzie LM, Guo R, Witter RZ, et al. Birth outcomes and maternal residential proximity to natural gas development in rural colorado. *Environmental health perspectives* 2014;122(4):412-7.

41. Whitworth KW, Marshall AK, Symanski E. Drilling and Production Activity Related to Unconventional Gas Development and Severity of Preterm Birth. *Environmental health perspectives* 2018;126(3):037006.
42. Whitworth KW, Marshall AM, E S. Maternal residential proximity to unconventional gas development and perinatal outcomes among a diverse urban population in Texas. *PLosOne* 2017;Under Review.
43. Janitz AE, Dao HD, Campbell JE, et al. The association between natural gas well activity and specific congenital anomalies in Oklahoma, 1997–2009. *Environment international* 2019;122:381-8.
44. Caron-Beaudoin É, Whitworth KW, Bosson-Rieutort D, et al. Density and proximity to hydraulic fracturing wells and birth outcomes in Northeastern British Columbia, Canada. *Journal of exposure science & environmental epidemiology* 2021;31(1):53-61.
45. Willis MD, Carozza SE, Hystad P. Congenital anomalies associated with oil and gas development and resource extraction: a population-based retrospective cohort study in Texas. *Journal of exposure science & environmental epidemiology* 2023;33(1):84-93.
46. Gonzalez DJX, Sherris AR, Yang W, et al. Oil and gas production and spontaneous preterm birth in the San Joaquin Valley, CA: A case–control study. *Environmental Epidemiology* 2020;4(4):e099.
47. Casey JA, Savitz DA, Rasmussen SG, et al. Unconventional Natural Gas Development and Birth Outcomes in Pennsylvania, USA. *Epidemiology (Cambridge, Mass)* 2016;27(2):163-72.
48. Casey JA, Goin DE, Rudolph KE, et al. Unconventional natural gas development and adverse birth outcomes in Pennsylvania: The potential mediating role of antenatal anxiety and depression. *Environmental research* 2019;177:108598.
49. McAlexander TP, Bandeen-Roche K, Buckley JP, et al. Unconventional Natural Gas Development and Hospitalization for Heart Failure in Pennsylvania. *Journal of the American College of Cardiology* 2020;76(24):2862-74.
50. Tustin AW, Hirsch AG, Rasmussen SG, et al. Associations between Unconventional Natural Gas Development and Nasal and Sinus, Migraine Headache, and Fatigue Symptoms in Pennsylvania. *Environmental health perspectives* 2016.
51. Casey JA, Wilcox HC, Hirsch AG, et al. Associations of unconventional natural gas development with depression symptoms and disordered sleep in Pennsylvania. *Sci Rep* 2018;8(1):11375.
52. McKenzie LM, Crooks J, Peel JL, et al. Relationships between indicators of cardiovascular disease and intensity of oil and natural gas activity in Northeastern Colorado. *Environmental research* 2019;170:56-64.
53. McKenzie LM, Allshouse W, Daniels S. Congenital heart defects and intensity of oil and gas well site activities in early pregnancy. *Environ Int* 2019;132:104949.
54. Cushing LJ, Vavra-Musser K, Chau K, et al. Flaring from unconventional oil and gas development and birth outcomes in the Eagle Ford Shale in south Texas. *Environmental health perspectives* 2020;128(7):077003.
55. Han J, Zhang B, Zhang X, et al. Associations between occurrence of birth defects and hydraulic fracturing activities in Barnett shale region, Texas. *Heliyon* 2023.
56. Elser H, Kempinsky A, Goldman-Mellor S, et al. Manmade earthquakes and healthcare visits for anxiety disorders in Oklahoma, 2010–2019. *Environmental Epidemiology* 2023;7(1):e232.
57. Shonkoff SB, Morello-Frosch R, Casey J, et al. RE: Response to CalGEM Questions for the California Oil and Gas Public Health Rulemaking Scientific Advisory Panel. *Published online October* 2021;1.
58. Elliott EG, Ettinger AS, Leaderer BP, et al. A systematic evaluation of chemicals in hydraulic-fracturing fluids and wastewater for reproductive and developmental toxicity. *Journal of exposure science & environmental epidemiology* 2016.
59. Elliott EG, Trinh P, Ma X, et al. Unconventional oil and gas development and risk of childhood leukemia: Assessing the evidence. *Science of The Total Environment* 2017;576:138-47.

60. Kassotis CD, Tillitt DE, Lin CH, 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):256-64.
61. Responsibility. HDPfS. Fracking with "Forever Chemicals". 2021.
62. Hoelzer K, Sumner AJ, Karatum O, et al. Indications of Transformation Products from Hydraulic Fracturing Additives in Shale-Gas Wastewater. *Environmental science & technology* 2016;50(15):8036-48.
63. Sumner AJ, Plata Desiree L. Exploring the hydraulic fracturing parameter space: a novel high-pressure, high-throughput reactor system for investigating subsurface chemical transformations. *Environmental Science: Processes & Impacts* 2018;20(2):318-31.
64. Stringfellow WT, Domen JK, Camarillo MK, et al. Physical, chemical, and biological characteristics of compounds used in hydraulic fracturing. *Journal of hazardous materials* 2014;275:37-54.
65. Agency USEP. Hydraulic Fracturing for Oil and Gas: Impacts from the Hydraulic Fracturing Water Cycle on Drinking Water Resources in the United States (Final Report). Washington, DC, EPA/600/R-16/236F, 2016. 2016.
66. Brantley SL, Yoxtheimer D, Arjmand S, et al. Water resource impacts during unconventional shale gas development: The Pennsylvania Experience. *International Journal of Coal Geology* 2014;126:140-56.
67. Cozzarelli IM, Kent DB, Briggs M, et al. Geochemical and geophysical indicators of oil and gas wastewater can trace potential exposure pathways following releases to surface waters. *Science of The Total Environment* 2021;755:142909.
68. DiGiulio DC, Jackson RB. Impact to Underground Sources of Drinking Water and Domestic Wells from Production Well Stimulation and Completion Practices in the Pavillion, Wyoming, Field. *Environmental science & technology* 2016;50(8):4524-36.
69. Ferrar KJ, Michanowicz DR, Christen CL, et al. Assessment of effluent contaminants from three facilities discharging Marcellus Shale wastewater to surface waters in Pennsylvania. *Environmental science & technology* 2013;47(7):3472-81.
70. Burgos WD, Castillo-Meza L, Tasker TL, et al. Watershed-Scale Impacts from Surface Water Disposal of Oil and Gas Wastewater in Western Pennsylvania. *Environmental science & technology* 2017;51(15):8851-60.
71. Drollette BD, Hoelzer K, Warner NR, et al. Elevated levels of diesel range organic compounds in groundwater near Marcellus gas operations are derived from surface activities. *Proceedings of the National Academy of Sciences of the United States of America* 2015;112(43):13184-9.
72. Harkness JS, Dwyer GS, Warner NR, et al. Iodide, bromide, and ammonium in hydraulic fracturing and oil and gas wastewaters: environmental implications. *Environmental science & technology* 2015;49(3):1955-63.
73. Elliott EG, Ma X, Leaderer BP, 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;167:550-7.
74. Fontenot BE, Hunt LR, Hildenbrand ZL, et al. An evaluation of water quality in private drinking water wells near natural gas extraction sites in the Barnett Shale formation. *Environmental science & technology* 2013;47(17):10032-40.
75. McMahon PB, Lindsey BD, Conlon MD, et al. Hydrocarbons in Upland Groundwater, Marcellus Shale Region, Northeastern Pennsylvania and Southern New York, U.S.A. *Environmental science & technology* 2019;53(14):8027-35.
76. Wen T, Niu X, Gonzales M, et al. Big Groundwater Data Sets Reveal Possible Rare Contamination Amid Otherwise Improved Water Quality for Some Analytes in a Region of Marcellus Shale Development. *Environmental science & technology* 2018;52(12):7149-59.

77. Clancy SA, Worrall F, Davies RJ, et al. The potential for spills and leaks of contaminated liquids from shale gas developments. *Science of The Total Environment* 2018;626:1463-73.
78. Maloney KO, Baruch-Mordo S, Patterson LA, et al. Unconventional oil and gas spills: Materials, volumes, and risks to surface waters in four states of the U.S. *The Science of the total environment* 2017;581-582:369-77.
79. Akob DM, Mumford AC, Orem W, et al. Wastewater Disposal from Unconventional Oil and Gas Development Degrades Stream Quality at a West Virginia Injection Facility. *Environmental science & technology* 2016;50(11):5517-25.
80. Lauer NE, Harkness JS, Vengosh A. Brine Spills Associated with Unconventional Oil Development in North Dakota. *Environmental science & technology* 2016;50(10):5389-97.
81. Warner NR, Jackson RB, Darrah TH, et al. Geochemical evidence for possible natural migration of Marcellus Formation brine to shallow aquifers in Pennsylvania. *Proceedings of the National Academy of Sciences of the United States of America* 2012;109(30):11961-6.
82. Clark CJ, Warren JL, Kadan-Lottick N, et al. Community concern and government response: Identifying socio-economic and demographic predictors of oil and gas complaints and drinking water impairments in Pennsylvania. *Energy Research & Social Science* 2021;76:102070.
83. Allshouse WB, McKenzie LM, Barton K, et al. Community Noise and Air Pollution Exposure During the Development of a Multi-Well Oil and Gas Pad. *Environmental science & technology* 2019;53(12):7126-35.
84. Garcia-Gonzales DA, Shonkoff SBC, Hays J, et al. Hazardous Air Pollutants Associated with Upstream Oil and Natural Gas Development: A Critical Synthesis of Current Peer-Reviewed Literature. *Annual Review of Public Health* 2019;40(1):283-304.
85. Allshouse WB, Adgate JL, Blair BD, et al. Spatiotemporal industrial activity model for estimating the intensity of oil and gas operations in Colorado. *Environmental science & technology* 2017;51(17):10243-50.
86. McKenzie LM, Blair B, Hughes J, et al. Ambient Nonmethane Hydrocarbon Levels Along Colorado's Northern Front Range: Acute and Chronic Health Risks. *Environmental science & technology* 2018;52(8):4514-25.
87. Goetz JD, Floerchinger C, Fortner EC, et al. Atmospheric Emission Characterization of Marcellus Shale Natural Gas Development Sites. *Environmental science & technology* 2015.
88. Macey GP, Breech R, Chernaik M, et al. Air Concentrations of Volatile Compounds near Oil and Gas Production: A Community-based Exploartory Study. *Environmental Health* 2014;13.
89. Colborn T, Schultz K, Herrick L, et al. An Exploratory Study of Air Quality Near Natural Gas Operations. *Human and Ecological Risk Assessment: An International Journal* 2014;20(1):86-105.
90. Paulik LB, Hobbie KA, Rohlman D, et al. Environmental and individual PAH exposures near rural natural gas extraction. *Environmental Pollution* 2018;241:397-405.
91. Torres L, Yadav OP, Khan E. Risk assessment of human exposure to Ra-226 in oil produced water from the Bakken Shale. *The Science of the total environment* 2018;626:867-74.
92. Brown VJ. Radionuclides in fracking wastewater: managing a toxic blend. *Environmental health perspectives* 2014;122(2):A50-5.
93. Eitrheim ES, May D, Forbes TZ, et al. Disequilibrium of Naturally Occurring Radioactive Materials (NORM) in Drill Cuttings from a Horizontal Drilling Operation. *Environmental Science & Technology Letters* 2016;3(12):425-9.
94. Rich AL, Crosby EC. Analysis of reserve pit sludge from unconventional natural gas hydraulic fracturing and drilling operations for the presence of technologically enhanced naturally occurring radioactive material (TENORM). *New solutions : a journal of environmental and occupational health policy : NS* 2013;23(1):117-35.

95. Lauer NE, Warner NR, Vengosh A. Sources of Radium Accumulation in Stream Sediments near Disposal Sites in Pennsylvania: Implications for Disposal of Conventional Oil and Gas Wastewater. *Environmental science & technology* 2018;52(3):955-62.
96. Casey JA, Ogburn EL, Rasmussen SG, et al. Predictors of Indoor Radon Concentrations in Pennsylvania, 1989-2013. *Environmental health perspectives* 2015;123(11):1130-7.
97. Xu Y, Sajja M, Kumar A. Impact of the Hydraulic Fracturing on Indoor Radon Concentrations in Ohio: A Multilevel Modeling Approach. *Front Public Health* 2019;7:76.
98. Nyhan MM, Rice M, Blomberg A, et al. Associations between ambient particle radioactivity and lung function. *Environment International* 2019;130:104795.
99. Nyhan MM, Coull BA, Blomberg AJ, et al. Associations Between Ambient Particle Radioactivity and Blood Pressure: The NAS (Normative Aging Study). *J Am Heart Assoc* 2018;7(6).
100. Li W, Nyhan MM, Wilker EH, et al. Recent exposure to particle radioactivity and biomarkers of oxidative stress and inflammation: The Framingham Heart Study. *Environ Int* 2018;121(Pt 2):1210-6.
101. Fisher MP, Mayer A, Vollet K, et al. Psychosocial implications of unconventional natural gas development: Quality of life in Ohio's Guernsey and Noble Counties. *Journal of Environmental Psychology* 2018;55:90-8.
102. Ferrar KJ, Kriesky J, Christen CL, et al. Assessment and longitudinal analysis of health impacts and stressors perceived to result from unconventional shale gas development in the Marcellus Shale region. *Int J Occup Environ Health* 2013;19(2):104-12.
103. Boslett A, Hill E, Ma L, et al. Rural light pollution from shale gas development and associated sleep and subjective well-being. *Resource and Energy Economics* 2021;64:101220.
104. Basner M, Babisch W, Davis A, et al. Auditory and non-auditory effects of noise on health. *Lancet* 2014;383(9925):1325-32.
105. Axelsson G, Stockfelt L, Andersson E, et al. Annoyance and Worry in a Petrochemical Industrial Area—Prevalence, Time Trends and Risk Indicators. *International Journal of Environmental Research and Public Health* 2013;10(4):1418-38.
106. Shusterman D. Critical Review: The Health Significance of Environmental Odor Pollution. *Archives of Environmental Health: An International Journal* 1992;47(1):76-87.
107. Caulton DR, Shepson PB, Santoro RL, et al. Toward a better understanding and quantification of methane emissions from shale gas development. *Proceedings of the National Academy of Sciences of the United States of America* 2014;111(17):6237-42.
108. Johnston JE, Werder E, Sebastian D. Wastewater Disposal Wells, Fracking, and Environmental Injustice in Southern Texas. *American journal of public health* 2016;106(3):550-6.
109. Silva GS, Warren JL, Deziel NC. Spatial Modeling to Identify Sociodemographic Predictors of Hydraulic Fracturing Wastewater Injection Wells in Ohio Census Block Groups. *Environmental health perspectives* 2018;126(6):067008.
110. Franklin M, Chau K, Cushing LJ, et al. Characterizing flaring from unconventional oil and gas operations in south Texas using satellite observations. *Environmental science & technology* 2019;53(4):2220-8.
111. Soriano MA, Jr., Warren JL, Clark CJ, et al. Social Vulnerability and Groundwater Vulnerability to Contamination From Unconventional Hydrocarbon Extraction in the Appalachian Basin. *Geohealth* 2023;7(4):e2022GH000758.
112. González DJX, Morton CM, Hill LAL, et al. Temporal Trends of Racial and Socioeconomic Disparities in Population Exposures to Upstream Oil and Gas Development in California. *GeoHealth* 2023;7(3):e2022GH000690.
113. Vidic RD, Brantley SL, Vandenbossche JM, et al. Impact of shale gas development on regional water quality. *science* 2013;340(6134):1235009.

114. Xiong B, Soriano MA, Gutchess KM, et al. Groundwaters in Northeastern Pennsylvania near intense hydraulic fracturing activities exhibit few organic chemical impacts. *Environmental Science: Processes & Impacts* 2022;24(2):252-64.
115. Bonetti P, Leuz C, Michelon G. Large-sample evidence on the impact of unconventional oil and gas development on surface waters. *Science* 2021;373(6557):896-902.
116. Lee D, Murphy HM. Private wells and rural health: groundwater contaminants of emerging concern. *Current environmental health reports* 2020;7:129-39.
117. Deziel NC, McKenzie LM, Casey JA, et al. Applying the Hierarchy of Controls to Oil and Gas Development. *Environ Res Lett* 2022;17(7).
118. Deziel NC, Shamasunder B, Pejchar L. Synergies and Trade-Offs in Reducing Impacts of Unconventional Oil and Gas Development on Wildlife and Human Health. *BioScience* 2022;72(5):472-80.
119. Ericson SJ, Kaffine DT, Maniloff P. Costs of increasing oil and gas setbacks are initially modest but rise sharply. *Energy Policy* 2020;146:111749.