Oxford Research Encyclopedia of Global Public Health

Environmental Health Concerns From Unconventional Natural Gas Development

Irena Gorski and Brian S. Schwartz

Subject: Environmental Health, Global Health Online Publication Date: Feb 2019 DOI: 10.1093/acrefore/9780190632366.013.44

Summary and Keywords

Unconventional natural gas development (UNGD), which includes the processes of horizontal drilling and hydraulic fracturing to extract natural gas from unconventional reservoirs such as shale, has dramatically expanded since 2000. In parallel, concern over environmental and community impacts has increased along with the threats they pose for health. Shale gas reservoirs are present on all continents, but only a small proportion of global reserves has been extracted through 2016. Natural gas production from UNGD is highest in the United States in Pennsylvania, Texas, Louisiana, Oklahoma, and Arkansas. But unconventional production is also in practice elsewhere, including in eighteen other U.S. states, Canada, and China. Given the rapid development of the industry coupled with its likelihood of further growth and public concern about potential cumulative and long-term environmental and health impacts, it is important to review what is currently known about these topics.

The environmental impacts from UNGD include chemical, physical, and psychosocial hazards as well as more general community impacts. Chemical hazards commonly include detection of chemical odors; volatile organic compounds (including BTEX chemicals [benzene, toluene, ethylbenzene, and xylene], and several that have been implicated in endocrine disruption) in air, soil, and surface and groundwater; particulate matter, ozone, and oxides of nitrogen (NOx) in air; and inorganic compounds, including heavy metals, in soil and water, particularly near wastewater disposal sites. Physical hazards include noise, light, vibration, and ionizing radiation (including technologically enhanced naturally occurring radioactive materials [TENORMs] in air and water), which can affect health directly or through stress pathways. Psychosocial hazards can also operate through stress pathways and include exposure to increases in traffic accidents, heavy truck traffic, transient workforces, rapid industrialization of previously rural areas, increased crime rates, and changes in employment opportunities as well as land and home values. In addition, the deep-well injection of wastewater from UNGD has been associated with increased seismic activity.

These environmental and community impacts have generated considerable concern about potential health effects and corresponding political debate over whether UNGD should be promoted, regulated, or banned. For several years after the expansion of the industry, there were no well-designed, population-based studies that objectively measured UNGD activity or associated exposures in relation to health outcomes. This delay is inherent after the introduction of new industries, but hundreds of thousands of wells were drilled before any health studies were completed. By 2017, there were a number of important, peer-reviewed studies published in the scientific literature that raised concern about potential ongoing health impacts. These studies have reported associations between proximity to UNGD and pregnancy and birth outcomes; migraine headache, chronic rhinosinusitis, severe fatigue, and other symptoms; asthma exacerbations; and psychological and stress-related concerns. Beyond its direct health impacts, UNGD may be substantially contributing to climate change (due to fugitive emissions of methane, a powerful greenhouse gas), which has further health impacts. Certain health outcomes, such as cancer and neurodegenerative diseases, cannot yet be studied because insufficient time has passed in most regions since the expansion of UNGD to allow for latency considerations. With the potential for tens of thousands of additional wells across large geographic areas, these early health studies should give pause about whether and how UNGD should proceed. Citing health concerns, several U.S. states and nations in Europe have already decided to not allow UNGD.

Keywords: air pollution, asthma, birth outcomes, climate change, community-wide impacts, fossil fuels, hydraulic fracturing, natural gas, symptom-based conditions, water pollution

Introduction

History of UNGD

While conventional drilling has been used to extract natural gas since the 1940s, unconventional gas wells have only been widely used since 2004, with 18% of global gas production now coming from unconventional sources (International Energy Agency, 2016). Conventional gas wells are drilled vertically and only access gas that has escaped from a high permeability source rock into a reservoir. Unconventional gas wells, on the other hand, use horizontal drilling and hydraulic fracturing to access natural gas still trapped in low permeability source rock, resulting in generally higher yields from these wells. Although hydraulic fracturing has existed in different forms since an “exploding torpedo” was first patented in 1865, the current process is much different from its early practice commercialized by Halliburton and Stanolind in the late 1940s. The current process has been termed “high-volume slick-water hydraulic fracturing” because the total volume of injected water and the many chemical additives (hence “slick”) have dramatically changed along with the conversion from vertical to horizontal drilling over the past several decades (Arthur, Bohm, & Layne, 2008; Montgomery & Smith, 2010). The large injected volumes and the range of chemicals used, initially not disclosed in areas of use, contributed to early concerns about the potential environmental and health impacts. This article will focus on operations to extract natural gas via horizontal hydraulic fracturing, which will henceforth be referred to collectively here as unconventional natural gas development (UNGD); this does not include the related but distinct practices of conventional drilling, extraction of shale oil, mining of tar sands, or “dry fracking.”

Benefits of UNGD

Natural gas, consisting of methane, is the cleanest burning of the fossil fuels, with lower emissions of carbon dioxide per unit of derived energy and virtually no release of combustion toxicants. The rise of unconventional shale gas has resulted in power plants switching from coal to shale gas for electricity generation resulting in lower emissions from the electricity sector. This rise in unconventional shale gas production in the United States has provided the country with a strong domestic energy industry and dramatically lowered the costs of fuel while creating local and national economic benefits. In addition to being used for electricity and residential heating and cooking, natural gas also has industrial uses and can be used as a fuel in transportation. Natural gas currently provides 29% of the total U.S. energy supply and accounts for approximately 33% of the country’s electricity generation (U.S. Energy Information Administration, 2017).

Growth of UNGD and Resultant Public Concerns

While the largest increases in natural gas production from UNGD have occurred to date in the United States, and particularly in the states of Pennsylvania and Texas, shale gas reserves are widely distributed throughout the world, with an estimated total global availability of around 7,500 trillion cubic feet (Figure 1) (U.S. Energy Information Administration, 2015).

Click to view larger

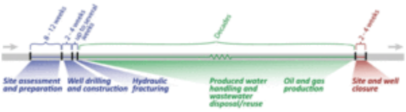
Figure 1. Global shale gas reserves.

Source: U.S. Energy Information Administration (2015).

UNGD has received a great deal of media attention in the United States, especially since the release of the documentary *Gasland* in 2010. Filmmaker Josh Fox interviewed residents of towns where UNGD was occurring in Pennsylvania, infamously showing these residents lighting their tap water on fire. *Gasland* was widely viewed in the United States over the following year, concomitant with a spike in public concern over UNGD. The *New York Times* and *National Geographic* also did extensive reporting on UNGD and environmental, community, and public health impacts. Informally referred to as "fracking," UNGD has been highly politicized and information on the benefits and consequences highly questioned (Brantley & Meyendorff, 2013). The core of the argument in the political arena has often come down to "claimed" environmental and health consequences versus "claimed" economic benefits. Proponents of UNGD have sponsored several studies that have estimated high economic value and employment opportunities (Hoy, Kelsey, & Shields, 2017).

The UNGD Process

To understand what people who live near UNGD operations may be exposed to, it is important to understand the UNGD process (Figure 2). UNGD begins with the construction of roads and then the clearing of three to five acres of land for the well pad. Additional infrastructure built on or near well pads includes water holding ponds (formally termed impoundments) to hold water for hydraulic fracturing. This pre-drilling activity typically requires 400 to 2,000 truck trips to and from the well pad. To create the well, a rig drills down vertically to 7,000 to 10,000 feet before turning horizontally to drill for another 2,000 to 10,000 feet. Flexible steel is put down the hole to keep the well open and cemented to seal it, typically including four layers of steel pipe: conduction casing down to around 40 feet; surface casing down to around 50 feet below groundwater; intermediate casing down to around 1,000 feet; and production casing all the way to the end. A perforation gun is then sent down into the horizontal part of the well to perforate the steel to allow access to the shale.



Click to view larger

Figure 2. UNGD well pad timeline.

Source: United States Environmental Protection Agency (2016).

In the next phase, termed "hydraulic fracturing" or "stimulation," millions of gallons of water are pumped into the well under high pressure mixed with a proppant (usually sand) and a number of chemical additives that vary in composition by drilling company and geology. Chemical additives include many classes of chemicals including friction reducers, gelling and foaming agents, antibacterial agents, surfactants, cross-linkers, breakers, pH buffers, iron control chemicals, clay protection chemicals, and scale inhibitors (Board on Chemical Sciences and Technology, 2015). Fracking with this mixture at high pressure opens and extends the fractures so that the natural gas can leave the formation and enter the drilling pipe. The injected frac fluid transports the proppant along the fracture length to promote patency of the fracture and, in some cases, transports radioactive tracers through the fractures to determine the injection profile and track the locations of fractures (Harper, 2008). Five to 30% of the fracking fluid injected returns to the surface as "flowback water" (Kondash, Albright, & Vengosh, 2017; United States Environmental Protection Agency, 2016), followed by "produced water" (i.e., water that is extracted along with gas from the shale at depth during production), which contains organic molecules as well as several inorganic ions (e.g., sodium, barium, strontium) eroded out of the geologic formations at depth (Vengosh, Jackson, Warner, Darrah, & Kondash, 2014). The drilling process and fracking fluids also acquire and bring to the surface a number of naturally occurring radioactive materials (NORMs) (Brown, 2014).

The well pad surface is prepared to receive natural gas and process (i.e., separate it from other organics and water vapor), compress (with diesel-powered compressor engines), store (in tanks with relief valves for off-gassing), and transport it via pipeline. Waste liquids from the water that returns to the surface, including the aforementioned flowback waters and also water that returns more slowly over many months, termed "produced waters," are primarily contaminated by salts, organics, and TENORMs; this aqueous mixture is stored in the impoundments until it can be treated, reused, or disposed. This UNGD process from well pad to the start of natural gas production usually requires only several months. Production drops rapidly from unconventional wells, with generally around an 80% to 90% decline in gas production from the initial peak within the first three years (Hughes, 2018). This has important implications including that for the industry to increase gas production over time, many wells must be continually drilled. Wells also may be re-stimulated to boost production, so some of the early development concerns can happen later at the same well. Residents in UNGD areas typically experience development over many years, because of the large number of drilled wells at each well pad, which are closer to homes compared to wells for conventional gas production (Adgate, Goldstein, & McKenzie, 2014). After development, gas production is expected to last decades, with much less visible activity but many potential ongoing environmental and community impacts (Shonkoff, Hays, & Finkel, 2014), which will be discussed in the "Environmental and Community Impacts from UNGD" section. While Pennsylvania had approximately 8,000 wells in production, some have estimated that at full development, the state could have as many as 50,000 wells (Johnson, 2010).

Regulatory and Legal Issues

In the Energy Policy Act deliberations led by then Vice President Dick Cheney in 2005, several long-standing exemptions of the oil and gas industry from environmental regulations were expanded and extended (U. S. Congress, 2005). Termed "The Halliburton Loophole" because of Cheney's prior position as CEO of Halliburton, the U.S. oil and gas industry was declared in this legislation to no longer be subjected to many or all provisions of a range of important environmental legislation, including the Clean Water Act, Safe Drinking Water Act, Superfund Act (CERCLA), and the Resource Conservation and Recovery Act (RCRA) (Patterson et al., 2017). This has forced the states to shoulder the bulk of responsibility for UNGD governance risks, with some local officials disputing control over land use, and most states are not fully equipped or motivated to adequately govern UNGD's risks (Davis, 2017; Wiseman, 2014). Even among the air and water standards that apply to UNGD (mostly at the state level), there have been many violations of these regulations, and there is no legislation that governs inter-state waste disposal issues (Alawattegama et al., 2015; Rabe, 2014).

Methods, Scope, and Organization

This article reviews the evidence on environmental and community impacts from UNGD and then the associated health concerns as of mid-2017. These topics are organized into two separate sections:

• The section “Environmental and Community Impacts from UNGD”: A literature review was conducted in October 2017 in PubMed with the search terms (((“natural gas” [MeSH *[“Medical Subject Heading”]*]) OR “hydraulic fracturing” OR “shale gas”) AND health AND (exposure OR toxic) AND (air OR water OR “climate change” OR environment OR social). A total of 340 articles arose from this search, of which the authors excluded the non-relevant articles that focused on natural gas in other contexts such as cooking, and/or they did not discuss health and/or unconventional natural gas development. Additional articles were identified from the reference sections of these articles in order to further explore relevant areas of environmental and community impacts. This section includes information from exposure studies, risk assessments, health impact assessments, community focus groups, toxicology studies, environmental hazard assessments, and other articles proposing health concerns from one or multiple aspects of UNGD, further sorted into articles on:

o water quality impacts,

o air quality impacts,

o physical hazards,

o climate change implications, and

o toxicity concerns of chemicals used and produced.

• The section “Emerging Public Health Impacts of UNGD”): A literature review was conducted in October 2017 in PubMed with the search terms ((“natural gas”[MeSH Terms]) OR “hydraulic fracturing” OR “shale gas”) AND “environmental exposure” AND epidemiology AND health. A total of 90 articles arose from this search, of which the authors excluded the non-relevant studies that focused only on animal health, occupational health, health concerns from conventional oil and/or gas extraction, and/or health concerns from using natural gas for cooking. This section only includes information from original epidemiologic studies that include an assessment of UNGD exposure and one or multiple health outcomes. After application of these additional criteria, fourteen studies remained for detailed review, including prospective and retrospective cohort studies, cross-sectional studies, a nested case-control study, and ecologic studies, all of which will be explored in this section.

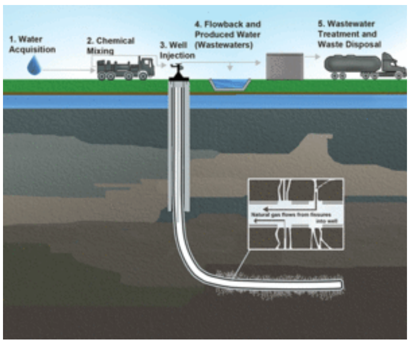
None of the studies included have been solicited and paid for by the natural gas industry. After summarizing the evidence for environmental and community impacts as well as health concerns from UNGD, this article discusses implications for policy and areas for future research.

Environmental and Community Impacts From UNGD

A systematic review of scientific articles published between 2010 and 2015 on environmental and community impacts from UNGD found six main categories of impacts: water resources, atmospheric emissions, land use, induced seismicity, occupational and public health and safety, and other impacts (Costa, Jesus, Branco, Danko, & Fiuza, 2017). UNGD activity can lead to human exposure to a number of hazards that can be evaluated and measured using standard methods. Environmental sampling of air, water, and soil for measurement of toxicants is a challenge for UNGD because there are thousands of emission sources across typically large geographies consisting of thousands of square miles (Field, Soltis, & Murphy, 2014).

Water Quality Impacts

Early concerns surrounding UNGD focused on impacts on water resources, as evidenced by an extensive review of the subject by the U.S. Environmental Protection Agency, which showed that despite data gaps and uncertainties, there is sufficient scientific evidence that hydraulic fracturing activities are impacting drinking water in several ways (Figure 3). These were summarized as: (1) from water withdrawals being made in times or areas of low water availability; (2) large volumes or high concentrations of chemicals from produced water and other fluids onsite spilling; (3) hydraulic fracturing fluids being injected into wells with inadequate mechanical integrity as well as directly into groundwater; (4) hydraulic fracturing wastewater being inadequately treated and discharged into surface water; and (5) hydraulic fracturing wastewater being disposed of or stored in unlined pits and leaching into groundwater (United States Environmental Protection Agency, 2016). Another comprehensive review found that risks to water resources from UNGD activity also include the contamination of shallow aquifers with fugitive hydrocarbon gases and the accumulation of toxic and radioactive elements in soil or stream sediments near disposal or spill sites (Vengosh et al., 2014).



Click to view larger

Figure 3. UNGD well pad water activities.

Source: United States Environmental Protection Agency (2016).

Specific agents of concern that contaminate water include BTEX (butane, benzene, toluene, ethylbenzene, and xylene) and other volatile organic compounds (VOCs) (Drollette et al., 2015), and salts and metals (including mercury, bromide, iodide, and ammonium) (Grant et al., 2015; Harkness et al., 2015). Prior to UNGD, many areas with underlying shale gas reservoirs already had natural background levels of methane in groundwater due to upward migration of natural gas from the shale formation (Brantley et al., 2014). A series of studies has reported that methane and ethane levels in groundwater were higher from water wells that were closer to, particularly within 1 km, of UNGD wells; while the methane could be from preexisting biogenic sources, ethane is only from thermogenic sources (Jackson et al., 2013; Osborn, Vengosh, Warner, & Jackson, 2011; Warner et al., 2012) and thus had to arise from fossil fuel deposits. Further evaluation of seven candidate scenarios that could account for hydrocarbon gases in shallow aquifers identified faulty production casing and gas traveling through the void between the well casing and piping as the likely culprits (Darrah, Vengosh, Jackson, Warner, & Poreda, 2014).

Toxicity Concerns of Chemicals Used and Produced

Several reviews of the toxicity of chemicals used for UNGD have found Category 2 oral toxicants (second highest category of toxicity out of 4) (Stringfellow, Domen, Camarillo, Sandelin, & Borglin, 2014; Yost, Stanek, DeWoskin, & Burgoon, 2016a, 2016b) as well as reproductive and developmental toxicity (Elliott, Ettinger, Leaderer, Bracken, & Deziel, 2017) and carcinogenicity (Yost, Stanek, & Burgoon, 2017). A series of water quality as well as in vitro and in vivo studies have also generated concern for the potential reproductive health impacts (Kassotis, Bromfield, et al., 2016; Kassotis, Iwanowicz, et al., 2016; Kassotis et al., 2015; Kassotis, Tillitt, Davis, Hormann, & Nagel, 2014). While many of these chemicals used in and produced from hydraulic fracturing are known to be toxic, many of them are lacking well-characterized exposure pathways to impacting human health, and others may be present in doses that are likely too low to cause a health response.

Physical Hazards

Physical hazards from UNGD activities include high noise from drilling, hydraulic fracturing, and increased truck traffic (Goodman et al., 2016); light pollution from flaring of natural gas and also from large lights illuminating the well pad and far beyond at night (Kiviat, 2013); radioactive elements from drill tailings and flowback fluids (Casey et al., 2015; Field et al., 2014; Konkel, 2015); and induced seismicity from deep underground injection (Carpenter, 2016). Exposure to excess noise, light, and vibration can potentially impact health by disturbing sleep, exposure to increased earthquakes can potentially impact health through injuries as well as through stress pathways and anxiety, and exposure to radioactive materials can potentially impact health through various outcomes, greatly depending on the intensity, frequency, and duration of the exposure (Hays, McCawley, & Shonkoff, 2017; Zhang, Hammack, & Vidic, 2015).

Community/Social Impacts

UNGD in a community has many potential impacts on its built and social environments, including changing roads and inhabitants, decreasing green space, and increasing traffic that lead to changes in social capital, social support, crime, civic engagement, employment opportunities, and land and home values (Adgate, Goldstein, & McKenzie, 2014). The increased truck traffic is often a major change and has the potential to lead to more motor vehicle accidents (Goodman et al., 2016). Home value changes can also be major, with one study showing that the price of a house using groundwater and within 2 km of a spudded well lost, on average, $16,059 of value, but the price of a house with public water and within 2 km of a well gained $5,070 on average (Muehlenbachs, Spiller, & Timmins, 2015). Focus groups conducted with residents of UNGD-impacted communities of West Virginia found that UNGD contributed to a disruption in these residents' sense of place and social identity, generating widespread social stress (Sangaramoorthy et al., 2016). Another study analyzed 215 letters to the editor in the newspaper from the most heavily drilled county in Pennsylvania and found that these letters showed that citizens were facing discord and stress in four major areas: socioeconomic impacts, perceived threats to water, population growth and implications, and changes to the rural landscape (Powers et al., 2015).

Air Quality Impacts

A comprehensive literature review conducted by the Natural Resources Defense Council found that fifteen different UNGD processes and sources—including the drilling process, wastewater, and condensate tanks—release air contaminants including

- particulate matter (diesel PM and PM_{10}), which is emitted during all stages of UNGD operations from well site preparation through drilling, production, processing, transmission, and well abandonment from sources including trucks and heavy machinery, as well as the drill rig and compressor stations;
- VOCs (including BTEX, polycyclic aromatic hydrocarbons, formaldehyde, ethylene glycol, and methanol), which are also emitted during all stages of UNGD operations from similar sources as PM as well as from produced water and gas venting (Paulik et al., 2016);
- hydrogen sulfide (H_2S, a toxic and explosive gas), which is emitted during hydraulic fracturing, well completion, production, and processing from flowback and produced waters as well as from gas venting;
- respirable crystalline silica (from sand), which reemerges from the well during hydraulic fracturing;
- nitrogen oxides (NO_x), which are emitted during all stages of UNGD from trucks, heavy machinery, and compressor stations as well as from the processes of drilling, hydraulic fracturing, and gas venting (Moore, Zielinska, Petron, & Jackson, 2014); and
- greenhouse gases (including methane and carbon dioxide), which are emitted during all stages from the same sources as NO_X as well as from separators, condensate tanks, and pipelines (Natural Resources Defense Council, 2014).

These air quality impacts are of concern because, in studies from related industries, exposure to these elevated levels of diesel PM, H_2S, and VOCs has been linked to eye, nose, and throat irritation, respiratory illnesses, cardiovascular problems, central nervous system damage, birth defects, cancer, or premature death (Macey et al., 2014). While some of these air contaminants mainly have negative impacts in communities close to well pads, significant amounts are emitted from natural gas infrastructure located offsite (Litovitz, Curtright, Abramzon, Burger, & Samaras, 2013), as well as from several thousand truck trips per well pad. These truck trips create diesel PM, VOC, CO_2, and NO_x emissions over wide areas away from the pad causing regional air quality impacts including ground-level ozone (McCawley, 2015). Ozone exposure is associated with a variety of respiratory and cardiovascular effects, and its formation is highest from UNGD activity in the winter (Edwards et al., 2014). Regulations on air quality continue to evolve including the USEPA issuing performance standards for VOCs emitted from new wells in 2015 (United States Environmental Protection Agency, 2012). However, air quality is still a concern for health, especially since EPA monitoring relies heavily on self-reported emissions data, the rules only apply to new gas wells, and protocols used for assessing compliance with air standards generally do not adequately determine the intensity, frequency, or durations of actual human exposures to the mixtures of toxic materials released regularly at UNGD sites (Brown, Weinberger, Lewis, & Bonaparte, 2014).

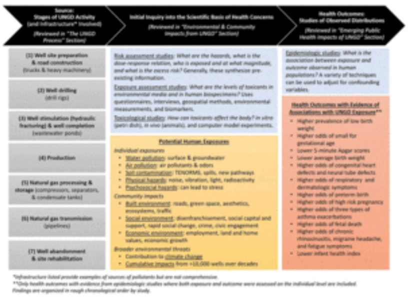
Climate Change Implications

Natural gas is a fossil fuel that can contribute to climate change in several ways including from (1) clearing of land (i.e., the loss of carbon dioxide sinks from forests); (2) fugitive emissions (i.e., emissions of methane from pressurized UNGD equipment due to leaks during drilling, storage, and transport operations); and (3) combustion during use. Direct measurements of methane emissions at 190 onshore natural gas sites in the United States found 957 Gg (gigagrams) in emissions for completion flowbacks, pneumatics, and equipment leaks; coupled with EPA national inventory estimates for other categories, the authors estimated natural gas production contributed 2,300 Gg of methane emissions per year (Allen et al., 2013). Subsequent investigation expressed concern about the substantial amount of methane (which has ~20x the global warming potential as carbon dioxide over 100 years [Howarth, 2015]) that leaks from UNGD operations and how there is a clear need to help obtain better fugitive emissions data and to increase efforts on reducing methane leakage in order to minimize the climate footprint of natural gas (Jiang et al., 2011). Estimates for fugitive emissions from UNGD (coal and petroleum do not have fugitive emissions) range from 1% to 6% and some estimate that if fugitive emissions exceed 3% or so then UNGD and subsequent natural gas use are worse for climate than is coal use (Howard, 2015).

Researchers compared the cumulative radiative forcing (defined as the difference between sunlight energy absorbed by the Earth and energy radiated back to space, measured in watts per square meter over the planet's surface) created by alternative technologies fueled by UNGD compared to other fossil fuels using the best available estimates of greenhouse gas emissions from production, transportation, and use of each. They found that while using natural gas instead of coal for electric power plants can reduce radiative forcing immediately, a shift to compressed natural gas vehicles from gasoline or diesel vehicles leads to greater radiative forcing of the climate for 80 or 280 years, respectively, before beginning to produce benefits but that compressed natural gas vehicles could produce climate benefits sooner if fugitive emissions were prevented (Alvarez, Pacala, Winebrake, Chameides, & Hamburg, 2012). The impacts of climate change on health have been the subject of public health research for decades and include heat-related illness and death, increased respiratory diseases, increases in vector-borne diseases, increased mental health impacts from forced migration and civil conflict, and health impacts from severe weather events (Frumkin & McMichael, 2008; Haines, Kovats, Campbell-Lendrum, & Corvalán, 2006; Luber & Lemery, 2015; Patz et al., 2000).

Emerging Public Health Impacts of UNGD

There have been many review articles on the health impacts of hydraulic fracturing which have found that most original research studies relevant to UNGD and public health indicate public health hazards, elevated risks, or adverse public health outcomes (Figure 4) (Adgate et al., 2014; Hays & Shonkoff, 2016; Health Effects Institute, 2015; McKenzie, Witter, Newman, & Adgate, 2012; Milton et al., 2014; Saunders, McCoy, Goldstein, Saunders, & Munroe, 2016; The League of Women Voters of Pennsylvania, 2016).



Click to view larger

Figure 4. Pathways from UNGD exposure to discovering health outcomes.

This section will explore the 14 original epidemiologic studies published in the scientific literature as of 2017 that have reported associations between proximity to UNGD and health outcomes. Table 1 includes details about each of the study designs, study population, sample size, health outcomes and how they were measured, the metric used to assess UNGD activity or exposure, confounding variables that were adjusted for, what method of data analysis was used, limitations of the study, and the authors' conclusions.

Citation	Study design	Study population	Sample size	Health outcomes studied + how measured	UNGD exposure metric	Confounding variables	Data analysis	Limitations	Author conclusions
Exposure and Health Outcome Both Assessed on Individual Level									
(Hill, 2012)	Retro-spective cohort	PA mothers and their neonates with births recorded in the Vital Statistics Natality records from 2003-2010	1,069,699 births	Low birth weight, premature birth, 5-minute Apgar score, and small for gestational age determined from Vital Statistics Natality records	Distance between mother's residence and closest existing Marcellus Shale gas well or permits that had not yet been drilled; linked to timing	Mother's education, age, race/ethnicity; received Women, Infants, and Children (WIC); her method of payment for medical care, mother's marital status, sex of the child, and whether mother smoked during pregnancy	Difference-in-differences estimator of the impact of a UNGD well completion using a linear probability model	Not yet peer-reviewed	UNGD wells close to pregnant mothers' residences increased LBW prevalence by 25%, increased small for gestational age prevalence by 17% and reduced 5-minute Apgar scores, when compared to pregnant mothers' residences that were close to a future well (permitted only)
(McKenzie et al., 2014)	Retro-spective cohort	CO births 1996-2009	124,842 births	Congenital heart defects, neural tube defects, oral clefts, preterm	Inverse distance to spudded well, included conventional	Maternal age, education, tobacco use, ethnicity, alcohol use, parity, and infant sex.	Linear and logistic regression models	Activity assessment temporally vague (matched	UNGD associated with 30% increased odds of

				birth, and term low birth weight identified from CO Vital Birth Statistics; also had ICD-9 (International Classification of Diseases) diagnostic codes and matched birth certificates with registry of birth defects	and un-conventional			wells & births by year); dataset included conventional & unconven-tional natural gas wells.	congenital heart defect; statistically significant small magnitude negative association with preterm birth, positive association with fetal growth, and positive association with neural tube defects
(Stacy et al., 2015)	Retro-spective cohort	PA mothers and their neonates born in Butler, Washington and Westmoreland counties 2007-2010	15,451 births	Birth weight, small for gestational age, and prematurity identified from birth records obtained from PA Department of Health Bureau of Vital Statistics which were geocoded to residence	Inverse distance to spudded well; well data from PA Department of Environmental Protection (DEP)	Adjusted for mother's age, education, pre-pregnancy weight, gestational age, child gender, prenatal visits, smoking, gestational diabetes, WIC, race/ethnicity, and birth order.	Linear and logistic regression models	Likely biased towards null because activity indicators determined by UNGD well site only, not by phase of development	UNGD was associated with lower birth weight and 34% higher odds of small for gestational age
(Rabinowitz et al., 2015)	Cross-sectional	PA residents of Washington County (selected because of high density of drilling; 38 rural townships selected within the center of the county)	180 survey responders in Washington County, PA reporting on the health status of 492 household members in 2012	Symptoms self-reported on a questionnaire from past year (broad questions on health-related symptoms were classified into categories of: dermal, upper respiratory, lower respiratory, gastrointestinal, neurological, and cardiovascular)	Proximity to active UNGD wells from PA DEP, classified residences in distance categories of < 1 km, 1–2 km, or > 2 km from the nearest active well	Adjusted for individual age, sex, average adult household education, smoker present in household, awareness of environmental hazard nearby, employment type, and presence of animals in the backyard or home	Generalized linear mixed model	Potential for individual bias in self-reported health outcomes	Proximity to UNGD wells was associated with increased odds of dermal and respiratory symptoms (e.g., for skin conditions, was 4-fold increased odds)
(Casey et al., 2016)	Retro-spective cohort	PA mothers and their neonates born 2009-2013 in the Geisinger Health System	9384 mothers who delivered 10496 neonates	Term birth weight, preterm birth, low 5-minute Apgar score, and small for gestational age determined from electronic health record (EHR) ICD-9 codes	Inverse distance squared UNGD activity metric incorporating four phases of well development	Neonate sex, gestational age, season and year of birth, maternal age, race/ethnicity, Geisinger primary care provider status, smoking status during pregnancy, pre-pregnancy body mass index (BMI), parity, antibiotic orders during pregnancy,	Multilevel linear and logistic regression models	Like all other studies here, did not make any measurements of environmental exposure levels	UNGD was associated with 41% higher odds of preterm birth and also high-risk pregnancy

						Medical Assistance, distance to nearest major road, community socioeconomic deprivation, residential greenness, and household water source			
(Rasmussen et al., 2016)	Nested case-control	PA patients with asthma with and without exacerbations from 2005 through 2012 treated at the Geisinger Clinic	35,508 patients with asthma	Mild, moderate, and severe asthma exacerbations identified from ICD-9 codes in EHRs for new oral corticosteroid medication orders, emergency department visits, and hospitalization, for mild, moderate, and severe, respectively. Subject residential addresses geocoded.	Inverse distance squared UNGD activity metric incorporating four phases of well development and size of wells	Adjusted for age, sex, race/ethnicity, family history of asthma, smoking status, season, Medical Assistance, and overweight/obesity status	Multilevel logistic regression model	Like all other studies here, did not make any measurements of environmental exposure levels	Asthma patients in the highest quartile of residential UNGD activity had significantly higher odds of all 3 types of asthma exacerbations than those in the lowest quartile
(Tustin et al., 2017)	Cross-sectional	Geisinger primary care patients with EHR data living in 39 counties in central and northeastern PA in 2014, in regions with and without UNGD	7785 questionnaire responders	Chronic rhinosinusitis (CRS), migraine headache, and fatigue symptoms self-reported on a questionnaire	Inverse distance squared UNGD activity metric incorporating four phases of well development and size of wells	Adjusted for sex, race/ethnicity, age, receipt of Medical Assistance, and smoking status; also evaluated additional confounding by BMI and community socioeconomic deprivation	Survey-weighted logistic regression	Low participation rates; and symptoms were self-reported. Analysis was weighted to refer back to source population, mitigating possible participation bias	UNGD was associated with increased odds of CRS and fatigue together, migraine and fatigue together, and all three outcomes together (for example, 84% increased odds of all three conditions in highest quartile of UNGD)
(Whitworth, Marshall, & Symanski, 2017)	Retro-spective cohort	TX women with births or fetal deaths November 2010-November 2012 in the Barnett shale	158,894 women with a birth or fetal death	Preterm birth, small-for gestational age, fetal death, and birthweight determined from governmental	Three UNGD-activity metrics by calculating the inverse distance-weighted sum of active wells	Maternal age, race/ethnicity, education, pre-pregnancy BMI, parity, smoking, adequacy of prenatal care, previous poor	Linear and logistic regression models	Like all other studies here, did not make any measurements of environmental exposure	Increased adjusted odds of preterm birth associated with UNGD-activity in the highest

		Barnett shale, in North Texas		governmental registry	of active wells within three separate geographic buffers surrounding the maternal residence: <½, 2, or 10-miles.	previous poor pregnancy outcome, and/or infant sex		exposure levels	highest tertiles of the ½- (14%), 2- (14%), and 10-mile (15%) metrics; increased adjusted odds of fetal death were found in the second tertile of the 2-mile metric (56%) and the highest tertile of the 10-mile metric (34%)
(Currie, Greenstone, and Meckel, 2017)	Retro-spective cohort	Infants born in PA during the period 2004–2013	1,125,748 infants from singleton births	Birthweight, low birthweight, and health index determined from PA certificates of live births	Tested various distances of maternal residence from UNGD sites	Maternal marriage, maternal race and ethnicity, maternal education, maternal age, child sex, and child parity	Linear and logistic regression models; and difference-in-differences approach	Like all other studies here, did not make any measurements of environmental exposure levels; and effective sample size limits ability to examine the shape of the distance-exposure relationship	Introduction of fracking reduces health among infants born to mothers living within 3 km of a well site during pregnancy. Found a 25% increase in the probability of a low–birth weight birth for mothers living within 1 km of a UNGD site and significant declines in average birth weight, as well as in an index of infant health
(Whitworth, Marshall, & Symanski, 2018)	Nested case-control	TX women with births November 2010-November 2012 in the 24 counties covering the Barnett Shale area, Texas	166,966 women with a singleton birth	Preterm birth determined from governmental registry	Inverse distance squared UNGD activity metric incorporating four phases of well development and size of wells	Maternal education, parity, smoking during pregnancy, pre-pregnancy BMI, infant sex, and previous poor pregnancy outcome	Conditional logistic regression model	Like all other studies here, did not make any measurements of environmental exposure levels	Increased adjusted odds of preterm birth in the third tertile of UNGD, with strongest associations between UNGD in the production phase and women in trimesters one and two of pregnancy

Exposure and Health Outcome Both Assessed from the Same Source									
e	Pro-spective longi-tudinal cohort	Convenience sample of community members living near UNGD activities in PA	Baseline n=33; Follow up n=20	Phone interview collected self-reported symptoms at baseline and follow-up	Phone interview of self-reported stressors at baseline and follow-up	None	Descriptive statistics	UNGD activity & outcome both assessed by self-report (same-source bias); small sample size	Participants attributed 59 unique health impacts and 13 stressors to UNGD.
(Saberi, Propert, Powers, Emmett, & Green-McKenzie, 2014)	Cross-sectional	PA adult volunteers with medical complaints in a primary-care medical office in a county where UNGD was present	72 responders	Symptoms self-reported on a questionnaire	Questionnaire asked whether responder attributed symptoms to UNGD	None	Descriptive statistics	UNGD activity and outcome both assessed by self-report (same-source bias); conducted over a one-week period during the summer	13% of responders attributed a symptom to UNGD
Exposure and Health Outcome Both Assessed on Population Level (Ecologic Studies)									
(Fryzek, Pastula, Jiang, & Garabrant, 2013)	Ecologic	PA children with cancer 1990-2009	10,708 childhood cancer cases	New cases of cancer (all cancers, central nervous system tumors, and leukemia) by county identified through the PA DOH Childhood Cancer Registry	Before vs. after drilling by county	Stratified by 5-year age groups, race/ethnicity, and sex	Standardized incidence ratios (SIR) at county level	Lack of individual-level health data; does not take into account long latency period of cancer	Null findings except counties after drilling had 13% higher rate of central nervous system tumors compared to before drilling
(Jemielita et al., 2015)	Ecologic	PA residents who were hospitalized 2007-2011	92805 hospitalizations	Inpatient prevalence rates by medical category per zip code identified through a government database	Wells per zip code; wells per km^2	Sex and age	Poisson regression models	Lack of individual-level health data	Cardiology inpatient rates were associated with number of UNDG wells per zip code and per km^2; neurology inpatient rates associated with UNDG wells/km^2.
(Graham et al., 2015)	Ecologic	PA residents experiencing a car crash 2005-2012	6,432 car crashes	Car crashes identified through a government database	County level high vs. low drilling activity	Not specified	Linear generalized estimating equation models	Lack of individual-level health data	Counties with high drilling were associated with higher vehicle crash rates (up to 15% higher).
(Finkel, 2016)	Ecologic	PA residents with cancer 2000-2012	11,508 urinary bladder cancer cases, 6,222 thyroid cancer cases, and 5,061 leukemia cases	New cases of urinary bladder cancer, thyroid cancer, and leukemia identified through the PA Cancer Registry	County count of producing UNGD wells (high vs. low) in	Sex, age, race/ethnicity, poverty	Standardized incidence ratios (SIR) at county level	Lack of individual-level health data; does not take into	Counties with higher well counts had higher rates of urinary bladder cancer compared to

					six counties			account long latency period of cancer	those without UNGD (e.g. in Washington county from 2008-12, 31% increased SIR for urinary cancer).
(Deziel et al., 2018)	Ecologic	Ohio residents with reportable STIs 2000-2016	Not reported	Reported cases of chlamydia, gonorrhea, and syphilis by county and year obtained from government database	No vs. low vs. high UNGD activity by county	Median household income, percent population with health insurance, percent white, percent Hispanic, percent population 15±29 years, percent females, population density, and year	Mixed-effects poisson regression models	Lack of individual-level health data; STIs not inherently related to UNGD	Compared to counties with no UNGD activity, counties with high activity had 21% increased rates of chlamydia and 19% increased rates of gonorrhea; no association observed for syphilis.

Study Designs

The study designs employed are mostly retrospective cohorts (n = 6), followed by ecologic (n = 5), cross-sectional (n = 3), prospective longitudinal cohort (n = 1), and nested case-control (n = 2). Most were conducted with study populations in Pennsylvania (n = 13) plus one each in Colorado and Ohio, and two in Texas. Unfortunately, several of these studies had limitations, including three that only analyzed population-level data allowing inferences about predictors of population rates and not individual-level causes (Graham et al., 2015; Jemielita et al., 2015; Deziel et al., 2018); two that evaluated cancer that did not allow a sufficient latency period (time from first exposure to development of clinical disease) to pass before evaluating associations with cancer outcomes that can require many decades to appear after an exposure (Finkel, 2016; Fryzek et al., 2013); one that included primarily conventional wells in their well metric (McKenzie et al., 2014); and two which assessed both UNGD activity or exposure and the health outcome by self-report leading to same-source bias (Ferrar et al., 2013; Saberi, Propert, Powers, Emmett, & Green-McKenzie, 2014).

Measurement of the Outcome

The remaining nine studies categorized study participants by UNGD, identified a health outcome, and evaluated associations between UNGD and the health outcome. All of these studies necessarily focused on health outcomes that had a biologically plausible way in which UNGD could affect the outcome with a short latency period; the studies also focused on health outcomes that had a relatively high prevalence, since these are the ones that should first appear and also be amenable to study. The measurement of the health outcome varied: two used self-reported information from questionnaires and found positive associations for various symptoms including dermal and respiratory symptoms (Rabinowitz et al., 2015) as well as chronic rhinosinusitis, migraine, and fatigue symptoms (Tustin et al., 2017); five used birth records from governmental registries and found positive associations with various pregnancy and birth outcomes (Currie, Greenstone, & Meckel, 2017; Hill, 2012; Stacy et al., 2015; Whitworth, Marshall, & Symanski, 2017; Whitworth, Marshall, & Symanski, 2018); and three applied analytics to electronic health records (EHR) data to find these associations including with preterm birth and high-risk pregnancy (Casey et al., 2016) and asthma exacerbations (Rasmussen et al., 2016). One of the studies that used questionnaires had a limited sample size (n = 180), while the other was a large sample size (n = 7,785); for both studies, the assessment of the health outcome was not clinician verified. Using EHR data as well as governmental databases to identify cases allowed researchers to objectively obtain large sample sizes (n = 15,451 to 1,125,748), but using these strategies necessarily focused the studies on health conditions that were severe enough for patients to seek health care.

Measurement of UNGD Activity or Exposure

A key requirement of environmental epidemiology is the need to rank subjects along a gradient of exposure or dose. Exposure is defined as hazardous agents that are external to the human body and can be measured, for example, as concentrations of toxicants in air or sound levels for noise. Hazardous agents must have an exposure pathway to the human body and then are internalized through inhalation, ingestion, or dermal absorption. Exposure is considered in terms of the intensity (i.e., concentration), frequency, and duration of the exposure. Dose is defined after the exposure becomes internalized, and can be measured, for example, as blood or urine levels of toxicants or their metabolites. These measurements can be expensive, especially in large-scale studies, and current measurements are difficult to make relevant retrospectively for health outcomes that occurred many years in the past. Environmental epidemiology studies attempt to assign measures of recent or cumulative exposure or dose, depending on how the health outcome is hypothesized to occur, to individuals, and then perform analysis to evaluate whether risk of illness is higher or severity of illness is worse as exposure or dose is estimated to be higher.

A complexity of research on the potential health impacts of UNGD is that UNGD could affect health through several different hazardous exposures and through behavioral or stress pathways. As discussed in the “Environmental and Community Impacts from UNGD” section, a variety of chemical and physical hazards are introduced to communities during development, and community impacts (e.g., industrialization, truck traffic, transient workforces) can influence behaviors or stress pathways. These in turn can affect health alone or especially in combination. Methods are available to estimate exposure or dose in individuals from each of these pathways, but studies that considered them all would be prohibitively expensive and could not be done retrospectively.

Most existing studies have thus used surrogates of exposure, in two primary categories. In the first, subjects were asked about what they saw and experienced around their residences and communities and this self-reported information was used to estimate proximity, intensity, frequency, and duration of exposure. Studies that used self-reported information about exposure and health outcomes are subject to same source bias, in that associations between exposure and health can be observed but are spurious due to biased reporting in persons concerned about what they are seeing in their communities and linking it to perceived health impacts. The second major approach was to use publicly available information on well locations, phase of development (e.g., well pad, drilling, stimulation, production), dates of development, well depth (a surrogate for volume of injected fluids and number of truck trips to site), and gas production (a surrogate for compressor engine activity and possibly VOC off-gassing), impoundment size and locations (a surrogate for VOC off-gassing from ponds), and compressor stations (locations, dates, number of compressor engines, estimated emissions from compressor engines). This information was available in space and time and geographic information systems (GIS) were used to link this UNGD activity to the residential address of study subjects. GIS-based approaches to UNGD activity characterization usually were based on proximity models, in which the inverse of distance or distance-squared is used to weight the information about the UNGD wells and infrastructure surrounding the residential address.

Health Impacts With the Most Evidence of Concern: Pregnancy and Birth Outcomes and Asthma Exacerbations

As of mid-2018, there have been six primary health studies investigating the potential impact of UNGD on pregnancy and birth outcomes (McKenzie et al., 2014 is not included here because most wells in Colorado at the time of the study were conventional and the information available at the time could not distinguish conventional from unconventional [McKenzie et al., 2014]). Hill used the gradual introduction of UNGD wells in Pennsylvania as a natural experiment to identify the potential impacts on infant health (Hill, 2012). The study examined the natality records of 2,437 singleton births to mothers residing within 2.5 km of a UNGD well in the state from 2003 to 2010. The authors compared birth outcomes (including low birth weight, premature birth, small for gestational age, and five-minute Apgar scores) before and after a gas well was completed for these mothers. Their results suggested that prenatal proximity to UNGD increased the overall prevalence of low birth weight by 25%, increased overall prevalence of small for gestational age by 17%, reduced five-minute Apgar scores, and was not associated with premature birth.

Stacy and colleagues investigated records for 15,451 live births in southwest Pennsylvania from 2007 to 2010 to examine the association of proximity to UNGD (mothers categorized into exposure quartiles based on inverse distance weighted well count) and perinatal outcomes (birth weight, small for gestational age, and prematurity, accounting for differences in maternal and child risk factors) (Stacy et al., 2015). The study found no significant association of UNGD activity with prematurity, but the authors found a positive association of UNGD activity with lower birth weight and a higher prevalence of small for gestational age (highest quartile had 34% increased odds over the lowest quartile).

Casey and colleagues conducted a retrospective cohort study examining the association between exposure to UNGD activity (cumulative exposure estimated with an inverse-distance squared model incorporating distance to the mother's home; dates and durations of well pad development, drilling, and hydraulic fracturing; and production volume during the pregnancy) and birth outcomes (term birth weight, preterm birth, low five-minute Apgar score, small size for gestational age birth, and physician-recorded high-risk pregnancy, controlling for potential confounding variables) (Casey et al., 2016). The researchers analyzed EHR data on 9,384 mothers and their 10,946 neonates in Pennsylvania from 2009 to 2013 and found an association between UNGD activity and preterm birth that increased across quartiles (highest quartile had 40% increased odds over the lowest), an association with physician-recorded high-risk pregnancy (highest quartile had 30% increased odds over the lowest), and no associations with Apgar score, small for gestational age birth, or term birth weight.

Whitworth, Marshall, and Symanski have conducted both a retrospective cohort study (2017) and a nested case control study (2018) in Texas, using the same exposure method as Casey et al. (2016). The research team analyzed the association between UNGD and birth outcomes using birth certificates from the Texas Department of State Health Services for over 150,000 singleton babies born between November 2010 and November 2012 and adjusting for confounders including maternal age, race/ethnicity, pre-pregnancy BMI, and adequacy of prenatal care. In their retrospective cohort study, they found 14% to 15% increased adjusted odds of preterm birth associated with UNGD activity in the highest tertiles of the half, two, and ten-mile metrics; 56% increased adjusted odds of fetal death in the second tertile of the two-mile metric and 34% increased adjusted odds in the highest tertile of the 10-mile metric. In their nested case-control study, they found increased adjusted odds of preterm birth in the third tertile of UNGD activity, with strongest associations between UNGD in the production phase and women in trimesters one and two of pregnancy.

Currie, Greenstone, and Meckel conducted a retrospective cohort study (2017) with a cohort of 1,125,748 infants from singleton births in Pennsylvania during the period from 2004 to 2013. Testing various distances of maternal residence from UNGD sites, analyzing data from Pennsylvania birth certificates, and adjusting for confounders including maternal marriage, maternal education, maternal age, and child sex in a difference-in-differences approach, they found that the introduction of UNGD reduces health among infants born to mothers living within three kilometers of a well site during pregnancy. They also found a 25% increase in the probability of a low-birth-weight birth for mothers living within one kilometer of a UNGD site and significant declines in average birth weight, as well as in an index of infant health. Overall, the three birth outcome studies have consistently revealed associations of UNGD activity with adverse birth outcomes. There were some methodologic differences between the studies that could explain the contrasting associations, but these health outcomes are the only ones for which multiple independent studies can be evaluated as a body of evidence. The findings, while not conclusive, are strong preliminary evidence that UNGD is associated with adverse birth outcomes from pregnancies in UNGD areas.

Asthma is a suitable health outcome to study in relation to UNGD because it is well known that air pollution and stress can both exacerbate asthma. This happens with short latency after the increase in air pollution or activities that promote stress, and exacerbations often end up bringing patients to see a health professional which provides a record in EHRs with dates, diagnoses, and treatments. To evaluate the association between UNGD and asthma exacerbations, Rasmussen and colleagues conducted a nested case-control study comparing 35,508 asthma patients treated at the Geisinger Clinic from 2005 to 2012 (Rasmussen et al., 2016). Patients were identified in EHRs and cases (asthma patients with exacerbations) were frequency matched with controls (asthma patients without exacerbations) on age, sex, and year of event. Cases were categorized into three groups based on mild exacerbation (new oral corticosteroid medication order), moderate (emergency department encounter), or severe (hospitalization). UNGD activity was assessed based on the distance from the patient's home to each well and the well's estimated activity metrics for four UNGD phases (well pad preparation, drilling, hydraulic fracturing, and production) on the day before each patient's index date (date of exacerbation for cases, contact date for controls). The UNGD metrics also accounted for number of wells, for all wells in the state, and the size of the well. The analysis adjusted for several confounders and found associations between the highest quartile of the activity metric for each UNGD phase versus the lowest group for 11 of 12 UNGD-outcome pairs, with increased odds of 50% to 440% (the highest for the association of the production metric with mild exacerbations); several of the associations evidenced exposure-effect trends, with increasing odds along increasing quartiles of UNGD activity. They concluded that residential UNGD activity metrics were statistically associated with increased risk of mild, moderate, and severe asthma exacerbations.

UNGD and Policy

The world is now in an era here conventional oil reserves are declining and hence oil companies are being driven to engage in riskier, more expensive, and more environmentally damaging practices to access energy reserves with lower returns of energy on the amount of energy invested in extraction and production, at the same time that the effects of climate change and there is a need for integrated policy to tackle these competing, intertwined issues. *The Lancet* described climate change as "the greatest global health threat of the 21st century," in 2009, and there has since been outcry for action from many public health leaders including Dr. Margaret Chan, WHO Director-General, who in 2015 said, "The evidence is overwhelming: climate change endangers human health. Solutions exist and we need to act decisively to change this trajectory" (The Lancet, 2009; World Health Organization, 2015). While natural gas has been promoted as a "bridge fuel" to "bridge" the transition from fossil fuels to renewable energy sources, this term does not give full consideration to the use of natural gas. Natural gas is still a fossil fuel contributing to climate change, renewable energy sources are becoming more economically viable every year, and there continues to be heavy investment in UNGD infrastructure that will not be temporary during a "bridge" period. If countries allow extensive development, the industry will likely produce unconventional natural gas for as long as it is economically viable and not in consideration of continuing and possibly worsening climate change.

UNGD has had some positive impacts, including fuel switching of electricity generation from coal to natural gas. However, if the world is to keep all cumulative emissions below 765 gigatons of carbon dioxide equivalents through 2050 (Peters, Andrew, Solomon, & Friedlingstein, 2015) in order to prevent dangerous climate change, governments will likely find it difficult to meet targets while investing in another fossil fuel. UNGD is also likely slowing the development of renewables for the same reason it is closing coal production (low natural gas prices). Integrated energy and climate policy would suggest that policymakers should end the externalities by putting a price on carbon emissions; if a price were to be set on carbon emissions, unconventional natural gas would have fewer competitive advantages compared to renewables.

Several other policy options have been proposed to provide protective measures for health concerns from UNGD activity including regulating the industry, implementing a moratorium on operations, and banning it altogether. Regulations proposed and implemented include mandates on thickness of well casing, engineering controls to reduce the amount of methane leaking from the well, and fines for spilling wastewater off of the well pad. The argument for regulations centers on a compromise to allow the industry to operate while offering restrictions to prevent environmental contamination; however, all of the environmental exposures and health concerns explained in this article were evaluated despite regulations in place. A moratorium entails not allowing UNGD for a specified time period. This solution is also promoted as a compromise, with the argument often including that the jurisdiction should wait to make a more permanent decision on allowing UNGD until the evidence on the environmental health impacts "is better established." Finally, a complete ban of UNGD has also been proposed as a solution to prevent all related exposures coming from within the jurisdiction and hence offer the best protection for health; this proposal has passed as of mid-2017 in the U.S. states of Maryland, Vermont, Massachusetts, and New York (Brydon, 2012).

Conclusion

The body of research to date on UNGD and health would allow several conclusions. UNGD activity metrics have been found to be associated with preterm birth, high-risk pregnancy, and possibly low birth weight; three types of asthma exacerbations; and nasal and sinus, migraine headache, fatigue, dermatologic, and other symptoms. In these studies, associations were robust to increasing covariate control; the associations were robust in several sensitivity analyses, in which researchers evaluated whether observed associations decline or disappear under certain varying assumptions; and the associations were biologically plausible. Because of the approach to UNGD activity measurement in these studies, in which no hazardous exposures in air, water, soil, or communities was directly measured, the current evidence does not allow inferences about responsible pathways or mechanisms, such as air pollution versus stress for asthma exacerbations.

This emerging evidence is of concern, and it is somewhat surprising that any health impacts have been reported given the relatively limited funding, to date, that has been devoted to finding them. Nearly every author of these studies suggests larger, longer-term quantitative epidemiology studies with more detailed, direct exposure assessments of UNGD (e.g., measurement of specific air and water contaminants). Finally, given that this article was written less than a decade after the expansion of UNGD, the studies in these sections have been limited to investigation of short-latency health outcomes in the context of UNGD. Other health outcomes such as cancer and neurodegenerative disease await future studies.

In the history of public health, industrial development has always gotten ahead of public health protections. The UNGD industry has developed particularly rapidly. When is there enough evidence to regulate UNGD on the basis of health? At what point does society require evidence of benefits to proceed with development as opposed to evidence of negative impacts to slow development? Given the limited resources devoted to these investigations, along with the difficulty of obtaining information on the industry early on, and that in environmental epidemiology there are often many biases that result in difficulty uncovering evidence (called bias toward the null), what has been reported to date offers no reassurance that UNGD is likely to be safe for public health. Some have suggested that regulations will prevent health impacts, but no health studies provide guidance on what regulations, if any, will get the health effects to go away. In an era of climate change, and with emerging evidence that UNGD not only continues to contribute to climate change but also has local and regional direct health impacts, this is further scientific basis to put a robust price on carbon emissions and stop subsidies for fossil fuels.

References

Adgate, J. L., Goldstein, B. D., & McKenzie, L. M. (2014). **Potential public health hazards, exposures and health effects from unconventional natural gas development**. *Environmental Science & Technology*, *48*(15), **8307–8320**.
[+] Find this resource:

Alawattegama, S. K., Kondratyuk, T., Krynock, R., Bricker, M., Rutter, J. K., Bain, D. J., . . . Stolz, J. F. (2015). **Well water contamination in a rural community in southwestern Pennsylvania near unconventional shale gas extraction**. *Journal of Environmental Science and Health, Part A: Toxic/Hazardardous Substances and Environmental Engineering*, *50*(5), 516–528.
[+] Find this resource:

Allen, D. T., Torres, V. M., Thomas, J., Sullivan, D. W., Harrison, M., Hendler, A., . . . Hill, A. D. (2013). Measurements of methane emissions at natural gas production sites in the United States. *Proceedings of the National Academy of Sciences*, *110*(44), 17768–17773.
[+] Find this resource:

Alvarez, R. A., Pacala, S. W., Winebrake, J. J., Chameides, W. L., & Hamburg, S. P. (2012). **Greater focus needed on methane leakage from natural gas infrastructure**. *Proceedings of the National Academy of Sciences*, *109*(17), **6435–6440**.
[+] Find this resource:

Arthur, B., & Layne Arthur, J. D., Bohm, B., & Layne, M. (2008, September 21). ***Hydraulic fracturing considerations for natural gas wells of the Marcellus Shale***. Cincinanati, Ohio: The Ground Water Protection Council Annual Forum.
[+] Find this resource:

Baihly, J. D., Altman, R. M., Malpani, R., & Luo, F. (2010, September 19). **Shale gas production decline trend comparison over time and basins**. Florence, Italy: Society of Petroleum Engineers annual technical conference and exhibition.

[+] Find this resource:

Board on Chemical Sciences and Technology. (2015, May 18). ***Chemistry and engineering of shale gas and tight oil resource*** **development**. Washington, DC: A Workshop for the Chemical Sciences Roundtable.
[+] Find this resource:

Brantley, S., & Meyendorff, A. (2013, March 14). **The facts on fracking**. *New York Times*.
[+] Find this resource:

Brantley, S. L., Yoxtheimer, D., Arjmand, S., Grieve, P., Vidic, R., Pollak, J., . . . & Simon, C. (2014). Water resource impacts during unconventional shale gas development: The Pennsylvania experience. *International Journal of Coal Geology*, *126*, 140–156.
[+] Find this resource:

Brown, D., Weinberger, B., Lewis, C., & Bonaparte, H. (2014). Understanding exposure from natural gas drilling puts current air standards to the test. *Review of Environmental Health*, *29*(4), 277–292.
[+] Find this resource:

Brown, V. J. (2014). **Radionuclides in fracking wastewater: Managing a toxic blend**. *Environmental Health Perspectives*, *122*(2), A50–55.
[+] Find this resource:

Brydon, R. (2012). ***Hydraulic fracturing—an introduction and policy considerations for states***. The Book of the States: Energy and Environment. The Council of State Governments.
[+] Find this resource:

Carpenter, D. O. (2016). **Hydraulic fracturing for natural gas: Impact on health and environment**. *Review of Environmental Health*, *31*(1), 47–51.
[+] Find this resource:

Casey, J. A., Ogburn, E. L., Rasmussen, S. G., Irving, J. K., Pollak, J., Locke, P. A., & Schwartz, B. S. (2015). Predictors of indoor radon concentrations in Pennsylvania, 1989–2013. *Environmental Health Perspectives*, *123*(11), 1130.
[+] Find this resource:

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*, *27*(2), 163–172.
[+] Find this resource:

Costa, D., Jesus, J., Branco, D., Danko, A., & Fiuza, A. (2017). **Extensive review of shale gas environmental impacts from scientific literature (2010-2015)**. *Environmental Science and Pollution Research International*, *24*(17), 14579–14594.
[+] Find this resource:

Currie, J., Greenstone, M., & Meckel, K. (2017). Hydraulic fracturing and infant health: New evidence from Pennsylvania. *Science Advances*, *3*(12), e1603021.
[+] Find this resource:

Darrah, T. H., Vengosh, A., Jackson, R. B., Warner, N. R., & Poreda, R. J. (2014). Noble gases identify the mechanisms of fugitive gas contamination in drinking-water wells overlying the Marcellus and Barnett Shales. *Proceedings of the National Academy of Sciences*, *111*(39), 14076–14081.
[+] Find this resource:

Davis, C. E. (2017). **Shaping state fracking policies in the United States**. *State and Local Government Review*, *49*(2), 140–150.
[+] Find this resource:

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.
[+] Find this resource:

Drollette, B. D., Hoelzer, K., Warner, N. R., Darrah, T. H., Karatum, O., O'Connor, M. P., . . Plata, D. L. (2015). **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*, *112*(43), 13184–13189.
[+] Find this resource:

Edwards, P. M., Brown, S. S., Roberts, J. M., Ahmadov, R., Banta, R. M., deGouw, J. A., . . . Zamora, R. (2014). **High winter ozone pollution from carbonyl photolysis in an oil and gas basin**. *Nature*, *514*(7522), 351–354.
[+] Find this resource:

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.
[+] Find this resource:

Ferrar, K. J., Kriesky, J., Christen, C. L., Marshall, L. P., Malone, S. L., Sharma, R. K., . . . Goldstein, B. D. (2013). **Assessment and longitudinal analysis of health impacts and stressors perceived to result from unconventional shale gas development in the Marcellus Shale region**. *International Journal of Occupational and Environmental Health*, *19*(2), 104–112.
[+] Find this resource:

Field, R. A., Soltis, J., & Murphy, S. (2014). **Air quality concerns of unconventional oil and natural gas production**. *Environmental Science: Process and Impacts*, *16*(5), 954–969.
[+] Find this resource:

Finkel, M. L. (2016). **Shale gas development and cancer incidence in southwest Pennsylvania**. *Public Health*, *141*, 198–206.

[+] Find this resource:

Frumkin, H., & McMichael, A. J. (2008). Climate change and public health. *American Journal of Preventive Medicine*, *35*(5), 403–410.
[+] Find this resource:

Fryzek, J., Pastula, S., Jiang, X., & Garabrant, D. H. (2013). **Childhood cancer incidence in Pennsylvania counties in relation to living in counties with hydraulic fracturing sites**. *Journal of Occupational and Environmental Medicine*, *55*(7), 796–801.
[+] Find this resource:

Goodman, P. S., Galatioto, F., Thorpe, N., Namdeo, A. K., Davies, R. J., & Bird, R. N. (2016). **Investigating the traffic-related environmental impacts of hydraulic-fracturing (fracking) operations**. *Environment International*, *89*, 248–260.
[+] Find this resource:

Graham, J., Irving, J., Tang, X., Sellers, S., Crisp, J., Horwitz, D., . . . Carey, D. (2015). **Increased traffic accident rates associated with shale gas drilling in Pennsylvania**. *Accident Analysis and Prevention*, *74*, 203–209.
[+] Find this resource:

Grant, C. J., Weimer, A. B., Marks, N. K., Perow, E. S., Oster, J. M., Brubaker, K. M., . . . Lamendella, R. (2015). **Marcellus and mercury: Assessing potential impacts of unconventional natural gas extraction on aquatic ecosystems in northwestern Pennsylvania**. *Journal of Environmental Science and Health, Part A: Toxic/Hazardous Substances and Environmental Engineering*, *50*(5), 482–500.
[+] Find this resource:

Haines, A., Kovats, R. S., Campbell-Lendrum, D., & Corvalán, C. (2006). Climate change and human health: Impacts, vulnerability and public health. *Public Health*, *120*(7), 585–596.
[+] Find this resource:

Harkness, J. S., Dwyer, G. S., Warner, N. R., Parker, K. M., Mitch, W. A., & Vengosh, A. (2015). **Iodide, bromide, and ammonium in hydraulic fracturing and oil and gas wastewaters: Environmental implications**. *Environmental Science and Technology*, *49*(3), 1955–1963.
[+] Find this resource:

Harper, J. A. (2008). The Marcellus shale–an old 'new' gas reservoir in Pennsylvania. *Pennsylvania Geology*, *38*(1), 2–13.
[+] Find this resource:

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*, 448–456.
[+] Find this resource:

Hays, J., & Shonkoff, S. B. (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.
[+] Find this resource:

Health Effects Institute. (2015, November 4). ***Strategic research agenda on the potential impacts of 21st century oil and natural gas development in the Appalachian region and beyond***. Boston, MA.
[+] Find this resource:

Hill, E. L. (2012). ***Unconventional natural gas development and infant health: evidence from Pennsylvania***. Ithaca, New York: Working paper: Cornell University, Charles H. Dyson School of Applied Economics and Management [ch. 12].

Howard, T. (2015). **University of Texas study underestimates national methane emissions at natural gas production sites due to instrument sensor failure**. *Energy Science & Engineering*, *3*(5), 443–455.
[+] Find this resource:

Howarth, R. (2015). **Methane emissions and climatic warming risk from hydraulic fracturing and shale gas development: Implications for policy**. *Energy and Emission Control Technologies*, *3*, 45–54.
[+] Find this resource:

Hoy, K. A., Kelsey, T. W., & Shields, M. (2017). **An economic impact report of shale gas extraction in Pennsylvania with stricter assumptions**. *Ecological Economics*, *138*, 178–185.
[+] Find this resource:

Hughes, J. D. (2018). *Shale gas reality check*. Santa Rosa, CA: Post Carbon Institute.
[+] Find this resource:

Intergovernmental Panel on Climate Change. (2014). ***Climate Change: Synthesis Report*. Contribution of Working Groups I, II, and III to the fifth assessment report of the IPCC** (p. 155) [Core Writing Team, Pachauri, R. K. and Meter, L. A. (Eds.)]. Geneva, Switzerland: IPCC.
[+] Find this resource:

International Energy Agency. (2016). ***World energy outlook***. Paris, France: IEA.
[+] Find this resource:

Jackson, R. B., Vengosh, A., Darrah, T. H., Warner, N. R., Down, A., Poreda, R. J., . . . Karr, J. D. (2013). Increased stray gas abundance in a subset of drinking water wells near Marcellus shale gas extraction. *Proceedings of the National Academy of Sciences*, *110*(28), 11250–11255.
[+] Find this resource:

Jemielita, T., Gerton, G. L., Neidell, M., Chillrud, S., Yan, B., Stute, M., . . . Panettieri, R. A., Jr. (2015). **Unconventional gas and oil drilling is associated with increased hospital utilization rates**. *PLoS One*, *10*(7), e0131093.
[+] Find this resource:

Jiang, M., Griffin, M., Hendrickson, C., Jaramillo, P., VanBriesen, J., & Venkatesh, A. (2011). **Life cycle greenhouse gas emissions of Marcellus shale gas**. *Environmental Research Letters*, *6*(3), 034014.
[+] Find this resource:

Johnson, N. (2010). ***Pennsylvania energy impacts assessment, report 1: Marcellus shale natural gas and wind***. Arlington, VA: The Nature Conservatory.
[+] Find this resource:

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**.
[+] Find this resource:

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.
[+] Find this resource:

Kassotis, C. D., Klemp, K. C., Vu, D. C., Lin, C. H., Meng, C. X., Besch-Williford, C. L., . . . Nagel, S. C. (2015). **Endocrine-disrupting activity of hydraulic fracturing chemicals and adverse health outcomes after prenatal exposure in male mice**. *Endocrinology*, *156*(12), **4458–4473**.
[+] Find this resource:

Kassotis, C. D., Tillitt, D. E., Davis, J. W., Hormann, A. M., & Nagel, S. C. (2014). **Estrogen and androgen receptor activities of hydraulic fracturing chemicals and surface and ground water in a drilling-dense region**. *Endocrinology*, *155*(3), 897–907.
[+] Find this resource:

Kiviat, E. (2013). **Risks to biodiversity from hydraulic fracturing for natural gas in the Marcellus and Utica shales**. *Annals of the New York Academy of Sciences*, *1286*, 1–14.
[+] Find this resource:

Kondash, A. J., Albright, E., & Vengosh, A. (2017). **Quantity of flowback and produced waters from unconventional oil and gas exploration**. *Science of the Total Environment*, *574*, 314–321.
[+] Find this resource:

Konkel, L. (2015). **What's NORMal for fracking? Estimating total radioactivity of produced fluids**. *Environmental Health Perspectives*, *123*(7), A186.
[+] Find this resource:

The Lancet. (2009). A commission on climate change. *Lancet*, *373*, 1659.
[+] Find this resource:

Litovitz, A., Curtright, A., Abramzon, S., Burger, N., & Samaras, C. (2013). **Estimation of regional air-quality damages from Marcellus Shale natural gas extraction in Pennsylvania**. *Environmental Research Letters*, *8*(1), 014017.
[+] Find this resource:

Luber, G., & Lemery, J. (2015). *Global climate change and human health: From science to practice*: Chichester, U.K.: John Wiley.
[+] Find this resource:

Macey, G. P., Breech, R., Chernaik, M., Cox, C., Larson, D., Thomas, D., . . . Carpente, D. O. (2014). Air concentrations of volatile compounds near oil and gas production: A community-based exploratory study. *Environmental Health*, *13*(1), 82.
[+] Find this resource:

McCawley, M. (2015). **Air contaminants associated with potential respiratory effects from unconventional resource development activities**. *Seminars in Respiratory Critical Care Medicine*, *36*(3), 379–387.
[+] Find this resource:

McKenzie, L. M., Guo, R., Witter, R. Z., Savitz, D. A., Newman, L. S., & Adgate, J. L. (2014). **Birth outcomes and maternal residential proximity to natural gas development in rural Colorado**. *Environmental Health Perspectives*, *122*(4), 412–417.
[+] Find this resource:

McKenzie, L. M., Witter, R. Z., Newman, L. S., & Adgate, J. L. (2012). **Human health risk assessment of air emissions from development of unconventional natural gas resources**. *Science of the Total Environment*, *424*, 79–87.
[+] Find this resource:

Milton, D., Wilson, S., Jiang, C., Dalemarre, L., Sapkota, A., Sangaramoorthy, T., . . . Trowell, J. (2014). ***Potential public health impacts of natural gas development and production in the Marcellus shale in western Maryland***. College Park, MD: Maryland Institute for Applied Environmental Health School of Public Health.
[+] Find this resource:

Montgomery, C. T., & Smith, M. B. (2010). Hydraulic fracturing. History of an enduring technology. *JPT Online: Society of Petroleum Engineers*, *62*(12), 26–41.
[+] Find this resource:

Moore, C. W., Zielinska, B., Petron, G., & Jackson, R. B. (2014). **Air impacts of increased natural gas acquisition, processing, and use: A critical review**. *Environmental Science and Technology*, *48*(15), **8349–8359**.
[+] Find this resource:

Muehlenbachs, L., Spiller, E., & Timmins, C. (2015). The housing market impacts of shale gas development. *The American Economic Review*, *105*(12), **3633–3659**.
[+] Find this resource:

Natural Resources Defense Council. (2014). ***Fracking fumes: Air pollution from hydraulic fracturing threatens public health and communities***. Natural Resources Defense Council.
[+] Find this resource:

Osborn, S. G., Vengosh, A., Warner, N. R., & Jackson, R. B. (2011). **Methane contamination of drinking water accompanying gas-well drilling and hydraulic fracturing**. *Proceedings of the National Academy of Sciences*, *108*(20), **8172–8176**.
[+] Find this resource:

Patterson, L. A., Konschnik, K. E., Wiseman, H., Fargione, J., Maloney, K. O., Kiesecker, J., . . . Saiers, J. E. (2017). **Unconventional oil and gas spills: Risks, mitigation priorities, and state reporting requirements**. *Environmental Science and Technology*, *51*(5), **2563–2573**.
[+] Find this resource:

Patz, J. A., McGeehin, M. A., Bernard, S. M., Ebi, K. L., Epstein, P. R., Grambsch, A., & Samet, J. M. (2000). The potential health impacts of climate variability and change for the United States: Executive summary of the report of the health sector of the US National Assessment. *Environmental Health Perspectives*, *108*(4), 367.
[+] Find this resource:

Paulik, L. B., Donald, C. E., Smith, B. W., Tidwell, L. G., Hobbie, K. A., Kincl, L., . . . Anderson, K. A. (2016). **Emissions of polycyclic aromatic hydrocarbons from natural gas extraction into air**. *Environmental Science and Technology*, *50*(14), **7921–7929**.
[+] Find this resource:

Peters, G. P., Andrew, R. M., Solomon, S., & Friedlingstein, P. (2015). **Measuring a fair and ambitious climate agreement using cumulative emissions**. *Environmental Research Letters*, *10*(10), 105004.
[+] Find this resource:

Powers, M., Saberi, P., Pepino, R., Strupp, E., Bugos, E., & Cannuscio, C. C. (2015). **Popular epidemiology and 'fracking': Citizens' concerns regarding the economic, environmental, health and social impacts of unconventional natural gas drilling operations**. *Journal of Community Health*, *40*(3), 534–541.
[+] Find this resource:

Rabe, B. G. (2014). **Shale play politics: The intergovernmental Odyssey of American shale governance**. *Environmental Science and Technology*, *48*(15), **8369–8375**.
[+] Find this resource:

Rabinowitz, P. M., Slizovskiy, I. B., Lamers, V., Trufan, S. J., Holford, T. R., Dziura, J. D., . . . Stowe, M. H. (2015). **Proximity to natural gas wells and reported health status: Results of a household survey in Washington County, Pennsylvania**. *Environmental Health Perspectives*, *123*(1), 21–26.
[+] Find this resource:

Rasmussen, S. G., Ogburn, E. L., McCormack, M., Casey, J. A., Bandeen-Roche, K., Mercer, D. G., . . . Schwartz, B. S. (2016). **Association between unconventional natural gas development in the Marcellus shale and asthma exacerbations**. *JAMA Internal Medicine*, *176*(9), 1334–1343.
[+] Find this resource:

Saberi, P., Propert, K., Powers, M., Emmett, E., & Green-McKenzie, J. (2014). **Field survey of health perception and complaints of Pennsylvania residents in the Marcellus shale region**. *International Journal of Environmental Research and Public Health*, *11*(6), **6517–6527**.
[+] Find this resource:

Saberi, P., Propert, K. J., Powers, M., Emmett, E., & Green-McKenzie, J. (2014). Field survey of health perception and complaints of Pennsylvania residents in the Marcellus shale region. *International Journal of Environmental Research and Public Health*, *11*(6), **6517–6527**.
[+] Find this resource:

Sangaramoorthy, T., Jamison, A. M., Boyle, M. D., Payne-Sturges, D. C., Sapkota, A., Milton, D. K., & Wilson, S. M. (2016). **Place-based perceptions of the impacts of fracking along the Marcellus shale**. *Social Science and Medicine*, *151*, 27–37.
[+] Find this resource:

Saunders, P. J., McCoy, D., Goldstein, R., Saunders, A. T., & Munroe, A. (2016). **A review of the public health impacts of unconventional natural gas development**. *Environmental Geochemistry and Health*, *40*, 1–57.
[+] Find this resource:

Shonkoff, S. B., Hays, J., & Finkel, M. L. (2014). Environmental public health dimensions of shale and tight gas development. *Environmental Health Perspectives*, *122*(8), 787.
[+] Find this resource:

Stacy, S. L., Brink, L. L., Larkin, J. C., Sadovsky, Y., Goldstein, B. D., Pitt, B. R., . . . Talbott, E. O. (2015). **Perinatal outcomes and unconventional natural gas operations in Southwest Pennsylvania**. *PLoS One*, *10*(6), e0126425.
[+] Find this resource:

Stringfellow, W. T., Domen, J. K., Camarillo, M. K., Sandelin, W. L., & Borglin, S. (2014). **Physical, chemical, and biological characteristics of compounds used in hydraulic fracturing**. *Journal of Hazardous Materials*, *275*, 37–54.
[+] Find this resource:

The League of Women Voters of Pennsylvania. (2016). ***Shale gas extraction & public health: A resource guide***. Lead writer on report: Vera Bonnet.
[+] Find this resource:

Tustin, A. W., Hirsch, A. G., Rasmussen, S. G., Casey, J. A., Bandeen-Roche, K., & Schwartz, B. S. (2017). **Associations between unconventional natural gas development and nasal and sinus, migraine headache, and fatigue symptoms in Pennsylvania**. *Environmental Health Perspectives*, *125*(2), 189–197.

[+] Find this resource:

U.S. Congress. (2005). ***Energy Policy Act of 2005***. Passed by the 109th U.S. Congress and signed into law by President George W. Bush on August 8, 2005.
[+] Find this resource:

U.S. Energy Information Administration. (2015). **World shale resource assessments**. Washington, DC: EIA.
[+] Find this resource:

U.S. Energy Information Administration. (2017). ***Monthly Energy Review, May 2017***. Washington, DC: EIA.
[+] Find this resource:

United States Environmental Protection Agency. (2012). ***Oil and natural gas air pollution standards***. Washington, DC: United States Environmental Protection Agency.
[+] Find this resource:

United States Environmental Protection Agency. (2016). ***Hydraulic fracturing for oil and gas: Impacts from the hydraulic fracturing water cycle on drinking water resources in the United States***. Washington, DC: United States Environmental Protection Agency.
[+] Find this resource:

Vengosh, A., Jackson, R. B., Warner, N., Darrah, T. H., & Kondash, A. (2014). A critical review of the risks to water resources from unconventional shale gas development and hydraulic fracturing in the United States. *Environmental Science and Technology*, *48*(15), **8334–8348**.
[+] Find this resource:

Warner, N. R., Jackson, R. B., Darrah, T. H., Osborn, S. G., Down, A., Zhao, K., . . . Vengosh, A. (2012). **Geochemical evidence for possible natural migration of Marcellus Formation brine to shallow aquifers in Pennsylvania**. *Proceedings of the National Academy of Sciences*, *109*(30), 11961–11966.
[+] Find this resource:

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), e0180966.
[+] Find this resource:

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*, *37006*, 1.
[+] Find this resource:

Wiseman, H. J. (2014). **The capacity of states to govern shale gas development risks**. *Environmental Science and Technology*, *48*(15), **8376–8387**.
[+] Find this resource:

World Health Organization. (2015). **WHO calls for urgent action to protect health from climate change**.
[+] Find this resource:

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**. *Science of the Total Environment*, *574*, 1544–1558.
[+] Find this resource:

Yost, E. E., Stanek, J., DeWoskin, R. S., & Burgoon, L. D. (2016a). **Estimating the potential toxicity of chemicals associated with hydraulic fracturing operations using quantitative structure-activity relationship modeling**. *Environmental Science and Technology*, *50*(14), **7732–7742**.
[+] Find this resource:

Yost, E. E., Stanek, J., DeWoskin, R. S., & Burgoon, L. D. (2016b). **Overview of chronic oral toxicity values for chemicals present in hydraulic fracturing fluids, flowback, and produced waters** *Environmental Science and Technology*, *50*(9), **4788–4797**.
[+] Find this resource:

Zhang, T., Hammack, R. W., & Vidic, R. D. (2015). **Fate of radium in Marcellus shale flowback water impoundments and assessment of associated health risks**. *Environmental Science and Technology*, *49*(15), **9347–9354**.
[+] Find this resource:

Irena Gorski

Center for a Livable Future, Johns Hopkins Bloomberg School of Public Health

Brian S. Schwartz

Department of Environmental Health and Engineering, Johns Hopkins Bloomberg School of Public Health