Chapter

Human Health Risks of Unconventional Oil and Gas Development Using Hydraulic Fracturing

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Abstract

Advances in hydraulic fracturing technologies, and unconventional oil and gas (UOG) generally, spurred a boom in energy production in the United States. The rapid expansion of UOG has brought oil and gas production closer to homes, schools, and work places and thus increased potential human exposure to a range of chemicals, pollutants, and other health risks. Releases of such chemicals and pollutants occur throughout the full life cycle of UOG beginning with well-site preparation and continuing through hydraulic fracturing, well completion into production, well maintenance, and finally the plugging or abandoning of the well. While the risks to workers on UOG sites differ from those living, working or recreating nearby, both groups may be exposed to chemical and hazardous materials and injuries related to accidents and spills. This chapter characterizes the main occupational and public health risks throughout the life cycle of a hydraulically fractured well. Focusing on common practices in the United States, it identifies the main types of risks and pathways for human exposure. As a review, the chapter summarizes the peer-reviewed literature available to date, highlighting regulatory responses and identifying gaps in the current understanding of the risks involved in hydraulic fracturing.

Keywords: hydraulic fracturing, unconventional oil and gas development, health risk, air pollution, water pollution, occupational health risks, psychosocial health risks

1. Introduction

Advances in technologies that allow directional drilling coupled with high-volume hydraulic fracturing have made large unconventional oil and gas deposits accessible in the United States. The Energy Information Agency (EIA) estimates that in 2017 approximately 60% of U.S. dry natural gas production came from shale resources [1]. Similarly, oil production from tight oil formations rose from a negligible fraction in 2000 to 50% of total crude oil production in 2017 [2]. This growth has brought oil and gas production and related infrastructure closer to towns and communities in more than 20 states, with more than 15 active shale plays, and raised concerns about the risks to public health from chemical and nonchemical stressors associated with unconventional oil and gas production (UOG) [3]. This chapter provides a summary of these risks by taking a life cycle approach to characterizing the sources and types of health stressors and their likely exposure pathways. While UOG shares a number of processes with conventional oil and gas production, it differs in several important aspects, noticeably the use of directional (horizontal drilling) and large-volume hydraulic fracturing to stimulate the flow of natural gas or oil to the wellhead. These differences are particularly important as they pose additional, and to date not exhaustively regulated health, risks. There is also still greater uncertainty compared with conventional oil and gas production regarding the lack of information about the content of hydraulic fracturing fluids (HFF) and their health effects.

2. Life cycle risks of hydraulically fractured wells

As with any fossil fuel production, a hydraulically fractured ('fracked') well has the potential to release air and water pollutants, pose physical and public safety hazards, and contribute to psychosocial stressors for nearby residents and communities. The life cycle of a well consists of several phases shown in **Figure 1** [4].

Each life cycle phase generates emissions, effluents and waste that may pose health risks to workers and nearby communities. They are discussed in this chapter according to their exposure pathway, e.g., via air or water, and by exposed population groups, e.g., oil and gas workers or nearby communities. It is noted that the likelihood of health impacts is generally a function of the hazardousness of the chemical and nonchemical stressor (i.e., the stimulus causing undesirable health

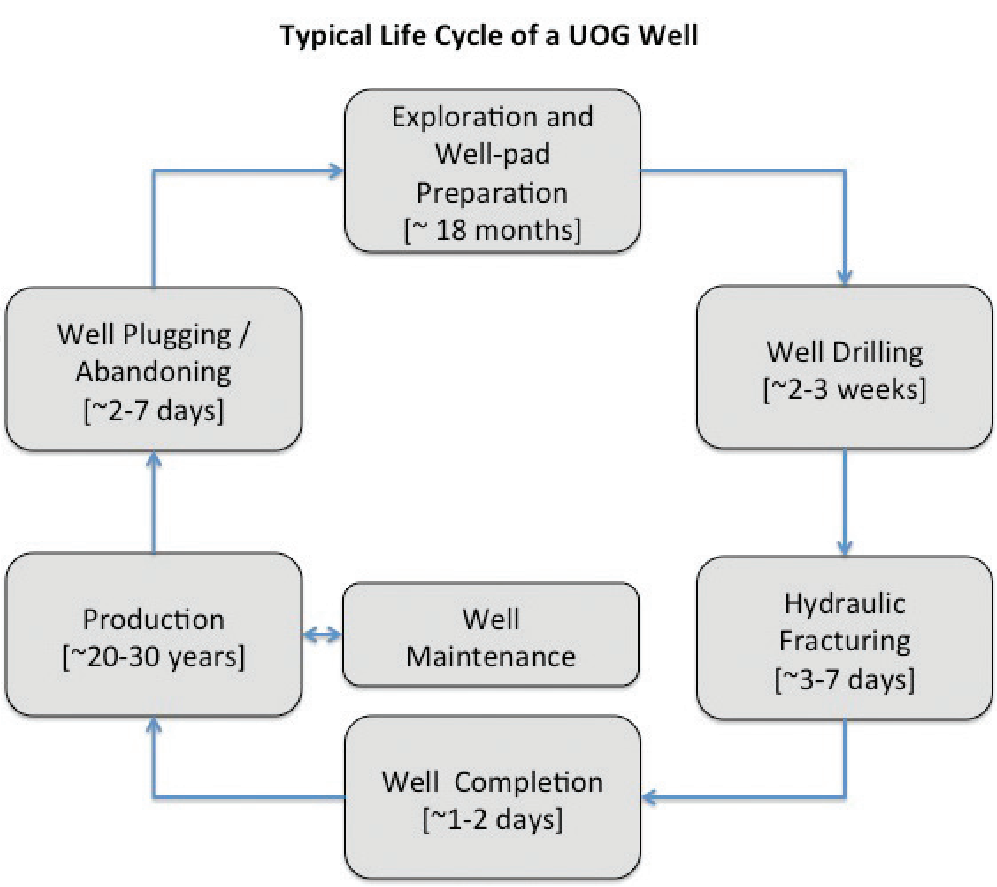

Figure 1.
The typical life cycle of an unconventional oil or gas well.

effects), the exposure duration and the pathway. The spatial reach of the stressor is also important and may range from the immediate well-pad area to local (up to 10 km), regional (up to 100 km) and local distances (farther than 100 km). Thus, the following sections are organized to describe human health risks according to pathway and spatial distance.

3. Occupational risks

The most significant types of occupational risks for UOG workers are accidents, malfunctions, and exposure to on-site air pollution. Accidents and malfunctions can bring workers in contact with hazardous and toxic materials via inhalation, dermal contact, or ingestion. They can also pose thermal radiation risks due to fires and explosions. Air pollution may be the result of accidents and malfunctions but is also a side effect of typical well-site activities such as oil and gas drilling, production, flaring, venting, storage of liquids and maintenance operations.

3.1 Accidents and unintentional releases

UOG wells are industrial sites with heavy and moving equipment, hazardous and toxic substances, and harsh environmental conditions. As a result, accidents and malfunctions (e.g., well blowouts, explosions, failure in well integrity such as sustained casing pressure and communication of the well with other, often orphaned wells) are the cause for most documented deaths and injuries for workers at unconventional well sites [5, 6].

Although it is difficult to obtain detailed information on worker-related injuries and fatalities for UOG, the oil and gas extraction industry in general has an occupational fatality rate that is 2.5-times that of the construction industry and 7-fold higher than the industry average [5, 6]. Fatalities are primarily caused by traffic-accidents (nearly a third of all confirmed fatalities), and smaller producers tend to have a higher mortality rate than larger and multi-national companies [7]. The traffic-related occupational risk to UOG workers is not surprising considering the substantial amount of material (e.g., water, HFF chemicals and additives, proppant), equipment (e.g., pipes, compressors, work-over equipment), and waste products (e.g., flowback and produced water, used drilling mud and drill cuttings) that need to be transported to and from the well site. Drilling and fracturing a well usually involves more than 1000 truck trips, often on narrow country roads not designed for such heavy use [8]. In contrast to UOG worker fatalities, the oil and gas industry has below-average injury rates, a fact that has been attributed to underreporting [6, 7, 9]. Although most accidents and fatalities occur among oil and gas workers, they also impact nearby communities. Truck accidents, well blowouts and explosions have caused injuries and fatalities among residents (see Section 4 for details).

3.2 Air pollution risks

The main sources of air pollution on UOG sites are [4]:

- Direct and fugitive emissions of methane and other hydrocarbons from wellheads and other production and transmission infrastructure on the well site (e.g., flowback and produced water holding tanks or evaporation ponds, valves, pipelines, processing equipment).

- Intentional venting and flaring of gas and hydrocarbon products.

- Diesel emissions from trucks, generators and diesel-powered equipment.
- Volatile organic compounds from drilling muds, HFF, flowback and produced water.

Workers may suffer from acute exposure to hazardous and toxic air pollutants such as hydrogen sulfide, benzene, formaldehyde and other volatile organic compounds [5]. Hydrogen sulfide arguably poses the greatest acute toxicity risk, causing irritation and central nervous system effects at concentrations as low as 100 ppm and death at around 1000 ppm [10]. Other risks arise from exposure to hydrocarbons, including aromatics such as benzene, ethylbenzene, toluene and the isomers of xylene (collectively referred to as BTEX). The health effects associated with BTEX include several types of leukemia, non-Hodgkin's lymphoma, anemia and other hematopoietic disorders, immunological effects, and reproductive and developmental effects [4, 11, 12]. While the health effects of BTEX are well documented and health-based regulatory exposure standards exist, other sources of exposure are less well characterized and not regulated. These include chemicals in HFF and volatilized components in drilling muds. A sizeable fraction of compounds used in HFF do not have Chemical Abstract Service (CAS) identifiers [13].

In addition, workers may suffer chronic exposure to stressors such as crystalline silica, which is the main proppant used in hydraulic fracturing to hold open rock fractures and ease the flow of oil and gas to the surface. Prolonged inhalation of silica can cause silicosis and lung cancer, and it is also associated with chronic obstructive pulmonary disease, kidney disease and autoimmune diseases [14]. OSHA has issued a health alert for workers concerning exposure to silica during hydraulic fracturing [15]. Esswein et al. reports a study by the National Institute for Occupational Safety and Health (NIOSH), which collected and analyzed 111 samples of personal breathing zone data for respirable crystalline silica exposure at 11 UOG sites in five states (Colorado, Texas, North Dakota, Arkansas, and Pennsylvania) [16]. They found that 93% of samples exceeded the threshold limit value (TLV) of the American Conference of Industrial Hygienists of 0.025 mg/m^3, 76% exceeded the Recommended Exposure Limit (REL) of the National Institute of Occupational Safety and Health (NIOSH) of 0.05 mg/m^3 and 51% were higher than the permissible exposure limit (PEL) by the Occupational Safety and Health Administration (OSHA) of 0.05 mg/m^3 averaged over an 8 hour-day. The differences in limits reflect the health protection goal of the respective institutions and the contexts and situations in which exposures are evaluated. Much of the silica sand (also known as 'frac sand') is mined in Wisconsin and Minnesota, thereby extending the occupational health risks to workers outside of the oil and gas industry and to regions where no hydraulic fracturing takes place [5]. Esswein et al. in a separate study also identified chemical exposure risks, including benzene, at six UOG sites in Colorado and Wyoming in 2013 and again found that wearable personal breathing zone monitors provided insufficient protection and were not always worn because of malfunctions [17].

3.3 Risks from soil contamination

Soil contamination from UOG operations can occur through surface spills of HFF, chemicals, drilling muds, and other compounds used during all life cycle phases of the well [18]. Health risks in these instances are largely limited to on-site workers and occur primarily through dermal contact. Workers may also carry contaminants indoors on their clothes and boots. Soil contamination has not yet been extensively studied in the UOG literature.

4. Non-occupational health risks

4.1 Accidents and unintentional releases

The heavy truck traffic associated with UOG, especially during the phases of well preparation, well drilling and hydraulic fracturing pose risks for vehicular accidents. In Bradford County, Pennsylvania, for example, the rise in truck traffic was concomitant with a rise in traffic accidents involving large trucks [8]. Similar statistics were observed in the Eagle Ford Shale in Texas. A study by Patterson et al. focusing on waste transport in the UOG sector in Pennsylvania found that UOG wells produced a median wastewater amount of 1294 m^3, requiring 122 heavy-truck trips for transportation off-site [19]. Throughout the full life cycle of a UOG well, and especially during the drilling and hydraulic fracturing stages, more than a thousand truck trips are required to transport water, chemicals, proppants, and equipment to and from the site. Since many well sites are now occupied by multiple wells, the health risks, such as air pollution from diesel engines and traffic accidents, increase even further.

Throughout most of the well's life cycle residents are also at risk of accidents due to malfunctions such as well blowouts, explosions, fire, spills, and leaks. These may release hazardous chemicals into the air and pose thermal radiation risks. Extreme weather events put oil and gas sites and associated infrastructure at risk. For example, holding and evaporation ponds for flowback and produced water overflowed in Colorado during the 2013 floods and released chemical and hydrocarbon laced liquids across the landscape and into nearby surface waters [20].

4.2 Air pollution risks

The around-the-clock operations of UOG production sites mean that people and communities in the vicinity may experience a continuous, albeit variable, exposure to airborne pollutants. In addition to infrequent but acute symptoms, they may thus suffer effects from cumulative exposure. The drilling, fracking and operation of UOG wells releases VOCs, from valves, pipes, condensate tanks, flowback and produced water tanks, and other infrastructure. Well maintenance operations such as offloading, additional fracking stages, etc. are often episodes of high air emissions of hydrocarbons, especially for natural gas wells. Residents have complained about odors and health symptoms such as headaches, nose bleeds, skin irritation, chronic fatigue, and neurological effects. A number of observational studies has shown associations between the occurrence of health symptoms and distance to the well, well density, and temporal coincidence with well-site activities [21–24]. Well completions, condensate storage tanks and compressors have been shown to release VOCs, including C2–C8 alkanes, aromatic hydrocarbons, methyl mercaptan, and carbon disulfide [4]. Also process-related is a study that found elevated concentrations of benzene, several aliphatic hydrocarbons in samples taken 130–500 feet from five well pads in Colorado during high-emission periods of uncontrolled flowback [4, 25]. The increased truck traffic also degrades local air quality through diesel exhaust, nitrogen oxides, dust, and other pollutants associated with diesel fuel combustion. Several studies of ambient air quality in densely populated areas with high UOG activity have shown that while the majority of wells produce emissions below regulatory standards and action levels, a few high-emitters can be responsible for the majority of emissions [26–28].

At the regional level, ozone, methane, benzene, and alkanes have been traced back to UOG production and installations, notably in Colorado's Front Range, the Denver-Julesburg Basin, the Niobrara Basin, the Uintah Basin, and the Upper Green

River Basin [29–32]. Winter ozone levels in some of these regions have reached levels (149 ppb) exceeding the worst days of day-time ozone levels in Los Angeles, one of the most ozone-polluted cities in America. Emission inventories showed that 98–99% of the VOCs and 57–61% of NO_x were attributable to unconventional oil and gas production [33]. Texas and Louisiana are also projecting increases in ground-level ozone concentrations of between 9 and 17 ppb above current concentrations for the low and high-emission scenarios, which may push some counties into non-attainment status of the federal ozone air quality standard (70 ppb).

Global effects of the growth in UOG arise from increases in methane emissions. Bottom-up and top-down studies have revealed higher methane levels in areas with UOG production, mostly natural gas shale plays, than under previous emission inventories released by the U.S. Environmental Protection Agency (EPA). According to the Intergovernmental Panel on Climate Change (IPCC) 5th Assessment Report (AR5), methane has a global warming potential that is 28 times that of carbon dioxide over a 100-year time horizon. Thus, while the transition of electric power generation from old, dirty coal-fired power plants to more efficient and cleaner natural gas plants is associated with regional air quality improvements, the climate benefits of UOG for shale gas remain somewhat disputed [34–37].

4.3 Water pollution risks

Most of the public attention surrounding hydraulic fracturing concerns the risks of surface and groundwater pollution, especially in the context of drinking water wells. There are several pathways for such pollution [4], including:

- Surface spills on-site and during transportation involving HFF, liquid drilling mud, and chemicals.

- Well casing leaks.

- Migration of gases and liquids through fractured rock into groundwater aquifers and to the surface.

- Leaks from abandoned wells.

- Wastewater discharges on-site or at wastewater treatment facilities.

A study by Gross for Colorado found that water pollution from surface spills is a relatively frequent occurrence: groundwater were impaired in 77 surface spills that were reported between July 2010–July 2011 and representing ~0.5% of active wells in densely drilled Wells County, Colorado [38]. Such impairment occurs primarily when spilled fluids percolate through the soil into shallow groundwater aquifers.

Vengosh et al. undertook a detailed study to understand which pathways were most likely for surface and subsurface migration. They distinguished between (i) the contamination of shallow aquifers with fugitive hydrocarbon gases (stray gas contamination, (ii) contamination of surface water and shallow groundwater from spills, leaks, and/or the disposal of inadequately treated shale gas wastewater, and (iii) the accumulation of toxic and radioactive elements in soil or stream sediments near disposal spill sites [3]. Using published data and studies from across the U.S. the results indicate that there is evidence for stray gas contamination, surface water impacts, and accumulation of radium isotopes at some disposal and spill sites. A critical issue in conclusively attributing the pollution of drinking water wells or other water sources to UOG operations is the lack of baseline data, i.e., data on water quality before UOG commenced. In particular, methane, heavy metals, and radioactive compounds may have been in the water long before the arrival of unconventional oil and gas production as a result of the aquifers' geology or due to other man-made activities. In order to better understand and attribute the sources of water contamination, states such as California now require water quality monitoring before and after unconventional well drilling and stimulation activities. Overall, the evidence for methane contamination of groundwater and drinking water wells from hydraulic fracturing remains controversial in many cases [39–41].

4.4 Water resource depletion

While the debate and study of how water quality may be impacted by UOG activities continues, there is clear evidence that water abstraction for hydraulic fracturing in water-scarce areas can lead to increased competition and shortages. A report by Ceres, a sustainability non-profit organization formerly known as the Coalition for Environmentally Responsible Economies, examined the relationship between water use by UOG and other sectors in water-stressed regions and found that water resources are negatively impacted [42]. Nationwide, Ceres looked at nearly 110,000 UOG wells and estimated that 57% of oil and gas wells hydraulically fractured between 2011 and 2015 were in water-scarce regions and where water is a subject of competition among farmers, towns and cities, and the oil and gas industry. Overall, fracking-related water use during the 5-year study period totaled 358 billion gallons. Put into perspective, this amount of water is consumed by approximately 200 mid-sized U.S. cities. States with significant oil and gas production that are particularly impacted by the threat of increasing water competition are Texas, Colorado, and California. These states are also home of some of the leading shale plays, including the Eagle Ford and the Midland Play (part of the Permian Basin) in Texas. Other plays characterized by high water use are the Marcellus Shale and the Niobrara in Colorado, Wyoming, and Nebraska. The county with the highest number of UOG wells (~7000 wells) and water use for hydraulic fracturing (>16 billion gallons) is Weld County, CO [42].

4.5 Waste management and disposal risks

Wastewater is the largest waste stream in oil and gas production. It consists primarily of produced water, which is for the most part brine mixed with hydrocarbons and suspended solids. Produced water is distinct from flowback water, which consists primarily of HFF and is generated for the first few days after hydraulic fracturing operations. Produced water may contain chemicals and additives used in drilling mud, methane, petroleum condensate, heavy metals, naturally occurring radioactive materials (NORM). Typically, flowback and produced water are temporarily stored in on-site pits (also called evaporation sumps) or tanks prior to disposal or reuse/recycling. These pits pose air and water pollution risks, from the release of volatile compounds into the air (evaporation is the purpose of some pits and may be supported by aerators) and the use of unlined pits. Flooding can also lead to pits overflowing and dispersing their hazardous contents across the landscape and potentially contaminating groundwater and nearby surface streams. On-site spills due to broken pipes or deterioration of the exterior walls of pits can also lead to localized soil and water contamination. California's oil-rich Central Valley has a legacy of unlined pits and at least one of the sites is known to have a sub-surface pollution plume that is threatening the Kern River [43].

The majority of produced water is disposed of through deep-injection wells (class II wells according to the UIC program by EPA). In Pennsylvania, produced water was initially send to publicly owned treatment works, but the treatment processes were not adequate to handle the high TDS and chemical-contaminated water and the state prohibited the practice. If the injection wells reach aquifers that may potentially be used as a source of water for drinking or other purposes, the practice may threaten the water supply in water-stressed regions. This is the case in California, where hundreds of injection wells were found to be in potential violation of the Safe Drinking Water Act [44].

4.6 Socioeconomic and psychosocial risks

In addition to the potential health benefits arising from the replacement of coal-fired power plants with plants using shale gas, the development of UOG can generate local and regional economic benefits that can improve the overall health of the population. Additional jobs and UPG producer taxes can stimulate the economy and lead to greater public investments in education and healthcare. The estimates vary but UOG related employment in the U.S. might be in the order of 1.7 million people with further growth projected [45]. However, negative health effects of UOG expansion can occur from "boomtown" effects, i.e., the extractive-resource driven rapid expansion of local economies, which is followed by equally fast declines when resource prices decline or other market forces throttle production. These effects have been well-documented in the 1970s and 1980s and they tend to hit the most vulnerable members of communities first and hardest [4]. Psychosocial studies have also documented the tensions that can rise in communities split into supporters and opponents of UOG, by concerns of the local residents about known and unknown side-effects of UOG production such as air and water contamination, and concern over social disruptions due to the sudden influx of mostly male workers from other parts of the country. Residents surveyed in rural parts of Pennsylvania, where Marcellus Shale development has grown rapidly, have mentioned feelings of loss concerning their old way of living, the degradation of pristine environments, and their sense of place. Psychosocial stress can manifest itself in a variety of symptoms that are difficult to diagnose. They can be exacerbated by a lack of trust in the UOG producers and local and state government regarding the safe development of these unconventional resources. The Geisinger Health System in Pennsylvania is undertaking a series of coordinated studies of the population it serves regarding self-reported symptoms [46].

5. Health research needs

Considering the diverse range of potential health risks emanating from UOG operations and the role that local factors such as regulations, geology, climate, proximity to population centers, etc. play, there are a number of open research questions that should be addressed. Arguably the most pressing issue is the lack of information about UOG activities followed by the need for toxicological and epidemiological studies.

In particular, the major information gaps and uncertainties regarding our understanding of the health risks of UOG development impact the ability of regulators, healthcare professionals, communities, and individuals to take appropriate measures to protect against them, to inform others, and to work with the industry to mitigate the negative effects of UOG. The most important issues to be addressed from a research and data development perspective are shown in **Table 1**.

These gaps and uncertainties should be systematically addressed in future studies, which require improved cooperation between UOG producers, federal,

Occupational health and safety	Public health
Study the occupational health and safety risks of UOG with respect to the use and regulation of personal protective equipment and the activities that put oil and gas workers at most risk.	Collect and release timely and complete information about the composition of hydraulic fracturing fluids, in particular, addressing the use of trade secret protections and the accessibility of information by emergency responders, public health officials, oil and gas regulators, the scientific community, and the general public.
Assess the differences of UOG activities compared with conventional oil and gas development and determine targeted and effective occupational health protections for them.	Continue efforts to close the knowledge gap on the health risks of UOG through toxicological and exposure-effect studies of HFF constituents.
Fix the incomplete reporting of occupational health and safety incidents, especially with respect to injuries in order to reduce underreporting in state and federal statistics.	Conduct longer-term epidemiological studies to improve the scientific understanding of the associations and causalities between exposure to UOG-related hazards and reported health symptoms. These include the systematic description and assessment of exposure pathways and severity and their duration as well as developing an improved understanding of the effects of multiple well sites with regard to cumulative and aggregate exposures.
	Invest in community-based studies on the psychosocial stresses and associated health outcomes resulting from the expansion of UOG activities into rural communities.
	Develop databases and systematic guidelines for air and water quality monitoring before and during UOG activities with the goal to improve source-attribution in cases of deteriorated air and/or water quality.
	Develop tracers and other solutions to better identify and attribute the causes of drinking water well contamination in the context of UOG activities.

Table 1.
List of proposed research and development activities needed to fully understand and mitigate the risks of UOG on worker and public health.

state and local government, and community health and environmental advocacy groups. FracFocus, an industry-sponsored database providing information on hydraulically fractured wells and the HFF used, is a step towards addressing this information gap, but it is voluntary, incomplete, and lacks some important functionality.

Occupational health risks would benefit from better surveillance and reporting, especially of injuries. Focus should be on monitoring exposure to benzene, toluene, silica, aliphatic hydrocarbons, diesel exhaust, HFF chemicals, hydrogen sulfide, NORM, and traffic related exposures [4]. In addition, studies on both chronic and acute exposures are relevant in the occupational health context.

The proposed before-and-after monitoring of water and air quality, in the context of planned UOG development, could provide a stronger foundation to accurately and conclusively determine if contamination events occurred and what their source was. The variable and locally specific context of UOG development calls for studies that assess the magnitude and duration of human exposure to stressors during the various life cycle phases of UOG wells. For example, HFF mixture, geology, type of unconventional resource, and environmental factors all influence the potential for exposure and resulting health effects. In addition, the dense clustering of wells typical for UOG development creates the risk of aggregate effects that need to be further assessed.

With regard to psychosocial and community health impacts, current knowledge could be enhanced through greater involvement of community organizations as a source of information and for building trust between community members on the one hand and scientists, public health officials, and regulators on the other. These community organizations can furthermore serve as a bridge for continued outreach, education, and data collection after studies have been completed. UOG producers could rebuild trust by actively engaging with the community in the planning processes of new UOG development, providing fact-based information about the development, and supporting community activities aimed at identifying and reducing sources of stress. Public-private partnerships, such as the Health Effects Institute, have been able to bridge the trust-deficit and can serve as a model for working to solve the often-contentious health issues [4].

6. Conclusions

The use of large-volume, horizontal hydraulic fracturing has expanded across the U.S. and inspired talk of American energy independence and a renaissance of manufacturing. At the same time hydraulic fracturing has also become a lightning rod in public debates that pitches neighbors against each other and prompted calls for moratoria and greater scientific scrutiny from environmental groups and community health advocates. This chapter is an attempt to summarize the main sources of environmental pollution and health risks that arise during the lifespan of a hydraulically fractured well. It is a reminder that the reader that unconventional oil and gas production is an industrial activity that is noisy, dirty, and that generates substantial amounts of waste. Some of these side effects occur primarily on the well pad and in its immediate vicinity, where they pose risks to workers and residents. Others manifest themselves regionally and even globally and thus add to the pollution burden of people and communities who are far away from oil and gas production. The regulatory environment in which oil and gas development takes place usually creates obstacles for people to receive information and seek redress for pollution and health effects they might experience. Indeed, the burden of proof of causality between unconventional oil and gas operations as the source of the impacts is often on the individual or community and requires a level of scientific knowledge and information that is beyond their capacity. This is where regulators, public health officials, and the scientific community need to focus and together with the oil and gas industry develop mechanisms for greater transparency, meaningful data collection, and targeted epidemiological and toxicological studies. Unconventional oil and gas development is projected to continue its growth path and will remain a part of life in many rural and also urban communities across the U.S. In order to facilitate a co-existence that is based on trust, prioritizes safety over profits, and invests in local communities, the discussed health risks need to be addressed comprehensively and form the evidentiary basis for regulatory action.

Conflict of interest

I declare that I have no conflict of interest.

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References

[1] EIA. 2018. Available from: https://www.eia.gov/tools/faqs/faq.php?id=907&t=8 [Accessed: Sep 3, 2018]

[2] EIA. 2018. Available from: https://www.eia.gov/tools/faqs/faq.php?id=847&t=6 [Accessed: Sep 3, 2018]

[3] Vengosh A, Jackson RB, Warner N, Darrah TH, Kondash A. A critical review of the risks to water resources from unconventional shale gas development and hydraulic fracturing in the United States. Environmental Science & Technology. 2014;**48**(15):8334-8348

[4] Adgate JL, Goldstein BD, McKenzie LM. Potential public health hazards, exposures and health effects from unconventional natural gas development. Environmental Science & Technology. 2014;**48**(15):8307-8320

[5] Witter RZ, Tenney L, Clark S, Newman LS. Occupational exposures in the oil and gas extraction industry: State of the science and research recommendations. American Journal of Industrial Medicine. 2014;**57**(7):847-856

[6] Bureau of Labor Statistics. Census of Fatal Occupational Injuries. Washington, DC; 2009. Available from: http://www.bls.gov/iif/oshcfoi1.htm

[7] Retzer KD, Hill RD, Pratt SG. Motor vehicle fatalities among oil and gas extraction workers. Accident Analysis & Prevention. 2013;**51**:168-174

[8] NY Department of Environmental Conservation. Revised Draft SGEIS on the Oil, Gas, and Solution Mining Regulatory Program: Well Permit Issuance for Horizontal Drilling and High Volume Hydraulic Fracturing in the Marcellus Shale and Other Low Permeability Gas Reservoirs. New York State; 2011. Available from: http://www.dec.ny.gov/data/dmn/rdsgeisfull0911.pdf

[9] Mendeloff J, Burns R. States with low non-fatal injury rates have high fatality rates and vice-versa. American Journal of Industrial Medicine. 2013;**56**(5):509-519

[10] ATSDR. Toxicological Profile of Toluene. 2018. Available from: https://www.atsdr.cdc.gov/toxprofiles/TP.asp?id=161&tid=29 [Accessed: Sep 12, 2018]

[11] ATSDR. Toxicological Profile of Ethylbenzene. 2010. Available from: https://www.atsdr.cdc.gov/toxprofiles/TP.asp?id=383&tid=66 [Accessed: Sep 12, 2018]

[12] ATSDR. Toxicological Profile of Hydrogen Sulfide/Carbonyl Sulfide. 2018. Available from: https://www.atsdr.cdc.gov/toxprofiles/tp.asp?id=389&tid=67 [Accessed: Sep 12, 2018]

[13] Colborn T, Kwiatkowski C, Schultz K, Bachran M. Natural gas operations from a public health perspective. Human and Ecological Risk Assessment: An International Journal. 2011;**17**(5):1039-1056

[14] ATSDR. Toxicological Profile of Silica. 2017. Available from: https://www.atsdr.cdc.gov/toxprofiles/TP.asp?id=1483&tid=290 [Accessed: Sep 12, 2018]

[15] OSHA. 2018. Available from: https://www.osha.gov/dts/hazardalerts/hydraulic_frac_hazard_alert.html [Accessed: Aug 29, 2018]

[16] Esswein EJ, Breitenstein M, Snawder J, Kiefer M, Sieber WK. Occupational exposures to respirable crystalline silica during hydraulic fracturing. Journal

of Occupational and Environmental Hygiene. 2013;**10**(7):347-356

[17] Esswein EJ, Snawder J, King B, Breitenstein M, Alexander-Scott M, Kiefer M. Evaluation of some potential chemical exposure risks during flowback operations in unconventional oil and gas extraction: Preliminary results. Journal of Occupational and Environmental Hygiene. 2014;**11**(10):D174-D184

[18] Finkel ML, Law A. The rush to drill for natural gas: A public health cautionary tale. American Journal of Public Health. 2011;**101**(5):784-785

[19] Patterson LA, Maloney KO. Transport of hydraulic fracturing waste from Pennsylvania wells: A county-level analysis of road use and associated road repair costs. Journal of Environmental Management. 2016;**181**:353-362

[20] CO Oil and Gas Conservation Commission. COGCC Flood Information. 2013. Available from: http://cogcc.state.co.us/Announcements/Hot_Topics/Flood2013/Flodd.htm

[21] McKenzie LM, Witter RZ, Newman LS, Adgate JL. Human health risk assessment of air emissions from development of unconventional natural gas resources. Science of the Total Environment. 2012;**424**:79-87

[22] Ferrar KJ, Kriesky J, Christen CL, Marshall LP, Malone SL, Sharma RK, et al. 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. 2013;**19**(2):104-112

[23] Steinzor N, Subra W, Sumi L. Investigating links between shale gas development and health impacts through a community survey project in Pennsylvania. New solutions: A Journal of Environmental and Occupational Health Policy. 2013;**23**(1):55-83

[24] Rabinowitz PM, Slizovskiy IB, Lamers V, Trufan SJ, Holford TR, Dziura JD, et al. Proximity to natural gas wells and reported health status: Results of a household survey in Washington County, Pennsylvania. Environmental Health Perspectives. 2014;**123**(1):21-26

[25] Colborn T, Schultz K, Herrick L, Kwiatkowski C. An exploratory study of air quality near natural gas operations. Human and Ecological Risk Assessment: An International Journal. 2014;**20**(1):86-105

[26] Pring MO, Wilhelmi J. Fort Worth Natural Gas Air Quality Study. 2017. Available from: https://www3.epa.gov/ttnchie1/conference/ei20/session6/mpring.pdf [Accessed: Sep 12, 2018]

[27] ERG. City of Fort Worth Natural Gas Air Quality Study. Final Report. Eastern Resources Group, Inc. (ERG); 2011. Available from: http://fortworthtexas.gov/uploadedFiles/Gas_Wells/AirQualityStudy_final.pdf [Accessed: Sep 12, 2018]

[28] Zielinska B, Campbell D, Samburova V. Impact of emissions from natural gas production facilities on ambient air quality in the Barnett Shale area: A pilot study. Journal of the Air & Waste Management Association. 2014;**64**(12):1369-1383

[29] Mallula S. Effects of non-conventional gas and oil production activities on local and regional fine particles and ground-level ozone [doctoral dissertation]. The University of North Dakota; 2017

[30] Ahmadov R, McKeen S, Trainer M, Banta R, Brewer A, Brown S, et al. Understanding high wintertime ozone pollution events in an oil-and natural gas-producing region of the western

US. Atmospheric Chemistry and Physics. 2015;**15**(1):411-429

[31] Helmig D, Thompson CR, Evans J, Boylan P, Hueber J, Park JH. Highly elevated atmospheric levels of volatile organic compounds in the Uintah Basin, Utah. Environmental Science & Technology. 2014;**48**(9):4707-4715

[32] Pétron G, Karion A, Sweeney C, Miller BR, Montzka SA, Frost GJ, et al. A new look at methane and nonmethane hydrocarbon emissions from oil and natural gas operations in the Colorado Denver-Julesburg Basin. Journal of Geophysical Research: Atmospheres. 2014;**119**(11):6836-6852

[33] Utah Dept. of Environmental Quality. 2012 Uintah Basin Winter Ozone & Air Study. Final Report. 2012. Available from: http://rd.usu.edu/files/uploads/ubos_2011-12_final_report.pdf [Accessed: Sep 12, 2018]

[34] Howarth RW, Santoro R, Ingraffea A. Methane and the greenhouse-gas footprint of natural gas from shale formations. Climatic Change. 2011;**106**(4):679

[35] Jiang M, Griffin WM, Hendrickson C, Jaramillo P, Van Briesen J, Venkatesh A. Life cycle greenhouse gas emissions of Marcellus Shale gas. Environmental Research Letters. 2011;**6**(3):034014

[36] Burnham A, Han J, Clark CE, Wang M, Dunn JB, Palou-Rivera I. Life-cycle greenhouse gas emissions of shale gas, natural gas, coal, and petroleum. Environmental Science & Technology. 2011;**46**(2):619-627

[37] O'Sullivan F, Paltsev S. Shale gas production: Potential versus actual greenhouse gas emissions. Environmental Research Letters. 2012;**7**(4):044030

[38] Gross SA, Avens HJ, Banducci AM, Sahmel J, Panko JM, Tvermoes BE. Analysis of BTEX groundwater concentrations from surface spills associated with hydraulic fracturing operations. Journal of the Air & Waste Management Association. 2013;**63**(4):424-432

[39] Osborn SG, Vengosh A, Warner NR, Jackson RB. Methane contamination of drinking water accompanying gas-well drilling and hydraulic fracturing. Proceedings of the National Academy of Sciences. 2011;**108**(20):8172-8176

[40] Davies RJ. Methane contamination of drinking water caused by hydraulic fracturing remains unproven. Proceedings of the National Academy of Sciences. 2011;108(43). https://doi.org/10.1073/pnas.1113299108

[41] Jackson RB, Vengosh A, Darrah TH, Warner NR, Down A, Poreda RJ, et al. Increased stray gas abundance in a subset of drinking water wells near Marcellus Shale gas extraction. Proceedings of the National Academy of Sciences. 2013;**110**(28):11250-11255

[42] Ceres. New Data: Water Use in Hydraulic Fracturing a Key Risk in Water Stressed Regions in Colorado and Texas. 2016. Available from: https://www.ceres.org/news-center/press-releases/new-data-water-use-hydraulic-fracturing-key-risk-water-stressed-regions [Accessed: Sep 12, 2018]

[43] SF Chronicle. Pits of Drilling Waste threaten Water, Air Quality, Report says. 2016. Available from: https://www.sfchronicle.com/science/article/Pits-of-drilling-waste-threaten-water-air-6873892.php [Accessed: Sep 12, 2018]

[44] EPA. EPA's Oversight of California's UIC Program. 2018. Available from: https://www.epa.gov/uic/epas-oversight-californias-underground-injection-control-uic-program [Accessed: Sep 12, 2018]

[45] IHS. The Economic and Employment Contribution of Unconventional Gas Development in State Economies. Washington, DC; 2012. Available from: http://marcelluscoalition.org/wp-content/uploads/2012/06/State_Unconv_Gas_Economic_Contribution_Main.pdf [Accessed: Sep 12, 2018]

[46] Geisinger Caring. Unconventional Natural Gas Development. 2018. Available from: https://www.geisinger.edu/research/departments-and-centers/environmental-health-institute/unconventional-natural-gas-development [Accessed: Sep 12, 2018]