National Collaborating Centre for Environmental Health
Centre de collaboration nationale en santé environnementale

JANUARY 2016

Understanding the Public Health Implications Concerning Shale Gas Production and Hydraulic Fracturing

Helen Ward, PhD[1] and Anne-Marie Nicol, PhD[1]

Introduction

The intent of this document is to synthesize scientific information related to public health concerns of relevance to Canada about shale gas production (including the pre-production stages of drilling, hydraulic fracturing, and well completion, as well as abandonment). Current policy and regulations are not considered. For the most part, the environmental and public health implications relating to shale gas production also apply to other types of unconventional natural gas production using hydraulic fracturing, including that of tight gas and coal bed methane. Basic descriptions and definition of terms for shale gas production and the hydraulic fracturing process are provided in the NCCEH summary "Overview of Shale Gas and Hydraulic Fracturing in Canada": http://www.ncceh.ca/environmental-health-in-canada/health-agency-projects/hydraulic-fracturing-shale-gas

In general, public health impacts related to hydraulic fracturing and shale gas production are determined by the relative proximity of communities as well as by the pathways of exposure. In addition to distinct differences in the extent of shale gas production across Canada, it is recognized that there are variations in geological, hydrologic, landscape, cultural, social, and economic conditions, which also have a bearing on the potential public health impacts of shale gas production.[1]

Shale gas production involves continuous activity over the day for seven days a week, often for a number of years.[2] With hydraulic fracturing, there is added effort of injecting large volumes of water mixtures at high rates and pressures required to extract natural gas; more trucks are involved, drilling times are longer, pumps are more powerful and holding ponds are larger than in conventional gas production. The multi-stage fracturing is repeated consecutively on multi-well pad sites, which may house six to 21 wells per drilling pad.[3] Due to the large number and size of the storage containers, mixers and pressure pump trucks, and the control operations, a multi-well pad can be 3-7 acres in size.[4] Figure 1 depicts a representative hydraulic fracturing operation in the US.

[1]National Collaborating Centre for Environmental Health

Figure 1. *A hydraulic fracturing operation at a Marcellus Shale drill pad in Pennsylvania, US, showing pumps, generators, fuel, chemicals, sand, pipes, service trucks (Creative Commons, US Geological Survey, photo credit: Doug Duncan[5])*

Methods

The present document incorporates some of the information covered in a recent comprehensive 266-page report on the "Environmental Impacts of Shale Gas Extraction" published by the Council of Canadian Academies that was prepared for the Government of Canada in response to a request from the Minister of Environment.[6] The council includes members of the Royal Society of Canada, the Canadian Academy of Engineering, and the Canadian Academy of Health Sciences. The citation is:

Council of Canadian Academies, 2014. *Environmental Impacts of Shale Gas Extraction in Canada*. Ottawa (ON): The Expert Panel on Harnessing Science and Technology to Understand the Environmental Impacts of Shale Gas Extraction.[6]

Due to the rapidly evolving literature on this topic, recent publications and reports were sought and relevant citations were added to this document. A literature search of published and grey literature since 2013 to 2015 was conducted using google and University of British Columbia databases, with the keywords "hydraulic fracturing" or "shale gas" and "public health," "community health," "air," "water," "seismic," or "earthquake," and further references obtained from hand searches and bibliographic citations. The majority of relevant published studies originated from the US, which has a more extensive history of unconventional natural gas production.

This document is organized under the following major headings:

- Drinking Water
- Air Quality
- Seismic Activity
- Other Community Impacts
- Conclusion
- References

Drinking Water

Shale gas production is a water-intensive process that has implications for water quantity and contamination of drinking water. Water serves as the primary carrier fluid when hydraulic fracturing (fracking) for shale gas. Large volumes of water, usually acquired from surface water sources (streams, rivers, and lakes) but also from groundwater, are transported to the well pad (the surface area of the wells) containing the drilling and production equipment. Typically, there is more than one well per well pad. More water is required for extracting shale gas than for conventional gas, although the amounts are less than that of conventional oil.[7] However, a large volume of water for shale gas extraction is needed in short time periods. In BC, reported volumes of water used during hydraulic fracturing range from 2,000 m^3 to over 75,000 m^3 (equivalent to millions of gallons) per well.[3] In 2013 alone, there were 5,341,635 m^3 of water injected into 433 shale wells in BC.[1] Although there is generally little concern about water quantity in Canada, seasonal effects such as frozen surface waters in the winter and local drought conditions in the summer may temporarily diminish water supply.

A major concern about shale gas production is the potential impact on chemical and radiological contamination of drinking water resources sourced from groundwater (e.g., drinking water wells) and surface water (e.g., from lakes, rivers, or creeks). The principal component of natural gas, methane, can occur naturally in small quantities in groundwater sources. However, ignition and explosion could be a concern when a high concentration of methane bubbles out of solution in the well to a gaseous form.

Accidental spills, leaks, and runoff during different stages of shale gas production may contaminate natural surface water, and groundwater.[8] Figure 2 below is a diagram of the basic processes of a horizontally drilled well that involve potential areas of leakage, which may lead to contamination of groundwater. These include acquisition (obtaining water), chemical mixing for injection (hydraulic fracturing), storage of wastewater (flowback and produced water) on-site, often in open pits or tanks, and transportation of wastewater for treatment or disposal.

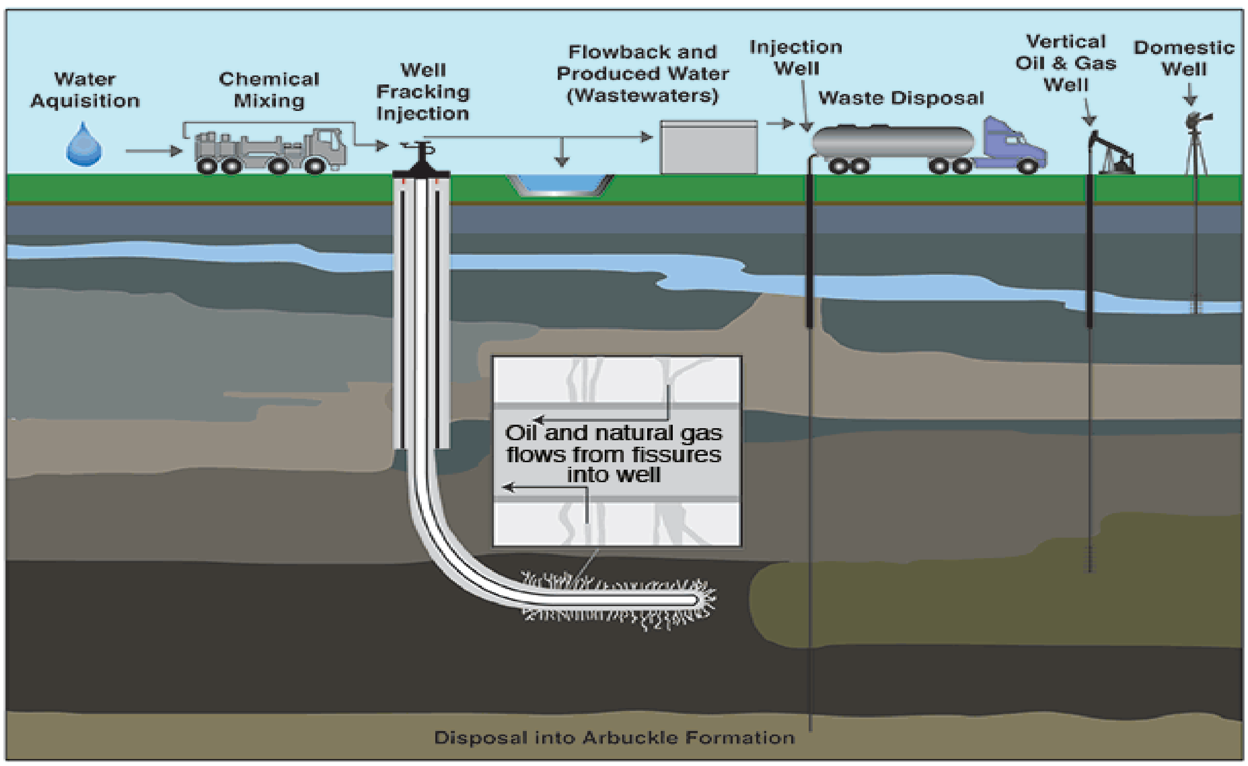

Figure 2. *Schematic of potential sources of water contamination associated with shale gas extraction through hydraulic fracturing (Creative Commons, U.S. Environmental Protection Agency[9])*

What is the impact of surface spills during shale gas production?

Leaks or spills of chemicals, oils, drilling mud, and fracture fluids, as well as flowback and produced water, can occur during many shale gas production processes. Potential pathways include storage, mixing or pumping of fracturing fluids, inadequate storage or disposal of wastewater, and truck transport of fluids to and from the pad. Flowback and produced water from the hydraulic fracturing process especially can be a source of water contamination since these contain fracturing chemicals as well as compounds from the shale reservoir, including salts, natural occurring radioactive material such as radon gas, trace metals (e.g., arsenic), and natural gas (predominantly methane).

Episodes of contamination from large spills linked to shale gas production activities are described in a few published reports. For example, a January 2012 spill near Red Deer, Alberta, of 500 barrels of flowback and produced fluid, affected 4.5 hectares of surface area.[3] In this case, the majority of the clean-up operations were complete within 72 hours, aided by the frozen ground conditions that prevented much of the fluid from seeping into the ground. Contamination of surface water occurred in Kentucky in 2007, in which toxic effects on fish, including gill lesions, were observed after an accidental release of fracturing fluids to a creek.[10] Analysis of a database consisting of reports by operators of oil and gas sites in Colorado found that the majority of spills were in the counties with the highest density of fractured wells. In a one-year period, there were 77 reported surface spills impacting groundwater (<0.5% of the active wells).[11] Of 60 reports of groundwater samples, 90% of the benzene measurements exceeded the US EPA National Drinking Water maximum contaminant level of 5 ppb. Actions taken to remediate the spills, and therefore reducing the potential impact on communities, were effective for most (84%) of the spills.

Can hydraulic fracturing contaminate groundwater?

When shale reservoirs are fractured with fluids injected under high pressure, new flow paths are opened that allow upward gas or fluid migration along existing faults or newly created fractures. The majority of the fluid injected underground is water, and approximately 2% of the millions of gallons of fluid are fracturing additives (amounting to tons of chemicals for 5 million tons of fluid per fracturing event), many of which have hazardous or carcinogenic properties.[8] At issue is whether the gas, brine, and fracturing fluid migrating up from the fractured shale play to overlying aquifers (an underground layer of water-bearing permeable rock from which groundwater can be extracted using water wells).

To date, there is little evidence of upward migration of fracturing fluid from fractures to aquifers, in part, due to the depth of the wells.[8] A recent report from the US Department of Energy evaluated gas/fluid migration during and after hydraulic fracturing in six Marcellus Shale gas wells in Pennsylvania using chemical and isotopic analysis of gas and water and monitoring for tracers in gas produced from the wells.[12] There was no evidence of gas or brine migration 3,800 feet (approximately 1.5 km) upwards from the shale to a monitored overlying gas field situated at least 1,300 feet below a freshwater aquifer. However, it is unclear whether the process of hydraulic fracturing can provide a path for vertical migration of gas by opening existing fractures in the rock.

To what extent does well integrity affect groundwater sources?

The quality of a well and how is it constructed to prevent leaks of gas and fluids upward (known as well integrity) can affect groundwater sources if and where leaks occur. Gas and fluid migration from leaks in active, old, or abandoned wells is considered to be the primary cause of water contamination.[6] Well integrity problems can result from imperfections in the well cement and well bore casing (steel pipe that is inserted into a drilled section of a borehole and held in place by cement). Poor concrete coverage and degradation over time of the casing and cement sheath would allow buoyant natural gas and saline waters from leaky well casings to migrate upwards.[6]

Well integrity is an issue across many types of wells, including those from conventional and unconventional oil and gas production. Up to 2013, there have been over 550,000 gas and oil wellbores (the hole that forms the well, usually encased by cement) drilled in Canada.[13] Inadequate cement seals are a long-recognized yet unresolved problem. Leakage of natural gas (as well as drilling mud, fracturing fluids, and produced water) from a shale gas wellbore can occur as it passes through the water aquifer.[3]

An analysis of 75,505 compliance reports for 41,381 oil and gas wells drilled from 2000 to 2012 in the state of Pennsylvania demonstrated that there was a higher incidence of cement and/or casing issues for shale gas wells in comparison to conventional wells.[14] For the 4-year period since 2009, there were 2,714 unconventional (shale) gas wells with loss of structural integrity. In another study, the percentage of unconventional wells estimated in the Marcellus Shale Formation that had integrity failure ranged from 2.58% to 6.2% over different periods of time, with measurable concentrations of gas present at the surface for most wells with casing or cementing violations.[15]

Abandoned oil and gas wellbores are widespread across oil and gas regions in Canada.[13] Abandoned wells that have not been properly decommissioned (sealed and permanently closed) may be a source of leakage of brine fluids and especially, methane gas. Over an extended length of time, a cement plug used to isolate liquid and gas hydrocarbons and saline water in an abandoned well can shrink, crack, or degrade, and may contaminate fresh water aquifers it passes through.[6]

What is done with wastewater?

Wastewater consists of drilling fluids or muds (water, oil, or gas-based fluids used to drill boreholes into the earth), flowback fluids, and produced water and can be stored in surface ponds, treated, recycled, or disposed of. Their high saline content can pose a problem for surface pond storage by eroding the material used to line the ponds, causing leaks.

If untreated, wastewater can contain such heavy metals as chromium, arsenic, and mercury, natural occurring radioactive materials, including radium and beta radiation, very high levels of salt, and volatile organic compounds, such as toluene and ethylbenzene. Analysis of constituents of produced water from 541 shale gas sites in the US showed that maximum measurements for a number of inorganic compounds, such as zinc, aluminum, and magnesium, exceeded guidelines for surface water discharge.[16]

Some of the wastewater can be recycled after dilution or pre-treatment and reused in the hydraulic fracturing process. Although wastewater recycling has economic advantages by reducing the need for water acquisition, concerns include unanticipated chemical reactions and exposure to radioactive materials in the wastewater.[17] Wastewater that is not stored or recycled may be trucked to industrial wastewater treatment facilities or to deep injection wells.[7]

Industrial wastewater treatment may be inadequate if it is not designed to treat total dissolved solids. For example, a study of a Pennsylvanian wastewater treatment facility from the Marcellus shale examined the water quality of discharged effluents and nearby surface waters and stream sediments.[18] In addition to downstream concentrations of chloride and bromide above background levels, radium-226 levels were measured in stream sediments at the point of discharge at approximately 200 times greater than upstream; this exceeded radioactive waste disposal threshold regulations and poses risks of radium bioaccumulation.

With injection of wastewater underground into deep, porous rock formations through disposal wells, there is a risk of groundwater contamination if the injection well lacks mechanical integrity, allowing fluids to leak through improperly sealed casings directly into aquifers.[3] In Western Canada, the method of choice for disposing of wastewater is through deep well injection; whereas for Eastern Canada, the geology is inappropriate for this disposal method.[1]

Is there evidence of contamination of drinking water wells from shale gas production?

Without pre-drilling baseline characterization of underground water resources, it is difficult to determine if drinking water resources have been contaminated due to shale gas production. Differences in drinking water quality have been demonstrated for residents in US regions close to shale gas wells, compared to those more distally located. In a study of 141 drinking water wells in northeastern Pennsylvania, methane (the main component of natural gas) was detected in 82% of drinking water samples with average concentrations six times higher for homes less than one km from natural gas wells.[19] Analysis of the water composition indicated that, although naturally occurring methane is usually present to some extent, groundwater contamination from the shale region was the probable cause. Another study of the Marcellus and Utica shale formations in the US also showed that average and maximum methane concentrations in drinking water wells increased with proximity to the nearest gas well, but there was no evidence for contamination of drinking-water samples with deep saline brines or fracturing fluids.[20]

Another study assessed the quality of private well water in aquifers overlying the Barnett Shale formation in Texas.[21] Total dissolved solids, arsenic, and selenium exceeded the EPA Drinking Water Maximum Contaminant Limit for 55%, 32%, and 20%, respectively, of samples from 91 private water wells located within 3 km of active natural gas wells. The levels of some contaminants, such as arsenic, strontium, and barium, were lower on average in non-active well areas. Because a number of private water wells in close proximity to natural gas wells had no elevated constituents, the authors suggested the possibility that industrial accidents, such as equipment failure, faulty casings, and spills may have occurred. Many of the hundreds of chemicals used in hydraulic fracturing fluid are known or suspected endocrine-disrupting chemicals. Most of the surface and groundwater samples collected from sites with known drilling-related spill incidents in a natural gas drilling region of Colorado exhibited more estrogenic activity than those taken from reference sites with limited drilling operations.[22]

Results of a study of community residents in Pennsylvania illustrate the complexity of attributing well water contamination to shale gas production.[23] Almost one half of respondents reported changes in water quality or quantity of well water since drilling for shale gas began and some wells had elevated manganese, iron, bromide, and chloride. However, because the community lies over an oil field and had previous mining and oil and gas activities, the source of water contamination could not be conclusively determined.

Gaps in Research and Knowledge Concerning Drinking Water

- Without good baseline data on the quality of drinking water resources, it is difficult to differentiate contamination from methane and other substances through natural pathways from what is potentially caused by drilling, hydraulic fracturing, and other shale gas production activities. There is a need for monitoring groundwater quality at all stages of shale well exploration and development.
- The interactions of chemicals associated with shale gas production are generally unknown and untested, making it difficult to predict and assess risk from direct or indirect exposures. It is not known whether reactions between chemicals in reuse of wastewater may produce new toxic chemicals and complex mixtures that may have cumulative or synergistic properties.[6]
- More research is needed to determine the potential for upward migration of fluids to aquifers after hydraulic fracturing or through poorly cemented casing and improperly abandoned wells.
- There is a need to develop well casings and plugs that are resistant to corrosion and leakage.

Summary on Drinking Water

The scientific evidence on public health implications of shale gas production on water quality is aptly summarized in a recent (June 2015) assessment by the US Environmental Protection Agency (EPA) on the potential impacts of hydraulic fracturing for oil and gas on drinking water resources.[24] Excerpts from the executive summary follow[24]:

“From our assessment, we conclude there are above and below ground mechanisms by which hydraulic fracturing activities have the potential to impact drinking water resources. These mechanisms include: water withdrawals in times of, or in areas with, low water availability; spills of hydraulic fracturing fluids and produced water; fracturing directly into underground drinking water resources; below ground migration of liquids and gases; and inadequate treatment and discharge of wastewater.”

“Of the potential mechanisms identified in this report we found specific instances where one or more mechanisms led to impacts on drinking water resources, including contamination of drinking water wells. The number of identified cases, however, was small compared to the number of hydraulically fractured wells. This finding could reflect a rarity of effects on drinking water resources, but may also be due to other limiting factors. These factors include: insufficient pre- and post-fracturing data on the quality of drinking water resources; the paucity of long-term systematic studies; the presence of other sources of contamination precluding a definitive link between hydraulic fracturing activities and an impact; and the inaccessibility of some information on hydraulic fracturing activities and potential impacts."

Air Quality

Shale gas extraction and processing can generate a wide variety of air pollutants that vary in type and amount throughout the production process. These emissions differ from that of conventional oil and gas development in that there are more extensive well completion activities, including hydraulic fracturing, along with a greater density of wells and intensity of trucking activities. Table 1 itemizes the main air pollutants (along with their chemical symbols) that can be emitted during different stages of shale gas production, along with potential health effects from excessive exposures.

Figure 3. *Natural gas flare (Creative Commons, Tod Baker[25])*

Table 1. *Air pollutants associated with shale gas production and their potential health effects.[8,26-28]*

Agent	Potential Health Effects
Nitrogen and Sulphur Oxides (NOx, SOx)	Lung diseases, asthma, cardiovascular diseases Contributes to ground level ozone production
Ozone (O_3)	Asthma, cardiovascular effects, irritation of mucous membranes, particularly significant for the elderly and vulnerable populations
Volatile Organic Compounds (VOCs): Benzene, Toluene, Ethylbenzene and Xylene (BTEX)	Cancer (leukemias), birth defects, lung, and nervous system diseases
Crystalline Silica (respirable fraction)	Silicosis and lung cancer, kidney disease, particularly for occupational exposures
Diesel exhaust (includes particulate matter (PM) Carbon monoxide (CO) Hydrocarbons (HC), NOx and VOCs)	Lung and bladder cancer, asthma, other lung diseases, heart disease
Hydrogen Sulphide (H_2S)	Lethal if inhaled at high concentrations Headache, respiratory and mucous membrane irritation, central nervous system effects, e.g., confusion, memory loss, and prolonged reaction time. Sensory irritation from rotten egg smell

Agent	Potential Health Effects
Particulate Matter (PM)	Respiratory disease, including asthma, cardiovascular disease, and premature death for cardiorespiratory patients
Methane, ethane, propane and butane (light VOCs)	Methane contributes to greenhouse gases and can cause explosions or lead to asphyxiation at high concentrations
Carbon Dioxide (CO_2)	Greenhouse gas contributor
Radioactive materials (radon)	Radon exposure associated with lung cancer.

How is air quality impacted by shale gas production?

Shale gas production generates a range of emissions that can be classified as point sources (from a stack or pipe), mobile sources (from trucks or drill rigs), fugitive sources (from leaks), and area sources (aggregate emissions).[29] Each stage of pre-production and production of shale gas introduces different types of air pollutants that can vary both in the amount and duration of exposure (Table 2).

The pre-production stage includes site clearing and road construction, drilling, hydraulic fracturing, and well completion.[30] During the construction of well pads, holding ponds, and the supporting road network, vehicle traffic to and from the site are sources of diesel exhaust and PM. Diesel emissions also occur during drilling and hydraulic fracturing from a wide range of heavy diesel equipment and trucks transporting water, sand, and chemicals to and from the well pads. Truck traffic also generates PM emitted from tire and brake wear and suspended road dust.[30] It has been estimated that approximately 4000 heavy and light-duty truck trips are required for each horizontal well, given that each well can be hydraulically fractured multiple times during its productive life.[31]

During the initial drilling and completion of wells, the fracturing fluid and produced water from the shale rock that returns to the surface (flowback) includes chemicals, a small amount of proppant, and natural gas (methane and some hydrocarbons). The flowback fluid can emit air toxins such as VOCs, methane, benzene, ethylbenzene, and n-hexane. The gas portion from the flowback fluid is often vented (controlled release) or flared off (controlled combustion) because it is not salable when contaminated with the other agents in the flowback mix (Figure 3). Venting and flaring can emit carbon dioxide, benzene, and formaldehyde, along with other known toxic air pollutants depending on what compounds returned to the surface from the well completion. It has been estimated that from 3.6% to 7.9% of the methane from shale gas production escapes to the atmosphere in venting and leaks over the lifetime of a well.[32]

The production phase emits compounds similar to those found in conventional oil and gas extraction. At the well pad, pressure and heat are used to separate the gas from produced water and liquid hydrocarbons. When raw natural gas is heated in a glycol dehydrator, non-methane hydrocarbons are vented or piped to a condensate tank on the pad. VOCs and BTEX have been detected in the air around condensate tanks.[4] Production water and hydrocarbons can be stored in pits or tanks, which are a source of fugitive emissions such as methane and VOCs.[29] Natural gas compressor stations used to transfer the gas into high pressure pipelines are a source of combustion emissions, including BTEX and NOx.[4]

Table 2. *Sources of emissions associated with shale gas production.*[8,26,29,33]

Agent	Source
Nitrogen Oxides and Sulphur Oxides (NOx, SOx)	Diesel engines, natural gas compressors, fluid evaporation, flaring.
Ozone (O_3)	By-product, created by mix of NOx and VOC at ground level.

Agent	Source
Volatile Organic Compounds (VOCs): Benzene, Toluene, Ethylbenzene, and Xylene (BTEX)	Flowback during well completion, dehydration, condensate, evaporation processes, fugitive emissions, venting and flaring, spills
Crystalline Silica (respirable fraction)	Large amounts used as proppant in fracturing fluids, exposure during loading and unloading can be considerable
Diesel exhaust (includes particulate matter (PM) Carbon monoxide (CO), Hydrocarbons (HC), NOx and VOCs)	Large number of heavy vehicles travelling to and from drilling sites, diesel engines use, including generators, during drilling and production, compressors.
Hydrogen Sulphide (H_2S)	Released during flaring and venting, well blowouts, line releases, and fugitive emissions from equipment and compressors
Particulate Matter (PM)	Site preparation, fracturing process, road building, traffic, venting and flaring, engine exhaust from equipment on site
Methane, ethane, propane and butane (light VOCs)	Fugitive emissions during drilling and production, engine exhaust from production equipment and pneumatic pumps on site, leakage from well integrity problems (i.e., from poorly constructed wells). Routine venting and flaring, engine exhaust from equipment on site and improperly decommissioned sites
Carbon Dioxide (CO_2)	Venting and flaring
Radioactive materials (Radon)	Present naturally in varying concentrations in the earth. Can be brought to the surface through flow back fluids and produced water brine.[34] Airborne exposure is via radon gas

How do geology and meteorological conditions affect air pollutant levels?

The geology of a shale play (geographic area conducive to shale gas exploration) influences the type and amount of emissions as well as the type of fracturing fluids required and the processes required to extract the natural gas. “Sour” natural gas has a higher concentration of hydrogen sulphide (H_2S) than “sweet” gas condensate.[33] Sour gas is considered more of a health risk than sweet gas given the acute hazards associated with exposure to H_2S. Shale gas is also classified as “wet” or “dry” depending on the amount of methane and VOCs (higher in wet areas) emitted during shale gas production.[35] Wet natural gas generally contains less than 85% methane and more complex hydrocarbons than dry natural gas.

Weather conditions, including wind speed and direction upwind or downwind from the emission source and mixing of the air column, also can affect air pollution levels.[36] Emissions can persist near ground level when topography encourages air inversions. Climatic conditions (such as sunlight and temperature) can interact with fugitive emissions of methane, vehicle and engine exhausts, and ambient VOCs to generate ozone and photochemical smog.[4] Winter conditions can exacerbate the development of ground level ozone. Recent studies in Utah, Wyoming, and Texas report high ground level ozone near gas fields and operations.[4,37,38]

Do air pollutants from shale gas production impact the health of community residents?

Proximity to shale gas operations is an important determinant of exposure to average and peak levels of air pollution.[26] In the US, some states, such as Texas, have permitted shale gas operations to be built amidst existing communities and within city jurisdictions[39] (referred to as “urban drilling”), leading to mounting concerns about air pollution for residents whose homes are close to drilling sites. In addition to outdoor exposure, air contaminants can migrate into homes and influence indoor air quality.[40]

A direct link on health effects from air pollution attributed to shale gas production has not yet been demonstrated in epidemiological research as few studies have been designed to evaluate health effects from measured air exposures on a population level. Residents of communities in the US situated closer to well sites have reported a greater prevalence of symptoms than those situated farther away.[41,42] In an area of active shale-based natural gas drilling in Pennsylvania, dermal conditions and respiratory symptoms were reported more frequently by surveyed residents living within 1 km of extraction activities.[41] The respiratory symptoms were suggestive of effects from air emissions, but well water contamination was also considered to be a risk factor.

Two exploratory studies undertook air monitoring during specific stages of shale production. In a community-based study of five US states, residents were instructed to take grab samples and place formaldehyde badges near various sites such as production pads, compressor stations, condensate tank farms, gas processing stations, and wastewater and produced water impoundments.[43] Locations were chosen on the basis of residents' concerns and complaints. Benzene, formaldehyde, and hydrogen sulfide were the most common compounds to exceed acute and other health-based risk levels. High concentrations of volatile substances were found to exceed existing setbacks of 150 to 500 feet from wellheads to homes including that of formaldehyde (up to 2,591 feet) and benzene (up to 895 feet).[44] In a study in Colorado, weekly sampling over one year conducted during drilling and hydraulic fracturing of a natural gas well pad detected the VOCs of methane, ethane, propane, and toluene as well as formaldehyde and acetaldehyde and the PAH naphthalene in every sample.[45] The greatest percentage of detections occurred during the initial drilling phase, prior to hydraulic fracturing. Both studies did not directly evaluate exposure-response relationships, which would allow for causal inferences.

A recent study linked higher first floor indoor air radon concentrations to proximity of drilled unconventional natural gas wells and their production activity in Pennsylvania.[46] The impetus to the study was the demonstration of elevated radon concentrations in the Marcellus shale region.[47] Further research on the source of radon is needed, particularly given the known relationship between radon exposure and lung cancer.

Gaps in Research and Knowledge Concerning Air Quality

- Data on repeated air quality measurements throughout the stages of production are sparse. Baseline air quality and variability of emissions throughout the production process need to be considered.
- More epidemiological and health impact studies of community residents near shale gas well pads are needed that incorporate quantitative exposure assessment through monitoring of air emissions.
- Given the high level of heavy vehicle traffic involved in shale gas production, more research needs to address the impact of truck exhaust and road and tire-related emissions and its contribution to air pollution in the area of activity.

Summary on Air Quality

Local community air quality can be impacted by shale gas production. The processes involved in pre- and post-production of shale gas can expose workers and community residents to a wide range of emissions; many being associated with respiratory and cardiovascular disease. For community residents, air pollutant exposures from shale gas production can vary significantly depending on the proximity of the communities to well sites as well as the stages of shale production, local weather conditions, and geology. The discovery of elevated levels of radon gas, a known lung carcinogen, inside homes near shale gas wells is a newly recognized concern. To date, there is insufficient peer-reviewed epidemiological literature on shale gas production and air quality to adequately characterize direct health impacts, although the small number of exposure studies illustrates the potential for air exposures to exceed air quality guidelines.

Induced Seismicity

Shale gas production is being recognized as having the potential to be a source of injection-induced (human-generated) earthquakes in which seismic activity is increased beyond historical levels.[48,49]

Earthquakes are measured in a variety of ways. Table 3 describes a magnitude (M) scale for earthquakes, with consideration of whether they can be felt and their potential for damaging effects. Magnitude is measured logarithmically (base 10): each step is a ten-fold increase in wave motion. In terms of their intensity, magnitudes of 3–4 can create a sensation similar to a passing truck, while magnitudes of 4–5 may be noisy, cause vibrations, and overturn unstable objects.[50] The Moment Magnitude Scale (M_W) has been adopted more recently to describe seismic events,[51] replacing the older Richter magnitude scale (also called the Local Magnitude, M_L).

Table 3. *Earthquake Magnitude Scale*[51]

Magnitude	Earthquake Effects
2.5 or less	Usually not felt, but can be recorded by seismograph.
2.5 to 5.4	Often felt, but only causes minor damage.
5.5 to 6.0	Slight damage to buildings and other structures.
6.1 to 6.9	May cause a lot of damage in very populated areas.
7.0 to 7.9	Major earthquake. Serious damage.
8.0 or greater	Great earthquake. Can totally destroy communities near the epicenter.

How does hydraulic fracturing induce seismicity?

The intention of hydraulic fracturing is to induce numerous micro-earthquakes (magnitude <2) that stimulate the flow of gas trapped in rock into a well.[52] Initially, when a well is created and activated, fractures (cracks and breaks) in the shale are created through high-pressure injection of fracturing fluids. These fractures release gas and fluids trapped in the ground, but they can also change the stress or strain energy stored in the rocks, releasing stored elastic strain energy. If there are faults nearby, this can cause seismic movement through “fault slips.”

The seismic activity that results from the hydraulic fracturing phase is minor, and movement or damage rarely occurs on the surface. However, occasional seismicity events have been linked directly to hydraulic fracturing processes in the Horn River Basin Area of northeastern BC. [53] The largest earthquake to date attributed to fluid injection from hydraulic fracturing was a 4.6 magnitude earthquake in August 2015 in the Fort St. John area of northeastern BC.[54] As well, between August 2013 to October 2014, 193 of 231 seismic events within the Montney Trend of northeastern BC (2.6 per cent of the 7,400 hydraulic fracturing stages[55]) were triggered by hydraulic fracturing. The small town of Fox Creek, Alberta, previous to hydraulic fracturing, had been a region of low seismicity. Since drilling began in 2013, hundreds of earthquakes have been recorded, mostly small, but ranging up to 4.4.[50,56]

Can deep well injection of wastewater induce earthquakes?

The waste fluids, including flowback and produced water (or brine) that result from shale gas production are often disposed of deep underground through a process known as deep well injection of wastewater. This practice, which is used for both conventional and unconventional production of oil and gas as well as for other industries, has been associated with induced seismicity.[52] However, the majority of injection wells do not cause seismic events that can be felt on the surface.[57] Disposal of large volumes of water into deep sedimentary formations can raise pressure underground and induce slips of existing faults. The US Geological Survey has determined that the total volume of fluid (a particularly high-rate injection of >300,000 barrels per month) was associated with induced earthquakes from wastewater injection.[58]

In 2011, three moderate earthquakes of magnitude 5.0, 5.6, and 5.0 in Oklahoma were attributed to injection of wastewater into deep disposal sites near shale gas operations.[59] The largest earthquake in this series destroyed 14 homes and injured two people.[52] Earthquakes, up to magnitude 4.7, have also been linked directly to deep well injection disposal of produced water from shale gas production in Ohio, Arkansas, West Virginia, and Texas. For example, in Arkansas, 98% of recent earthquakes occurred within 6 km of a waste disposal well after the start of injection.[60] Based on analyses of waveforms of earthquakes in the Cordel Field of Alberta, a strong correlation was found between seismicity and month-to-month operations at a nearby disposal well.[61]

While it is clear that deep well injection of wastewater can induce larger seismic events, there is currently little ability to forecast which of the wastewater injection wells will trigger earthquakes that are large enough to cause structural problems to settlements.[62]

Are induced seismic events related to shale gas production increasing?

In Canada, the number of seismic events in the Horn River Basin of BC increased from 24 in 2002–2003, prior to hydraulic fracturing operations, to 131 in 2011, with peak production. Along with the increasing number of events, the maximum magnitude of the events also shifted from 2.9 to 3.6 as the scale of HF operations expanded.[63 64]

In Oklahoma there is an issue of increasingly larger seismic activity in regions of intense shale gas production that include wastewater injection disposal. The US Geological Service reported a record number of annual earthquakes in the first four months of 2014 (see Figure 7).[65]

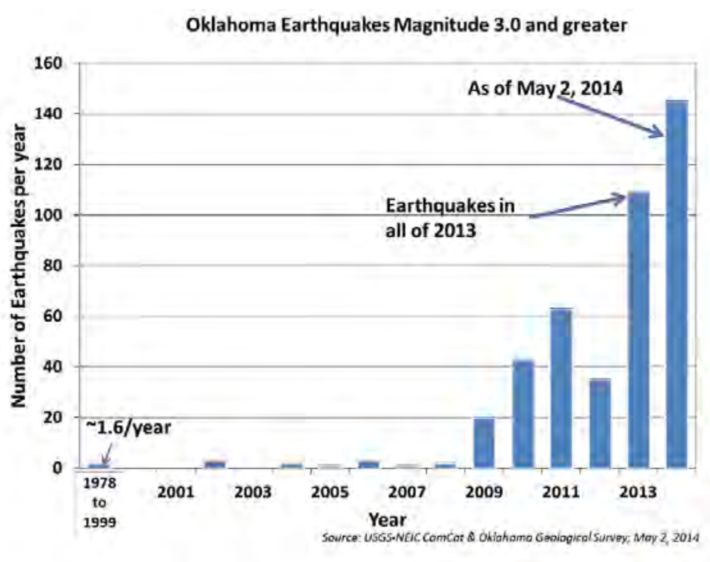

Figure 7. *Histogram of earthquakes of magnitude 3.0 and higher in Oklahoma, 1978 to May 2014 (Creative Commons, US Geological Survey, photo credit: NEIC ComCat & Oklahoma Geological Survey[65])*

In the short period between January and May 2014, there were 145 earthquakes of magnitude 3.0 or greater; in 2013 there were 109 earthquakes, compared to the long-term average rate from 1978 to 2008 of only two earthquakes of magnitude 3.0 or greater earthquakes per year.[65] Given concerns about the rapidly increased rate of earthquakes in this region of the US, an earthquake preparedness advisory was issued for residents, schools, and businesses in May of 2014.

What are the public health concerns from induced seismic activity?

In regions where hydraulic fracturing and deep well wastewater injection are increasing seismic activity, the potential exists for the occurrences of larger magnitude earthquakes that could damage infrastructure and result in injuries to workers and community residents. Concerns have been raised regarding the lack of regulations that could curb seismic impacts from shale gas production and wastewater disposal wells situated near critical facilities such as hospitals, schools, dams, and power generation plants.[60] At least two cities (Dallas Fort Worth and Pittsburgh) have shale gas operations very close to their international airports.[66,67]

The largest earthquake to date linked to a nearby deep wastewater injection well was a Mw 5.6 event near Prague, Oklahoma, in 2011.[68] The earthquake was felt in at least 17 states and occurred in a sequence, after an earthquake of Mw 5.0 and followed by many aftershocks. It caused injuries to two people, destroyed 14 homes, damaged many other buildings, and buckled pavement and is the subject of individual and class-action lawsuits. Damage to buildings and homes in Oklahoma has prompted an increase in the purchasing of earthquake insurance coverage in this state. In Rocky Mountain House, Alberta, an M 3.9 earthquake associated with wastewater disposal injection caused a power outage and resulted in a shut-down of a local gas well site.[48] A review of seismic risks done by Taylor for the US Army Corp of Engineers concluded that the communities most at risk of seismic hazards from nearby shale gas production facilities are those that have been previously aseismic or quasi-stable.[69] Such regions may have building codes that have not had to consider seismic stressors, leaving infrastructure more vulnerable to impacts.

Other than structural damage, seismic impacts can cause other forms of harm. Toxic chemical and petroleum products may be released from an earthquake-damaged well or disrupted pipelines, leading to contaminated air and water resources.[70] Earthquakes in general have also been associated with mental health concerns. For example, in California, 65% of surveyed residents who experienced a magnitude 6.0 quake (the South Napa Earthquake of 2014) reported that one or more household members had experienced anxiety, fear, or distraction since the earthquake.[71]

Gaps in Research and Knowledge on Seismic Activity

There are significant knowledge gaps in our understanding of the seismic risks from shale gas production:

- More research is needed on the potential for larger slips or quakes that could result from the micro-events due to intensive hydraulic fracturing or from wastewater injection in a region.
- More research of community impacts and public health is needed in regions where induced seismicity may be of potential concern.
- The use of advance earthquake warning systems or earthquake advisories for communities in seismically sensitive areas needs to be considered.
- More comprehensive information is needed for public health officials to plan for potential impacts from induced seismicity; this could include inventories of seismically sensitive infrastructure near well sites such as schools, hospitals, utilities, and airports.

Summary on Seismic Activity

The risk of earthquakes from shale gas extraction is a growing area of research. Initial concerns focused on deep well injection of wastewater as a cause of induced seismic activity that can be felt in surrounding communities. Hydraulic fracturing is meant to cause small micro-earthquakes, which can, on rare occasions, result in injection-induced seismic activity. These phenomena suggest that as the shale gas industry expands, greater care needs to be taken to determine potential earthquake hazards before shale gas exploration is initiated and to monitor and restrict volume and flow of injected fluids.

Other Community Impacts

Shale gas development could provide the stimulus for improved economic opportunities through diversification of the local economy and creation of jobs. Appropriately regulated and managed production of shale gas can offer economic benefits to communities, such as locally contracted goods, services and employment, and improved road networks. Improved energy security and less reliance on coal and oil-based energy through development of natural gas resources will also have indirect benefits for population health.[72]

At the same time, economic costs could accrue, compromising tourism and causing ecosystem disruption.[6] In addition to potential risks of water contamination, air pollution, or increased seismic activity (described in previous sections), there is the potential for negative health impacts from road traffic, noise, socioeconomic issues, and disruption of the ecosystem on towns or in rural communities located close to shale gas production sites.

What are the potential effects of road infrastructure?

Ecosystem integrity and plant and animal habitat are affected by extensive land clearing and fragmenting of large contiguous forests, due to the siting of well pads and their service roads, pipeline, and other support infrastructure systems.[6] Improved road networks can be beneficial to the economy and to tourism by expanding opportunities for hunting, fishing, and trapping. However, road infrastructure can also increase erosion, alter stream flow, restrict fish passage, and result in a loss of species, habitat, and vegetation.[6]

Materials must be transported by truck to build the well pad and its surrounding infrastructure. Hydraulic fracturing of shale gas wells requires delivery of large amounts of water, sand, and chemicals and use of large pumper trucks on site. Traffic load is greatest during well pad construction, drilling, and well completion (readying the well for production). Truck traffic can damage rural roads and increase congestion and the risk of motor vehicle accidents, as well as contribute to elevated exposures of vehicle exhaust (including diesel emissions), noise, and dust. A health impact evaluation in a community in Colorado concluded that traffic noise in the range of 30 to 70 decibels has been associated with a number of health effects including sleep disturbance, diminished school performance, and hypertension. It was recommended that roads be built to shunt industrial traffic outside the community to reduce associated safety hazards, diesel emissions, and noise.[73]

Figure 8. *Shale gas trucks carrying water in a hydraulic fracturing site (Creative Commons, National Public Radio[74])*

What occupational hazards are relevant to community exposures?

High levels of noise are generated from drilling, hydraulic fracturing (multiple fracturing trucks operate simultaneously at top output during the injection phase), continuously running compressors, and construction activities.[6] However, the noise levels and associated health effects to workers and nearby residents from shale gas production operations have not been systematically studied.[6] Long-term noise exposure from any source is generally associated with stress and annoyance, sleep disturbances, hypertension, and cardiovascular disease.[75] Workers may choose to use hearing protection and noise levels can be reduced by increasing the distance away from the industrial site and road. ,

Known worker safety concerns derive from on-site and transportation-related risks of accidents and injuries, explosions, and acute exposures to toxic vapours and high dust levels, including that of silica used in hydraulic fracturing fluid.[76] For residents, acute exposures to toxic substances are less likely, but chronic exposures are a concern. Odours attributed to natural gas production such as odours of rotten eggs, burnt butter, or sickly sweet or chemical-like smells are commonly reported.[8]

Figure 9. *Worker poses while hydraulic fracturing is undertaken in the Bakken oil formation, North Dakota (Creative Commons, photo credit: Joshua Doubek[77]).*

What are the psychosocial implications?

Rural residents affected by unconventional natural gas development have witnessed dramatic increases in truck traffic and population growth, coincident with inflation and stress on infrastructure (roadways, law enforcement, schools, and housing).[4] A "boomtown effect" is associated with a transient work force and disruptions in community cohesion with consequent increases in crime rates, substance abuse, and sexually transmitted infections.

For aboriginal peoples especially, habitat destruction can affect cultural practices and identity, impacting health and resilience.[6] A decline in property values was identified by the Colorado health impact assessment study as an important factor for psychosocial stress.[73] Lack of transparency, conflicting messages, and the perception that industry and government authorities are hiding the truth about potential risks also can create psychosocial stress and foster anxiety about potential adverse effects of shale gas production to the community.[6] An analysis of letters to the editor concerning unconventional natural gas operations in Pennsylvania found that citizens' distress was related to a lack of information regarding economic, health, environment, and social issues, including changes to the rural landscape.[78]

A US survey on the public perception of "fracking" found that the majority of Americans know little about hydraulic fracturing, or are undecided as to the risks involved.[79] Drinking water contamination was the main concern.

Is there evidence of community impacts on health?

There are a number of case reports of effects on agricultural animals grazing in the vicinity of shale gas production areas. For example, for production animals in the vicinity of hydraulic fracturing drilling and production areas, reproductive problems were related to flaring or exposure to contaminated pond and creek water or wastewater.[80] After follow-up (averaging two years), flaring was still ongoing in most cases and while reproductive problems were minimized, respiratory and growth-related concerns increased. Apart from the implications for agriculture, disruption of animal behavior may indicate the potential for health effects in people who are exposed to pollution from shale gas production.

The majority of the scientific literature on community impacts attributed to nearby shale gas production sites is from US-based studies. Anecdotal reports of symptoms of US residents in proximity to shale production sites and to occupational exposed workers include headaches, nose, eye and throat irritation, respiratory symptoms, rash, and fatigue, often in relation to odours.[81] In a self-reported survey completed by 108 residents from 14 Pennsylvania counties, 81% detected odours, which were frequently linked to nausea, dizziness, headaches, and respiratory and ear/nose/throat problems, among other complaints.[82] Convenience (non-randomized) sample surveys have found a high prevalence of self-reported symptoms among concerned citizens, particularly for those living near natural gas facilities.[80] For example, in a survey of volunteer residents living near unconventional gas facilities in the Marcellus

Shale region, stress was reported as the most common of 59 health impacts and concern for health was predominant among 13 perceived stressors.[83]

Adverse health consequences for community residents could implicate exposure to air emissions, water contaminants or psychosocial stressors, or a combination of these sources. One recent ecological study compared hospital utilization rates in Pennsylvania by zip codes for two counties with active hydraulic fracturing in shale gas production regions to one with no such activity.[84] Due to multiple comparisons, a stringent level of statistical significance was applied. Cardiology inpatient and neurology impatient prevalence rates were associated with the number of gas wells per km^2. Further research is needed to determine the relevance of these findings.

Currently there are very few epidemiological studies concerning public health risks related to unconventional natural gas production, due in part to the relatively short time the industry has been established and the latency of chronic illnesses to develop, such as cancer. A cross-sectional survey involved a randomized sample of 492 residents in 180 households with ground-fed wells near active hydraulic fracturing sites in the Marcellus shale formation in Pennsylvania.[41] The odds of reporting of skin conditions and upper respiratory symptoms were significantly higher in persons living in households less than 1 km from gas wells compared to those living at least 2 km away, even after adjustment for differences in age, sex, education, smoking, awareness of environmental risk, work type, and pets. There was no association between gas well proximity and reports of neurological, cardiovascular or gastrointestinal conditions. The authors speculated that exposure to air pollutants such as from flaring or diesel sources, contaminated well water or the effects of stress may be related to skin and respiratory symptoms, but further study is warranted.

Infants and children are especially vulnerable to environmental exposures during growth and development. A record linkage study related birth outcomes to maternal residential proximity to natural gas production sites in Colorado. Within a 10-mile radius of natural gas wells and with greater gas well density there were statistically significant positive associations with congenital heart defects, but not of oral clefts, nor were there positive associations with preterm birth or term low birth weight.[85] Exposure to benzene and volatile aromatic hydrocarbons were suggested to be causal factors; however, these exposures were not measured. Another retrospective cohort study evaluated fetal growth in infants born to mothers, according to the density of shale gas wells near their residence in Pennsylvania.[86] Infants of mothers in the higher exposure categories had lower birth weight and a higher incidence of small-for-gestational age, but not of preterm birth. Potential air pollutants associated with shale gas production that are linked to low birth weight include diesel exhaust, heavy metals, benzene, and other VOCs. Another data linkage study in Pennsylvania found an association between unconventional natural gas development activity incorporating distance to the mother's home and production volume during pregnancy.[87] They found an increase in preterm births (odds ratio of 1.4 (95% CI 1.0,1.9) but not small-for-gestational age or term birth weight. Differences in the study findings concerning fetal growth highlight the need for further investigation and improved exposure assessment as well as consideration of regional differences in the assessment of shale gas production impacts on public health.

Knowledge and Research Gaps on Community Impacts

- There is minimal Information on toxicological characteristics of shale gas industry products. A further issue is determining the combined effects of exposures to multiple cumulative chemical and physical hazards and their interactions with psychosocial stressors.[88]
- Baseline studies of the air shed and water quality of potentially affected communities are needed to track health indicators. Addressing ecological concerns, including species at risk and critical wildlife habitats and waterways also require baseline data to observe any changes related to shale gas development.
- There is a need for epidemiological studies that incorporate measurement-based exposure assessment when evaluating the risk of acute and chronic health effects for residents in close proximity to shale gas production sites. More studies are needed, not only to determine any associations but also to replicate findings and refine the study methods. Chronic diseases, particularly cancers, require latency periods to develop disease from initial exposure, and therefore associations with exposures from this relatively recent industry are difficult to assess.

- Consideration should be given to social, economic, geographic and individual-level vulnerabilities in the affected population, such as to children and pregnant women and also to Indigenous communities.
- Occupational health studies are needed since shale gas exploration and production workers are more likely to experience acute toxic exposures.[88]
- There is a lack of standard methods for measuring social impacts in communities and applying evidence-based approaches for prevention and mitigation.[89]

Summary on Other Community Impacts

A unique aspect of shale gas production, as opposed to that of conventional gas and oil, is the large number of gas wells and infrastructure required for multi-stage hydraulic fracturing. In addition to concerns of diminished air quality and contamination of drinking water resources, residents in communities nearby shale gas production facilities may be vulnerable to psychosocial stress and compromised health due to increased road traffic and noise, as well as from socioeconomic problems related to a "boomtown" effect attracting migrant workers. To date, there are few epidemiological studies to determine whether community residents exposed to contaminants originating from shale gas production activities are at risk for adverse health impacts.

Conclusion

At this point in time, concerns about public health impacts attributed to shale gas production and hydraulic fracturing are mostly based on plausible risks rather than evidence. The science to determine public health risks associated with shale gas production is rapidly evolving. Risks of adverse health outcomes for residents in communities close to shale gas production sites can vary greatly and are largely dependent upon the extent of exposure to physical factors (such as noise, radioactive gases and materials, and seismic effects) and chemical contaminants (including fracturing fluid and methane gas). A number of determinants can affect exposures related to shale gas production including:

- *Proximity to communities* – introduces population exposures to water and air toxics, physical intrusion (noise, roads) as well the potential for socioeconomic disruption with a temporary workforce;
- *Geology* – composition of shale rock, including age, mineralogy and thickness, dictates the extraction process (such as fracturing chemicals used) and the seismic risks related to existing faults;
- *Intensity of production* – the extent of infrastructure, including the number of gas wells per pad, increases the potential for water and air contamination including truck traffic-related emissions.

Acute health effects from toxic physical and chemical exposures from shale gas production are generally an occupational health issue. Community-level chronic health concerns relate more to long-term, low-level exposures to air contaminants, such as benzene and VOCs, and to radionuclides in drinking water, all of which have the potential to cause cancer and other chronic health effects. Potential stressors such as noise and "boomtown" effects add to psychosocial stress. The emerging evidence on injection-induced seismic activity related to shale gas production, including deep-well disposal of wastewater, suggests that some nearby communities may be at risk from earthquake damage. Because the shale gas industry is relatively new, good quality epidemiological studies (not just surveys) that link measured exposures to adverse health outcomes are difficult to undertake at this stage. There is suggestive evidence only of adverse birth outcomes associated with mothers' proximity to unconventional gas drilling during pregnancy. Further research, including epidemiological studies, is needed to more firmly establish the relationship between measured exposures and health outcomes related to hydraulic fracturing and all stages of shale gas production.

At present, it remains unclear as to what extent suggested public health risks are inevitable consequences of hydraulic fracturing and shale gas production in Canada. Many of the peer-reviewed papers apply to potential exposures for population centers in close proximity to drilling sites in the US shale basins. Currently, much of the shale gas production in Canada is done in relatively sparsely populated rural areas although any contamination of water and the air shed can be more widespread. On-going monitoring of air and water quality and seismic activity of new and existing shale gas industry sites is essential to safeguard public health.

Acknowledgements

The authors would like to acknowledge the contributions of the following individuals. Michele Wiens, Information Specialist, NCCEH, provided literature searches and referencing; Merry Turtiak, MSc, Catherine Donovan, MD, Roy Purssell, MD, Emily Peterson, MPH, and Lydia Ma, PhD reviewed the documents. This project builds upon work at the NCCEH initiated by Luisa Giles, PhD.

References

1. Canadian Water Network, Goss G (lead researcher). Water and hydraulic fracturing report. Waterloo, ON: Canadian Water Network; 2015. Available from: http://www.cwn-rce.ca/focus-areas/energy-and-resources/water-and-hydraulic-fracturing-report.

2. McCoy D, Saunders P. Health and fracking. The impacts & opportunity costs. London, UK: Medact; 2015. Available from: http://www.medact.org/wp-content/uploads/2015/03/medact_fracking-report_WEB3.pdf.

3. Rivard C, Lavoie D, Lefebvre R, Séjourné S, Lamontagne C, Duchesne M. An overview of Canadian shale gas production and environmental concerns. Int J Coal Geol. 2014. Available from: http://www.sciencedirect.com/science/article/pii/S0166516213002711.

4. Lampe DJ, Stolz JF. Current perspectives on unconventional shale gas extraction in the Appalachian Basin. J Environ Sci Health Part A Tox Hazard Subst Environ Eng. 2015;50(5):434-46. Available from: http://dx.doi.org/10.1080/10934529.2015.992653.

5. U.S. Geological Survey. Energy multimedia gallery: hydraulic fracturing ("fracking") /unconventional oil & gas. Reston, VA: USGS; 2014 May 2. Available from: http://energy.usgs.gov/Portals/0/EasyGalleryImages/12/95/DSCN040118287.JPG.

6. Council of Canadian Academies. Environmental impacts of shale gas extraction in Canada. Ottawa, ON: The Expert Panel on Harnessing Science and Technology to Understand the Environmental Impacts of Shale Gas Extraction, Council of Canadian Academies; 2014. Available from: http://www.scienceadvice.ca/uploads/eng/assessments%20and%20publications%20and%20news%20releases/shale%20gas/shalegas_fullreporten.pdf.

7. Kuwayama Y, Olmstead S, Krupnick A. Water quality and quantity impacts of hydraulic fracturing. Curr Sustain/Renewa Energy Rep. 2015;2(1):17-24.

8. Werner AK, Vink S, Watt K, Jagals P. Environmental health impacts of unconventional natural gas development: a review of the current strength of evidence. Sci Total Environ. 2015 Feb 1;505:1127-41. Available from: http://www.ncbi.nlm.nih.gov/pubmed/25461113.

9. U.S. Environmental Protection Agency. EPA's study of hydraulic fracturing and its potential impact on drinking water resources. Figure of the stages of the hydraulic fracturing water cycle. Washington, DC: EPA; 2015 [updated Jun 1]; Available from: http://www2.epa.gov/hfstudy/hydraulic-fracturing-water-cycle.

10. Papoulias DM, Velasco AL. Histopathological analysis of fish from Acorn Fork Creek, Kentucky exposed to hydraulic fracturing fluid releases. Southeast Nat. 2013;12(4). Available from: http://pubs.er.usgs.gov/publication/70047892.

11. 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. J Air Waste Manag Assoc. 2013 Apr;63(4):424-32. Available from: http://www.ncbi.nlm.nih.gov/pubmed/23687727.

12. Hammack R, Harbert W, Sharma S, Stewart B, Capo R, Wall A, et al. An evaluation of fracture growth and gas/fluid migration as horizontal Marcellus shale gas wells are hydraulically fractured in Greene County, Pennsylvania. Pittsburgh, PA: U.S. Department of Energy, National Energy Technology Laboratory; 2014 Sep.

Available from: http://www.netl.doe.gov/File%20Library/Research/onsite%20research/publications/NETL-TRS-3-2014_Greene-County-Site_20140915_1_1.pdf.

13. Dusseault MB, Jackson RE, Macdonald D. Towards a road map for mitigating the rates and occurrences of long-term wellbore leakage. Waterloo, ON: University of Waterloo; 2014 May. Available from: http://www.geofirma.com/Links/Wellbore_Leakage_Study%20compressed.pdf.

14. Ingraffea AR, Wells MT, Santoro RL, Shonkoff SB. Assessment and risk analysis of casing and cement impairment in oil and gas wells in Pennsylvania, 2000-2012. Proc Natl Acad Sci U S A. 2014 Jul 29;111(30):10955-60. Available from: http://www.ncbi.nlm.nih.gov/pubmed/24982144.

15. Davies RJ, Almond S, Ward RS, Jackson RB, Adams C, Worrall F, et al. Oil and gas wells and their integrity: implications for shale and unconventional resource exploitation. Marine Petrol Geol. 2014;56:239-54. Available from: http://www.sciencedirect.com/science/article/pii/S0264817214000609.

16. Alley B, Beebe A, Rodgers J, Jr., Castle JW. Chemical and physical characterization of produced waters from conventional and unconventional fossil fuel resources. Chemosphere. 2011 Sep;85(1):74-82. Available from: http://www.ncbi.nlm.nih.gov/pubmed/21680012.

17. Vidic RD, Brantley SL, Vandenbossche JM, Yoxtheimer D, Abad JD. Impact of shale gas development on regional water quality. Science. 2013 May 17;340(6134):1235009. Available from: http://www.ncbi.nlm.nih.gov/pubmed/23687049.

18. Warner NR, Christie CA, Jackson RB, Vengosh A. Impacts of shale gas wastewater disposal on water quality in western Pennsylvania. Environ Sci Technol. 2013 Oct 15;47(20):11849-57. Available from: http://www.ncbi.nlm.nih.gov/pubmed/24087919.

19. 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. Proc Natl Acad Sci U S A. 2013 Jul 9;110(28):11250-5. Available from: http://www.ncbi.nlm.nih.gov/pubmed/23798404.

20. Osborn SG, Vengosh A, Warner NR, Jackson RB. Methane contamination of drinking water accompanying gas-well drilling and hydraulic fracturing. Proc Natl Acad Sci U S A. 2011 May 9. Available from: http://www.pnas.org/content/early/2011/05/02/1100682108.abstract.

21. Fontenot BE, Hunt LR, Hildenbrand ZL, Carlton DD, Jr., Oka H, Walton JL, et al. An evaluation of water quality in private drinking water wells near natural gas extraction sites in the Barnett Shale formation. Environ Sci Technol. 2013 Sep 3;47(17):10032-40. Available from: http://www.ncbi.nlm.nih.gov/pubmed/23885945.

22. Kassotis CD, Tillitt DE, Davis JW, Hormann AM, Nagel SC. Estrogen and androgen receptor activities of hydraulic fracturing chemicals and surface and ground water in a drilling-dense region. Endocrinology. 2014 Mar;155(3):897-907. Available from: http://www.ncbi.nlm.nih.gov/pubmed/24424034.

23. Alawattegama SK, Kondratyuk T, Krynock R, Bricker M, Rutter JK, Bain DJ, et al. Well water contamination in a rural community in southwestern Pennsylvania near unconventional shale gas extraction. J Environ Sci Health A Tox Hazard Subst Environ Eng. 2015;50(5):516-28. Available from: http://www.ncbi.nlm.nih.gov/pubmed/25734827.

24. U.S. Environmental Protection Agency. Assessment of the potential impacts of hydraulic fracturing for oil and gas on drinking water resources (external review draft). Washington, DC: U.S. EPA; 2015 Jun. Available from: http://cfpub.epa.gov/ncea/hfstudy/recordisplay.cfm?deid=244651.

25. Baker T. Natural gas: Flickr; 2005. Available from: https://www.flickr.com/photos/todbaker/9148692/.

26. Brown DR, Lewis C, Weinberger BI. Human exposure to unconventional natural gas development: a public health demonstration of periodic high exposure to chemical mixtures in ambient air. J Environ Sci Health Part A Tox Hazard Subst Environ Eng. 2015;50(5):460-72. Available from: http://dx.doi.org/10.1080/10934529.2015.992663.

27. Goldstein BD, Brooks BW, Cohen SD, Gates AE, Honeycutt ME, Morris JB, et al. The role of toxicological science in meeting the challenges and opportunities of hydraulic fracturing. Toxicol Sci. 2014 Jun;139(2):271-83. Available from: http://www.ncbi.nlm.nih.gov/pubmed/24706166.

28. U.S. Centers for Disease Control and Prevention. Air pollutants. Atlanta, GA: CDC; 2010 [updated 24 Nov 2014; cited 2016 Jan 12]; Available from: http://www.cdc.gov/air/pollutants.htm.

29. Field RA, Soltis J, Murphy S. Air quality concerns of unconventional oil and natural gas production. Environ Sci Process Impacts. 2014;16(5):954-69. Available from: http://pubs.rsc.org/en/Content/ArticleLanding/2014/EM/C4EM00081A#!divAbstract.

30. Moore CW, Zielinska B, Petron G, Jackson RB. Air impacts of increased natural gas acquisition, processing, and use: a critical review. Environ Sci Technol. 2014 Aug 5;48(15):8349-59. Available from: http://www.ncbi.nlm.nih.gov/pubmed/24588259.

31. Hays J, Law A. Public health concerns of shale gas development. Washington, DC: Physicians For Social Responsibility; 2012. Available from: http://www.psr.org/environment-and-health/environmental-health-policy-institute/responses/public-health-concerns-of-shale-gas-development.html.

32. Howarth R, Santoro R, Ingraffea A. Methane and the greenhouse-gas footprint of natural gas from shale formations. Climatic Change. 2011;106(4):679-90. Available from: http://dx.doi.org/10.1007/s10584-011-0061-5.

33. Eapi GR, Sabnis MS, Sattler ML. Mobile measurement of methane and hydrogen sulfide at natural gas production site fence lines in the Texas Barnett Shale. J Air Waste Manag Assoc. 2014;64(8):927-44. Available from: http://dx.doi.org/10.1080/10962247.2014.907098.

34. Burkhart J, Huber T, Bolling G. Potential radon release during fracking in Colorado. In: Burkhart JF, Brodhead W, George A, Hodgden G, Jenkins P, Moorman L, et al., editors. Proceedings of the 2013 International AARST Symposium; Sep 22-25; Springfield, IL: American Association of Radon Scientists and Technologists; 2013. p. 22-9. Available from: http://www.aarst.org/proceedings/2013/PROCEEDINGS_OF_THE_2013_INTERNATIONAL_AARST_SYMPOSIUM.pdf.

35. Bunch AG, Perry CS, Abraham L, Wikoff DS, Tachovsky JA, Hixon JG, et al. Evaluation of impact of shale gas operations in the Barnett Shale region on volatile organic compounds in air and potential human health risks. Sci Total Environ. 2014 Jan 15;468-469:832-42. Available from: http://www.ncbi.nlm.nih.gov/pubmed/24076504.

36. Allen DT. Atmospheric emissions and air quality impacts from natural gas production and use. Annu Rev Chem Biomol Eng. 2014;5:55-75. Available from: http://www.ncbi.nlm.nih.gov/pubmed/24498952.

37. Pacsi AP, Kimura Y, McGaughey G, McDonald-Buller EC, Allen DT. Regional ozone impacts of increased natural gas use in the Texas power sector and development in the Eagle Ford Shale. Environ Sci Tech. 2015;49(6):3966-73. Available from: http://dx.doi.org/10.1021/es5055012.

38. 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. Environ Sci Tech. 2014;48(9):4707-15. Available from: http://dx.doi.org/10.1021/es405046r.

39. Baker MB. Drilling bill revised to address concern from cities. Star-Telegram. 2015 Mar 30. Available from: http://www.star-telegram.com/news/business/barnett-shale/article16919810.html.

40. Leung DYC. Outdoor-indoor air pollution in urban environment: challenges and opportunity. Front Environ Sci. 2015 Jan;2. Available from: http://www.frontiersin.org/Journal/Abstract.aspx?s=1478&name=air_pollution&ART_DOI=10.3389/fenvs.2014.00069.

41. 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. Environ Health Perspect. 2015 Jan;123(1):21-6. Available from: http://www.ncbi.nlm.nih.gov/pubmed/25204871.

42. McKenzie LM, Witter RZ, Newman LS, Adgate JL. Human health risk assessment of air emissions from development of unconventional natural gas resources. Sci Total Environ. 2012;424:79-87. Available from: http://cogcc.state.co.us/library/setbackstakeholdergroup/Presentations/Health%20Risk%20Assessment%20of%20Air%20Emissions%20From%20Unconventional%20Natural%20Gas%20-%20HMcKenzie2012.pdf.

43. Rich A, Grover JP, Sattler ML. An exploratory study of air emissions associated with shale gas development and production in the Barnett Shale. J Air Waste Manag Assoc. 2013 2014/01/02;64(1):61-72. Available from: http://dx.doi.org/10.1080/10962247.2013.832713.

44. Macey GP, Breech R, Chernaik M, Cox C, Larson D, Thomas D, et al. Air concentrations of volatile compounds near oil and gas production: a community-based exploratory study. Environ Health. 2014;13:82. Available from: http://www.ncbi.nlm.nih.gov/pubmed/25355625.

45. Colborn T, Schultz K, Herrick L, Kwiatkowski C. An exploratory study of air quality near natural gas operations. Hum Ecol Risk Assess. 2012;20(1):86-105. Available from: http://dx.doi.org/10.1080/10807039.2012.749447.

46. Casey JA, Ogburn EL, Rasmussen SG, Irving JK, Pollak J, Locke PA, et al. Predictors of indoor radon concentrations in Pennsylvania, 1989-2013. Environ Health Perspect. 2015 Apr 9. Available from: http://www.ncbi.nlm.nih.gov/pubmed/25856050.

47. Rowan EL. Radon-222 Content of natural gas samples from Upper and Middle Devonian sandstone and shale reservoirs in Pennsylvania—Preliminary data. Reston, VA: U.S. Geological Survey; 2012. Available from: http://pubs.usgs.gov/of/2012/1159.

48. Atkinson G, Assatourians K, Cheadle B, Greig W. Ground motions from three recent earthquakes in Western Alberta and Northeastern British Columbia and their implications for induced- seismicity hazard in eastern regions. Seismol Res Lett. 2015 Apr. Available from: http://srl.geoscienceworld.org/content/early/2015/03/30/0220140195.abstract.

49. Eaton DW, Rubinstein JL. Preface to the focus section on injection- induced seismicity. Seismol Res Lett. 2015 Jul;86(4):1058-9. Available from: http://srl.geoscienceworld.org/content/86/4/1058.short.

50. Alberta Energy Regulator. Seismicity in Alberta. Calgary, AB: AER; [cited 2015 Jul 19]; Available from: https://www.aer.ca/about-aer/spotlight-on/seismicity-in-alberta.

51. UPSeis. Earthquake magnitude scale. Houghton, MI: Michigan Techological University; [cited 2015 Jul 21]; Available from: http://www.geo.mtu.edu/UPSeis/magnitude.html.

52. Ellsworth WL. Injection-induced earthquakes. Science. 2013 Jul 12;341(6142). Available from: http://www.sciencemag.org/content/341/6142/1225942.abstract.

53. Farahbod AM, Kao H, Cassidy JF, Walker D. How did hydraulic-fracturing operations in the Horn River Basin change seismicity patterns in northeastern British Columbia, Canada? The Leading Edge. 2015;34(6):658-63. Available from: http://tle.geoscienceworld.org/content/34/6/658.abstract.

54. British Columbia Oil and Gas Commission. August seismic event determination [Industry bulletin]. Victoria, BC: BC Oil and Gas Commission; 2015 Dec 15. Available from: http://www.bcogc.ca/node/8233/download.

55. British Columbia Oil and Gas Commission. Defining induced seismicity. Victoria, BC: BC Oil and Gas Commission; 2015 Nov. Available from: http://www.bcogc.ca/node/12925/download.

56. Alberta Energy Regulator. Subsurface order no. 2: Monitoring and reporting of seismicity in the vicinity of hydraulic fracturing operations in the Duvernay Zone, Fox Creek, Alberta. Calgary, AB: AER; 2015 Feb 19. Available from: https://www.aer.ca/documents/bulletins/Bulletin-2015-07.pdf.

57. Rubinstein JL, Mahani AB. Myths and facts on wastewater injection, hydraulic fracturing, enhanced oil recovery, and induced seismicity. Seismol Res Lett. 2015 Jul/Aug;86(4):1-8. Available from: https://profile.usgs.gov/myscience/upload_folder/ci2015Jun1012005755600Induced_EQs_Review.pdf.

58. Weingarten M, Ge S, Godt JW, Bekins BA, Rubinstein JL. High-rate injection is associated with the increase in U.S. mid-continent seismicity. Science. 2015 Jun;348(6241):1336-40. Available from: https://profile.usgs.gov/myscience/upload_folder/ci2015Jun1814143055600Weingarten_etal.pdf.

59. Folger P, Tiemann M. Human-induced earthquakes from deep-well injection: a brief overview. Washington, DC: Congressional Research Service; 2015 May. Available from: https://www.fas.org/sgp/crs/misc/R43836.pdf.

60. Horton S. Disposal of hydrofracking waste fluid by injection into subsurface aquifers triggers earthquake swarm in central Arkansas with potential for damaging earthquake. Seismol Res Lett. 2012 Mar/Apr;83(2):250-60.

Available from: http://yosemite.epa.gov/oa/eab_web_docket.nsf/Attachments%20By%20ParentFilingId/8D96B3596E81A7A285257DE30050EE10/$FILE/T%20Arkansas%20EQ%20article.pdf.

61. Schultz R, Stern V, Gu YJ. An investigation of seismicity clustered near the Cordel Field, west central Alberta, and its relation to a nearby disposal well. J Geophys Res: Solid Earth. 2014;119(4):3410-23. Available from: http://dx.doi.org/10.1002/2013JB010836.

62. U.S. Geological Survey. Earthquakes induced by fluid injection FAQs. Reston, VA: USGS; [updated 2015 Aug 19; cited 2015 Oct 15]; Available from: http://www.usgs.gov/faq/categories/9833/3418.

63. Farahbod AM, Kao H, Walker DM, Cassidy JF. Investigation of regional seismicity before and after hydraulic fracturing in the Horn River Basin, northeast British Columbia. Can J Earth Sci. 2015 Feb;52(2):112-22. Available from: http://dx.doi.org/10.1139/cjes-2014-0162.

64. Kao H. Natural Resources Canada's induced seismicity research Geological Survey of Canada (presentation). Ottawa, ON: Natural Resources Canada; 2015. Available from: http://www.seismo.ethz.ch/research/groups/schatzalp/Download/Kao.pdf.

65. U.S. Geological Survey. Record number of Oklahoma tremors raises possibility of damaging earthquakes. Reston, VA: USGS; 2014 May 2. Available from: http://earthquake.usgs.gov/contactus/golden/newsrelease_05022014.php.

66. Frohlich C, Hayward C, Stump B, Potter E. The Dallas–Fort Worth earthquake sequence: October 2008 through May 2009. Bull Seismol Society Amer. 2011 Feb;101(1):327–40. Available from: https://scits.stanford.edu/sites/default/files/327.full__1.pdf.

67. Wald ML. Now Arriving at Pittsburgh International: fracking. New York Times. 2014 Aug 11. Available from: http://www.nytimes.com/2014/08/12/business/energy-environment/frackers-trove-under-airport-in-pittsburgh.html?_r=1.

68. Keranen KM, Weingarten M, Abers GA, Bekins BA, Ge S. Induced earthquakes. Sharp increase in central Oklahoma seismicity since 2008 induced by massive wastewater injection. Science. 2014 Jul 25;345(6195):448-51. Available from: http://www.ncbi.nlm.nih.gov/pubmed/24993347.

69. Taylor O, Lee T, III, Lester A. Hazard and risk potential of unconventional hydrocarbon development-induced seismicity within the Central United States. Nat Hazards Rev. 2015;16(4):04015008. Available from: http://ascelibrary.org/doi/abs/10.1061/%28ASCE%29NH.1527-6996.0000178.

70. Naghii MR. Public health impact and medical consequences of earthquakes. Rev Panam Salud Publica. 2005 Sep;18(3):216-21. Available from: http://www.ncbi.nlm.nih.gov/pubmed/16269124.

71. Attfield KR, Dobson CB, Henn JB, Acosta M, Smorodinsky S, Wilken JA, et al. Injuries and traumatic psychological exposures associated with the South Napa Earthquake — California, 2014. MMWR Morb Mortal Wkly Rep. 2015 Sep;64(35):975-8. Available from: http://www.cdc.gov/mmwr/preview/mmwrhtml/mm6435a4.htm.

72. Wheeler D, MacGregor M, Atherton F, Christmas K, Dalton S, Dusseault M, et al. Hydraulic fracturing – Integrating public participation with an independent review of the risks and benefits. Energy Policy. 2015;85:299-308. Available from: http://www.sciencedirect.com/science/article/pii/S0301421515002268.

73. Witter RZ, McKenzie L, Stinson KE, Scott K, Newman LS, Adgate J. The use of health impact assessment for a community undergoing natural gas development. Am J Public Health. 2013 Jun;103(6):1002-10. Available from: http://www.ncbi.nlm.nih.gov/pubmed/23597363.

74. Henry T. Northeast debates benefits and dangers of hydrofracking. Figure - Shale gas trucks carrying water in a hydraulic fracturing site. Houston, TX: National Public Radio; 2012 Aug 23. Available from: https://stateimpact.npr.org/texas/2012/08/23/what-texas-can-do-about-roads-damaged-by-drilling/northeast-debates-benefits-and-dangers-of-hydrofracking-2/.

75. Stansfeld SA, Matheson MP. Noise pollution: non-auditory effects on health. Br Med Bull. 2003;68:243-57. Available from: http://www.ncbi.nlm.nih.gov/pubmed/14757721.

76. Small MJ, Stern PC, Bomberg E, Christopherson SM, Goldstein BD, Israel AL, et al. Risks and risk governance in unconventional shale gas development. Environ Sci Tech. 2014. Available from: http://www.ncbi.nlm.nih.gov/pubmed/24983403.

77. Doubek J. Fracking the Bakken keeping American energy independent: Wikimedia Commons; 2011. Available from: https://commons.wikimedia.org/wiki/File:Fracking_the_Bakken_keeping_American_energy_independent.JPG.

78. Powers M, Saberi P, Pepino R, Strupp E, Bugos E, Cannuscio CC. Popular epidemiology and "fracking": citizens' concerns regarding the economic, environmental, health and social impacts of unconventional natural gas drilling operations. J Community Health. 2015 Jun;40(3):534-41. Available from: http://www.ncbi.nlm.nih.gov/pubmed/25392053.

79. Boudet H, Clarke C, Bugden D, Maibach E, Roser-Renouf C, Leiserowitz A. “Fracking” controversy and communication: Using national survey data to understand public perceptions of hydraulic fracturing. Energy Policy. 2014;65:57-67. Available from: http://www.sciencedirect.com/science/article/pii/S0301421513010392.

80. Bamberger M, Oswald RE. Long-term impacts of unconventional drilling operations on human and animal health. J Environ Sci Health Part A Tox Hazard Subst Environ Eng. 2015 2015/04/16;50(5):447-59. Available from: http://dx.doi.org/10.1080/10934529.2015.992655.

81. Rafferty MA, Limonik E. Is shale gas drilling an energy solution or public health crisis? Public Health Nurs. 2013;30(5):454-62. Available from: http://dx.doi.org/10.1111/phn.12036.

82. Steinzor N, Subra W, Sumi L. Investigating links between shale gas development and health impacts through a community survey project in Pennsylvania. New Solut. 2013;23(1):55-83. Available from: http://www.ncbi.nlm.nih.gov/pubmed/23552648.

83. 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. Int J Occup Environ Health. 2013 Apr-Jun;19(2):104-12. Available from: http://www.ncbi.nlm.nih.gov/pubmed/23684268.

84. Jemielita T, Gerton GL, Neidell M, Chillrud S, Yan B, Stute M, et al. Unconventional gas and oil drilling is associated with increased hospital utilization rates. PLoS ONE. 2015;10(7):e0131093. Available from: http://www.ncbi.nlm.nih.gov/pubmed/26176544.

85. McKenzie LM, Guo R, Witter RZ, Savitz DA, Newman LS, Adgate JL. Birth outcomes and maternal residential proximity to natural gas development in Rural Colorado. Environ Health Perspect. 2014 Jan 28. Available from: http://www.ncbi.nlm.nih.gov/pubmed/24474681.

86. Stacy SL, Brink LL, Larkin JC, Sadovsky Y, Goldstein BD, Pitt BR, et al. Perinatal outcomes and unconventional natural gas operations in Southwest Pennsylvania. PLoS ONE. 2015 Jun;10(6). Available from: http://www.ncbi.nlm.nih.gov/pmc/articles/PMC4454655/.

87. Casey JA, Savitz DA, Rasmussen SG, Ogburn EL, Pollak J, Mercer DG, et al. Unconventional natural gas development and birth outcomes in Pennsylvania, USA. Epidemiology. 2015 Sep 30. Available from: http://www.ncbi.nlm.nih.gov/pubmed/26426945.

88. Shonkoff SB, Hays J, Finkel ML. Environmental public health dimensions of shale and tight gas development. Environ Health Perspect. 2014. Available from: http://ehp.niehs.nih.gov/wp-content/uploads/advpub/2014/4/ehp.1307866.pdf.

89. Office of the Chief Medical Officer of Health (OCMOH). Chief Medical Officer of Health’s recommendations concerning shale gas development in New Brunswick. Fredericton, NB: New Brunswick Department of Health; 2012 Sept. Available from: http://www2.gnb.ca/content/dam/gnb/Departments/h-s/pdf/en/HealthyEnvironments/Recommendations_ShaleGasDevelopment.pdf.

This document was produced by the National Collaborating Centre for Environmental Health at the British Columbia Centre for Disease Control, January 2016.

Production of this document has been made possible through a financial contribution from the Public Health Agency of Canada through the National Collaborating Centre for Environmental Health.

Photo Credits: JamesReillyWilson; licensed through iStockphoto.

ISBN: 978-1-988234-00-7

200 – 601 West Broadway
Vancouver, BC V5Z 4C2

Tel.: 604-829-2551
contact@ncceh.ca

National Collaborating Centre for Environmental Health

Centre de collaboration nationale en santé environnementale

To provide feedback on this document, please visit http://www.ncceh.ca/forms/feedback-form