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Review

Environmental health impacts of unconventional natural gas development: A review of the current strength of evidence

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HIGHLIGHTS

- The main body of research is dominated by traditional environmental health issues.
- Highly relevant evidence of direct health outcomes caused by UNGD is lacking.
- There are few methodologically rigorous studies of UNGD and actual health outcomes.
- Most studies focus on short-term, rather than long-term, health impacts.
- The evidence (or lack thereof) is not sufficient to rule out possible health impacts.

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ABSTRACT

Rapid global expansion of unconventional natural gas development (UNGD) raises environmental health concerns. Many studies present information on these concerns, yet the strength of epidemiological evidence remains tenuous. This paper is a review of the strength of evidence in scientific reporting of environmental hazards from UNGD activities associated with adverse human health outcomes. Studies were drawn from peer-reviewed and grey literature following a systematic search. Five databases were searched for studies published from January 1995 through March 2014 using key search terms relevant to environmental health. Studies were screened, ranked and then reviewed according to the strength of the evidence presented on adverse environmental health outcomes associated with UNGD. The initial searches yielded >1000 studies, but this was reduced to 109 relevant studies after the ranking process. Only seven studies were considered highly relevant based on strength of evidence. Articles spanned several relevant topics, but most focussed on impacts on typical environmental media, such as water and air, with much of the health impacts inferred rather than evidenced. Additionally, the majority of studies focussed on short-term, rather than long-term, health impacts, which is expected considering the timeframe of UNGD; therefore, very few studies examined health outcomes with longer latencies such as cancer or developmental outcomes. Current scientific evidence for UNGD that demonstrates associations between adverse health outcomes directly with environmental health hazards resulting from UNGD activities generally lacks methodological rigour. Importantly, however, there is also no evidence to rule out such health impacts. While the current evidence in the scientific research reporting leaves questions unanswered about the actual environmental health impacts, public health concerns remain intense. This is a clear gap in the scientific knowledge that requires urgent attention.

Abbreviations: CSG, Coal seam gas; NO_x, Nitrogen oxides; PAHs, Polycyclic aromatic hydrocarbons; $PM_{2.5}/PM_{10}$, Particulate matter; UNGD, Unconventional natural gas development; VOCs, Volatile organic compounds.

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Contents

1. Introduction

Unconventional natural gas development (UNGD) is rapidly expanding globally with a number of countries expressing interest in developing these resources. To date, major shale gas reserves include those in the Algeria, Argentina, Australia, Brazil, Canada, China, Mexico, Russia, South Africa, and the USA (U.S. Energy Information Administration, 2013), while coal seam gas (CSG) is produced on a major scale in Australia, Canada, China, and the USA (McGlade et al., 2013). Unconventional gas differs from conventional gas in that larger volumes of gas in more difficult to access places are being developed (Canadian Association of Petroleum Producers, 2012), with unconventional gas usually coming from low-permeability reservoirs, such as coal seams, shale formations, tight sand formations, and conventional gas coming from porous carbonate and sandstone formations (Vidic et al., 2013).

Shale gas is trapped in shale formations and, due to its low permeability, shale gas production typically utilises two major technologies: hydraulic fracturing and horizontal drilling (U.S. Department of Energy, 2013). Tight gas is similar to some conventional gas formations in that it is trapped in limestone and sandstone (U.S. Department of Energy, 2013); however, it has lower permeability and uses similar processes to shale such as hydraulic fracturing (Cook et al., 2013). Production processes for shale gas and tight gas require large volumes of water (Cook et al., 2013). On the contrary, CSG is found in coal seams and, unlike shale gas and tight gas, CSG is held in place by underground water, hence the need for dewatering (Ross and Darby, 2013; Rutovitz et al., 2011). CSG produces large volumes of water because wells must be depressurised to release the water, which then allows the gas to flow (Cook et al., 2013; Rutovitz et al., 2011). While hydraulic fracturing is a necessity for shale gas and tight gas (Cook et al., 2013; Ross and Darby, 2013; Rutovitz et al., 2011), CSG does not always use hydraulic fracturing, unless permeability must be increased in order to increase production (Cook et al., 2013; CSIRO, 2014; Ross and Darby, 2013; Rutovitz et al., 2011). Natural gas fields can be classified as either 'dry' (almost pure methane) or 'wet' (methane mixed with hydrocarbons such as ethane, propane, and butane, as well as condensate) (Williams et al., 2012). In shale gas production, the gases are separated out and hydrocarbon liquid, referred to as condensate, is stored in condensate/hydrocarbon storage tanks (Kibble et al., 2013). Conversely, CSG is termed a 'dry' gas as it is mostly methane and has no condensate (Williams et al., 2012).

Development of this resource has created concern in some communities and amongst some medical and public health professionals about potential environmental health issues and the potential, or actual, adverse health impacts these may have, especially on people living in nearby communities (Bamberger and Oswald, 2012; Colborn et al., 2011; Colorado Department of Public Health and Environment, 2010b; Ferrar et al., 2013; McDermott-Levy et al., 2013; McKenzie et al., 2012; Queensland Government, 2013). This has resulted in calls for more research in this area, but it is unclear if the risks associated with UNGD are beyond what is experienced with any resource development, such as coal mining, that has rapid growth in smaller communities, e.g., diesel emissions from trucks, emissions associated with extraction and processing, contaminated water, risk perception of affected communities, and concerns about impacts on mental health. Ahern et al. (2011) noted that mounting evidence is showing that coal mining and coal processing areas are associated with environmental toxicity; therefore, it is important to determine the extent to which risks associated with UNGD are greater than or less than those in other extractive industries or if unique risks are present. The majority of reports have been related to environmental impacts of UNGD activities. Detrimental changes in water quality and quantity, air quality, noise, and odours are commonly reported (Bamberger and Oswald, 2012; Colorado Department of Public Health and Environment, 2010b; Queensland Government, 2013). Concerns have also been raised about food safety, for instance, with potential exposure of farm animals to environmental contaminants from UNGD (Bamberger and Oswald, 2012).

Health outcomes reported to be in some way associated to these environmental impacts are symptoms of upper respiratory tract ailments, burning eyes, headaches, vomiting, diarrhoea, rashes, and nosebleeds (Bamberger and Oswald, 2012; Colorado Department of Public Health and Environment, 2010b; McDermott-Levy et al., 2013; Queensland Government, 2013; Saberi, 2013; Subra, 2009, 2010). It should be noted that these reported symptoms are acute, short-term impacts and, while there may be the potential for chronic, long-term impacts (as discussed later), most of the impacts that have been reported thus far are short-term impacts due to the timeframe of UNGD and its rapid expansion. While the potential for adverse health outcomes as a result of UNGD is strongly advocated for in these studies, there appears to be a dearth of reporting on scientific and epidemiological evidence of the measurable extent of environmental health outcomes, i.e., human exposure to environmental hazards of UNGD and consequent health effects of these exposures, especially in relation to longer term impacts.

While we recognise that the concerns voiced may yet prove to be valid, the aim of this review is to present a strength-of-evidence analysis of scientific reports on the environmental health impacts of UNGD. The purpose is to determine the current state of environmental hazard, exposure, and health outcome knowledge and to reflect on what needs to be done to strengthen the evidence base of pressing concerns.

This article presents a comprehensive review of science-based studies of environmental health impacts caused by the development of unconventional natural gas resources, specifically shale gas, tight gas, and CSG. The primary focus of the review was on studies that examined direct exposure to environmental hazards reportedly caused by UNGD and/or direct health outcomes from this exposure. The review then concludes with a discussion of potential shortcomings in how these studies address the reported environmental health concerns.

1.1. Scope of the review

1.1.1. Environmental health impact

The World Health Organization (WHO) (2012) defines environmental health as human health determined by exposure to external environmental factors. For this review, environmental health impact is, therefore, health outcomes that can be related to human exposure to environmental factors including health hazards in environmental media, such as air, water, food, and soil, as well as environmental conditions such as noise and light.

UNGD processes are environmental activities with a predicted average of a 20–30 year lifespan (Adgate et al., 2014), depending on conditions in the respective gas fields. A number of its processes are reported to have the potential to create environmental hazards that could potentially lead to adverse health impacts, assuming people are exposed to the associated environmental exposure media and pathways.

1.1.2. Focus and scope

This review focusses on studies about evidence of health outcomes associated with measurable exposure to the environmental activities of UNGD. The scope of this activity is limited to unconventional gas, namely shale gas, tight gas, and coal seam gas, which mostly consists of methane (CH_4).

UNGD activities present numerous, complex environmental health issues (Kaktins, 2011; Lauver, 2012; McDermott-Levy and Kaktins, 2012). It should be noted that UNGD activities are now moving closer to residential areas and schools, which may be due to technological innovations that have allowed access to gas in formations that were previously inaccessible (Colborn et al., 2014; Korfmacher et al., 2013). This raises the imperative for providing a clear evidence base of human consequences of this activity.

UNGD is often a rapid process, with typical drilling and fracturing of a well requiring approximately three weeks (Zoback et al., 2010). The process generally consists of different phases of development: exploration; well pad development and well drilling; hydraulic fracturing (if needed); capture and processing of gas or flaring/venting of gas during exploration; transportation; storage, treatment and/or disposal of produced water or flowback water from hydraulic fracturing and other wastes; and decommissioning and rehabilitation (Kibble et al., 2013). Our scope for this review encompasses exploration, well drilling, the process of hydraulic fracturing, including transport, storage, and handling of chemicals associated with hydraulic fracturing, and gas extraction. It also includes capping of non-production wells, as well as rehabilitation of spent extraction fields. This review does not include downstream processes of transporting the raw gas and purifying it to yield saleable gas.

1.2. Objectives of the review

We reviewed both the extent of reporting, meaning the number of studies, as well as the scientific content, meaning the strength of evidence, of studies with the objectives of:

(1) identifying and obtaining relevant scientific research reported in peer-reviewed literature (including editorials/commentaries) and grey literature (including white papers, non-peer reviewed studies, and accessible government documents) from January 1995 through March 2014, and;
(2) reviewing and evaluating studies of relevant scientific investigation of UNGD activities, associated environmental hazards, and adverse human health outcomes.

2. Search and review strategy

This was a narrative review of current and past literature, which were systematically searched and screened for evidence of environmental health impacts associated with UNGD. Initially, literature databases were searched for studies based on primary research where authors collected original primary data. However, we encountered a dearth of strong scientific evidence and expanded the search to include studies based on secondary data, as well as studies more generally dealing with various levels of health risks and impacts related to UNGD. Studies were finally included/excluded according to a further classification of 'relevancy' (discussed below).

2.1. Search criteria

2.1.1. Reporting period

Studies published from January 1995 through March 2014 were searched, screened, and then reviewed for relevancy.

2.1.2. Key search terms

Key search terms were developed to ensure that all potentially relevant studies with content relating to 'environmental health', 'health impact', 'health effect', and 'environmental health impact' were identified. The searches were based on one primary key search term "…and health" and a range of secondary key search terms used with the primary key search term, e.g., 'natural gas' and 'health'. Key secondary search terms that ensured searches identified studies containing information on environmental hazards and exposure relevant to UNGD were 'unconventional gas', 'natural gas', 'natural resource development', 'coal seam gas', 'coalbed methane', 'coal bed methane', 'tight gas', and 'shale gas'.

2.1.3. Searches

Databases searched were: PubMed, ScienceDirect, and Scopus. Internet searches were conducted using Google Scholar, screening the first 50 results for potentially relevant studies. In addition, the PSE study citation database (http://psehealthyenergy.org/site/view/1180), which is regularly updated with peer-reviewed literature related to shale gas and tight oil development, was reviewed for potentially relevant studies. If the identified study was reported in a scientific journal article, it was likely already identified in one of the science-reporting databases and thus, the duplicates were ignored. Studies not mapping to a science journal — deemed grey literature — i.e., studies from government, research institutions, and other interested parties, were also retained and screened for relevancy.

Reference lists in the relevant studies were scanned for studies relevant to the scope of our review, as some of these were not initially identified by the database and Google Scholar searches.

2.2. Determining relevancy of a reported study according to strength of evidence

Relevant studies were identified following a two-step process: (1) search and pre-screening and (2) assessing against the inclusion criteria according to strength of evidence of health impact that is related to/caused by environmental hazards released by UNGD activities — which included qualitative and/or quantitative studies. Inclusion criteria were:

- *Highly relevant*: Evidence is presented of health impacts, or lack thereof, based on primary and/or secondary data that has been collected and/or analysed by the authors. These studies contained evidence of *direct* causality or *strong* associations between environmental health hazards related to UNGD activities and health outcomes (direct symptoms, disease, illness);
- *Relevant*: *Indirect* assessment of health impacts, or lack thereof, based on primary and/or secondary data. These studies contained evidence of indirect associations between environmental health hazards related to UNGD activities and potential health outcomes. This means that these associations were mostly inferred, e.g., risk assessments, risk characterisation, calculations of cancer and non-cancer endpoints, indirect health impact assessment, or monitoring and assessment protocols designed to characterise risks, e.g., air and water quality monitoring and comparison against reference values;
- *Not very relevant*: General discussion with allusion to implications for health. There is generally no clear evidence of, nor implications of or inferences to, hazards, exposures, and/or health consequences. This includes papers that discussed health in relation to UNGD without utilising data, e.g., discussion of other studies, and;
- *Irrelevant*: The following studies were excluded:
  - Studies that reported on potentially hazardous discharges and emissions for purposes clearly related to describing environmental impacts, with no discussion of human health issues;
  - Studies published prior to 1995, conference abstracts, or published in non-English;
  - Studies that focussed on sour gas, natural gas combustion, oil and oil-related studies, or offshore drilling;
  - Studies on technical aspects of natural gas processing;
  - Occupational health studies focussed on human factors and/or fatalities/injuries;
  - Animal studies related to biodiversity, habitat selection, and species occurrence, and;
  - Studies, predominantly from internet searches, that included views from environmental, industry, and social action groups due to the bias associated with such studies; however, it is acknowledged that studies in the peer-reviewed literature can also be biased towards specific groups.

3. Results and discussion

The initial search terms yielded a substantial number of studies (>1000 studies) from the search results, with overlapping search results across the four databases, as well as Google Scholar. After an initial review of the title and abstract of each article, according to the relevancy criteria, a much smaller number of relevant publications was retained for the review, with 70 studies from the peer-reviewed literature and 39 studies from the grey literature. Relevancy (according to strength of evidence) of the scientific journal articles from these sources is shown in Table 1.

Table 1
Number of reviewed studies categorised by type of study and by relevancy to the scope of the review.

	Highly relevant	Relevant	Not very relevant
Scientific journal articles	4	17	49
Grey literature	3	21	15

Only seven of these studies were ‘highly relevant’ — that is, provided evidence about direct associations between environmental health hazards related to UNGD activities and health outcomes, with one being a qualitative study (Fryzek et al., 2013b; Hill, 2012; McKenzie et al., 2014; Perry, 2013; Steinzor et al., 2012, 2013; Texas Department of State Health Services, 2010a). Thirty eight studies were ‘relevant’ and 64 studies were ‘not very relevant’.

The number of shale gas and tight gas-related studies greatly outweighed the number of CSG-related studies. Most of the reviewed literature focussed on a specific aspect of environmental impact of UNGD and would mostly provide speculative comments about the threat this could pose to health, but it did not provide any direct health outcome measures as caused by the particular hazard. Examples are the hazard posed by water polluted with chemicals used for hydraulic fracturing (Colborn et al., 2011; Maule et al., 2013) and human exposure with no measured health outcome to fugitive gas emissions in relation to residents living varying distances from gas wells (McKenzie et al., 2012). Jenner and Lamadrid (2013) noted the lack of information on health cases to demonstrate how shale gas development impacts vulnerable populations. A few studies also examined occupational health and/or animal health in relation to UNGD.

Table 2 shows that the reviewed literature is dominated by reporting on typical environmental exposure media, such as water and air pollution, that in some way relate to health outcomes. Adgate et al. (2014) noted that human health risk assessments have mostly focussed on risks from polluted air exposure. A small number of studies reported on other relevant environmental health topics related to the development of infrastructure in UNGD areas such as traffic, noise, and light. A number of studies also discussed symptomatology associated with UNGD, as well as risk perception and regulatory aspects. Any one study in Table 2 could cover more than one topic area, which is indicative of the general nature of the investigations and discussions in these studies.

Additionally, the majority of the studies that were classified as ‘highly relevant’ or ‘relevant’ were related to short-term impacts as opposed to long-term impacts. Very few, if any, studies focussed on long-term exposure to UNGD and/or health outcomes with long latency periods. Those that did discuss potential long-term health impacts were risk assessment and risk screening studies, which were generally found within the grey literature. These studies compared measured values against reference values (AEA Technology, 2012; Barnett Shale Energy Education Council (BSEEC), 2010; Bunch et al., 2014; City of Fort Worth, 2011; Colorado Department

Table 2
Environmental health impact areas derived from reviewed studies.[a]

	Peer-reviewed literature	Grey literature
Impact on typical environmental exposure media		
Water and water quality	39	20
Air and air quality	30	32
Soil and soil quality	1	6
Impact of infrastructure		
Noise and light	5	8
Traffic	2	9
Societal impact		
Symptomatology	12	9
Risk perception	6	3
Government and/or regulations	26	10

[a] Any one study in the Table could cover more than one topic area — therefore the Table's total studies will not add up to the total number of studies shown in Table 1.

of Public Health and Environment, 2007; Colorado Department of Public Health and Environment, 2010a; Colorado Department of Public Health and Environment, 2010b; Colorado Department of Public Health and Environment, 2012; Coons and Walker, 2008; McKenzie et al., 2012; Subra, 2009; Walther, 2011; Witter et al., 2011; Wolf Eagle Environmental, 2009; Zielinska et al., 2011), while other studies only allude to potential long-term health impacts and are speculative in nature. McDermott-Levy et al. (2013) noted that longitudinal studies on long-term exposure to either air or water contaminated by UNGD do not exist. Some health impacts related to UNGD may present relatively quickly after exposure; however, other health impacts, such as cancer, as well as endocrine disruption and developmental, nervous system, and reproductive effects, may not present for years due to longer latency periods (Finkel and Hays, 2013; Finkel et al., 2013a). For example, in terms of cancer, leukaemia has a relatively short lag period and it was noted that a 4-year lag period has been observed, but cases can appear up to 15 years later (Goldstein and Malone, 2013). Additionally, chemical exposures can result in unpredictable effects and certain effects can span generations (Colborn et al., 2011). In terms of occupational health, Witter et al. (2014) noted that many occupational health outcomes, such as noise-induced hearing loss, benzene-related disease, and silica-related lung disorders, have long latency periods, thus require years of follow-up for outcomes that can be measured in epidemiological studies.

3.1. Health-related impacts of UNGD activities on typical environmental exposure media

3.1.1. Water

Large volumes of water (both in terms of ground and surface waters) are used and produced during UNGD. The main water-related concern reported in the literature is related to hydraulic fracturing ('fracking'), both in terms of surface and groundwater contamination (AEA Technology, 2012; Colborn et al., 2011; Coram et al., 2014; Eaton, 2013; Finkel and Hays, 2013; Finkel et al., 2013a; Gordalla et al., 2013; Kaktins, 2011; Kassotis et al., 2014; Korfmacher et al., 2013; Lauver, 2012; McDermott-Levy and Kaktins, 2012; Perry, 2012; Tillett, 2013); however, it has been noted that it is likely that the greater threat is to surface water due to water demand and wastewater disposal (Eaton, 2013). Sixty-nine percent (69%) of the reviewed studies discussed hydraulic fracturing and/or raised concerns about fracking in relation to health.

Another concern raised is that of pollution of aquifers caused by the movement of naturally occurring chemicals or elements as a result of UNGD activities. This includes methane gas migrating from the shale formations to shallower aquifers during UNGD activities (Osborn et al., 2011), as well as elevated levels of naturally occurring radioactive material (NORM), which are found in shale formations (Kargbo et al., 2010). Radioactive materials can become concentrated, creating technologically enhanced NORM (TENORM), thereby posing the greatest risk to workers who remove solids from tanks and pits, refurbish equipment, and handle drill cuttings (Lechtenböhmer et al., 2011; McDermott-Levy et al., 2013; Railroad Commission of Texas, 2014). There are also concerns surrounding organic compounds in coal seams (Orem et al., 2007).

Finally, concerns were reported about potential surface discharges of contaminated produced water (water drawn from the formation to initiate production, which flows to the surface for life of the well) and flowback water (predominantly fracturing fluids, which comes to surface after fracking is completed and before production begins) from shale gas production that could contaminate natural surface waters (Adgate et al., 2014; AEA Technology, 2012; Finkel et al., 2013a; Kaktins, 2011; U.S. Department of Energy, 2009; Vidic et al., 2013).

The controlled storage of these waters will result in an increasing number of static surface water bodies, providing increasing numbers of potential breeding habitats for mosquitoes and other water-borne pests (Norris, 2004; World Health Organization, 2010; Zou et al., 2006). While the risk of mosquito-borne disease is determined by a multitude of factors, increasing numbers of water bodies could cause mosquito proliferation in UNGD areas (Zou et al., 2006).

3.1.1.1. Hydraulic fracturing. Hydraulic fracturing and improved directional drilling technology have allowed companies to explore for, and collect, gas from areas that were previously inaccessible, especially with shale gas (Korfmacher et al., 2013; U.S. Department of Energy, 2009) and CSG in Australia (Freij-Ayoub, 2012). Although some have argued that hydraulic fracturing has resulted in an expanding industry that has benefits for employment rates, the economy, and greenhouse-gas emissions (Engelder, 2011), hydraulic fracturing has not been popular with various groups, as well as some residents, and campaigners have spoken out against the process (Mackie et al., 2013). The reviewed literature reported persistent environmental and public health concerns about chemicals used in hydraulic fracturing, including concerns expressed by medical and associated health professionals (Kaktins, 2011; Lauver, 2012; McDermott-Levy and Kaktins, 2012; McDermott-Levy et al., 2013; Queensland Government, 2013; Rafferty and Limonik, 2013). Typically, two issues are brought up in the case against hydraulic fracturing. These include environmental impacts and potential human health risks, along with how these two intersect (Mackie et al., 2013). Various discussion groups recommended increased actions around the issue of hydraulic fracturing, e.g., health impact assessment (HIA), baseline data, and exposure and epidemiological studies (Down, 2012; Down et al., 2013; Kovats et al., 2014).

Concerns of fracking-related chemical contamination persist because the composition of the chemical mixtures used in the process is often unknown, leading to repeated calls for full disclosure of chemicals being used and/or use of fracking fluids with additives of no/low toxicity (Cleary, 2012; Kibble et al., 2013; Peduzzi and Harding Rohr Reis, 2013). Also of concern are the quantities of fracking fluids being used. While it is said that chemical additives are approximately 2% of the total volume of fracturing fluid (Eaton, 2013; Wang et al., 2014), each well requires up to 5 million gallons of fluid per fracking event, amounting to tons of chemicals being used (Finkel and Hays, 2013; Finkel et al., 2013a; Goldstein and Malone, 2013). However, Gordalla et al. (2013) noted that, in terms of human toxicological threats, flowback water is more of a concern with respect to drinking water than fracking fluids because flowback water has organic compounds from the formation, as well as heavy metals. Additional concerns are that, even at low concentrations, these chemicals pose a health risk because of the potential for subsequent and chronic exposure to potentially polluted water sources (Colborn et al., 2011). Systems in the human body, especially the endocrine system, are sensitive to low-dose exposures, even at levels containing only parts-per-billion or less (Colborn et al., 2011). Kassotis et al. noted that more than 100 known or suspected endocrine-disrupting chemicals could potentially be used in natural gas extraction processes (Kassotis et al., 2014).

Relatively few studies attempted to actually link fracking chemicals to what is known about health effects of exposure to specific chemicals, or mixtures of such chemicals. A recent study by Kassotis et al. (2014) suggested that tight gas drilling operations *may* result in higher estrogenic, antiestrogenic, or antiandrogenic activities in ground and surface water. Other studies discuss how exposure to specific fracking chemicals could result in various health effects should these be inhaled and ingested, as well as absorbed through the skin (Colborn et al., 2011). Examples of such chemicals are (2-BE) ethylene glycol monobutyl ether, acetic acid, ammonia, ethylene glycol, isopropanol (propan-2-ol), methanol, and sodium nitrate. These can cause effects on skin, eyes, and other sensory organs, respiratory system, gastrointestinal system, and the liver, as well as effects on the brain, nervous system, and immune system (Colborn et al., 2011; Kargbo et al., 2010). However, these studies did not address the contaminant release from UNGD activities to environmental exposure pathways, actual exposure doses and/or actual causality in terms of health outcomes in nearby communities in the UNGD areas.

Colborn et al. (2011) and the Queensland Government (2013) submit that many of the toxicity and metabolic pathways that could link the environmental activity of UNGD to the health of communities in adjacent areas have not been fully studied. In a review conducted by Public Health England, which examined potential public health impacts of exposures to chemical and radiological pollutants from shale gas extraction in the United Kingdom, it was concluded that the process of hydraulic fracturing is unlikely to cause contamination of groundwater and risks to the public are low — if operations are properly conducted (Kibble et al., 2013). One of the authors from the Public Health England report, Robie Kamanyire, reported that where groundwater had been contaminated there was no clear evidence of adverse health effects, except for reports of non-specific symptoms, which cannot be attributed to shale gas (Torjesen, 2013). However, others have noted that this report is problematic, noting that the conclusions that were drawn in the report were not well-founded, there was a lack of attention on densely populated areas, and there was too much reliance on the assumption that regulations in place will ensure that development proceeds without problems (Law et al., 2014). Instead, it was suggested that the Public Health England authors should have concluded, 'that the public health impacts remain undetermined and that more environmental and public health studies are needed' (Law et al., 2014).

A small number of animal studies were related to UNGD, which are important to discuss because animals can be sentinels for human health. Animals are continually exposed to traditional environmental health media and have shorter lives and more frequent reproductive cycles (Bamberger and Oswald, 2012; Finkel and Hays, 2013; Finkel et al., 2013b). One study examined fish that were exposed to fracking fluids due to a spill in Acorn Fork Creek, Kentucky and found that exposed fish had more gill lesions and signs of stress as a result of exposure to heavy metals and a drop in pH compared to unexposed fish (Papoulias and Velasco, 2013). Another study examined potential pathways of risk in relation to UNGD and brook trout (Weltman-Fahs and Taylor, 2013). Of most relevance here is the chemical waste pathway, which in turn affects water quality and brook trout health. Weltman-Fahs and Taylor (2013) noted that elevated concentrations of metals, which may occur in streams as a result of UNGD, affect growth, fecundity, and survival in brook trout. Bamberger and Oswald (2012) documented effects on cats, chickens, cows, dogs, goats, horses, koi, and llamas and found that the most common exposure was to contaminated water wells and/or springs, followed by ponds and/or creeks. The authors documented reproductive effects such as increased incidence of stillborn calves and congenital anomalies, seizures, vomiting, and rashes, as well as death from acute liver or kidney failure or respiratory failure with circulatory collapse (Bamberger and Oswald, 2012). Ferrar et al. (2013) also noted reports of animal death and sickness reported to be associated with flaring or hydraulic fracturing in the Marcellus Shale region.

Finally, two studies examined Marcellus Shale drilling and the impact on dairy cows in Pennsylvania (Adams and Kelsey, 2012; Finkel et al., 2013b). While one study did not specifically address hydraulic fracturing, both studies will be discussed here as hydraulic fracturing was likely used in those areas due to shale gas development. Adams and Kelsey (2012) examined changes in milk production and number of cows in relation to drilling activity for the period 2007–2010 and found that a higher level of drilling activity was associated with larger declines in numbers of cows, as well as milk production. Likewise, Finkel et al. (2013b) conducted a study comparing milk production, number of cows, and production per cow in Pennsylvania counties with significant UNGD to counties with less UNGD for the period 1996–2011. Finkel et al. (2013b) noted similar findings in that counties with the highest levels of drilling activity had greater declines in milk production and number of cows compared to counties with very little drilling. Both studies concluded that the data do not demonstrate a causal association between drilling activity and milk production or numbers of cows, but it is important to examine further (Adams and Kelsey, 2012; Finkel et al., 2013b).

One additional topic that is important to discuss in this section is that of occupational health and emerging exposures as a result of hydraulic fracturing. Workers are often exposed to higher concentrations of chemicals for shorter periods of time, which is what government standards are typically based on (Colborn et al., 2014). It was noted that occupational safety hazards in the oil and gas industry are well known, but the same is not true of occupational health hazards and there are very few studies on chemical exposure risks for workers in relation to hydraulic fracturing operations (Coussens et al., 2013; Esswein et al., 2013). Several studies discussed health hazards related to hydraulic fracturing operations and respirable crystalline silica (from quartz sand), which is a concern for workers near mining operations and well pads (Chalupka, 2012; Coussens et al., 2013; Esswein et al., 2013; Korfmacher et al., 2013; Laney and Weissman, 2012; Witter et al., 2014). Respirable crystalline silica is associated with numerous health effects, including silicosis, lung cancer, increased risk of tuberculosis, autoimmune diseases, and kidney disease (Esswein et al., 2013; Laney and Weissman, 2012). Silicosis is often underreported because it has a long latency period and can develop decades after first exposure (Laney and Weissman, 2012). The National Institute for Occupational Safety and Health (NIOSH) undertook an exposure assessment study of worker exposure to respirable crystalline silica during hydraulic fracturing operations and found that many of the samples exceeded occupational exposure limits (Esswein et al., 2013). Certain workers, such as sand movers and blender operators, had the highest exposures (Esswein et al., 2013; National Institute for Occupational Safety and Health, 2012).

None of the 'highly relevant' studies focussed specifically on hydraulic fracturing, its impact on water sources, and how this affects human health. A number of the 'relevant' studies followed a risk screening approach to fracking in shale gas or tight gas operations by using available data or conducted their own water sampling for a hazard assessment of the chemicals used and potential adverse health effects (AEA Technology, 2012; Colborn et al., 2011; Fontenot et al., 2013; Gordalla et al., 2013; Kassotis et al., 2014).

3.1.1.2. Other forms of aquifer pollution. As with hydraulic fracturing fluid, organic compounds and other elements in produced water have potential to reach shallower aquifers from which drinking water is drawn. In this section, we reviewed potential pollution by: (1) naturally occurring organic compounds and (2) methane migration.

Of the naturally occurring organic compounds, it is the polycyclic aromatic hydrocarbons (PAHs), found in the water drawn from the coal seams, that are of highest concern for human and environmental health (Orem et al., 2007). Health effects will depend on exposure pathways and the dose of whatever compound actually ends up in aquifers (Orem et al., 2007). However, there is little research reported on water-related exposure pathways for organic compounds in produced water from UNGD activities. The review conducted by Public Health England noted that the shale gas extraction process has the potential to mobilise natural compounds within the water, but this will vary accordingly to the geology of the area — showing the importance of characterising the naturally occurring organic contaminants on a case by case basis (Kibble et al., 2013). The authors also noted that baseline data are needed prior to UNGD to ascertain background levels and are necessary during and after production. Adgate et al. (2014) echo this notion and state that the peer-reviewed literature lacks studies on 'before' (UNGD) and 'after' water quality comparisons.

Methane gas, once released from the shale formations or coal seams, could seep into the aquifers intended for drinking water. However, this process, as well as the likelihood of it happening, is not very well understood (Jackson et al., 2013; Osborn et al., 2011). Water samples sourced from water wells closer to shale gas wells have been shown to contain substantially higher concentrations of methane than groundwater wells farther away; however, while methane was found in these samples, there was no evidence of hydraulic fracturing fluids or formation waters in these samples (Jackson et al., 2013; Osborn et al., 2011).

Wellbore casings serve as the principal protection against groundwater contamination. Poor casing quality can lead to methane being released in groundwater, especially during gas production following well development (AEA Technology, 2012). Improper well construction and management increases the likelihood of methane migration to not only water, but also ambient air (House Republican Policy Committee, 2010; Ohio Department of Natural Resources Division of Mineral Resources Management, 2008).

Orem et al. (2007) reported on PAHs detected in water sampled from the Powder River Basin, USA thought to be from leaching from subbituminous coal. The PAHs were not at concentrations and composition sufficient to cause acute health effects, such as red blood cell damage or developmental and reproductive effects, nor were the well-known cancer-causing PAHs detected. The data, although dose-based, were not linked to specific health outcome data or information on likelihood of exposure. Furthermore, health effects of chronic exposure to many of the PAHs are unknown; so it is difficult to predict the entire range of chronic health effects that might occur over time (Orem et al., 2007). Another study examined total dissolved solids (TDS), as well as arsenic, barium, selenium, and strontium, and found that some private water well samples sourced from within a 3 km range of shale gas operations exceeded EPA's Drinking Water Maximum Contaminant Limit (MCL) (Fontenot et al., 2013). For example, 29 of 90 water wells exceeded EPA's MCL for arsenic. However, it was noted that this could be because of a variety of factors, such as faulty drilling equipment, reduction of the water table from drought, and mobilisation into groundwater if iron oxide complexes are agitated (e.g., from UNGD activities), and the levels of arsenic measured in the study warrants further investigation (Fontenot et al., 2013).

In the context of methane contamination of aquifers from which waters are sourced for drinking, evidence of health effects caused by ingestion of these waters are virtually non-existent; therefore, more research is needed in this area (Osborn et al., 2011; Schmidt, 2011). The better-known health hazards posed by methane would be from inhalation at high concentrations, with effects including headaches, asphyxiation, nausea, and vomiting (Minnesota Department of Health, 2013; National Institutes of Health, 2014). However, reports did not state whether methane, in synergy with other constituents in the water, may pose a health risk.

Injury can be a concern if methane gas, mixed with air in confined spaces, ignites and possibly explodes (Eltschlager et al., 2001; La Plata County, 2002). Reports tell of incidents where explosions are attributed to methane migration caused by shale gas and tight gas development, with natural gas entering homes via drinking water systems via well water sources (House Republican Policy Committee, 2010; Ohio Department of Natural Resources Division of Mineral Resources Management, 2008).

Many of the exposure pathways and subsequent health effects of exposure to potential pollutants, such as PAHs and methane, are unknown and the literature noted that more research is necessary. It was also clear that baseline studies are lacking to allow for 'before' and 'after' comparisons.

3.1.1.3. Water discharges and its management on the surface. Flowback fluid, as well as produced water, is typically treated to some degree, then discharged into surface waters, i.e., streams, rivers, etc. (Zoback et al., 2010), or they can be recycled or stored, usually in open ponds (Kibble et al., 2013). If not treated, this may lead to high levels of TDS, salts, and other chemicals (Kargbo et al., 2010; Zoback et al., 2010), as flowback fluid and produced water can contain heavy metals, NORM, very high levels of salt, and other volatile organic compounds (VOCs), including benzene (Finkel and Hays, 2013; Guidotti, 2011). Natural surface water can become contaminated by untreated waters leaking from plastic-lined storage ponds and wastewater pits, runoff, spills, and/or flood events and presents potential environmental health risks (AEA Technology, 2012; Guidotti, 2011; Korfmacher et al., 2013; Lechtenböhmer et al., 2011; Thompson, 2012; Zoback et al., 2010). In some areas, produced water is sprayed legally on the land, in which runoff could contaminate surface water (Coussens et al., 2013; Finkel and Hays, 2013). Concerns have been expressed in Pennsylvania (USA) about violations of UNGD water management protocols since shale gas drilling began. This led to increased spills, leaky waste-holding pits, improperly lined ponds, as well as failure to properly store, transport, or dispose wastes (Kaktins, 2011; Pennsylvania Department of Environmental Protection, 2012). In Garfield County, Colorado (USA), it has been shown that process and equipment malfunctions have been the most common cause of water contamination in relation to UNGD (Witter et al., 2011). It was also noted that these accidents and malfunctions can impact all environmental media and can impact the health of workers, as well as residents (Witter et al., 2011).

3.1.2. Impact on health-related air quality

Several types of volatile pollutants, such as VOCs, are released to ambient air from the various stages of UNGD activities such as well drilling, flowback, gas compression, condensation, and transport (McKenzie et al., 2012). The potential effects on air quality and consequent health outcomes in the UNGD areas, in relation to environmental health, are a major concern (McKenzie et al., 2012). One study estimated region-wide environmental and health damages in Pennsylvania resulting from air pollutant emissions associated with shale gas extraction at $7.2 to $32 million for 2011 (Litovitz et al., 2013).

Much of the reporting related to air quality and shale gas, tight gas, or CSG focussed on emissions inventories and air sampling, with some associated health risk characterisation (Barnett Shale Energy Education Council (BSEEC), 2010; Bunch et al., 2014; City of Fort Worth, 2011; Colorado Department of Public Health and Environment, 2007; Colorado Department of Public Health and Environment, 2009; Colorado Department of Public Health and Environment, 2010a; McKenzie et al., 2012; Pennsylvania Department of Environmental Protection, 2010; Pennsylvania Department of Environmental Protection, 2011; Queensland Government, 2013; Walther, 2011; Wolf Eagle Environmental, 2009). The review showed that, along with some studies from other areas, such as Pennsylvania and Texas (USA), the majority of the studies focussed on health and air quality impacts have been conducted in Garfield County, Colorado. We do acknowledge that additional health-related studies have been conducted elsewhere, especially in the USA; however, the systematic search did not pick up the aforementioned studies. Therefore, the geographic range of reporting on air quality in this review is, therefore, quite limited.

The review showed that air quality concerns are broadly twofold: (1) hazard descriptions of air-borne pollutants combined with how these pollutants are released into the atmosphere and (2) the health/injury concerns, which will be reviewed in the following sections.

3.1.2.1. Air-borne pollutants — hazard and release. Naturally occurring methane seeps from the ground are a concern, especially when in close proximity to residential areas, given their potential to ignite wildfires (La Plata County, 2002). However, most of the air quality concerns addressed in the literature related to venting, fugitive gas emissions, and diesel emissions from UNGD operations. Methane is the fugitive gas mostly referred to in this context. Some reporting from shale gas and tight gas development also indicated that other pollutants of concern, most of which are combustion-related, are: benzene, carbon monoxide, hydrogen sulfide, nitrogen oxides (NO_x), particulate matter

($PM_{2.5}$ and PM_{10}), sulfur dioxide, and VOCs (Colborn et al., 2011; Colorado Department of Public Health and Environment, 2009; Down, 2012; Kaktins, 2011; Kibble et al., 2013; Weinhold, 2012; Witter et al., 2008a,b; Zielinska et al., 2011). Nitrogen oxides can irritate the respiratory system, while particulate matter can exacerbate pre-existing respiratory and cardiovascular problems, cause respiratory health effects, and damage lung tissue (Colorado Department of Public Health and Environment, 2009). Acute exposure to benzene can cause drowsiness, headaches, and eye, skin, and respiratory tract infections and chronic exposure can cause blood disorders, including aplastic anaemia, as well as reproductive effects (Colorado Department of Public Health and Environment, 2009). Benzene is also a known human carcinogen, causing leukaemia (Colorado Department of Public Health and Environment, 2009).

Other sources of air pollutants include: direct emissions from engines and compressors (PMs, CO, NO_x); venting of condensate tanks (VOCs); and flaring (methane, NO_x, PM) (Kibble et al., 2013). Additionally, hydrocarbons in produced water in storage ponds are released through evaporation and could potentially be inhaled (Coons and Walker, 2008). When sunlight reacts with NO_x and VOCs, it develops excessive ground-level (tropospheric) ozone as a secondary contaminant (Walther, 2011; Witter et al., 2008a). Although the authors did not relate their findings to health, Kemball-Cook et al. (2010) found that, even if development of the Haynesville Shale moves ahead at a slow pace, emissions will be large enough to have impacts on ozone levels and potentially ozone attainment status in Northeast Texas and Northwest Louisiana. Likewise, Olaguer (2012) found models that predicted the emissions associated with compressor engines in the Barnett Shale could increase ambient ozone by more than 3 ppb and even more so with possible flaring activities.

Tropospheric ozone is a pulmonary irritant that can affect respiratory mucous membranes, as well as respiratory function (Ebi and McGregor, 2008). In studies unrelated to UNGD, authors have found that chronic exposure to ozone is associated with reduced lung function in adolescents, especially in adolescents with smaller airways (Tager et al., 2005), and exposure to relatively low levels of ozone has been found to increase respiratory symptoms in infants, especially in infants whose mothers have physician-diagnosed asthma (Triche et al., 2006). Short-term exposure increases in ozone, not in the context of UNGD, have been found to increase mortality (Bell et al., 2004) and the authors noted that community-level characteristics can modify this relationship (Bell and Dominici, 2008). Additionally, a small, controlled exposure study of young, healthy adults found increases in vascular markers of inflammation and changes in heart rate and fibrinolysis markers (Devlin et al., 2012).

The majority of the studies that were deemed 'relevant' were related to shale gas and/or tight gas and conducted air sampling or made use of data from air monitoring networks, then compared measured air concentrations to some air contaminant compliance values. These included values from the literature (Colborn et al., 2014), from federal and state health-based air comparison values (HBACVs) (Bunch et al., 2014), and Air Monitoring Comparison Values (AMCVs) and/or Effects Screening Levels (ESLs) (Barnett Shale Energy Education Council (BSEEC), 2010; City of Fort Worth, 2011; Wolf Eagle Environmental, 2009). Some studies calculated hazard quotients from reference concentrations (RfCs) and standards (Colorado Department of Public Health and Environment, 2012; Pennsylvania Department of Environmental Protection, 2010, 2011) to determine whether the measured air concentrations pose a risk to human health.

Some studies have evaluated hazard and release from different stages of well development in relation to shale gas and tight gas development (AEA Technology, 2012; Colborn et al., 2014) and have also modelled emission scenarios across all stages of development (Coons and Walker, 2008). For example, in one risk screening study, the possible cumulative impacts of exposure to elevated levels of ozone during the well design, drilling, casing, and cementing stage, as well as the well completion stage, were considered to be potentially major due to the adverse effects on respiratory health (AEA Technology, 2012). One study on tight gas development linked exposure to air emissions to distance from nearby gas wells (McKenzie et al., 2012) in an attempt to estimate cancer and non-cancer endpoints for residents at various distances from the well. Only one 'relevant' study focussed on CSG and air quality and the authors concluded that the results of air quality monitoring did not show pollutants at concentrations high enough to create adverse health impacts (Queensland Government, 2013).

A limited number of studies addressed worker health and did not focus on respirable crystalline silica. Two studies focussed on drilling fluids and potential exposure of workers (Broni-Bediako and Amorin, 2010; Searl and Galea, 2011). Broni-Bediako and Amorin (2010) concluded that exposure to drilling fluids is mainly through the inhalation, dermal, and oral routes and that circulation of drilling fluids can result in vapours, aerosol and/or dust, which can be inhaled. Searl and Galea (2011) undertook a toxicological review of drilling fluids and noted that the main health risks associated with inhalation of aerosol and vapour associated with oil-based drilling fluid are irritation of mucous membranes and neurotoxicity. Long-term exposure to drilling fluids is associated with increased risk of developing chronic respiratory illness, as well as impaired cognition, neurological impairment, and possibly dementia (Searl and Galea, 2011). However, effects will vary dependent on drilling fluid composition. Finally, Ovuakporaye et al. (2012) studied the impact of gas flaring on lung function and found that residents in communities with gas flaring had reduced peak expiratory flow rates; however, this was in a community associated with oil production. Predictably, lung function worsened with longer exposure to flaring (Ovuakporaye et al., 2012).

One of the most recent studies conducted evaluated exposures to VOCs in the Barnett Shale region (USA) on a community-wide basis (Bunch et al., 2014). The authors noted that it was the 'most robust assessment of potential human health effects conducted to date' due to the length of the data collection period, continuous sampling using monitors at multiple sites, and the use of multiple approaches to assess risks to human health (Bunch et al., 2014). However, the study has limitations in that air quality data were collected from fixed point monitors intended for regional atmospheric concentrations, rather than sampling at the community level, as seen in the study by McKenzie et al. (2012). With this type of monitoring, point sources cannot be identified and it is likely that some areas will have higher or lower concentrations of pollutants to which residents could be exposed, but this will not be detected (Bunch et al., 2014). Additionally, the fact that estimations of risk are employed in most of these studies implies that these efforts have yet to fully assess human health impact in these UNGD areas.

3.1.2.2. Inhalation-related toxicity values and biomonitoring. Reporting on air quality is appreciably on the increase, but these studies still have limitations in their relevance to human health impact. The toxicological data is limited, with only a few acceptable inhalation-related toxicity values (Colorado Department of Public Health and Environment, 2010b). For example, one study identified 86 contaminants; however, for 65 of these contaminants, data were limited, implying that health risks could be underestimated (Colorado Department of Public Health and Environment, 2010b). Moreover, while studies on ambient air monitoring and risk characterisation assessed human exposure and potential risks to human health, the data available to be used for these assessments do not necessarily provide information on what is taken up in an individual's body (Bunch et al., 2014), which suggests the need for concurrent biomonitoring studies. However, there were very few studies that have explored potential health risks and shale gas activities using biomonitoring (Adgate et al., 2014). The biomonitoring study conducted by the Texas Department of State Health Services (TXDSHS) followed a biomonitoring approach, collected blood and urine samples, and analysed these for VOCs (Texas Department of State Health

Services, 2010a). The authors concluded that the results were not consistent with community-wide exposures to airborne pollutants, e.g., those from shale gas development (Texas Department of State Health Services, 2010a). They also reported that other exposures might confound their findings, such as smoking or the use of consumer products containing these compounds (Texas Department of State Health Services, 2010a), meaning that there are many other likely sources for their results and it may not necessarily be attributable to UNGD.

3.1.2.3. Setback restrictions and exposure. A few studies also discussed setback (distance) restrictions in terms of air emissions from shale gas development and health. Gas wells are now being drilled in close proximity to more densely populated urban areas (Colborn et al., 2014). One study used ambient air monitoring data and modelling to examine if the city's setback requirements were sufficient to protect public health and found it sufficiently protective for most sites (City of Fort Worth, 2011). However, another study of setback distances noted that there is variability amongst setback distances in municipalities in Denton County, Texas (USA) and found that empirical research is not used to determine 'safe' distances; rather, they are often political negotiations (Fry, 2013). A tight gas-related study pointed out that each well pad is unique; so it is often difficult to determine one setback distance for all residences (Witter et al., 2013). Finally, one of the few Australian studies found for this review noted that current Australian CSG operations are substantial distances from major residential areas, making potential health impacts likely to be less pronounced compared to the USA; however, this could change with a shift in setback restrictions in Australia (Coram et al., 2014).

3.1.2.4. Health impact assessment and chemical air emissions. One of the relevant studies was an HIA conducted on tight gas in Colorado. It found that residents could potentially experience health effects from exposure to chemical air emissions (Witter et al., 2013). The HIA found that short-term health effects, including headaches and other neurologic symptoms, as well as airway and mucous membrane irritation were probable (Witter et al., 2013). Long-term health effects, such as cancer and birth defects, as well as exacerbation of chronic diseases, e.g., asthma and chronic obstructive pulmonary disease, were seen as possible (Witter et al., 2013).

3.1.2.5. Infant health and air quality. Infant health is also important to consider in all aspects of environmental health hazards, as UNGD presents multiple stressors that might affect a pregnant woman and the foetus. Two studies examining short-term impacts on infant health were reviewed (Hill, 2012; McKenzie et al., 2014). Maternal and infant outcomes can be separated into short-term and long-term outcomes. Short-term infant outcomes include preterm birth, low birth weight, congenital malformations, respiratory distress syndrome, and sepsis, while long-term outcomes include cerebral palsy, chronic pulmonary disease, and learning disabilities (Misra et al., 2003). While this research did not separate out effects of air pollution and water pollution, Hill (2012) suggested that exposure to shale gas development within at least 2.5 km from a gas well is detrimental to foetal development.

Some studies also discuss the potential for unmeasurable future health effects due to longer latencies, higher body burdens, endocrine disruption, synergistic and/or additive effects of likely exposures, pointing out that children may be more vulnerable to these exposures to the environmental pollutants generated by UNGD and must be considered in planning (Cleary, 2012; Colorado Department of Public Health and Environment, 2010b; Finkel et al., 2013a; Lauver, 2012). A more recent peer-reviewed study found an association with maternal residential proximity to tight gas well sites and prevalence of congenital heart defects, as well as neural tube defects (McKenzie et al., 2014). However, more information is needed to address the spatial and temporal variability and the lack of specificity in the exposure assessment (McKenzie et al., 2014); that is, it was acknowledged that there may have been some exposure misclassification in the study and additional data would be required in future studies to minimise this bias.

3.1.3. UNGD pollutants in soil

The review yielded a limited number of studies on pollutants in soil and/or their effect on soil quality as a result of UNGD activities (Coons and Walker, 2008; Queensland Government, 2013; Witter et al., 2008a,b, 2011). One Australian study reviewed environmental monitoring data and concluded that the soil sample results did not show any evidence of an association between the emissions from CSG operations and the symptoms reported by residents of a nearby community (Queensland Government, 2013).

Soil could become contaminated by spills, leaks, or other incidents. Chemicals used in hydraulic fracturing, as well as drilling sludge, may contaminate soil during operations, storage, transport, and disposal (Zoback et al., 2010). Drilling sludge may also be tilled into the soil in what has been termed 'land farms', a practice that has the potential to contaminate the soil (Finkel et al., 2013a; Witter et al., 2008a,b). The HIA on tight gas conducted by the Colorado School of Public Health (2011) noted that surface soil could be contaminated by spills of fracking fluids, drilling muds, and diesel fuel, while diesel engine exhaust and wind erosion from drill cuttings could also contaminate surface soil through the deposition of particulates.

Pollutants, such as benzene, toluene, other petroleum hydrocarbons, barium, and other metals that may occur in drilling fluids, can be adsorbed in/absorbed to soil, creating a residue that will leach with rain and/or snowmelt. Pollutants in the soil can also be ingested incidentally or purposefully (i.e., pica), inhaled on dusty days, and absorbed through the skin (Coons and Walker, 2008; Witter et al., 2011). The most probable route of exposure to pollutants in soil is through ingestion, and young children are typically at a higher risk than adults due to their hand-to-mouth behaviour (Coons and Walker, 2008). Data on soil and soil quality in relation to UNGD, exposure pathways, and health outcomes are lacking. This is another area where baseline studies to allow for 'before' and 'after' comparisons would be beneficial in order to understand the impact of UNGD on this exposure media.

3.2. Impacts from UNGD infrastructure

Equipment, such as compressors and drilling rigs, the many vehicles used daily to service the development, as well as production operations, create a suite of environmental nuisances, such as light and noise pollution, and hazards such as $PM_{2.5}/PM_{10}$ and traffic-related incidents. Yet studies about nuisance and hazard values, as well as health effects from site and infrastructure developments, were relatively few (Table 2) compared to the numbers of studies about the other typical environmental exposure media such as water and air.

3.2.1. Noise and light

Natural gas development processes are associated with noise pollution and light pollution, which can contribute to stress amongst those living in nearby communities (Down, 2012; Korfmacher et al., 2013; Peduzzi and Harding Rohr Reis, 2013; Witter et al., 2008a,b). Construction, vehicles, drilling, compressors, flaring, and other processing equipment and facilities can all pollute through excessive noise and continuous illumination (Cleary, 2012).

The HIA in Colorado identified noise pollution as an area of concern and noted that it occurs during drilling and completion operations, flaring, and as a result of traffic (Witter et al., 2013). Workers can be exposed to noise through many sources on site, including diesel engines, drilling, generators, mechanical brakes, operation of heavy equipment, and radiator fans (Witter et al., 2014); therefore, hearing impairment is a noise-related health concern for workers on site. The biomonitoring study from Texas found residents reporting concerns about odours and noise apparently related to shale gas well and compressor station operations, although this was a separate, independent component from the biomonitoring portion in order to address residents' concerns (Texas Department of State Health Services, 2010a). While the authors noted that it was difficult to determine if the levels were above acceptable limits that may be harmful to human health and that noise may affect quality of life (Texas Department of State Health Services, 2010a), this is speculative because noise levels were not measured to establish decibels of noise in the study area.

While the mechanics of exposure to noise pollution were not discussed, some studies reported on what would be acceptable noise levels for this industry and where to situate development and extraction activities to maintain an acceptable background level of noise (La Plata County, 2002). However, these authors also noted that while noise standards might be met for one gas operation, the cumulative effects of multiple operations in one area might exceed these established decibel levels. In terms of setback distances, some noise regulations distinguish between maximum decibels for day and night, while others distinguish between maximum decibels for certain phases of the operation such as drilling, fracturing, and production; however, there is often variability and, in some areas, it is suggested that distances are set as monitoring points, not necessarily points indicative of being protective of health (Fry, 2013).

Fewer studies discussed light pollution (ongoing exposure to light after dark) caused by UNGD activities that are conducted on a 24-hour basis. Some studies stated measures that can be taken to reduce light pollution such as directional lighting, glare restrictions, sodium vapour lights, light shields, and modifications to drilling rig placements (New York State Department of Environmental Conservation, 2011; Witter et al., 2011). However, no studies measured exposure to artificial light associated with UNGD nor spoke of the health risk it might pose.

None of the reviewed studies were highly relevant because they did not assess the links between noise and/or light and potential or actual health impacts. Witter and colleagues also found that almost no literature has been published on noise levels and potential health impacts related to UNGD and that no studies have been published on light pollution and impacts on communities near development sites (Witter et al., 2008a). The current review found that no studies have been published on light pollution as a result of UNGD and impacts on communities since the initial review by Witter et al.

Health symptoms related to low frequency noise exposure, which usually comes from continuously running compressors used in the operations, include stress, annoyance, irritation, fatigue, headache, unease, and disturbed sleep (Witter et al., 2008a). An additional concern is that noise, in combination with exposure to VOCs, can cause hearing loss at lower levels of noise exposure than exposure to noise alone (Witter et al., 2008b). The HIA conducted in Colorado noted that noise-related stress and sleep disturbance can probably affect health, while cardiovascular effects as a result of noise pollution are possible (Witter et al., 2011, 2013). In terms of light pollution, recent studies on other industries have suggested links between light pollution and an increased risk of cancer, especially for shift workers who are exposed to nighttime light (Witter et al., 2008a); however, there were no studies specific to communities in proximity of UNGD sites. Both noise and light pollution can contribute to stress in residents living near natural gas operations and have the potential to affect quality of life (Korfmacher et al., 2013).

3.2.2. UNGD related traffic

Traffic may increase in any given area as a result of UNGD, but the magnitude of this increase has not been studied in depth. The phases of development that require the most traffic load involve well pad construction, drilling and well completion, and pipeline construction (Witter et al., 2011). It appears that changes in traffic patterns will be dependent upon the area and the individual project or cumulative effects of multiple projects in an area. Industrial truck traffic can be detrimental to health-related air quality due to vehicle exhaust, as well as pose an increased risk of motor vehicle crashes. However, this section will focus mainly on what has been reported in terms of $PM_{2.5}$, PM_{10}, and/or noise caused by traffic and not on accidents and injuries.

Some shale gas and tight gas studies noted the cumulative impacts of multiple projects in a region because of increases in traffic due to construction, drilling, transport of wastewater, transport associated with hydraulic fracturing, as well as an overlap of development phases on different well pads (New York State Department of Environmental Conservation, 2011; Witter et al., 2011). One impact report focussing on CSG noted expectations of only minor increases in traffic (La Plata County, 2002).

Heavy truck traffic associated with UNGD projects is reported to increase air pollution around well sites (Hill, 2012), creating more particulate matter, higher levels of vehicle exhaust, and extra noise, which would reduce the quality of life for rural residents (Cleary, 2012; Down, 2012; Governor's Marcellus Shale Advisory Commission, 2011; Korfmacher et al., 2013; New York State Department of Environmental Conservation, 2011). For example, in Garfield County, increased levels of measured $PM_{2.5}$ are thought to be caused by tight gas development (Colorado Department of Public Health and Environment, 2009). Therefore, dust suppression measures should be included in traffic control plans (Korfmacher et al., 2013; La Plata County, 2002). The HIA conducted by the Colorado School of Public Health noted that diesel emissions, which are likely to occur from industrial truck traffic on residential roads, may result in increased risk of traffic accidents (probable), as well as health effects of diesel exhaust (possible) (Witter et al., 2013). While some research suggests minimal impact due to traffic and others suggest that traffic may be more of a key factor in development, this will likely depend on several factors, including the pace of development, as well as the number of operators in the area.

3.3. Societal impact

UNGD has the potential to affect people and communities through a variety of ways, including altering stress levels, financial concerns, chronic exposures, and perceived risks/impacts (Ferrar et al., 2013). Many individuals experience rapid change in their environments as UNGD occurs (Steinzor et al., 2013), which can contribute to societal impacts. Three environmental health-related societal impacts were identified in this review: (1) symptomatology (2) risk perception, and (3) governance and regulation.

3.3.1. Symptomatology

Nineteen studies fell under the symptomatology category, with six studies in the ‘highly relevant’ category — three from peer-reviewed literature and three from grey literature. However, one study from the grey literature was then published in the peer-reviewed literature; therefore, there are essentially five ‘highly relevant’ studies that discuss/examine symptomatology. The studies discussing infant health have been discussed in Section 3.1.2.5. Studies that included surveys on symptomatology or investigations of health complaints found that nearby residents (CSG areas in Australia and shale gas areas in USA) feel that their health is being adversely impacted by UNGD activities (Queensland Government, 2013; Steinzor et al., 2012, 2013). Residents reported numerous health symptoms they perceive to be related to UNGD (Bamberger and Oswald, 2012; Queensland Government, 2013; Saberi, 2013; Steinzor et al., 2012, 2013; Subra, 2009, 2010; Texas Department of State Health Services, 2010a). As stated earlier in our review, these include nose, eye, and throat irritation, respiratory symptoms, nausea, nosebleeds, sleep disturbance, rash, headaches, ringing in ears, abdominal pain or cramping, extreme drowsiness, fatigue, and weakness. However, no evidence could be found of direct cause and effect. It has also been suggested that many of these often nonspecific symptoms associated with UNGD could reflect psychosocial stress (Adgate et al., 2014), which could be seen as a health outcome in itself, but is as yet untested in literature.

Steinzor et al. (2012) found that health complaints in the USA showed a pattern — where distances from shale gas facilities increase, the number of respondents reporting health symptoms decrease. For example, throat irritation was noted in 27% of respondents at 1500–4000 ft away from facilities, while 74% of respondents reported throat irritation at less than 500 ft. Another reviewed study also noted that residents in CSG development areas in Queensland, Australia reported reduced symptoms when away from the area and recurrence upon return to the area (Queensland Government, 2013); however, this was not quantified in any manner and relied on anecdotal reports.

Studies in shale gas areas noted resident complaints of frequent odour events, some of which include odours of unidentified gas, rotten eggs, burnt butter, sulfur, sickly sweet smells, chemical-like smells, and propane (Steinzor et al., 2013; Subra, 2009, 2010). The study by Steinzor et al. (2012) noted that 81% of respondents reported noxious odours either sometimes or constantly, while 18% reported odours every day. Steinzor et al. (2012) attempted to link health symptoms to various odours that respondents reported on, such as nosebleeds being linked to kerosene and other petrochemical odours, and propane and skin irritation being linked to chemical odours, chlorine, and sulfur.

In addition to these studies, three studies specifically investigated cancer incidence. Two studies were related to one another. One study was a follow-up to include more recent cancer data and was prompted by community concerns of benzene from shale gas drilling and possible increased cancer diagnoses in the area (Texas Department of State Health Services, 2010b, 2011). The more recent, updated study concluded that childhood leukaemia subtypes, childhood brain/CNS cancer subtypes, all-age leukaemia subtypes, and all-age non-Hodgkin's lymphoma for the study area zip codes were within expected ranges for both genders; however, female breast cancer cases for both zip codes were statistically significantly higher than expected (Texas Department of State Health Services, 2011). Investigators concluded that this is likely explained by the rapid increase in the population and the expected number of cases was also likely underestimated due to basing calculations on the 2000 Census (Texas Department of State Health Services, 2011).

The third study that examined cancer incidence was focussed on childhood cancer incidence and hydraulic fracturing, specifically incidence before and after fracking (Fryzek et al., 2013b). The authors found that total number of cancers observed, as well as cases for childhood leukaemia, was close to expected before drilling began and after drilling, while there was a slightly elevated standardised incidence ratio for CNS tumours after drilling (Fryzek et al., 2013b). The authors ultimately concluded that the study 'offers comfort concerning health effects of HF on childhood cancers', meaning that they concluded communities exposed to hydraulic fracturing are not at increased risk of childhood cancer, childhood leukaemia, and childhood CNS tumours (Fryzek et al., 2013b). However, Goldstein and Malone (2013) have argued that there is no basis for this conclusion and that there are major flaws associated with the study. Additionally, the authors have pointed out that industry's funding of the study muddies the issue and adds to ongoing public controversy (Goldstein and Malone, 2013); however, the authors have addressed Goldstein and Malone's claims in a response (Fryzek et al., 2013a). It should be noted that the study time period (between 1995 and 2009) did not fully capture development of shale gas in the Marcellus. Pennsylvania's Bureau of Oil and Gas Management reported that only 1500 wells had been drilled through 2009 — two years after the start of drilling in the Marcellus Shale (U.S. Department of the Interior, 2009). So, not a significant amount of drilling had occurred during the time period and many of the wells accounted for would not include Marcellus Shale wells.

Many of the reported symptoms are generalised symptoms and studies have not been able to attribute causality, which is often difficult to do; however, some studies found that some residents reported that when they leave their area of residence, their symptoms dissipate (Queensland Government, 2013; Steinzor et al., 2013). Epidemiological studies investigating various types of cancer, including childhood cancer, have not linked UNGD to increased risk of cancer (Fryzek et al., 2013b; Texas Department of State Health Services, 2010b, 2011).

3.3.2. UNGD risk perception

While many residents in areas with prior resource development experiences form their perceptions based on those experiences (Witter et al., 2011), the public also create perceptions based on scientific and regulatory investigations into the potential impacts of UNGD (Perry, 2012). Challenges by companies and the associated trade organisations can then create a feeling of mistrust and appear as conflicting information, making the public uncertain on actual versus perceived impacts (Perry, 2012).

Perception of health risk posed by UNGD is therefore an important issue to consider (Perry, 2012). For many residents, fear of uncertainty surrounding UNGD can also lead to stress, worry, and anxiety (Perry, 2013). Our review shows a clear need for research that compares public perception to actual data, as well as the need for improved risk communication to communities that may be affected.

Nine studies (Table 2) were identified in this review that examined risk perception and health. Only one study was in the 'highly relevant' category, while seven studies were in the 'relevant' category. In one study, some Pennsylvanian parents, when questioned about using bottled water versus tap water, raised strong concerns about chemicals in tap water from Marcellus Shale drilling where fracking has been conducted and the risk of their child developing cancer (Merkel et al., 2011). This fear of the unknown caused great concern for parents, but whether this is actually causing health effects is not yet clear due to latency periods between exposure and effect and lack of empirical research in this area; however, it demonstrates the need for clear risk communication. Another study found that residents living in tight gas development areas perceived that their health was worse than neighbouring counties in the USA, even without the data supporting this perception (Coons and Walker, 2008). Finally, one survey examined two adjacent counties with varying levels of Marcellus Shale drilling activity (Kriesky et al., 2013). It found that perception of drilling as an environmental and public health threat is a significant predictor for the level of support of natural gas drilling; however, this did not differ between the two counties (Kriesky et al., 2013), once again demonstrating the importance of risk perception amongst community residents.

3.3.3. Regulatory aspects

Reviewed literature reporting directly on regulations related to UNGD and health is limited and the geographic scope of studies sourced for this review is limited. Most of the peer-reviewed literature focussed on specific aspects of regulation, such as shale gas development in the European Union and deregulatory trends in the United States (Kotsakis, 2012), state-level actions, such as New York and Vermont banning hydraulic fracturing until potential public health and environmental impacts are studied (Eaton, 2013; Weinhold, 2012), and concerns from the medical community about regulations that are currently in place (Marks, 2014; McDermott-Levy et al., 2013; Saberi, 2013; Thompson, 2012; Weinberger et al., 2012). Other aspects of regulation brought up in the peer-reviewed literature included the importance of political leaders supporting occupational health and safety research (Witter et al., 2014) and the U.S. EPA hydraulic fracturing study and current regulatory and institutional barriers such as the EPA's lack of regulation over private drinking water wells (Perry, 2012). The grey literature mostly focussed on policy recommendations (Cleary, 2012; Governor's Marcellus Shale Advisory Commission, 2011; Jackson et al., 2011), risk identification and public health implications (AEA Technology, 2012; Down, 2012; Kibble et al., 2013; Zoback et al., 2010) and aspects of regulation, whether general or related to specific projects (New York State Department of Environmental Conservation, 2011; U.S. Department of Energy, 2009; United States Government Accountability Office, 2012).

Environmental impact assessments (EIAs) are an important part of the planning process in order to determine environmental effects of the proposed project and to mitigate adverse effects; however, it was noted that, while projects could result in health impacts, oftentimes EIAs do not involve health experts and health is defined to a limited scope or ignored (Wernham, 2011). Determinants of health often include environmental and/or social factors, so it is beneficial to integrate health impact assessments into other impact assessments (World Health Organization, 2010). We did not review studies that appeared outside of the results using the methods described previously. Therefore, one supplemental environmental impact statement was reviewed (New York State) and we were not able to take EIAs, which may or may not integrate HIA, from other geographic regions into account.

However, some themes emerged from the government and regulatory-related literature that was reviewed. For one, public health professionals need to be sufficiently represented in government commissions and agencies (Goldstein, 2014; Korfmacher et al., 2013; Perry, 2012) and inter-agency cooperation (Kotsakis, 2012; Mitka, 2012). There is a need for increased transparency and public participation, calling for an open, public process that includes communities and relies on local knowledge while incorporating technical and scientific data (Jenner and Lamadrid, 2013; Perry, 2012). Additionally, stronger regulation should be considered to improve monitoring efforts, to ensure industry best practices, and strengthen the currently fragmented framework (Centner, 2013; Centner and O'Connell, 2014; Jackson et al., 2011; Jenner and Lamadrid, 2013; Kotsakis, 2012; Peduzzi and Harding Rohr Reis, 2013; Wang et al., 2014). While many public comments reflect a concern about public health, of 52 members on three different advisory boards related to UNGD decision making, no members had health, health care, or public health education and expertise (Goldstein et al., 2012). It will be difficult to increase research on environmental health as a priority for UNGD when the major groups involved may not have any understanding of the potential health impacts.

Several papers have emphasised the use of precaution and call for baseline and prospective epidemiological studies, which are currently lacking (de Melo-Martín et al., 2014; Finkel and Hays, 2013; Finkel and Law, 2011; Howarth and Ingraffea, 2011; Korfmacher et al., 2013; Mitka, 2012; Thompson, 2012). Most of these recommendations were made in the context of the United States and its current regulatory system, but can likely be applied elsewhere, especially the call for sufficient representation of public health professionals in government work, increased public participation, and baseline and prospective health studies.

4. Future studies and recommendations

While current unpublished work is not the focus of this review, it is worth mentioning ongoing epidemiological studies. There is a large-scale study currently underway, which investigates potential health impacts of shale gas development and possible exposures in Pennsylvania. Geisinger Health, a major healthcare provider in the Marcellus Shale region, plans on using electronic health records, direct data collection, and collection of samples (Geisinger Health System, 2013). The project has two main phases. The first phase is short-term (3–5 years) and will identify data sources, data gaps, and trends, as well as conduct pilot studies focussing on outcomes with shorter latency periods such as asthma and perinatal outcomes (Geisinger Health System, 2013). Subsequent phases will involve ongoing data collection and will utilise longitudinal data; however, it was noted that it may require decades of research in order to examine the possible longer term health effects (Geisinger Health System, 2013).

Additionally, we recommend the following for future studies to improve our understanding of potential health impacts. Firstly, direct and clear public health assessments should be included in EIAs that are required before approval of a gas development project. This will allow for other baseline studies to be conducted from where 'before' and 'after' comparative Environmental Health Impact Assessments were conducted. This should include data on infrastructure development, environmental carrier media, and health status. Such impact assessments should be programmes that include longitudinal studies, such as the current study by Geisinger Health, in order to track potential environmental health impacts. This will provide data for assessing short- and long-term impacts. This will also allow for comparing situations with and within UNGD areas. For example, comparisons of UNGD areas with and without hydraulic fracturing, UNGD areas with areas devoid of such development, or UNGD areas with other areas of high environmental activity, e.g., coal mining areas or dense urban developments. Electronic health records should be linked to environmental data in each area to assess exposure for residents living in those areas. Additionally, a biomonitoring programme could be included to have data on individual exposures where health and environmental records cannot plausibly be linked. Finally, healthcare professionals, including pharmacists, in UNGD areas can be a rich source of health impact data and should be considered in an impact assessment programme.

5. Conclusion

This paper presented a review of the available scientific evidence on environmental health impacts of UNGD, specifically shale gas, tight gas, and CSG. While some environmental health research has been conducted with regard to UNGD, it is clear that there is a lack of highly relevant evidence of direct health outcomes caused by the activities of UNGD. However, it should be noted that absence of evidence does not mean evidence of absence. The literature reviewed in this paper, as well as a persistent and substantial public response, continues to suggest concern.

The research reported here is dominated by traditional environmental health issues such as health-related impacts from air and water quality. There are still many unknowns such as vector-borne disease, the hazard potential of environmental pollutants, soil quality, noise and light pollution, traffic, and risk perception. More research is also needed into the impacts that these risk factors and exposures might have on human health outcomes. The research is also dominated by studies on short-term impacts, with some risk assessments on long-term impacts or discussions alluding to long-term impacts. This may be due to the rapid pace of development in recent years; however, it is imperative that longitudinal studies are put in place so that potential long-term impacts, or lack thereof, can be assessed.

With interest in researching UNGD and health rapidly increasing, it is inevitable that more studies will be published in the near future in peer-reviewed literature and in publically accessible media. While we attempted to do this review as exhaustively and comprehensively as possible, it is recognised that this review will have had shortcomings in terms of our search strategy, which may not have identified all relevant, and perhaps available, literature. Additionally, there may be more data in domains that cannot be searched so, regrettably, data from these sources were not included here. It is imperative for government and industry bodies to make the process as transparent and open as possible so that data can be accessed, which can help to add more studies to the 'highly relevant' category.

When considering UNGD on a more global scale, the majority of the reviewed research comes from the USA, with some also from Australia, and limited research being reported in the English-language databases from outside these two countries where UNGD is ongoing, e.g., Europe. The majority of research reviewed here focusses on shale gas, with some research on tight gas and even less research on CSG. This may be due to differences in the length and pace of development in various regions, as well as differences in emission profiles for the various types of gas. There can be little doubt that as many additional countries develop their natural gas resources, the hydrogeology and other environmental settings will vary from one area to another. Therefore, it is important that similar research is conducted in other regions to determine if environmental health hazards and impacts are similar, or if there are additional environmental health concerns that should be considered.

In reviewing available studies for strength of evidence, there are very few, if any, methodologically rigorous studies that have examined the potential cause-and-effect of UNGD in the construct of hazard analyses, linked to exposure pathways and the actual health outcomes. In fact, our review shows that most of the peer-reviewed research was 'not very relevant' in this context. Most of the 'highly relevant' studies cannot be described as scientifically rigorous, due to methodological limitations, such as measurement and selection bias, as well as potential confounding.

Overall, our review identified that adverse health impacts were most often alluded to only in the context of UNGD or perhaps attributed to these activities as a principle of precaution. Regarding the grey literature, most of the studies were in the 'relevant' to 'not very relevant' categories, with the majority of the reports considered 'relevant'.

Overall, there was very limited systematically gathered, scientific evidence of health effects directly caused by UNGD activity. Notably, this review identified only seven studies as 'highly relevant', demonstrating the lack of research on *direct* health impacts associated with UNGD. More importantly, while evidence of the environmental cause of adverse health impact was lacking, several scholars and experts voiced concerns about the potential for adverse health outcomes. These concerns were based on credible evidence of detrimental environmental impact and strongly suggest that the lack of evidence of health impact does not dismiss claims of health impact. The available evidence, or lack thereof, is not sufficient cause to rule in or rule out significant or specific, future, or cumulative health impacts of UNGD activities.

It is probable that the lack of evidence on direct causal links between environmental hazards and health outcomes is a result of the rapid expansion of this industry in a short period of time — leaving evidence-based research activities with very little time to respond. Additionally, there is the potential for environmental health outcomes with longer latencies for which effects may not yet be seen.

While some authors are adamant about the potential health harm, it remains difficult to credibly assess the extent of the risk posed to the public, and implications for government agencies and the resource companies, while this gap in scientific knowledge remains. Future work needs to be focussed on research that includes baseline monitoring and prospective studies to summarise, diagnose, and predict what environmental health impacts of UNGD might be.

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References

Adams R, Kelsey TW. Pennsylvania dairy farms and Marcellus Shale, 2007–2010. Penn State Cooperative Extension, College of Agricultural Sciences; 2012 [Available at: http://pubs.cas.psu.edu/freepubs/pdfs/ee0020.pdf].

Adgate JL, Goldstein BD, McKenzie LM. Potential public health hazards, exposures and health effects from unconventional natural gas development. Environ Sci Technol 2014;48:8307–20.

Ahern M, Mullett M, MacKay K, Hamilton C. Residence in coal-mining areas and low-birth weight outcomes. Matern Child Health J 2011;15:974–9.

Bamberger M, Oswald R. Impacts of gas drilling on human and animal health. New Solut 2012;22:51–77.

Barnett Shale Energy Education Council (BSEEC). Ambient air quality study — natural gas sites cities of Fort Worth & Arlington, Texas. Prepared by TITAN Engineering, Inc.; 2010 [Available at: http://www.barnettshalenews.com/documents/ntxairstudy/Barnett%20Shale%20Ambient%20Air%20Quality%20Study%20Titan%20Engr%20BSEEC%20July%202010r.pdf].

Bell ML, Dominici F. Effect modification by community characteristics on the short-term effects of ozone exposure and mortality in 98 US communities. Am J Epidemiol 2008;167:986–97.

Bell M, McDermott A, Zeger S, Samet J, Dominici F. Ozone and short-term mortality in 95 US urban communities, 1987–2000. J Am Med Assoc 2004;292:2372–8.

Broni-Bediako E, Amorin R. Effects of drilling fluid exposure to oil and gas workers presented with major areas of exposure and exposure indicators. Res J Appl Sci, Eng Technol 2010;2:710–9.

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;468–469:832–42.

Canadian Association of Petroleum Producers. Conventional & unconventional. Accessed December 18, 2013 at: http://www.capp.ca/CANADAINDUSTRY/NATURALGAS/CONVENTIONAL-UNCONVENTIONAL/Pages/default.aspx, 2012.

Centner TJ. Oversight of shale gas production in the United States and the disclosure of toxic substances. Resour Policy 2013;38:233–40.

Centner TJ, O'Connell LK. Unfinished business in the regulation of shale gas production in the United States. Sci Total Environ 2014;476–477:359–67.

Chalupka S. Occupational silica exposure in hydraulic fracturing. Work Health Saf 2012;60:460.

City of Fort Worth. City of Fort Worth natural gas air quality study final report. Prepared by Eastern Research Group and Sage Environmental; 2011 [Available at: http://fortworthtexas.gov/uploadedFiles/Gas_Wells/AirQualityStudy_final.pdf].

Cleary E. Chief Medical Officer of Health's recommendations concerning shale gas development in New Brunswick. New Brunswick Department of Health; 2012 [Available at: http://www2.gnb.ca/content/dam/gnb/Departments/h-s/pdf/en/HealthyEnvironments/Recommendations_ShaleGasDevelopment.pdf].

Colborn T, Kwiatkowski C, Schultz K, Bachran M. Natural gas operations from a public health perspective. Hum Ecol Risk Assess 2011;17:1039–56.

Colborn T, Schultz K, Herrick L, Kwiatkowski C. An exploratory study of air quality near natural gas operations. Hum Ecol Risk Assess 2014;20:86–105.

Colorado Department of Public Health and Environment. Garfield County air toxics inhalation: screening level human health risk assessment — inhalation of volatile organic compounds measured in rural, urban, and oil & gas areas in air monitoring study (June 2005–May 2007). Environmental Epidemiology Division; 2007 [Available at: http://www.garfield-county.com/public-health/documents/Working%20Draft%20CDPHE%20Screeing%20Level%20Risk%20Air%20Toxics%20Assessment%2012%2020%2007.pdf].

Colorado Department of Public Health and Environment. Garfield County emissions inventory. Air Pollution Control Division; 2009 [Available at: http://www.garfield-county.com/air-quality/documents/airquality/Garfield_County_Emissions_Inventory-2009.pdf].

Colorado Department of Public Health and Environment. Garfield County air toxics inhalation: screening level human health risk assessment — inhalation of volatile organic compounds measured in 2008 air quality monitoring study. Environmental Epidemiology Division; 2010a [Available at: http://www.garfield-county.com/public-health/documents/6%2030%2010%20%20RisK%20Assessment%20for%20Garfield%20County%20based%20on%202008%20air%20monitoring.pdf].

Colorado Department of Public Health and Environment. Public health implications of ambient air exposures as measured in rural and urban oil & gas development areas — an analysis of 2008 air sampling data. Available at: http://www.atsdr.cdc.gov/HAC/pha/GarfieldCountyColorado2010/GarfieldCountyColoradoHC08262010.pdf, 2010.

Colorado Department of Public Health and Environment. Air emissions case study related to oil and gas development in Erie, Colorado. Air Pollution Control Division, Technical Services Program; 2012 [Available at: http://www.colorado.gov/airquality/tech_doc_repository.aspx?action=open&file=Erie_Air_Emissions_Case_Study_2012.pdf].

Cook P, Beck V, Brereton D, Clark R, Fisher B, Kentish S, et al. Engineering energy: unconventional gas production. Report for the Australian Council of Learned Academies; 2013. [Available at: www.acola.org.au].

Coons T, Walker R. Community health risk analysis of oil and gas industry impacts in Garfield County. Available at: http://www.garfield-county.com/public-health/documents/1._COMMUNITY_HEALTH_RISK_ANALYSIS-(Complete_Report_16MB).pdf, 2008.

Coram A, Moss J, Blashki G. Harms unknown: health uncertainties cast doubt on the role of unconventional gas in Australia's energy future. Med J Aust 2014;4:210–3.

Coussens C, Martinez RM, Roundtable on Environmental Health Sciences, Research, and Medicine, The Board on Population Health and Public Health Practice, and the Institute of Medicine. Health impact assessment of shale gas extraction: workshop summary. Washington, DC: The National Academies Press; 2013.

CSIRO. Hydraulic fracturing in coal seams. Accessed September 26, 2014 at: http://www.csiro.au/~/media/CSIROau/Outcomes/Energy/Unconventional-gas/fact-sheets/1400589CSIRO2HydraulicFracturingWEB140819.pdf, 2014.

de Melo-Martín I, Hays J, Finkel ML. The role of ethics in shale gas policies. Sci Total Environ 2014;470–471:1114–9.

Devlin RB, Duncan KE, Jardim M, Schmitt MT, Rappold AG, Diaz-Sanchez D. Controlled exposure of healthy young volunteers to ozone causes cardiovascular effects. Circulation 2012;126:104–11.

Down A. Shale gas extraction in North Carolina: public health implications. Durham, NC: Research Triangle Environmental Health Collaborative; 2012.

Down A, Armes M, Jackson R. Shale gas extraction in North Carolina: research recommendations and public health implications. Environ Health Perspect 2013;121:A292–3.

Eaton TT. Science-based decision-making on complex issues: Marcellus shale gas hydrofracking and New York City water supply. Sci Total Environ 2013;461–462:158–69.

Ebi KL, McGregor G. Climate change, tropospheric ozone and particulate matter, and health impacts. Environ Health Perspect 2008;116:1449–55.
Eltschlager K, Hawkins J, Ehler W, Baldassare F. Technical measures for the investigation and mitigation of fugitive methane hazards in areas of coal mining. Office of Surface Mining Reclamation and Enforcement; 2001 [Available at: http://arblast.osmre.gov/downloads/Mine%20Gases%20and%20Dust/FINAL-Methane.pdf.].
Engelder T. Natural gas: should fracking stop? Counterpoint: no, it's too valuable. Nature 2011;477:271–5.
Esswein EJ, Breitenstein M, Snawder J, Kiefer M, Sieber WK. Occupational exposures to respirable crystalline silica during hydraulic fracturing. J Occup Environ Hyg 2013;10:347–56.
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;19:104–12.
Finkel ML, Hays J. The implications of unconventional drilling for natural gas: a global public health concern. Public Health 2013;127:889–93.
Finkel ML, Law A. The rush to drill for natural gas: a public health cautionary tale. Am J Public Health 2011;101:784–5.
Finkel ML, Hays J, Law A. Modern natural gas development and harm to health: the need for proactive public health policies. ISRN Public Health 2013a;2013:5.
Finkel ML, Selegean J, Hays J, Kondamudi N. Marcellus Shale drilling's impact on the dairy industry in Pennsylvania: a descriptive report. New Solut 2013b;23:189–201.
Fontenot BE, Hunt LR, Hildenbrand ZL, Carlton Jr DD, 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;47:10032–40.
Freij-Ayoub R. Opportunities and challenges to coal bed methane production in Australia. J Petrol Sci Eng 2012;88–89:1–4.
Fry M. Urban gas drilling and distance ordinances in the Texas Barnett Shale. Energ Policy 2013;62:79–89.
Fryzek J, Garabrant D, Pastula S, Jiang X. Response to Goldstein et al. J Occup Environ Med 2013a;55:1378.
Fryzek J, Pastula S, Jiang X, Garabrant D. Childhood cancer incidence in Pennsylvania counties in relation to living in counties with hydraulic fracturing sites. J Occup Environ Med 2013b;55:796–801.
Geisinger Health System. Geisinger research connections. Available at: http://www.geisinger.org/research/cx/73809-1-ResearchCnxWinter2013WEB.pdf, Winter 2013.
Goldstein B. The Importance of public health agency independence: Marcellus Shale gas drilling in Pennsylvania. Am J Public Health 2014;104:e13–5.
Goldstein B, Malone S. Obfuscation does not provide comfort: response to the article by Fryzek et al on hydraulic fracturing and childhood cancer. J Occup Environ Med 2013;55:1376–8.
Goldstein B, Kriesky J, Pavliakova B. Missing from the table: role of the environmental public health community in governmental advisory commissions related to Marcellus Shale drilling. Environ Health Perspect 2012;120:483–6.
Gordalla B, Ewers U, Frimmel F. Hydraulic fracturing: a toxicological threat for groundwater and drinking-water? Environ Earth Sci 2013;70:3875–93.
Governor's Marcellus Shale Advisory Commission. Governor's Marcellus Shale Advisory Commission report. Pennsylvania Department of Environmental Protection; 2011 [Available at: http://files.dep.state.pa.us/publicparticipation/marcellusshaleadvisorycommission/marcellusshaleadvisoryportalfiles/msac_final_report.pdf].
Guidotti TL. Shale gas comes into its own: at a cost. Arch Environ Occup Health 2011;66:1–2.
Hill E. Unconventional natural gas development and infant health: evidence from Pennsylvania — working paper. Cornell University, Charles H. Dyson School of Applied Economics and Management; 2012 [Available at: http://dyson.cornell.edu/research/researchpdf/wp/2012/Cornell-Dyson-wp1212.pdf].
Howarth R, Ingraffea A. Natural gas: should fracking stop? Point: yes, it's too high risk. Nature 2011;477:271–5.
Jackson RB, Rainey Pearson B, Osborn SG, Warner NR, Vengosh A. Research and policy recommendations for hydraulic fracturing and shale-gas extraction. Durham, NC: Center on Global Change, Duke University; 2011.
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;110:11250–5.
Jenner S, Lamadrid AJ. Shale gas vs. coal: policy implications from environmental impact comparisons of shale gas, conventional gas, and coal on air, water, and land in the United States. Energ Policy 2013;53:442–53.
Kaktins N. Drilling the Marcellus Shale for natural gas: environmental health issues for nursing. Pa Nurse 2011;66:4–9.
Kargbo DM, Wilhelm RG, Campbell DJ. Natural gas plays in the Marcellus Shale: challenges and potential opportunities. Environ Sci Technol 2010;44:5679–84.
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;155:897–907.
Kemball-Cook S, Bar-Ilan A, Grant J, Parker L, Jung J, Santamaria W, et al. Ozone impacts of natural gas development in the Haynesville Shale. Environ Sci Technol 2010;44:9357–63.
Kibble A, Cabianca T, Daraktchieva Z, Gooding T, Smithard J, Kowalczyk G, et al. Review of the potential public health impacts of exposure to chemical and radioactive pollutants as a result of shale gas extraction: draft for comment. Public Health England; 2013 [http://www.hpa.org.uk/webc/HPAwebFile/HPAweb_C/1317140158707].
Korfmacher KS, Jones WA, Malone SL, Vinci LF. Public health and high volume hydraulic fracturing. New Solut 2013;1:13–31.
Kotsakis A. The regulation of the technical, environmental and health aspects of current exploratory shale gas extraction in the United Kingdom: initial lessons for the future of European Union energy policy. Rev Eur Community Int Environ Law 2012;21:282–90.
Kovats S, Depledge M, Haines A, Fleming LE, Wilkinson P, Shonkoff SB, et al. The health implications of fracking. Lancet 2014;383:757–8.
Kriesky J, Goldstein BD, Zell K, Beach S. Differing opinions about natural gas drilling in two adjacent counties with different levels of drilling activity. Energ Policy 2013;58:228–36.
La Plata County. La Plata County impact report. Available at: http://www.co.laplata.co.us/departments_elected_officials/planning/natural_resources_oil_gas/impact_report, 2002.
Laney AS, Weissman DN. The classic pneumoconioses. Clin Chest Med 2012;33:745–58.
Lauver L. Environmental health advocacy: an overview of natural gas drilling in Northeast Pennsylvania and implications for pediatric nursing. J Pediatr Nurs 2012;27:383–9.
Law A, Hays J, Shonkoff SB, Finkel ML. Public Health England's draft report on shale gas extraction. BMJ 2014;348.
Lechtenböhmer S, Altmann M, Capito S, Matra Z, Weindrorf W, Zittel W. Impacts of shale gas and shale oil extraction on the environment and on human health. Committee on Environment Public Health and Food Safety; 2011 [Available at: http://www.europarl.europa.eu/document/activities/cont/201107/20110715ATT24183/20110715ATT24183EN.pdf].
Litovitz A, Curtright A, Abramzon S, Burger N, Samaras C. Estimation of regional air-quality damages from Marcellus Shale natural gas extraction in Pennsylvania. Environ Res Lett 2013;8:1–8.
Mackie P, Johnman C, Sim F. Hydraulic fracturing: a new public health problem 138 years in the making? Public Health 2013;127:887–8.
Marks JH. Silencing Marcellus: when the law fractures public health. Hastings Cent Rep 2014;44:8–10.
Maule A, Makey C, Benson E, Burrows I, Scammell M. Disclosure of hydraulic fracturing fluid chemical additives: analysis of regulations. New Solut 2013;23:167–87.
McDermott-Levy R, Kaktins N. Preserving health in the Marcellus region. Pa Nurse 2012;67:4–12.
McDermott-Levy R, Kaktins N, Sattler B. Fracking, the environment, and health. Am J Nurs 2013;113:45–51.
McGlade C, Speirs J, Sorrell S. Unconventional gas — a review of regional and global resource estimates. Energy 2013;55:571–84.
McKenzie L, Witter R, Newman L, Adgate J. Human health risk assessment of air emissions from development of unconventional natural gas resources. Sci Total Environ 2012;424:79–87.
McKenzie L, Guo R, Witter R, Savitz D, Newman L, Adgate J. Birth outcomes and maternal residential proximity to natural gas development in rural Colorado. Environ Health Perspect 2014;122:412–7.
Merkel L, Bicking C, Sekhar D. Parents' perceptions of water safety and quality. J Community Health 2011;37:1–7.
Minnesota Department of Health. Methane in well water. Accessed August 16, 2014 at: http://www.health.state.mn.us/divs/eh/wells/waterquality/methane.html, 2013.
Misra DP, Guyer B, Allston A. Integrated perinatal health framework: a multiple determinants model with a life span approach. Am J Prev Med 2003;25:65–75.
Mitka M. Rigorous evidence slim for determining health risks from natural gas fracking. J Am Med Assoc 2012;307:2135–6.
National Institute for Occupational Safety and Health. Worker exposure to silica during hydraulic fracturing hazard alert. Accessed October 5, 2014 at: https://www.osha.gov/dts/hazardalerts/hydraulic_frac_hazard_alert.pdf, 2012.
National Institutes of Health. Tox Town. Methane. Accessed August 16, 2014 at: http://toxtown.nlm.nih.gov/text_version/chemicals.php?id=92, 2014.
New York State Department of Environmental Conservation. Revised draft supplemental generic environmental impact statement on the oil, gas and solution mining regulatory program: well permit issuance for horizontal drilling and high-volume hydraulic fracturing to develop the Marcellus Shale and other low-permeability gas reservoirs. New York State. Available at: http://www.dec.ny.gov/energy/75370.html, 2011.
Norris D. Mosquito-borne diseases as a consequence of land use change. Ecohealth 2004;1:19–24.
Ohio Department of Natural Resources Division of Mineral Resources Management. Report on the investigation of the natural gas invasion of aquifers in Bainbridge Township of Geauga County, Ohio; 2008.
Olaguer EP. The potential near-source ozone impacts of upstream oil and gas industry emissions. J Air Waste Manag Assoc 2012;62:966–77.
Orem W, Tatu C, Lerch H, Rice C, Bartos T, Bates A, et al. Organic compounds in produced waters from coalbed natural gas wells in the Powder River Basin, Wyoming, USA. Appl Geochem 2007;22:2240–56.
Osborn S, Vengosh A, Warner N, Jackson R. Methane contamination of drinking water accompanying gas-well drilling and hydraulic fracturing. Proc Natl Acad Sci U S A 2011;108:8172–6.
Ovuakporaye SI, Aloamaka CP, Ojieh AE, Ejebe DE, Mordi JC. Effect of gas flaring on lung function among residents in gas flaring community in Delta State, Nigeria. Res J Environ Earth Sci 2012;4:525–8.
Papoulias DM, Velasco AL. Histopathological analysis of fish from Acorn Fork Creek, Kentucky, exposed to hydraulic fracturing fluid releases. Southeast Nat 2013;12:92–111.
Peduzzi P, Harding Rohr Reis R. Gas fracking: can we safely squeeze the rocks? Environ Dev 2013;6:86–99.
Pennsylvania Department of Environmental Protection. Southwestern Pennsylvania Marcellus shale short-term ambient air sampling report. Bureau of Air Quality; 2010 [Available at: http://www.dep.state.pa.us/dep/deputate/airwaste/aq/aqm/docs/Marcellus_SW_11-01-10.pdf].

Pennsylvania Department of Environmental Protection. Northeastern Pennsylvania Marcellus shale short-term ambient air sampling report. Bureau of Air Quality; 2011 [Available at: http://www.dep.state.pa.us/dep/deputate/airwaste/aq/aqm/docs/Marcellus_NE_01-12-11.pdf].

Pennsylvania Department of Environmental Protection. Oil and gas compliance report. Accessed August 13, 2012 at: http://www.portal.state.pa.us/portal/server.pt/community/oil_and_gas_compliance_report/20299, 2012.

Perry S. Environmental reviews and case studies: addressing the societal costs of unconventional oil and gas exploration and production: a framework for evaluating short-term, future, and cumulative risks and uncertainties of hydrofracking. Environ Pract 2012;14:352–65.

Perry S. Using ethnography to monitor the community health implications of onshore unconventional oil and gas developments: examples from Pennsylvania's Marcellus Shale. New Solut 2013;23:33–53.

Queensland Government. Coal seam gas in the Tara region: summary risk assessment of health complaints and environmental monitoring data. Department of Health; 2013.

Rafferty MA, Limonik E. Is shale gas drilling an energy solution or public health crisis? Public Health Nurs 2013;1–9.

Railroad Commission of Texas. NORM (naturally occurring radioactive material). Accessed October 6, 2014 at: http://www.rrc.state.tx.us/oil-gas/applications-and-permits/environmental-permit-types-information/norm/, 2014.

Republican Policy Committee House. Testimony of J. Scott Roberts, Deputy Secretary for Mineral Resources Management. Available at: http://www.pagoppolicy.com/Display/SiteFiles/112/Hearings/5_20_10/5_20_10_Roberts_Testimony.pdf, 2010.

Ross C, Darby P. Unconventional gas: coal seam gas, shale gas and tight gas. Department of Parliamentary Services; 2013 [Available at: http://www.parliament.vic.gov.au/publications/research-papers/8927-unconventional-gas-coal-seam-gas-shale-gas-and-tight-gas/download].

Rutovitz J, Harris S, Kuruppu N, Dunstan C. Drilling down. Coal seam gas: a background paper. Prepared for the City of Sydney Council by Institute for Sustainable Futures University of Technology Sydney; 2011.

Saberi P. Navigating medical issues in shale territory. New Solut 2013;23:209–21.

Schmidt C. Blind rush? Shale gas boom proceeds amid human health questions. Environ Health Perspect 2011;119:A348–53.

Searl A, Galea K. Toxicological review of the possible effects associated with inhalation and dermal exposure to drilling fluid production streams. Inst Med 2011:87.

Steinzor N, Subra W, Sumi L. Gas patch roulette: how shale gas development risks public health in Pennsylvania. Earthworks; 2012.

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;23:55–83.

Subra W. Results of health survey of current and former DISH/Clark, Texas residents. Earthworks; 2009.

Subra W. Community health survey results, Pavillion, Wyoming residents. Earthworks; 2010.

Tager I, Balmes J, Lurmann F, Ngo L, Alcorn S, Künzli N. Chronic exposure to ambient ozone and lung function in young adults. Epidemiology 2005;16:751–9.

A.E.A. Technology. Support to the identification of potential risks for the environment and human health arising from hydrocarbons operations involving hydraulic fracturing in Europe; 2012 [United Kingdom].

Texas Department of State Health Services. Final report DISH, Texas exposure investigation Dish, Denton County, Texas. Available at: www.dshs.state.tx.us/epitox/consults/dish_ei_2010.pdf, 2010.

Texas Department of State Health Services. Summary of investigation into the occurrence of cancer zip codes 75022 and 75028, Flower Mound, Denton County, Texas 1998–2007, 2007–2009. Available at: https://www.dshs.state.tx.us/epitox/consults/flower_mound32010.doc, 2010.

Texas Department of State Health Services. Updated summary report of Texas Department of State Health Services investigation of specific cancer occurrences within zip codes 75022 an 75028, Flower Mound, Denton County, Texas covering 1999–2008, 2008–2010. Available at: http://tx-flowermound.civicplus.com/DocumentCenter/Home/View/465, 2011.

Thompson H. Fracking boom spurs environmental audit. Nature 2012;485:556–7.

Tillett T. Summit discusses public health implications of fracking. Environ Health Perspect 2013;121:A15.

Torjesen I. Fracking poses little risk to public health, but evidence is limited. BMJ 2013;347.

Triche E, Gent J, Holford T, Belanger K, Bracken M, Beckett W, et al. Low-level ozone exposure and respiratory symptoms in infants. Environ Health Perspect 2006;114:911–6.

U.S. Department of Energy. Modern shale gas development in the United States: a primer. Office of Fossil Energy and National Energy Technology Laboratory; 2009 [Available at: http://www.netl.doe.gov/technologies/oil-gas/publications/EPreports/Shale_Gas_Primer_2009.pdf].

U.S. Department of Energy. U.S. Department of Energy. Accessed September, 26, 2014 at: http://energy.gov/sites/prod/files/2013/04/f0/how_is_shale_gas_produced.pdf, 2013.

U.S. Department of the Interior. Development of the natural gas resources in the Marcellus Shale. National Park Service; 2009. Available at: http://www.marcellus.psu.edu/resources/PDFs/Marcellus_Shale_Report_11-30-2009.pdf.

U.S. Energy Information Administration. Technically recoverable shale oil and shale gas resources: an assessment of 137 shale formations in 41 countries outside the United States. Available at: http://www.eia.gov/analysis/studies/worldshalegas/pdf/fullreport.pdf, 2013.

United States Government Accountability Office. Unconventional oil and gas development: key environmental and public health requirements. Available at: http://gao.gov/products/GAO-12-874, 2012.

Vidic R, Brantley S, Vandenbossche J, Yoxtheimer D, Abad J. Impact of shale gas development on regional water quality. Science 2013;340:826–35.

Walther E. Screening health risk assessment Sublette County, Wyoming. Pinedale, WY: Sierra Research, Inc.; 2011.

Wang Q, Chen X, Jha AN, Rogers H. Natural gas from shale formation — the evolution, evidences and challenges of shale gas revolution in United States. Renew Sust Energy Rev 2014;30:1–28.

Weinberger SE, Lawrence HC, Henley DE, Alden ER, Hoyt DB. Legislative interference with the patient–physician relationship. N Engl J Med 2012;367:1557–9.

Weinhold B. The future of fracking: new rules target air emissions for cleaner natural gas production. Environ Health Perspect 2012;120:A272–9.

Weltman-Fahs M, Taylor JM. Hydraulic fracturing and brook trout habitat in the Marcellus Shale region: potential impacts and research needs. Fisheries 2013;38:4–15.

Wernham A. Health impact assessments are needed in decision making about environmental and land-use policy. J Epidemiol Community Health 2011;65:947–56.

Williams J, Stubbs T, Milligan A. An analysis of coal seam gas production and natural resource management in Australia. A report prepared for the Australian Council of Environmental Deans and Directors. Canberra, Australia: John Williams Scientific Services Pty Ltd; 2012.

Witter R, Stinson K, Sackett H, Putter S, Kinney G, Teitelbaum D, et al. Potential exposure-related human health effects of oil and gas development: a literature review (2003–2008). Denver, CO: Colorado School of Public Health; 2008a.

Witter R, Stinson K, Sackett H, Putter S, Kinney G, Teitelbaum D, et al. Potential exposure-related human health effects of oil and gas development: a white paper. Denver, CO: Colorado School of Public Health; 2008b.

Witter RZ, McKenzie LM, Towle M, Stinson K, Scott K, Newman L, et al. Health impact assessment for Battlement Mesa, Garfield County Colorado. Colorado School of Public Health; 2011 [Available at: http://www.garfield-county.com/environmental-health/battlement-mesa-health-impact-assessment-draft2.aspx].

Witter R, McKenzie L, Stinson K, Scott K, Newman L, Adgate J. The use of health impact assessment for a community undergoing natural gas development. Am J Public Health 2013;103:1002–10.

Witter RZ, Tenney L, Clark S, Newman LS. Occupational exposures in the oil and gas extraction industry: state of the science and research recommendations. Am J Ind Med 2014;57:847–56.

Wolf Eagle Environmental. Town of DISH, Texas ambient air monitoring analysis final report; 2009.

World Health Organization. Managing the public health impacts of natural resource extraction activities: a framework for national and local health authorities — discussion draft. World Health Organization; 2010.

World Health Organization. Health topics: environmental health. Accessed January 3, 2013 at: http://www.who.int/topics/environmental_health/en/, 2012.

Zielinska B, Fujita E, Campbell D. Monitoring of emissions from Barnett Shale natural gas production facilities for population exposure assessment. Houston: Desert Research Institute; 2011.

Zoback M, Kitasei S, Copithorne B. Addressing the environmental risks from shale gas development: briefing paper 1. Worldwatch Institute; 2010.

Zou L, Miller S, Schmidtmann E. Mosquito larval habitat mapping using remote sensing and GIS: implications of coalbed methane development and West Nile Virus. J Med Entomol 2006;43:1034–41.