Environ Geochem Health (2018) 40:1–57
https://doi.org/10.1007/s10653-016-9898-x

REVIEW PAPER

A review of the public health impacts of unconventional natural gas development

P. J. Saunders · D. McCoy · R. Goldstein · A. T. Saunders · A. Munroe

Received: 22 August 2016 / Accepted: 13 November 2016 / Published online: 5 December 2016

Abstract The public health impact of hydraulic fracturing remains a high profile and controversial issue. While there has been a recent surge of published papers, it remains an under-researched area despite being possibly the most substantive change in energy production since the advent of the fossil fuel economy. We review the evidence of effects in five public health domains with a particular focus on the UK: exposure, health, socio-economic, climate change and seismicity. While the latter would seem not to be of significance for the UK, we conclude that serious gaps in our understanding of the other potential impacts persist together with some concerning signals in the literature and legitimate uncertainties derived from first principles. There is a fundamental requirement for high-quality epidemiological research incorporating real exposure measures, improved understanding of methane leakage throughout the process, and a rigorous analysis of the UK social and economic impacts. In the absence of such intelligence, we consider it prudent to incentivise further research and delay any proposed developments in the UK. Recognising the political realities of the planning and permitting process, we make a series of recommendations to protect public health in the event of hydraulic fracturing being approved in the UK.

Keywords Hydraulic fracturing · Fracking · Shale gas · Public health

Introduction

Unconventional natural gas development utilising the hydraulic fracturing of shale formations to extract natural gas (commonly known as 'fracking') continues to command a high public, political and media profile, especially in the light of recent planning decisions in the UK and elsewhere. It remains a controversial process with proponents arguing that it will safely provide cheap, secure and clean energy, local employment and economic development while opponents are sceptical about such claims and remain concerned about potential health, environmental, social and economic damage associated with the development, operation and decommissioning of sites and

P. J. Saunders (✉)
University of Staffordshire, Stoke-on-Trent, UK
e-mail: carolan57@icloud.com

D. McCoy
Queen Mary University of London, London, UK

R. Goldstein
West Midlands Public Health Training Scheme, Birmingham, UK

A. T. Saunders
carolan57 Ltd, Birmingham, UK

A. Munroe
Medact, London, UK

infrastructures. While these issues have been under-researched, and remain so, there has been a surge of peer-reviewed papers and reviews published in recent years with over 80% of the peer-reviewed scientific literature on shale and tight gas development published since 1 January 2013 and over 60% since 1 January 2014 (Hays and Shonkoff 2016). A number of detailed 'grey literature' reviews have also been published recently (Task Force on Shale Gas 2015; McCoy and Saunders 2015; Lightowlers 2015; Public Health England 2014; New York State Department of Health 2014; Maryland Institute for Applied Environmental Health School of Public Health 2014; The Royal Society and The Royal Academy of Engineering 2012; AEA Technology 2012), but there is considerable variability in the aspects of public health addressed. This paper attempts to capture, review and interpret the published literature across all the accepted domains of public health in a systematic way and consider specific implications for the UK. This review is comprehensive rather than exhaustive given the rapidly developing literature and challenges in capturing all public health dimensions.

The unconventional natural gas development process

There are several terms and colloquialisms used to describe this process and its various stages in both the media and scientific literature with some being used interchangeably (a glossary of abbreviations and acronyms used in this review is given in Appendix 1). This can cause confusion and the term 'fracking' has evolved into a generic description of the whole process rather than simply a contraction of 'hydraulic fracturing', a specific well stimulation technique. This is important in assessing public health effects, as there are concerns across the entire unconventional natural gas process and not simply the well stimulation element. Consequently, this review uses the term unconventional natural gas development (UNGD). This refers to natural gas produced from atypical reservoirs such as shale or coal seams and other low permeability formations requiring different techniques from those used for conventional formations which enable exploitation through natural pressure and pumping operations. Most natural gas is extracted from these 'conventional' deposits in porous rock such as sandstone. The significant amounts of gas in 'unconventional' deposits have become commercially accessible with the development of new technologies and techniques including high-volume hydraulic fracturing (HVHF), directional drilling, chemical engineering processes and intensive clustering of wells. HVHF wells can be drilled vertically for hundreds of metres and then horizontally for up to around 3 km. Small detonations and explosions are used to break up and fracture the rock and the injection of large volumes of pressurised fracturing fluid (a mix of water, particulates and a variety of other chemicals) deep underground to create or reopen cracks or fissures in the shale formation to release the trapped gas. While hydraulic fracturing has been used since the 1940s (Moore et al. 2014), the scale, coverage and intensity of the contemporary industry are of different magnitudes to that of the past. The consolidation of several wells on one well pad and the refracturing of wells to maintain gas flows establish an intense and prolonged level of industrial activity (Adgate et al. 2014). While there is no such thing as a standard UNGD site and each development will vary in terms of capacity, intensity and potential impact, an average fracking episode can inject 2–8 million gallons of fracturing fluid and each well can be hydraulically fractured multiple times during its operational life (New York State Department of Environmental Conservation 2011).

The development, functioning, decommissioning and remediation of UNGD sites are major engineering, logistical and construction projects involving the transport, use, extraction, distribution, storage and disposal of huge quantities of materials and waste, often 24 h a day for several years. The industry is long established and most intensive in the USA, and consequently, most of the published literature is from the US experience. There are major differences in the geology, size, population density and energy economies of the USA and the UK. The process, if approved in the UK, will also be managed and regulated differently. It is important to recognise, for example, that the UK commitment to ensure that UNGD operations will be sited close to mains water supply and the gas distribution network will considerably reduce the number of truck movements compared to the USA. However, many of the fundamentals of UNGD and its consequences will be similar, or broadly so, to those in other developed nations. It is important that administrations considering introducing or expanding UNGD are informed by the experiences of the most mature, intensive and significant industry.

Review methods

Public health is by its nature a broad concept open to different interpretations and understanding. The UK's Faculty of Public Health (FPH) defines it as 'the science and art of promoting and protecting health and well-being, preventing ill health and prolonging life through the organised efforts of society'. The FPH has further developed this definition by identifying three key domains of health protection, health improvement and service improvement (The UK's Faculty of Public Health 2016). There are also powerful proximal and distal interdependencies between the public health hazards, exposures and potential outcomes associated with UNGD at both temporal and spatial levels. The search terms used in this review and its structure reflect these issues and include conventionally accepted public health metrics and outcomes but also the effects of UNGD on economic activity, social cohesion, geology, and energy policy and security.

An initial scoping search and assessment of recent reviews together with the advice of key researchers, scientists and practitioners in public and environmental health were used to frame detailed search terms. The search strategy is based on five categories of potential impacts of UNGD, viz. exposure, health, socio-economic effects and public health nuisance, climate change, and seismicity.

The following databases were searched through January 2016: Ovid Medline, Economic and Social Research Council, Centre for Economic Policy Research, Physicians, Scientists, and Engineers for Healthy Energy (PSE Healthy Energy) Database on Shale and Tight Gas Development (the most comprehensive UNGD citation database) and Scopus. Appendix 2 gives details of the search strategies and inclusion/exclusion criteria. The grey literature, following advice from recognised experts in the field, was assessed including domestic and international government and key institutional websites. Searches were run independently by two reviewers who assessed titles and abstracts for relevance, and full copies were obtained for inclusion or further assessment. Reference lists were examined, forwards and backwards, for papers not identified in searches. Reviewers independently applied pre-defined inclusion/exclusion criteria, and unresolved disagreements were referred to the lead author for consideration. Full copies of included papers were randomly allocated to five reviewers, and key details and data recorded in extraction tables. Two reviewers independently assessed a random sample of 10% of papers.

Results

Initial agreement at the screening of titles and abstracts was 93 and 100% following discussion. An initial agreement at the full paper screening stage of 95% increased to 100% following discussion of differences. A summary of the five most common reasons for rejection is given in Table 1.

Figure 1 summarises the results of the search strategies and application of inclusion/exclusion criteria. A total of 156 peer-reviewed papers and reviews have been included: 70 relating to exposure, 34 to climate change, 23 to health, 19 to economic and/or social, and 7 to seismic (nine papers are discussed in two sections and one in three sections), and 14 relevant reviews covering two or more domains were also identified. Appendix 3 provides the included/excluded papers ($n = 175$) and reasons for exclusion. A list of the papers identified and included as meeting the inclusion criteria for each section together with their reported relationship with UNGD is given in Tables 2, 3, 4, 5, 6 and 7. Additional background papers are also used where required for clarity in the text.

Table 1 Summary of five most common reasons for rejection of papers

Reason for rejection	Number
Not UNGD or doesn't identify UNGD component	43
Not peer-reviewed	19
Methodological/experimental	13
Inadequate economic analysis	12
Hypothetical case studies	11

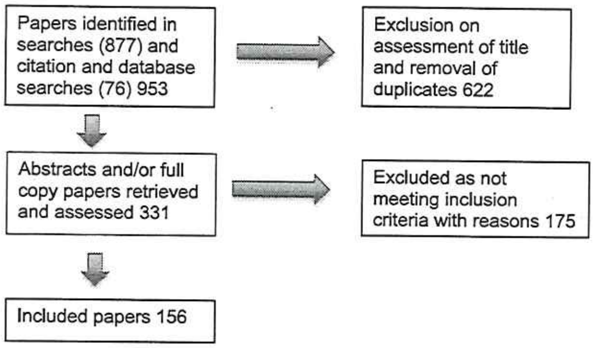

Fig. 1 Review flowchart

Discussion

Exposure pathways

In common with any complex industrial process, UNGD produces a range of chemical hazards (Adgate et al. 2014). While it is important to understand the toxic potential of the chemicals used and produced by the process, it is critical to understand the exposure potential. Without a plausible exposure pathway, these chemicals, no matter how toxic, will remain a *hazard* as opposed to presenting a *risk*. The former requires monitoring, the latter an intervention to prevent exposure or reduce it to a safe level. In addition, the magnitude of any health impact will be influenced by a range of factors including the rate of release of the chemicals, their fate and transport, persistence, human behaviour and the frequency and duration of human exposure (Adgate et al. 2014). A review of the toxicity of 352 chemicals used in US natural gas operations including UNGD found that 25% were potentially mutagenic or carcinogenic (Colborn et al. 2011). In addition, over 75% had the potential to cause effects on the skin, eyes, respiratory and gastrointestinal (GI) systems; 40–50% on the nervous, immune, cardiovascular and renal systems; and 37% on endocrine system. Inevitably, this is not a comprehensive review. Information on the full composition of the products used in the USA is limited, partly by commercial confidentiality, and some of the chemicals disclosed have not been subjected to a full toxicological assessment. A systematic evaluation of the potential reproductive and developmental toxicity of over 1000 chemicals identified in fracturing fluids and/or wastewater found that data were available for only 24% of these chemicals, 65% of which suggested potential toxicity (Elliott et al. 2016). An earlier literature review also concluded that chemicals used and produced in unconventional oil and gas operations were known developmental and reproductive toxins (Webb et al. 2014). A study for the German Federal Environment Agency considered that the lack of data on the composition of fluids used together with the chemical and toxicological properties of additives prevented a comprehensive risk assessment (Bergmann et al. 2014). This study found that critical data were either not openly accessible, not yet evaluated, or didn't exist; a gap which requires additional studies and research although it concluded that the process presented plausible exposure hazards. An analysis of fracturing fluids from almost 3000 wells over 4 years identified 347 constituents that could be identified by a Chemical Abstract Service Registration Number (Wattenberg et al. 2015). The paper assessed chronic and acute health hazards associated with those with 25 reports of use. Approximately one-third of the most hazardous were also in the top 30 most commonly used constituents including naphthalene and benzyl chloride. An assessment of the human toxicity potential of UK shale gas production for electricity generation has estimated it to be 3–4 times worse than that of conventional gas, although an order of magnitude better than nuclear, solar or coal power (Stamford and Azapagic 2014).

There is clear evidence of chemical releases from the UNGD process to the most important environmental media in this context, air and water. Jackson et al. (2014) and Shonkoff et al. (2014), for example, have identified the risk of toxic releases to water and air, especially if the process is not managed effectively. These exposure pathways will become more important if UNGD is introduced to new regions and populations or is extended in those regions where already established. It has been noted, for example, that the rapid increase in the technology's development in the USA has brought wells and related infrastructure closer to population centres (Adgate et al. 2014). These impacts can be proximal, e.g. quality of life (Lampe and Stolz 2015), local releases of pollutants such as diesel exhaust, oxides of nitrogen (NOx), particulate matter (PM) (Moore et al. 2014) and silica from transport and site equipment (Esswein

Table 2 Exposure papers

Paper	Reported impact/ association	Paper	Reported impact/ association	Paper	Reported impact/ association
Ahmadi and John (2015)	Yes	Jackson et al. (2013a, b)	Yes	Thompson et al. (2014)	Yes
Alawattegama et al. (2015)	Yes	Jackson et al. (2013a, b)	Yes	Vengosh et al. (2014)	Potential
Bergmann et al. (2014)	Uncertain	Jenner and Lamadrid (2013)	Potential	Vidic et al. (2013)	Potential
Bunch et al. (2014)	No	Kassotis et al. (2014)	Yes	Wattenberg et al. (2015)	Yes—potential
Casey et al. (2015)	Yes	Kemball-Cook et al. (2010)	Yes	Warner et al. (2012)	Yes
Chalupka (2012)	Yes	Kohl et al. (2014)	No	Warner et al. (2013a)	Potential
Colborn et al. (2011)	Potential	Li and Carlson (2014)	No	Warner et al. (2013b)	No
Colborn et al. (2014)	Yes	Litovitz et al. (2013)	Yes	Webb et al. (2014)	Potential
Darrah et al. (2014)	Yes	Llewellyn et al. (2015)	Yes	Zavala-Araiza et al. (2014)	Potential
Davies et al. (2014)	Yes	Macey et al. (2014)	Yes	Zhang et al. (2015)	Potential
Drollette et al. (2015)	Potential	Moore et al. (2014)	Potential	Zielinska et al. (2014)	Yes
Eapi et al. (2014)	Yes	Molofsky et al. (2013)	No	Ziemkiewicz et al. (2014)	Potential
Elliott et al. (2016)	Potential	Myers (2012)	Potential		
Engelder et al. (2014)	No	Nelson et al. (2015)	No		
Esswein et al. (2013)	Yes	Olmstead et al. (2013)	Yes		
Esswein et al. (2014)	Yes	Osborn et al. (2011)	Yes		
Ethridge et al. (2015)	No	Paulik et al. (2015)	Yes		
Ferrar et al. (2013a)	Yes	Pelak and Sharma (2014)	No		
Field et al. (2015)	Yes	Rahm and Riha (2014)	Potential		
Flewelling and Sharma (2014)	No	Rahm et al. (2015)	Potential		
Flewelling et al. (2013)	No	Reilly et al. (2015)	No		
Fontenot et al. (2013)	Yes	Rich et al. (2014)	Yes		
Gilman et al. (2013)	Yes	Roy et al. (2014)	Potential		
Goetz et al. (2015)	Potential	Rozell and Reaven (2012)	Potential		
Gross et al. (2013)	Yes	Sharma et al. (2015)	No		
Heilweil et al. (2015)	Yes	Siegel et al. (2015, 49)	No		
Hildenbrand et al. (2015)	Potential	Stamford and Azapagic (2014)	Uncertain		
Hladik et al. (2014)	Yes	Swarthout et al. (2013)	Yes		
Ingraffea et al. (2014)	Yes	Swarthout et al. (2015)	Yes		

Table 3 General reviews (peer-reviewed)

Paper	Reported association
Adgate et al. (2014)	Potential (hazards, exposures and health effects)
Allen (2014)	Uncertain (climate change, air pollution)
Beaver (2014)	More research required (environment and health, seismicity, healthcare infrastructure)
Eaton (2013)	Uncertain (environmental, ecological, climate change, economic and regulation)
Finkel and Hays (2013)	Potential (exposure, health, climate change)
Finkel et al. (2015)	Yes (health, exposure, climate change, social justice and seismicity)
Hays and Shonkoff (2016)	Yes (environmental, public health, climate change, economic and seismicity)
Jackson et al. (2014)	Neutral if well managed (economic/social, exposure and climate change)
Lampe and Stolz (2015)	Potential if not effectively regulated (exposure, health, regulation and quality of life)
Mash et al. (2014)	Potential (exposure, health and regulation)
Moore et al. (2014)	Yes (climate change, exposure)
Shonkoff et al. (2014)	Potential (environmental public health)
Sovacool (2014)	Uncertain (economic/social, seismic, climate change)
Werner et al. (2015)	Potential (health, exposure, regulation and societal)

Table 4 Health papers

Paper	Reported adverse association
Bamberger and Oswald (2012)	Yes
Bamberger and Oswald (2015)	Uncertain
Bloomdahl et al. (2014)	No
Bunch et al. (2014)	No
Casey et al. (2016)	Yes
Esswein et al. (2013)	Yes
Esswein et al. (2014)	Yes
Ethridge et al. (2015)	No
Ferrar et al. (2013b)	Yes
Fryzek et al. (2013)	No
Jemielita et al. (2015)	Yes
McKenzie et al. (2012)	Yes
McKenzie et al. (2014)	Yes
Paulik et al. (2015)	Yes
Rabinowitz et al. (2015)	Yes
Rosenman (2014)	Yes
Saberi et al. (2014)	Yes
Stacy et al. (2015)	Yes
Stamford and Azapagic (2014)	Better than coal/renewables, worse than conventional gas
Steinzor et al. (2013)	Yes
Swarthout et al. (2015)	No
Witter et al. (2013)	Yes
Zhang et al. (2015)	No

et al. 2013; Chalupka 2012), and the release of fracturing fluids and wastes through spills, leaks or accidents (Rahm and Riha 2014; Ingraffea et al. 2014; Davies et al. 2014; Ziemkiewicz et al. 2014; Jackson et al. 2013b). In the latter context, it is worth noting that anywhere between 9 and 80% of the contaminated fracking fluid (most estimates around 35%) could resurface following a fracking episode (Shonkoff et al. 2014). It is also accepted that some of the formations now accessible to unconventional drilling activities contain significant concentrations of Naturally Occurring Radioactive Materials (NORM) and therefore there is potential for their contamination of environmental media. Regional issues include water quality (Adgate et al. 2014), volatile organic compounds (VOCs), PM, NOx (Allen 2014) and ground-level ozone (Moore et al. 2014). Indeed, UNGD's photochemical oxidant formation potential has been estimated to be about nine times higher for UK shale gas compared to North Sea gas when used for electricity generation and 60% worse than coal power; the worst of the other technologies considered (Stamford and Azapagic 2014).

However, despite the potential for environmental and human exposures, any risks associated with UNGD also need to be considered against the environmental health benefits such as substitution of the gas produced for more polluting and water-intensive fuel stocks such as coal. This is discussed further in the climate change section.

Table 5 Economic/social papers

Paper	Reported negative impact
Abramzon et al. (2014)	Yes
Aguilera et al. (2014)	No
Barth (2013)	Uncertain
Bernstein et al. (2013)	Residents willing to pay $10.50 a month to protect watersheds
Finkel et al. (2013)	Yes
Haefele and Morton (2009)	Yes
Jones et al. (2014a)	Potential
Jones et al. (2014b)	Potential
Kinnaman (2011)	Benefits exaggerated
Lave and Lutz (2014)	Largely negative
Muehlenbachs et al. (2015)	Negative for property values with groundwater supply
Munasib and Rickman (2015)	Some positive effects offset by local negative impacts
Paredes et al. (2015)	Negligible local benefit
Popkin et al. (2013)	Yes
Throupe et al. (2013)	Yes
Weber et al. (2014)	Mostly negative although some positive reports
Weber (2012)	No
Witter et al. (2013)	Yes
Wrenn et al. (2015)	No

Air

A mobile laboratory was used to assess air samples from specifically targeted sites associated with shale gas extraction and distribution as well as during transit through areas of high UNGD activity in NE and SW Pennsylvania (Goetz et al. 2015). This included over 50 compressor stations and over 4200 wells. Samples were taken during August and September 2012 and analysed for a range of gas-phase species and PM. While submicrometre particle mass results were reported as not being elevated, the analyses did not monitor for particle numbers, considered a more important metric in relation to some health impacts (Seaton et al. 1995). While methanol was detected at one compressor station, levels of light aromatic compounds such as benzene or toluene were unremarkable. The latter result is to be expected given that the Marcellus play does not contain oil deposits. The authors recognise that this is a small sample and the results are not generalisable.

Current understanding of local and regional air quality impacts of the five stages of the natural gas life cycle, viz. pre-production; production; transmission, storage and distribution; end use; and well production end-of-life, was considered by Moore et al. (2014). This review identified clear potential for exposure to hazardous air pollutants (HAPs) from the use of large diesel powered equipment, truck traffic, diesel and gas powered engines for drilling rigs and pumps, volatilisation of components of fracturing fluid including flowback fluids, proppant injection, and venting and flaring. Chemicals include PM, NO_x, methane (covered in more detail in the climate change section) and non-methane volatile organic compounds, respirable silica, hydrogen sulphide (H_2S), sulphur dioxide (SO_2) and formaldehyde although the authors recognise the potential for reduced emissions of carbon dioxide (CO_2), SO_2, NO_x and mercury if natural gas replaced the use of coal or oil. The paper also recognises the lack of monitoring data stating that 'A full classification of all emissions during drilling and hydraulic fracturing does not to our knowledge exist'. They were concerned about the reliance of regulators on generic emission inventories which are based on limited, incomplete and outdated data to assess the air quality impacts of natural gas systems. The lack of data and intelligence on chemicals used and produced was noted, and the paper calls for more research, monitoring, source apportionment and the establishment of an inventory of abandoned wells.

Table 6 Climate change papers

Paper	Reported adverse climate change effects
Allen et al. (2013)	Uncertain
Brandt et al. (2014)	No
Burnham et al. (2012)	Uncertain
Caulton et al. (2014)	Yes
Dale et al. (2013)	Yes—insufficient to meet CC goals
Goetz et al. (2015)	Yes—in exposure as well
Heath et al. (2014)	Uncertain
Howarth et al. (2011)	Yes
Howarth (2014)	Yes
Hultman et al. (2011)	Potential
Jacoby and O'Sullivan (2012)	Uncertain
Jiang et al. (2011)	Potential
Jenner and Lamadrid (2013)	No
Lan et al. (2015)	Yes
Laurenzi and Jersey (2013)	Yes—positive
McLeod et al. (2014)	Potential
McJeon et al. (2014)	Does not change GHG trajectory
Newell and Raimi (2014)	Uncertain
Omara et al. (2016)	Potential
O'Sullivan and Paltsev (2012)	No
Peischl et al. (2015)	Potential
Pétron et al. (2014)	Potential
Schneising et al. (2014)	Yes
Schrag (2012)	Potentially no
Shahriar et al. (2014)	Lower impact than reported elsewhere
Stamford and Azapagic (2014)	Uncertain
Stephenson et al. (2011)	Potential
Tyner and Johnson (2014)	Uncertain
Vinciguerra et al. (2015)	Yes—negative
Wang et al. (2011)	No
Weber and Clavin (2012)	Uncertain
Weyant et al. (2016)	No
Zavala-Araiza et al. (2015a)	Potential
Zavala-Araiza et al. (2015b)	Uncertain

A number of studies, some of which have used source apportionment, have found hazardous airborne levels of VOCs, including polycyclic aromatic hydrocarbons (PAHs), in the vicinity of UNGD sites. The regional impact of UNGD on VOCs was assessed using air samples from across an 8050 km^2 region surrounding Pittsburgh and data from a mobile laboratory deployed at two sites, one with nearly 300 unconventional natural gas wells within 10 km and a remote location with a single well within 10 km (Swarthout et al. 2015). The VOC emissions from UNGD operations suggested that natural gas emissions could compromise meeting federal ozone standards, particularly in urban areas.

The Texas Commission on Environmental Quality (TCEQ) has undertaken extensive monitoring of airborne VOCs and a human health risk assessment in the Barnett Shale region (Ethridge et al. 2015). TCEQ developed an extensive inventory of emission sources including information on location, type and

Table 7 Seismicity papers

Paper	Reported association
Baisch (2013) (a peer-reviewed conference proceeding included as direct relevance to UK)	Negligible
Davies et al. (2013)	Negligible
Holland (2013)	Plausible
Kim (2013)	Plausible
van der Elst et al. (2013)	Modest plausibility
Wang et al. (2016)	Plausible
Westaway and Younger (2014)	Negligible

number of emission sources; equipment and activities conducted; releases to air; and proximity of receptors. A helicopter-mounted passive infrared camera was used to identify unreported VOC emission sources. A range of monitoring techniques was used to estimate long- and short-term exposures in areas with and without UNGD during 2009 and 2010 including mobile sampling teams and fixed VOC monitors. While several short-term samples exceeded odour-based air monitoring comparison values (AMCVs) and levels above typical background downwind of UNGD were detected, only three exceeded health-based AMCVs. Short-term sampling found elevated levels of VOCs, most notably benzene, being emitted from a small percentage of those facilities. All long-term VOC levels were below long-term health-based AMCVs. Data from the TCEQ monitoring network for the period 2000–2011 were also reviewed to identify whether UNGD activities were increasing community exposures to VOCs in the Barnett Shale region (Bunch et al. 2014). Comparison with health-based standards found no exceedences of any acute standards although one exceedence of the chronic standard was identified. The latter was not considered to be associated with UNGD activities. The study, supported by an industry representative Energy Education Council, concluded that shale gas production activities had not led to VOC exposures of public health concern. The analyses also suggest that VOC levels in general had not increased over time and in some cases had decreased.

Levels of 62 PAHs at 23 residential properties in Carroll County, Ohio, between 0.04 and 3.2 miles of an active well pad in early 2014 were assessed using passive air samplers (Paulik et al. 2015). Sampling sites excluded other sources of PAHs such as urban areas and proximity to airports, and samplers were deployed as far as possible from obvious potentially confounding sources for 3–4 weeks. Levels of total PAHs were an order of magnitude higher than results previously published for rural areas. Stratifying results by distance from active pad zones into 'close' (<0.1 mile from an active well), 'middle' (0.1–1.0 mile) and 'far' (>1.0 mile) found a clear pattern of increasing PAH levels with proximity to well pads. Using benzo[a]pyrene and phenanthrene as representative PAHs associated with cancer and respiratory outcomes found a similar pattern albeit weaker for the latter.

A local impact on levels of methane and H_2S was identified in an analysis of samples taken from around the perimeter of UNGD sites (Eapi et al. 2014). The study involved measuring levels at the perimeter fences of almost 4800 sites in four counties of the Barnett Shale Forth Worth Basin, an area which had experienced an enormous expansion of the industry from 726 wells to nearly 16,000 in the decade following 2001. Two sets of drive-by measurements were taken (the researchers did not have access to the sites), and the study defined 'high' levels as >3 ppm for methane and >4.7 ppb (the odour threshold) for H_2S. Elevated levels of methane and/or H_2S were found at 21% of sites (high methane levels at 16.5% of sites and high H_2S at 8% of sites). While mean methane concentrations at dry (where the produced gas is overwhelmingly methane) sites were significantly higher than those at wet sites (where produced gas is comprised of methane and other volatiles such as ethane and butane), no relationship with the size of the site or production volume was found. The authors recognise the importance of distinguishing the specific source of the methane and sampling from the site itself to improve accuracy and inform a definitive conclusion. Researchers from the Texas Center for Energy and Environmental Resources assessed hourly concentrations of 46 non-methane VOCs from three sites representative of locations in, on the periphery of, and an urban site more distant from, the Barnett Shale (Zavala-Araiza et al. 2014). These data were compared to predicted levels from a dispersion model and an emissions inventory. The dominance of light alkanes in the measured data including ethane, propane and *n*-butane reflected the composition of natural gas production emissions. There was modest temporal variability in emissions from natural gas largely due to meteorology rather than process-related sources such as well unloadings. Predicted concentrations were up to 40% lower than measured values.

Another assessment of the concentrations of airborne volatile compounds around UNGD sites subject of local concern used both community questionnaires and grab and passive air samples taken by trained members of those communities across five US states (Macey et al. 2014). Residents used an assessment of local conditions to determine the sites of 35 grab samples supplemented by 41 formaldehyde badges at production facilities and compressor stations. 46% of the former and 34% of the latter exceeded Agency for Toxic Substances and Disease Registry (ATSDR) and/or Environmental Protection Agency (EPA) Integrated Risk Information System (IRIS) standards. High concentrations of benzene, formaldehyde, hexane and H_2S were identified. In two states benzene levels exceeded standards, in some cases, by several orders of magnitude. Samples from three states exceeded the standard for formaldehyde and, in one state, for H_2S. Using the experience of local communities to determine sampling sites certainly has merit, but this study is limited by the small number of samples taken.

UNGD is increasingly being conducted in more urban areas in the USA increasing the populations potentially exposed to air emissions from the process. A collaboration between public health and engineering academics addressed four issues in an exploratory study in six counties of the Dallas/Fort Worth areas: the identity and concentration of chemicals in ambient air samples in residential areas near shale gas wells; whether methane-associated chemicals are the primary products of the process; the relationship between the chemicals present in residential ambient air samples near gas wells; and whether emission signatures are associated with the different phases and operations of the UNGD process (Rich et al. 2014). Ambient air samples were collected using 24-h passive samplers at 39 locations in residential areas within 61 m of a UNGD site from 2008 to 2010. Approximately 20% of the 101 chemicals identified are designated as HAPs by the EPA including 1,3-butadiene, tetrachloroethane and benzene with the latter being identified at 76% of sites. Virtually, all the analyses detected methane with levels in most areas much higher than urban background concentrations and the mean level six times higher. Principal component analysis, a technique to identify how much individual factors account for the variability in a data set, suggested the use of compressors at sample sites as being the dominant source of many of the chemicals, although it is not possible to entirely eliminate other potential contributing sources. Further studies using larger sample sizes and including shorter duration sampling periods are required to confirm these findings and refine source apportionment. A larger study of the impact of shale gas production on population exposure to air pollutants in the Barnett Shale region used a combination of active well VOC emission characterisation and apportionment, pollutant monitoring in a local residential community, and measurement of the pollutant gradient downwind of a gas well (Zielinska et al. 2014). The residential community was located in an area of high well density and comprised 250–300 occupied houses adjacent to, and screened from, a compressor station. There are also numerous production wells in the surrounding area. Monitoring included NOx, NO_2, SO_2, C5–C9 hydrocarbons, carbon disulphide (CS_2) and carbonyl compounds, $PM_{2.5}$ and PAHs. Several samples from wellhead condensate tank venting emissions were used to establish a source profile of a major source of VOC emissions in the study area. Average VOC and $PM_{2.5}$ concentrations in the residential area were generally low, below the National Ambient Air Quality Standard, uniformly distributed, and levels fell to near background at 100 m from the condensate tank. However, source apportionment suggested that gas production was significantly contributing to regional VOCs, an impact considered to be potentially associated with increased UNGD-related diesel vehicle movements.

In one of the few studies examining air quality before, during and after the development and operation of a hydraulically fractured gas well pad, levels of VOCs and carbonyls were measured using a monitoring station 1.1 km from the site in Western Colorado over the course of a year (Colborn et al. 2014). Of the range of VOCs monitored, four were detected in every sample: methane, ethane, propane and toluene. The highest average levels were for methane, methylene chloride, ethane, methanol, ethanol, acetone and propane. The carbonyls formaldehyde and acetaldehyde were also detected in every sample. Very low levels of chemicals associated with urban traffic emissions as opposed to gas operations such as ethane were found. There was considerable temporal variability in the number and concentrations of chemicals detected although both metrics for non-methane hydrocarbons (NMHCs) were highest during the initial drilling phase prior to fracturing. These results are noteworthy despite the limitations of a single site study with no comparison to air quality standards as it does present before and after data as advocated by several papers (Moore et al. 2014; Adgate et al. 2014; Nelson et al. 2015; Stamford and Azapagic 2014; Jackson et al. 2014).

A small-scale assessment of ambient NMHC levels in Erie Colorado, an area of rapid HVHF expansion in close proximity to residences and situated in a region designated as a federal ozone non-attainment zone, was conducted March–June 2013 (Thompson et al. 2014). Thirty whole air samples were collected March–June 2013 including sites proximate to seven residences near gas wells (the closest within 105 and 424 m), and two areas for comparison, rural farmland and a town on the edge of the Wattenberg Gas Field. A number of other data sources were accessed for comparison including the Boulder County Air Toxics Study, the Colorado Department of Public Health and Environment, the National Oceanic and Atmospheric Administration, and the Boulder County Air Toxics Study. Samples from residential areas close to wells showed mean mole fractions of the C2–C5 alkanes 18–77 higher than the regional background and above levels typically reported in large urban centres. Elevated levels were also reported for the region with the highest from the Greater Wattenberg Gas Field. The authors also expressed concern that some benzene analyses were within the chronic health effect range although benzene, toluene, ethylbezene and xylene (BTEX) compounds were generally comparable to, or lower then, large urban areas. The authors also note that, despite the introduction of tighter emission standards in 2008, ambient levels of NMHC seemed to have increased although they recognise that the data are not necessarily directly comparable. An earlier larger study of VOC levels in NE Colorado used the outputs of the Boulder Atmospheric Observatory during the winter of 2011 (Swarthout et al. (2013) and reported C2–C5 alkane mixing ratios an order of magnitude higher than regional background. The mixing ratios, meteorology and vertical profiling implicated natural gas production activities as the source of the elevated VOCs to the north-east of the observatory.

The Center for Atmospheric Particle Studies developed emission inventory for a region within the Marcellus Shale was used to estimate emissions of NOx, VOCs and $PM_{2.5}$ in Pennsylvania, New York and West Virginia for 2009 and 2020 (Roy et al. 2014). Monte Carlo modelling was used to address uncertainty. The analysis suggested Marcellus development will be an important source of regional NOx and VOCs contributing 12% (6–18%) of emissions in the region in 2020. This level of release was considered large enough to offset projected emissions reductions in other sectors, and NOx emissions would challenge ozone management in rural areas. While the Marcellus Shale was not predicted to contribute significantly to regional $PM_{2.5}$ emissions, it could account for 14% (2–36%) of elemental carbon. Modelling also identified the potential for stricter controls to significantly reduce the NOx contribution.

A RAND Corporation supported study of levels of VOC, NOx, PM_{10}, $PM_{2.5}$ and SO_2 emissions and the cost of the environmental and health damages associated with shale gas extraction in Pennsylvania found that, while emissions were a small proportion of the statewide total, NOx emissions were up to 40 times higher in areas with concentrated shale gas activities than permitted for a single minor source (Litovitz et al. 2013). The estimated environmental and health costs for 2011 ranged from \$7.2 to \$32 million with over 50% due to compressor stations. The authors emphasise that a substantial proportion of these damages cannot be specifically attributed to shale gas development and are less than those estimated for any of the state's large coal power plants. However, despite the uncertainties associated with the estimates, they consider the pollution emissions to be non-trivial and the scale of the industry to be the most important factor.

VOC concentrations measured at an atmospheric research facility located in the Colorado Wattenberg field were compared with the composition of the raw natural gas and ambient levels monitored in two other NE Colorado sites (Gilman et al. 2013). Oil and natural gas-related VOCs were identified at all three sites and were considered to represent a significant source of ozone precursors.

While the impact of a single UNGD site on ozone levels is likely to be negligible, the cumulative effect of many thousands of sites could be significant. The long-term relationship between shale gas development and ozone pollution in the Dallas/Fort Worth region of Texas was conducted through a comprehensive analysis of historical ozone data and a meteorologically adjusted ozone time series (Ahmadi and John 2015). Shale gas extraction had been confined to the Western half of the region, and this geological boundary enabled a comparative assessment with an adjacent non-shale gas region. In addition, regional air quality had been extensively monitored for over 30 years providing an exceptionally comprehensive and extensive data set. Sixteen Continuous Ambient Monitoring Stations provided a time series of 8-h average ozone concentrations. As the number of wells had significantly increased from 2007, the analysis considered trends during the periods 2000–2006 and from 2007 to 2013. This showed that ozone exceedences in the non-shale gas region decreased compared to the shale gas region. This difference was especially noteworthy during the high ozone season when the maximum reduction rate in exceedences in the non-shale gas region was c. 31% more than the shale gas area. The average long-term component of meteorologically adjusted ozone was 2% higher in the shale gas area from 2008, and the mean short-term meteorologically adjusted ozone was almost 10% higher.

Unexpectedly high ozone mixing ratios were identified in 2005 in the Upper Green River Basin region of Wyoming. These elevated wintertime episodes subsequently reoccurred and were linked to emissions from oil and natural gas sources. This prompted additional air quality network and meteorological monitoring to better identify the source of these events (Field et al. 2015). This study reported numerous localised ozone episodes during the winter of 2011 whereas none were identified in 2012, a period of significantly lower ambient total NMHCs. Characterisation of the NMHCs revealed a dominance of compounds associated with fugitive emissions of natural gas and condensate. The impact on ozone levels was also studied in response to the increase in UNGD in the Haynesville shale and the potential release of precursors from the process (Kemball-Cook et al. 2010). In the absence of basic peer-reviewed data, the best available production and activity data were accessed and crosschecked. Sources included state agencies, but the authors were unable to obtain data from any of the producers. This intelligence was used to develop projections for future production under three different intensity conditions based on the number of new wells drilled and production estimates for each new active well. These estimates were used to develop emission inventories for each scenario. Data from a development in a similar nearby formation, the Barnett Shale near Dallas/Fort Worth, were utilised as a surrogate for modelling growth in drilling activity. Estimated emissions of the ozone precursors NOx, VOCs, and carbon monoxide (CO) were large enough to justify an evaluation of the impact on ozone generation. This suggested that the effects in some areas would threaten achievement of proposed ozone standards even in the model assuming limited UNGD development of these areas. The study evaluated near-term ozone impacts, and projections indicated that emissions could increase through 2020. Drill rigs, compressor stations and gas plants were identified as the principal sources of NOx, and the authors suggest additional controls on these elements of the process.

Occupational studies can provide valuable data on the risk of community exposures. Huge quantities of hydraulic fracturing sand containing up to 99% silica (Chalupka 2012) are routinely used as a proppant to hold open the cracks and fissures created by UNGD. The use of this ‘frac sand’ creates respirable crystalline silica dust, potentially a serious occupational exposure hazard. Chalupka reported that the National Institute for Occupational Safety and Health (NIOSH) found potentially high occupational exposures and that the Occupational Safety and Health Administration (OSHA) had identified the following principal sources of exposure during the UNGD process-access ports on sand-movers; blender hopper; transfer belts; and on-site vehicle traffic. An assessment of 111 personal breathing zone (PBZ) samples from 11 sites in five US states found silica levels exceeded occupational health criteria at all sites and for some jobs by a factor of 10 or more (Esswein et al. 2013); 84, 69 and 51% of samples exceeded the ACGIH Threshold Limit Value (TLV), the NIOSH REL and the OSHA Permissible Exposure Limit (PEL), respectively. In the case of some sand mover operators, the level exceeded the occupational exposure limit (OEL) by a factor of 20, beyond the capacity of the respiratory protection being used. Several workers whose roles would not require close proximity to primary sources were also exposed above occupational standards. A subsequent occupational study assessed exposure data from six unconventional oil and gas sites in Colorado and Wyoming (Esswein et al. 2014). Full-shift and short-term PBZ samples were collected from volunteer workers together with urine samples. Ambient air samples from specific workplace areas were taken, typically over a 2-day period. Airborne concentrations of benzene exceeded NIOSH Recommended Exposure Limit (REL) and Short-Term Exposure Limit (STEL) concentrations and the American Conference of Governmental Industrial Hygienists (ACGIH) TLV in some cases. Full-shift PBZ exposures for some flowback work roles met or exceeded the NIOSH REL with time-weighted PBZ benzene concentrations for some roles an order of magnitude greater than others. Although real ambient and occupational measures contribute to the validity of the study and the authors considered their results as representative, they cautioned against generalising to all sites given the small size.

While UNGD has been reported as not representing a potential radon exposure source, at least one study has suggested an association. Casey et al. 2015 analysed a subset of indoor radon data in Pennsylvania, a state known for relatively high indoor concentrations, to evaluate associations with a range of factors including UNGD. The data set included 866,735 sample analyses from 762,725 buildings covering every county in the state during 1989–2013. Almost 7500 unconventional natural gas wells had been drilled in 39 counties during 2005–2013. There were no significant differences in radon levels between counties with high (≥ 100 wells by 2013), low (<100 wells by 2013) or no Marcellus activity before 2001. Consistently lower radon concentrations were identified in samples from counties with low Marcellus activity compared with those with high or no activity before and after drilling started. High-activity counties had significantly higher basement levels than low- or no activity counties from 2005 through 2013 with evidence of a significant upward trend. In addition, a significant upward trend in basement levels was reported from 2004 to 2012 ($p < 0.001$). A significant association between proximity to UNGD and first-floor summer radon concentration and an association for basement levels suggest a potential pathway. The paper recognises several limitations including limited data for the early years of the study, a lack of information on building construction and use, and meteorology. These limitations preclude establishing a causal link between radon levels and UNGD.

Water

Four potential UNGD-associated contamination routes were identified in a 2014 review: (1) stray gas contamination of shallow aquifers; (2) spills, leaks and/or the disposal of inadequately treated wastewater; (3) the accumulation of toxic and radioactive elements in soil or stream sediments near disposal or spill sites; and (4) the over extraction of water resources (Vengosh et al. 2014). The latter is not expected to be an issue in the UK (see discussion section). This review of published data (through January 2014) found that while direct contamination of water resources by fracturing fluids or the fracturing process was uncertain, there was some evidence for stray gas contamination of shallow aquifers and surface waters in areas of intensive shale gas development, and the accumulation of radium isotopes in some disposal and spill sites. The paper described engineering, monitoring, management and planning interventions to mitigate these risks including enforcing safe zones (1 km) between shale gas sites and drinking water wells, mandatory baseline monitoring, transparency and data sharing, a zero discharge policy for untreated wastewater, establishing effective remediation technologies for adequate treatment and safe disposal of wastewater, and limiting the use of fresh water resources for shale gas development through substitution or alternative fluids for hydraulic fracturing. Conceptual models and simulations have been used to evaluate contaminant pathways from the Marcellus Shale to the surface (Myers 2012), for example, concluded that UNGD can release fluids and contaminants from the shale by overburdening the hydrogeology or through the injected fluid forcing other fluids out. While recognising the uncertainties he suggests that transport times from the shale to the surface could be reduced from geological timescales to a few years. This plausibility was also reported following an innovative analysis of the contamination of a groundwater supply serving several properties (Llewellyn et al. 2015). This study identified a complex mixture of organic compounds consistent with flowback from Marcellus Shale gas wells and considered that stray natural gas and chemicals from the UNGD process were the most plausible sources, compounded by wastewaters from a pit leak. However, the lack of data on the composition of drilling, pit and HVHF fluids prevented confirmation of the source. Four studies considered structural integrity problems associated with UNGD (Ingraffea et al. 2014; Davies et al. 2014; Ziemkiewicz et al. 2014; Jackson et al. 2013b). Ingraffea examined inspection data from >41,000 oil and gas wells in the USA during 2000–2012 and found that unconventional shale gas wells were six times more likely to have such problems affecting cement and/or casings than conventional wells (6.2% cf 1.0%). Davies et al. examined published data sets from Australia, Austria, Bahrain, Brazil, Canada, the Netherlands, Poland, the UK and the USA on well barrier and well integrity failures supplemented with data from online repositories or national databases to estimate the frequency of such failures. Reporting systems were inconsistent leading to considerable uncertainties in the estimates or whether failures had led to leaks into environmental media. Well barrier or integrity failure ranged from 2 to 75%. Marcellus Shale wells (6.3%) were identified as having been reported for contraventions relating to well barrier or integrity failure between 2005 and 2013. Despite the uncertainties in the data sets, the authors considered that well barrier and integrity failure is an important issue for unconventional gas wells. Concerned about the potential risk of contamination due to defects in the construction and quality control of the geomembrane liners and geosynthetic piping components of flowback pits and waste fluid storage, Ziemkiewicz et al. examined 14 pits and impoundments associated with hydraulic fracture wells. They found widespread problems in the construction and maintenance of pipework and storage pit liners presenting risks of environmental contamination. In the absence of comprehensive data together with highly uncertain parameters, Jackson reviewed the evidence and pathways for the migration of gas, fracking fluids and formation water to shallow aquifers and assessed six US case histories including both unconventional and conventional extraction (Jackson et al. 2013b). Contamination was considered plausible, and important sources were described including uncemented annuli, well venting, casing failures and damaged seals, and abandoned wells. The authors recommended more baseline data and field testing of potential mechanisms.

The potential extent of UNGD contamination of water sources is considerable. A probability bounds analysis of the likelihood of natural gas operations in the Pennsylvania Marcellus Shale contaminating water, for example, estimated that development of 10% of the region's resource would generate a volume of contaminated water equivalent to thousands of Olympic-sized swimming pools and identified wastewater disposal as the most hazardous phase of the process (Rozell and Reaven 2012). The potential contribution of regulatory contraventions has been examined (Rahm et al. 2015). This examination of UNGD-related contraventions of environmental protection standards in Pennsylvania over 6.5 years included different phases of the shale boom cycle characterised by the authors as 'exploratory' (relatively low activity), 'intensification' (increased activity) and 'infil' (reduced drilling of new wells). This enabled an assessment of levels of UNGD activity on contraventions, and the authors also used contraventions reported in the conventional sector as a comparator. The study consider almost 3300 reported contraventions involving 80 companies and found that the rate of contravention increased dramatically from the exploratory period through the intensification period and then fell by 50% as drilling of new wells declined ('infill' period). The authors considered this fall as being due to a number of factors including improved management, inspection and regulation. The assessment of almost 5300 contraventions reported from the conventional sector revealed a different pattern with contraventions increasing with decreasing drilling activity due to inappropriate site restoration. UNGD contraventions were more likely to concern spillages and solid waste management compared to the conventional sector. The importance of effective regulation to protect watersheds was highlighted in a review of the environmental challenges presented by the potential extension of UNGD in Pennsylvania over the next 20 years (Lampe and Stolz 2015). Spillages have been identified as the cause of most incidents of environmental concern including some significant events with confirmed impacts on local water resources (Rahm and Riha 2014). This review of UNGD concluded that while good policy and practices can reduce some risks substantially, significant uncertainty remains and there is a need for more and longer-term water quality monitoring. Despite the potential for leakages, blowouts and spills one review reported just a single documented case of injected fracking fluid directly contaminating groundwater although the study highlighted the problems of commercial confidentiality and a lack of baseline data and research (Vidic et al. 2013). Following several large flowback spillages and associated concerns about contamination of groundwater in NE Pennsylvania, water samples from 21 drinking water wells whose owners suspected had been contaminated were analysed (Reilly et al. 2015). Well owners were recruited through local newspapers and social media outlets. Samples were taken during 2012 and 2013 and analysed for major and trace ions. Comparison data on groundwater well chemistry were obtained from the Pennsylvania Geological Survey and the US Geological Survey's reports for 1979–2006. Compositional data on Marcellus Shale flowback data were obtained from operators' mandatory annual chemical analyses reports although only around 5% of these reports were complete. Information on other potential causes of contamination such as animal waste, road salt and septic effluent were collected from various regulatory and academic sources. While the results revealed evidence of contamination by animal waste, septic effluent or road salt, there was no indication of contamination by Marcellus Shale flowback. Industry reported data were used to assess the potential impact of surface oil and/or recovered water spills on groundwater contamination over a year in Weld County, Colorado (Gross et al. 2013). UNGD operators reported 77 spills with potential for contamination. Analyses for BTEX showed exceedences of the maximum contaminant level (MCL) in 90% of cases for benzene, 30% for toluene, 12% for ethylbenzene and 8% for xylene. Given the delay between notification of the spill and the taking of samples the authors acknowledge that some levels may have been higher at the time of incident. The number of incidents is small in comparison with the 18,000 active wells although the self-reported nature of the data introduces potential for under-ascertainment. The authors conclude that surface spills represent a source of groundwater contamination.

Following reports of groundwater contamination in a south-western Pennsylvania community of 190 households, an assessment of the impact of UNGD activity on well water was undertaken using analysis of the chemical and microbiological quality of the water, community perceptions and the sequencing of UNGD operations and failures (Alawattegama et al. 2015). Drilling began in late 2007 with a major increase in activity during 2010/2011, and the study was conducted from late 2011 to early 2014. A total of 143 households were questioned about proximity to wells and the quality of their water supply. Fifty-seven samples from 33 wells were analysed for a range of inorganic chemicals, 18 wells were tested for six light hydrocarbons, and total coliforms and *E. coli* were tested for in 26 wells. A total of 143 households responded to the survey with 35% reporting changes in the quality of water; the majority concerning taste and/or smell; and 16% loss of quantity. Chemical analyses showed elevated levels of chloride, iron and manganese with the latter exceeding the MCL in 25 households which the authors considered a serious public health issue. While methane was identified in 78% of samples taken, the levels were low in the great majority of analyses. A review of the regulator's data identified several contraventions including compromised well casings and inadequate plugging that could have caused groundwater contamination. The microbiological analyses were reassuring. The authors acknowledge the challenges in definitively linking the contaminants to UNGD and recommend more effective pre-drilling testing together with long-term monitoring. This is a recurrent theme in the literature.

One of the largest studies of groundwater quality in an actively drilled shale formation associated with unconventional oil and gas extraction (UOG) in the Texas Barnett Shale formation with 550 private water well samples serving residential, agricultural and public water supplies was reported in 2015 (Hildenbrand et al. 2015). The majority of samples (83%) were taken from aquifers above the Barnett Shale formation, an area with over 20,000 UOG wells developed since the early 2000s. Analyses identified multiple VOCs including alcohols, BTEX and several chlorinated compounds. However, the authors were unable to confirm that UOG extraction was the source of contamination and again recommended further groundwater monitoring and analysis in the region.

A number of studies have used chemical signatures to more effectively identify the sources of contamination. Heilweil sampled 15 streams in the Marcellus Shale play and analysed using a combination of hydrocarbon and noble gas measurements with reach mass-balance modelling to estimate thermogenic methane concentrations and fluxes (Heilweil et al. 2015). High concentrations of methane consistent with a non-atmospheric source were found in four of the 15 streams. The isotopic and noble gas characteristics of the dissolved gas in one stream suggested a local shale source. Modelling indicated a thermogenic methane flux discharging into this stream which would have been consistent with a reported stray gas migration from a nearby well. Kohl used strontium as a marker for produced waters given the relatively specific and distinct isotopic well-water signatures (Kohl et al. 2014). Samples of produced waters were taken from six wells in the Marcellus Shale play and a nearby spring over a period 4 months prior to, and 14 months following, hydraulic fracturing. There was no evidence of migration of Marcellus-derived produced waters or contamination of groundwater although the short sampling period makes definitive conclusions problematic. Drollette examined health and safety contravention reports and sampled private residential groundwater wells in NE Pennsylvania ($n = 62$) and southern New York ($n = 2$) between 2012 and 2014 (Drollette et al. 2015). Fifty-nine samples were analysed for VOCs and gasoline range organic (GRO) compounds, and 41 samples were also analysed for diesel range organic (DRO) compounds. Organic and inorganic geochemical fingerprinting of inorganic constituents, groundwater residence times and dissolved methane concentrations were used to identify potential sources of any contamination. Trace levels of GRO and DRO compounds were detected in 15 and 26% of groundwater samples, respectively. The highest levels of both were invariably within 1 km of active UNGD operations, and in the case of DRO, these were significantly higher than samples taken beyond 1 km ($p = 0.01$). Trace levels, well below the EPA drinking water MCLs, of VOCs including BTEX compounds were detected in 10% of samples. Regulatory data revealed almost 5800 contraventions had been reported at 1729 UNGD sites in Pennsylvania between 2007 and June 2014. Levels of DRO were significantly elevated in groundwater samples in close proximity to these sites and in samples taken within 2 km compared with further than 2 km ($p = 0.03$ in both cases). These relationships were not found for GRO. Geochemical fingerprinting data found no evidence of upward migration and were consistent with a surface source of organic compounds in the study area such as UNGD sites. Sharma monitored the geochemistry of gas samples from seven vertical Upper Devonian/Lower Mississippian gas wells, two vertical Marcellus Shale gas wells and produced gas from six horizontal Marcellus Shale wells 2 months before, during and 14 months after the fracturing of the latter (Sharma et al. 2015). The results were used to assess gas migration pathways between the hydraulically fractured formation and protected shallow underground sources of drinking water. The isotopic and molecular compositions of gas from the two producing zones were distinct throughout and analysis indicated that no detectable gas migration had occurred although the authors were cautious, given the limited size of the study, about generalising these findings.

West Virginia University sampled 50 streams in a river basin of an area of West Virginia with a long history of coal mining and a then currently active (2012) UNGD industry with 250 wells (Pelak and Sharma 2014). Geochemical and isotopic parameters and sampling zones based on the intensity of shale production were used to identify sources of salinity and the effects of the mining and UNGD processes. There was no association between any of the geochemical or isotopic parameters and shale production intensity. The study concludes that there was no significant contamination from deep formation brines through natural faults/fractures, conventional oil and gas wells, or pathways created by shale gas drilling in the region. The authors recognised that this study represents a ‘one-time snapshot’ of water quality and recommended routine monitoring to more effectively assess any impact of shale gas drilling. Noble gas and hydrocarbon tracers were used to distinguish between natural and anthropogenic sources of methane in an analysis of water samples from 113 wells in the Marcellus Shale and 20 wells in the Barnett Shale during 2012/2013 (Darrah et al. 2014). Eight clusters of fugitive gas contamination with increasing levels of methane were identified. The chemical signature of these clusters suggested the cause to be failures of well integrity. Warner sampled 127 drinking water wells and compared with the composition of flowback water samples from Fayetteville Shale gas wells to assess potential contamination by stray gas or fluid migration associated with drilling and exploration (Warner et al. 2013a). Methane was detected in 63% of the drinking water wells, but isotopic characterisation found no spatial relationship with salinity occurrences and proximity to shale gas drilling sites.

Fontenot analysed water samples from 100 private drinking water wells (95 from aquifers in areas of active gas extraction in the Barnett Shale and five reference samples from areas with no wells within 60 km) (Fontenot et al. 2013). Levels of several inorganic substances were higher in samples taken within 3 km of active natural gas wells than both those taken more distant and the reference samples. A number of these elevated results exceeded the EPA drinking water MCL including arsenic in 32% of samples. These MCL breaches were randomly distributed within the active gas extraction zone, suggesting a variety of contributory factors including changes in the water table, activation of natural sources and industrial accidents. Twenty-nine private water wells contained detectable amounts of methanol with the highest concentrations from active extraction areas. Comparing sample results with 10 years of historical data from 330 private drinking water wells located in the same counties prior to gas activities showed significant increases in the mean concentration, maximum detected concentration and MCL exceedences for arsenic, selenium and strontium. While this study shows elevated concentrations of some toxic chemicals in the Barnett Shale region and postulates that the spatial distribution of these results is consistent with the likelihood of more frequent well disturbances and industrial accidents being associated with active gas extraction, the authors recognise that it was not possible to make a causal link.

The impact of the discharge of treated produced wastewater, including that generated by UNGD, on levels of toxic disinfection by-products (DBP) in a receiving Pennsylvanian river was undertaken during 2012 and 2013 (Hladik et al. 2014). Samples were taken from the outfalls from an oil and gas wastewater treatment plant (WWTP) and a municipal treatment plant that did not accept produced waters. Samples were also taken upstream and downstream of both plants, together with samples from the outfall of three other oil and gas wastewater treatment plants in Pennsylvania and three further plants not accepting produced waters in different states: Colorado, Maryland and Virginia. Samples were analysed for 29 DTPs. The range and levels of DBPs in samples taken from the outfalls of municipal treatment plant not accepting produced waters were characteristic of those reported from elsewhere in the USA. The DBP profile at the oil and gas WWTP was very different with relatively high levels of dibromochloronitromethane identified. These samples also included a mixture of inorganic and organic precursors including elevated concentrations of bromide and other organic DBP precursors. The authors concluded that disinfected produced water brines are potential sources of DBPs and DBP precursors to receiving surface waters. Olmstead also assessed the impact of discharged produced wastewater on surface water quality in Pennsylvania (Olmstead et al. 2013). This study developed a geographic information system (GIS) database from several publicly available sources including the results of over 20,000 water quality samples (2000–2011), UNGD locations, consignments of waste to treatment plants and data on the quality of the receiving water bodies. These data were used to model average impact of UNGD controlling for other factors. Relationships between increasing upstream density of WWTP releasing treated waste to surface water and increased downstream chloride (Cl^-) concentrations, and between the upstream density of well pads and increased downstream total suspended solid (TSS) concentrations were identified. Conversely, no significant relationship between wells and downstream Cl^- concentrations or waste treatment and downstream TSS concentrations were reported. Results suggest that that upstream shale gas wells do not increase Cl^- concentrations but the treatment and release of UNGD wastewater do. The authors also suggest that increases in downstream TSS associated with UNGD may be due to land clearance for infrastructure development. Drilling companies in Pennsylvania were advised to stop disposing of wastewater through WWTP in 2011 by the Department of Environmental Protection (DEP) (Ferrar et al. 2013a) and the composition of WWTP effluent prior to, and after, this voluntary intervention was assessed. Samples were taken from three WWTP (two public and one private) and analysed for 14 analytes. Results showed levels of several analytes, including Ba, Sr and bromides, exceeded the MCL in samples taken prior to the DEP advice. It is important to note that the MCL relates to the finished drinking water and levels could change before that stage. Samples taken after the DEP advice showed that the levels of most analytes decreased significantly ($p < 0.05$) although the study could not specifically identify UNGD as the source.

Warner also examined the impact on surface water quality following discharge of treated Marcellus liquid wastes (including UNGD derived) during 2010–2012 (Warner et al. 2013b). Samples were taken from the treatment plant effluent and downstream and upstream water and sediments. The latter, together with data from other streams, were used as comparators. Samples were analysed for a range of parameters including Cl, Br, Ca, Na, Sr, alkalinity and NORMs. Concentrations of these major elements in the treated wastewater reflected the composition of Marcellus produced waters. Levels varied during the sampling period with some concentrations up to 6700 times higher than the concentrations measured in the upstream river sites. The total radium (Ra) activity in the effluent was well below the industrial discharge limit although sediment levels adjacent to the treatment discharge site were over 200 times greater than background sediment samples. Chloride concentrations around a mile downstream were 2–10 times higher than background. The authors conclude that while treatment reduces the levels of contaminants, wastewater effluent discharge to surface water has a 'discernable impact'. Wastewater samples from three impoundments in southwestern Pennsylvania were sampled in 2010 and 2013 to examine the fate of, and potential health effects of exposure to, the most common NORM component radium-226. Each impoundment contained around five million gallons; two contained untreated wastewater and one held wastewater that had been treated by aeration and sulphate addition (Zhang et al. 2015). Analysis showed that Ra-226 accumulated in the bottom sludge at levels exceeding the landfill disposal limit and could accordingly be classified as radioactive solid waste. A small pilot study assessed the levels of natural uranium, lead-210 and polonium-210 in private drinking wells within 2000 m of a large hydraulic fracturing operation before and approximately 1 year after the start of drilling (Nelson et al. 2015). Groundwater samples from three residences in Colorado and single samples from surface water and a municipal water supply were analysed. There were no exceedences of standards and no significant changes in levels before and after drilling. Although the results are reassuring, the authors recognise the limitations of such a small sample size and recommend further and more extensive monitoring before and after hydraulic fracturing operations.

Osborn also used chemical characteristics to differentiate the source of methane contamination in active natural gas extraction areas in NE Pennsylvania (Osborn et al. 2011). Comparing levels of methane and higher chain hydrocarbons in private water wells ($n = 60$) serving areas with no wells to areas with more than one well within 1 km found 85% of the total number of wells contained methane but levels were significantly higher in areas proximal to gas wells. The average concentration was 17 times higher in shallow water wells in the proximal zones ($p < 0.05$) exceeding the US-defined action level for mitigation. The maximum recorded level was more than six times the lower range of the action level and more than twice the upper range and was considered an explosion hazard. Chemical characteristics and gas ratios strongly suggest the source to be UNGD activities, and the authors call for improved management, regulation and monitoring. This study has been criticised methodologically and for failing to adequately acknowledge the distances between hydraulically induced fractures and groundwater supplies, the natural migration of methane over millennia and the lack of pre-drilling samples (Schon 2011; Davies 2011). Data from this study were combined with 109 new samples from 49 wells and 83 samples from deeper formations in the region to determine whether there are pathways between deep underlying formations and shallow drinking water aquifers, a potential contamination route that has been widely dismissed given the reportedly large vertical separations and narrow seismic activity zones (Warner et al. 2012). The results indicate groundwater salinisation in some locations due to mixing of shallow groundwater and deep formation brine. Chemical characterisation suggested the potential migration of Marcellus brine through naturally occurring pathways. Another study using a chemical signature to improve source apportionment and building on, and responding to the criticisms of, the Osborn paper reported the contamination of drinking water sources by natural gas wells. Jackson et al. (2013a) analysed 141 drinking water samples from wells across the Appalachian Plateaus province of NE Pennsylvania for natural gases, isotopic signatures and proximity to gas wells. Methane was detected in 82% of samples with an average concentration six times higher in homes <1 km from natural gas wells compared to those further away ($p = 0.0006$). Ethane was identified in 30% of samples with an average 23 times higher in homes <1 km from gas wells ($p = 0.0013$). Propane was detected in 7.5% of samples, all of which were within approximately 1 km ($p = 0.01$). Proximity to gas wells was significantly associated with both methane and ethane levels ($p = 0.007$ and 0.005, respectively). The source of this contamination was examined using isotopic signatures and gas ratio characteristics which found that all the methane levels exceeding the US remediation threshold were associated with the industry and that most of the methane signals associated with shale were identified in those samples <1 km from wells. There was also an association with ethane although there were fewer data available and samples from one population close to wells were characteristic of a microbial rather than shale gas extraction source.

In contrast to the reported associations with UNGD, in an industry supported study, Molofsky et al. (2013) assessed the isotopic and molecular characteristics of hydrocarbons in wells in NE Pennsylvania and concluded that the methane concentrations in well waters were not necessarily due to migration of Marcellus Shale gas through fractures. Li and Carlson (2014) also used isotopic characterisation of produced gas and dissolved methane to examine groundwater wells in the North Colorado Wattenberg Oil and Gas Field finding little relationship. Over 95% of the methane was of microbial origin and neither density of, nor proximity to, oil/gas wells had a significant impact on methane concentration, suggesting other important factors influencing methane generation and distribution. Thermogenic methane was detected in two aquifer wells indicating a potential contamination pathway from the producing formation, but microbial-origin gas was by far the predominant source of dissolved methane. In response to the Osborn and Jackson results a data set of 11,300 pre-drilling samples of domestic well water supplies in the vicinity of 661 oil and gas wells (92% unconventionally drilled) taken between 2009 and 2011 was analysed (Siegel et al. 2015). The density of UNGD in this region of Pennsylvania enabled these ‘pre-drilling’ samples to be matched to one or more existing oil or gas wells reflecting, in the authors’ view, a post-drilling comparison. The multiple analyses conducted found no statistically significantly associations between methane levels in well water and proximity to pre-existing oil or gas wells.

The physics of osmotic and capillary forces has been reported as preventing the escape of residual treatment water (that portion of injected fluids not recovered), following a series of experiments conducted on cuttings from a horizontal well in the Marcellus Shale joint funded by the US Government and Shell (Engelder et al. 2014). A review of the literature on the physical constraints on upward migration of hydraulic fracturing fluid and brine concluded there were several features of sedimentary basins that limit the possibility of rapid upward migration (Flewelling and Sharma 2014). These include inherently low impermeability, the narrow bands of affected rock and the short-term and localised increases in pressure. The review concluded that, even in the case of an upward gradient, flow rates are low and travel times in the order of millions of years. In an earlier paper Flewelling et al. had noted a number of constraints on hydraulic fracture growth and fault movement that mitigated against upward migration of fluid and brine including the energy lost from the fracturing stimulation during the formation of complex fracture networks (Flewelling et al. 2013). They developed a simple physical relationship to describe the upper limit on fracture height growth as a function of hydraulic fracturing fluid volume and compared this to over 12,000 fracturing events which had been mapped with microseismic sensors. They reported that all microseismic events were less than 600 m above well perforations with the great majority being much lower. In addition, areas of shear displacement (including faults) were estimated to be relatively small with radii in the region of 10 m or less. The authors concluded that contamination of shallow groundwater through induced fractures and faults due to hydraulic fracturing of shale formations was not physically plausible.

Concerns about oestrogen and androgen receptor activity of chemicals used in the UNGD process contaminating drinking water supplies prompted a study of ground and surface water from an intense natural gas drilling area in Garfield County, Colorado (Kassotis et al. 2014). This study reported that most water samples from sites with confirmed drilling-related incidents exhibited more oestrogenic, antioestrogenic and/or antiandrogenic activity than reference samples and that 12 chemicals used in the process exhibited similar activities. Twenty-nine water samples from five sites with a reported spill or incident in the previous 6 years together with five surface water samples from the Colorado River, the drainage basin for the region, were taken. Groundwater reference samples were collected from an area with no drilling activity and from two zones with low activity (≤ 2

wells within 1 mile). Surface water references were taken from two locations with no activity; 89, 41, 12 and 46% of the 39 water samples showed oestrogenic, antioestrogenic, androgenic and antiandrogenic activities, respectively. Oestrogen or androgen receptor activity increased from very low in drilling sparse reference water samples, to moderate in samples from the Colorado River, to moderate to high in samples from spill sites. The authors recognised that such effects could be due to sources other than drilling activities such as agriculture, animal care and wastewater contamination but considered these to be extremely unlikely given the nature of the areas being sampled. Twelve chemicals used in the UNGD process known or suspected to be endocrine disruptors were also tested for oestrogenic activity and demonstrated novel antioestrogenic and antiandrogenic, and limited oestrogenic activities. The authors concluded that the results supported an association between gas drilling and endocrine disrupting chemical (EDC) activity in surface and groundwaters, and although the study did not definitively link such activity to UNGD wells, the authors considered the association to be plausible.

It is worth noting that while the sources of contamination of water resources by UNGD activity are relatively well understood, there is little, if any, understanding of the interactions between the chemicals in the fracturing fluid and naturally occurring chemicals in the well or their potentially adverse consequences (Moore et al. 2014). This contrasts markedly with UNGD's contribution to air pollution.

Health

Despite the potential for exposures to hazardous emissions and releases from UNGD described in the previous sections, the literature on linking those exposures to human health effects is extremely limited. Three occupational health studies suggest a clear potential for effects on health (Rosenman 2014; Esswein et al. 2013, 2014). The exceedences of occupational health criteria for silica at 11 sites in five US states (Esswein et al. 2013) were considered to put workers at risk of silicosis, plausibly accelerated silicosis after only 5–10 years of exposure, and other silica-related conditions including lung cancer, end-stage renal disease, chronic obstructive pulmonary disease, tuberculosis and connective tissue disease (Rosenman 2014). Rosenman also linked UNGD-driven demand for silica to a marked increase in sand mining which had also increased the risk of silica-related diseases in mine workers. Esswein et al. (2014) also assessed occupational exposure using PBZ data collected from volunteer workers which revealed airborne benzene levels above occupational standards for some work roles (Esswein et al. 2014). In addition, urine samples showed levels of a benzene metabolite that were moderately correlated with full-shift PBZ benzene TWA concentrations ($r = 0.56$) although none exceeded the ACGIH Biological Exposure Index. However, the analysis did not control for key confounding exposures including smoking. Two occupational studies reported no impact on health although neither used personal exposure data (Bloomdahl et al. 2014; Zhang et al. 2015). The former estimated the volatilisation rates of 12 VOCs from flowback pits using concentration data from 35,000 samples to predict local air concentrations. These were used to develop an inhalation exposure assessment for a worker near an open pit for 8 h/day 5 days/week, for 9 months and to calculate hazard quotients, hazard indices and excess cancer risk. None of the hazard quotients exceeded 1 and the mean hazard index was 0.09 although the 97.5 percentile did reach unity, suggesting some potential for adverse effects. The estimates of excess cancer risk were also reassuring being within the upper limit of the acceptable risk range for individual VOCs. In addition, the cancer risk for the five chemicals with cancer risk values were so low the values were summed and remained within the acceptable excess cancer risk range. This study assumed constant weather conditions and used a modelling method for a limited range of VOCs with no exposure data. While the results of the study were reassuring the authors recognised that its limitations precluded a definitive risk assessment. Zhang et al. 2015 used data on Ra-226 levels in impounded wastewater to derive a radiation dose equivalent to estimate direct exposure and the internal dose from inhalation of airborne radionuclides and ingestion of contaminated material. Both the total dose equivalent for on-site workers and the estimated worst-case event were well within the US Nuclear Regulatory Commission limit for the general public. The upper range of the total carcinogenic risk for on-site workers exceeded the EPA trigger for clean-up of remediation sites although the authors considered the risks to workers as minimal.

Five studies used clinically confirmed health outcomes. The relationship between total inpatient prevalence rates and 25 medical subcategories with well numbers (per zip code) and density (wells per km^2) was examined in three Pennsylvania counties during 2007–2011 (Jemielita et al. 2015). There had been a large increase in UNGD development in two of the counties during this period, while there had been no wells in the third county. The total population was 157,311, and almost 93,000 inpatient records were identified. Cardiology inpatient prevalence rates were significantly associated with well numbers ($p < 0.00096$) and density ($p < 0.00096$), and neurology inpatient prevalence rates were also significantly associated with density ($p < 0.00096$). While this study involved a large resident population, there are limitations which are mostly recognised by the authors. While population demographics were similar by county, there was no analysis by zip code and no control for smoking, a key confounder for cardiology inpatient prevalence. Most wells appear to have been established in last year of study which covered a relatively short period, and there was considerable variation in the number of wells by zip code adding to the potential for exposure misclassification that affects all studies with no direct measure of exposure.

Casey et al. examined the relationship between four adverse reproductive outcomes and proximity to UNGD and level of drilling activity in a retrospective cohort study using data on over 9000 mothers linked to almost 11,000 neonates over 4 years to January 2013 (Casey et al. 2016). Multilevel linear and logistic regression models explored associations between UNGD activity index quartile and term birth weight, preterm birth, the physical health of newborn babies (5-min Apgar score) and small for gestational age (SGA). An increasingly strong association between quartile of UNGD activity and preterm birth was identified. No association was found with the other two outcomes. A post hoc analysis also identified an association between physician recorded high-risk pregnancy (OR 1.3; 95% CI 1.1, 1.7). While this study controlled for a number of confounding factors, there is potential for residual confounding and the lack of exposure measures inevitably increases the risk of exposure misclassification; e.g. mother's address was available for 2013 only and this was assumed to be her address during the pregnancy.

A similar method had been used to examine the association of proximity to UNGD and birthweight, SGA and prematurity in SW Pennsylvania for the period 2007–2010 (Stacy et al. 2015). This study, which included over 15,000 live births, found lower birth weight in the 'most exposed' compared with the 'least exposed' populations (3323 ± 558 cf 3344 ± 544 g) and a significantly higher incidence of SGA (OR 1.34; 95% CI 1.10–1.63). There was no significant association with prematurity. The authors recognise the need for larger studies and improved exposure metrics.

In another analysis of adverse reproductive outcomes the relationship between maternal residential proximity to wells and the risk of oral cleft, neural tube defects (NTD), coronary heart defects (CHD), prematurity and low birth weight in almost 125,000 births in Colorado between 1996 and 2009 was examined (McKenzie et al. 2014). Exposure was imputed by calculating tertiles of inverse distance-weighted natural gas well counts within a 10-mile radius of maternal residence (range 1–1400 wells per mile) and a reference population with no wells within 10 miles. Associations were examined using logistic regression and multiple linear regression. The number of births was approximately equal in exposed/non-exposed groups. Prevalence of CHDs increased with exposure tertile with an OR in highest tertile of 1.3 (CI 1.2, 1.5). NTD prevalence was also associated with the highest tertile (OR 2.0; CI 1.0, 3.9), compared with the non-exposed group. Exposure was negatively associated with prematurity and low birthweight, and there was a modest positive association with foetal growth. No association was reported for oral clefts. This well-conducted analysis of a large population suggests a positive association between proximity and density of gas wells in relation to mothers' residence and an increased prevalence of CHDs and possibly NTDs. This type of study has several recognised limitations, which the authors acknowledge, including incomplete data, undercounting, the effect of folic acid supplements, residual confounding and lack of exposure measures. Again the authors call for further research addressing these issues.

An industry body funded study examined childhood cancer incidence in Pennsylvania counties before and after establishment of UNGD sites (Fryzek et al. 2013). Standardised incidence ratios (SIRs) and 95% CIs for childhood cancer, childhood leukaemia and central nervous system (CNS) tumours for a pre-UNGD period (1990 to year prior to UNGD, $n = 1874$) and post-UNGD (from year of first UNGD to 2009, $n = 1996$) were calculated. While the SIR for all cancers post-UNGD (1.02; 95% CI 0.98, 1.07) was higher than pre-UNGD (0.94; CI, 0.90 to 0.99), this difference was not statistically significant. This was also the case for childhood leukaemia (SIR before drilling = 0.97; CI 0.88, 1.06, after drilling 1.01; CI 0.92, 1.11). A significantly elevated SIR was found for CNS tumours after drilling (1.13; CI 1.02, 1.25) compared with pre-drilling (0.89; CI 0.79, 0.99). Analysis of the impact of the number of wells revealed a significantly elevated SIR for total cancers for counties with 500 wells or fewer (1.09; CI 1.03, 1.15) but not for counties with more than 500 wells. The authors recognise that SIRs should not be directly compared but actually do so to make reassuring conclusions which have been challenged on other key methodological issues (Goldstein and Malone 2013).

Six studies used self-reported symptoms. A household survey of residents' self-reported symptoms and views on environmental quality was conducted in Washington County, Pennsylvania, during summer 2012, a period during which there were 624 active wells (95% first drilled between 2008 and 2012) (Rabinowitz et al. 2015). Eligible homes closest to 20 random sampling points in each of 38 contiguous townships were visited to establish access to ground-fed water wells. Households were classified according to distance from the nearest well: <1, 1–2 or >2 km. A total of 208 of the 255 eligible households representing 492 residents were included, and an adult occupant was interviewed using a piloted questionnaire covering self-reported symptoms (overall symptoms; dermal, upper and lower respiratory, GI, neurological and cardiovascular) and qualitative assessment of environment. After adjustment for age, sex, household education level, smokers in household, job type, animals in household and awareness of environmental risk, household proximity to wells remained associated with the number of symptoms reported per person <1 km ($p = 0.002$) and 1–2 km ($p = 0.05$) compared with >2 km from gas wells, respectively. Living in a household <1 km from the nearest well remained associated with increased reporting of skin conditions (OR 4.13; 95% CI 1.38, 12.3) and upper respiratory symptoms (OR 3.10; 95% CI 1.45, 6.65) compared with households >2 km from the nearest gas well. Environmental risk awareness was significantly associated with reports of all groups of symptoms. This study controlled for several factors, but the sample size is small in epidemiological terms and has other limitations, recognised by the authors, including the self-reported nature of the symptoms, potential bias, the lack of direct exposure measures and the issue of multiple testing. These factors are reflected in the authors' modest recommendation for further research.

A cross-sectional study of patients presenting to a primary care centre in Pennsylvania used a self-administered questionnaire to explore attribution of health perceptions and 29 symptoms to environmental causes including UNGD over 1 week in 2012 (Saberi et al. 2014). Of the 72 participants 42% attributed at least one symptom to an environmental cause with 22% identifying unconventional natural gas development. There were two separate 'health' assessments. Twenty-two percentage of respondents linked a health problem to natural gas (16 of 72); however, some of these symptoms are of dubious plausibility. Nine of the 16 linked natural gas to a 'medical symptom', a reduced list of 15 drawn from the 29 in the questionnaire. Case reviews were conducted on six participants linking 'medical symptoms' to natural gas and only one had a record of both the symptom and the concern and in three cases there was no record of either. There was no measure of potential exposure, and while mapping of 74% of respondents showed residence within two miles of a well, it also demonstrated no evidence of clustering. The potential for bias is reflected in the high levels of symptom linkage to other environmental issues such as antibiotics in food (22%) and ageing due to free radicals (11%).

Another analysis of self-reported symptoms and perceptions described two sets of interviews conducted with a 'convenience sample' of residents living close to the Marcellus Shale development who had contacted the researchers through community outreach or had been referred by activists (Ferrar et al. 2013b). The first session involved the interviewing of 33 subjects with open-ended questions on concerns and symptoms. The second session held 19–22 months later involved 20 of the 33 with the aim of building on relevant issues identified in the first interview including community and individual health impacts and self-reported psychosocial stressors. The majority of participants lived in Pennsylvania counties with intensive UNGD activity, 17/20 owned their gas rights and 8/20 had outstanding litigation against the company. Symptoms of health impacts and sources of psychological stress were compared longitudinally, and participants attributed 59 different health impacts and 13 stressors to the Marcellus development. Stress was the most frequently reported symptom. Perceived health impacts increased over time ($p = 0.042$), while stressors remained constant ($p = 0.855$). This is a small and acknowledged biased sample. The range of identified symptoms is very broad and includes some questionably plausible conditions such as vitamin D deficiency.

A questionnaire-based community health survey was supplemented with environmental data (VOCs in air and heavy metals in well water) from sites close to participants' homes in 14 Pennsylvania counties (Steinzor et al. 2013). This study involved 108 individuals including people recruited by participants and at public events completing a survey instrument. All interviewees reported symptoms (range 2–111) with over 50% reporting more than 20. A wide variety of symptoms was identified including respiratory, behavioural, neurological, muscular, digestive, skin and vision symptoms. Throat and sinus issues increased with residential proximity to UNGD, and an association between odours and some symptoms was also identified. There is real potential for bias in the distribution of questionnaire, and while some environmental data were collected, this small sample study used distance as a proxy for exposure. Thirty-four air and nine water samples were taken at 35 households; locations were selected based on household interest, severity of reported symptoms and proximity to gas facilities. Nineteen air samples recorded a variety of VOCs, and while BTEX levels were higher than those previously reported in samples taken by the local Department for Environmental Protection and used as controls, no comparisons with regulatory or advisory standards were made. Twenty-six chemicals were detected in well water with 11 samples exceeding the MCL for manganese, iron, arsenic or lead. While the study reports some congruence between symptoms and chemicals identified by environmental testing all the symptoms were self-reported, mostly highly non-specific and cannot be confidently linked to emissions from UNGD sites.

An ecological study using interviews of farmers and families from six US states was supplemented with limited exposure, diagnostic and toxicological data to assess impact on humans and animals (Bamberger and Oswald 2012). The families were referred by environmental groups or activists and related to seven conventional well sites (two wells reported in one case) and 18 HVHF sites (25 wells reported in one case and six in another). In addition to collating information on human, livestock and pet health from interviews, the researchers were able to examine two opportunistic natural experiments where livestock had been exposed and non-exposed on the same farms. Exposures were alleged to have occurred through the contamination of water. Virtually all health data were self-reported and included a wide range of symptoms including for humans; neurological, GI, dermatological, headaches, nosebleeds, fatigue and backache; and for animals, mortality, reproductive, neurological, GI and dermatological symptoms.

Outcomes reported for the two incidents detailed included:

- Incident 1: 21/60 cattle exposed to fracking fluid had died and 16 failed to calve. There were no deaths of the 36 non-exposed cattle and one failure to calve (no significance levels reported).
- Incident 2: 70/140 exposed cattle died with no deaths in the 60 non-exposed.
- A child was reported as suffering fatigue, GI, throat and back pain. Following animal deaths on the farms, toxicological testing of the child showed elevated levels of arsenic but the metal was not found in drinking water. Further tests on the family and the residents of the neighbouring farm showed evidence of benzene exposure, but no analyses had been conducted prior to HVHF starting.

The paper recognises some of its limitations and acknowledges the paucity of available data. All the subjects were referred by environmental groups/activists, and the analysis used self-reported symptoms with no control populations with exception of the 'natural experiments'. Twenty-one of the interviewees were followed up 15–34 months after the initial interview and questioned about subsequent exposures and health effects (Bamberger and Oswald 2015). There were no significant health changes reported by those living in areas where industry activity had either increased or remained constant. Where industry activity had decreased, the total number of reported symptoms in humans and animals also decreased. This follow-up study is compromised by several of the same issues as its predecessor.

Nine studies, including Zhang 2015 and Bloomdahl 2014 discussed above, used derived hazard indices. Chronic and subchronic non-cancer hazard indices were calculated and, for exposure to hydrocarbons, cancer risks for residents living <1/2 mile and >1/2 mile from wells in Garfield Colorado (McKenzie et al. 2012). The study included 187 UNGD sites using air quality data from existing routine ambient air monitoring and data collected in Garfield from January 2008 to November 2010 to assess short-term exposures. These data were used to estimate both subchronic and chronic exposures and health risks. Residents living within 0.5 mile of wells were at greater risk for health effects than those >0.5 mile from wells. Subchronic exposures to air pollutants during well completion activities were the most important component of this risk. The subchronic non-cancer hazard index (HI) <0.5 mile was 5 compared to 0.2 for >0.5 mile principally due to exposure to trimethylbenzenes, xylene and aliphatic hydrocarbons. Chronic HIs were 1 and 0.4 for residents ≤0.5 mile from wells and >0.5 mile from wells, respectively. Cumulative cancer risks were 10 in a million for the proximal zone and 6 in a million for residents living >0.5 mile from wells, with benzene as the major contributor to the risk. The authors associated the largest HI to the relatively short-term but high-emission well completion period. This HI is driven principally by exposure to trimethylbenzenes, aliphatic hydrocarbons and xylene, all of which have neurological and/or respiratory effects and for which UNGD was considered the only plausible source. This is a well-conducted study, and the authors acknowledge its limitations. Distance as a proxy for exposure introduces the possibility of exposure misclassification although this is partially addressed by the use of odour complaints to define areas and the risk calculation included monitoring data. The health outcomes are plausible and consistent with risk assessments in the grey literature. The results contrast with a subsequent reassuring deterministic and probabilistic cancer risk assessment (Bunch et al. 2014). It is interesting to note that the air quality data included in this study were annual averages derived from a monitoring system for regional atmospheric quality as opposed to McKenzie et al. (2012) who used community-level sampling proximal to UNGD which is potentially more relevant for human health risk assessment.

The TCEQ extensive airborne VOC monitoring data were used to inform a human health risk assessment in the Barnett Shale region (Ethridge et al. 2015). While several short-term samples exceeded odour-based AMCVs and levels above typical background were detected downwind of UNGD, only three exceeded health-based AMCVs. All long-term VOC levels were below long-term health-based AMCVs. Hazard quotients and unit risk factor analyses were used to estimate non-cancer and cancer effects, respectively, and indicated no significant increased risks.

A health risk assessment of airborne VOCs close to UNGD wells in SW Pennsylvania suggested that while local people were exposed to levels of HAPs around four times higher than populations remote from gas operations, concentrations of unconventional natural gas-associated VOCs were well below hazardous levels (Swarthout et al. 2015). This was reflected in the low HI for both cancer and non-cancer risk calculated with a modified version of the method used by McKenzie et al. (2012). A quantitative risk assessment of the excess lifetime cancer risks for residents and workers associated with the levels of PAHs measured in the vicinity of operational well pads in Carroll County, Ohio, found the risk in the proximal residential exposure group exceeded the EPA acceptable range and was 30% higher compared to the distal population (0.04 cf 3.2 miles) (Paulik et al. 2015).

A health impact assessment was conducted in response to concerns reported by communities in Battlement Mesa (Witter et al. 2013). This analysis estimated an increased risk of non-cancer health effects from subchronic VOC exposures during the well completion period and a small increased lifetime excess cancer risk (10×10^{-6}) for those living close to wells compared with the risk for those living farther from wells (6×10^{-6}). Self-reported short-term symptoms such as headaches, nausea, upper respiratory irritation and nosebleeds in residents living within a half mile of well development were considered plausibly associated with odour events and that increased traffic associated with the process would increase the risk of accidents and reduce levels of walking and cycling. Recorded noise levels and complaint data suggested that noise levels related to the site could be in the range associated with health impacts. The paper also reported a 15% reduction in property values in the vicinity of the site and postulated that anxiety and stress levels would be increased as a result of community concerns.

An evaluation of the comparative impact of shale gas and coal, conventional gas, nuclear, wind and solar on a range of environmental and toxicological issues reported that shale gas was much less damaging in terms of human toxicity than coal, nuclear or solar although it was worse than conventional gas (Stamford and Azapagic 2014).

Economic and social

Several industry-sponsored reports published online rather than through the peer-review process have highlighted the economic benefits of UNGD. In response six of these analyses, three of which had an academic affiliation, were assessed (Kinnaman 2011). He identified several shortcomings in the analyses including assumptions that all the lease and royalty payments are spent locally, that the great majority of industry expenditure is local, that the level of well activity is a function solely of the current gas price, erroneous interpretation of data, disregard of the possibility of direct spending crowding out other users of the resource and no assessment as to whether the overall benefits of gas extraction exceed the costs. Kinnaman considered the consistent use of the term ‘conservative estimates’ in the industry-sponsored reportage to be misleading and that the estimates were in fact likely to be ‘overstated’. This theme was developed in a review of the physical and social research on UNGD (Lave and Lutz 2014). They noted that where research is available it is not necessarily of adequate quality; e.g. most of the economic analysis is currently speculative with very little of it in the peer-reviewed literature. This was considered at least partly due to the rapid expansion of UNGD since the mid-2000s which had ‘caught policymakers, environmentalists, and communities by surprise, and left physical and social scientists scrambling to catch up with the biosocial consequences’ and inadequate resources available to regulators for research. This lack of funding and research has had other consequences creating a knowledge vacuum which has left the industry to become a primary source of knowledge about UNGD. They found the research on social and cultural impacts to be overwhelmingly negative. The authors considered that while the landscape disturbance of UNGD sites is relatively small compared with other land-use activities, fragmentation of ecosystems was extensive. This necessitates further research to better protect important habitats, especially given that UNGD is possibly the most substantive change in energy production since the advent of the fossil fuel economy. The authors also note that government agencies value ostensibly apolitical economic arguments so highly that they behave less like mediators in the debate and more as advocates for the industry. The wide variance in opinions about the costs and benefits of UNGD has been reported elsewhere with some considering reality lies somewhere these extremes providing the process was managed well (Jackson et al. 2014).

Concerns of a UNGD-related boom-bust cycle have been described in an assessment of the impact of a large increase in natural gas wells in the Rocky Mountain region from 1998 to 2008 including a review of specific case studies which highlighted the spectre of a subsequent local economy ‘bust’ precipitated by a drop in natural gas prices (Haefele and Morton 2009).

Two econometric methods, propensity score matching (PSM) and panel-data techniques, were used to both isolate and quantify the effect of UNGD on local income and employment (Paredes et al. 2015). The PSM estimation of the growth rate of per-capita income and employment included all Pennsylvania counties with an active unconventional natural gas well between 2004 and 2011 ($n = 34$) and two control groups (any US county outside Pennsylvania and counties in New York where UNGD has been banned). The panel study used annual data from 2004 to 2011 to estimate the effect of unconventional natural gas wells on total county employment and income. The direct income effects of Marcellus Shale UNGD activities were found to have had a negligible indirect or induced income impact on the general population in counties with HVHF processes. The local employment effects were more substantial, but many of the new jobs were low-paid and accordingly may have been taken by outsiders who tend to spend/send their income home.

Economic benefits of a number of shale booms have been described (Sovacool 2014). These included about 29,000 new jobs and $238 m in tax revenues in Pennsylvania in 2008; a contribution of $4.8 billion to gross regional product, 57,000 new jobs and $1.7 billion in tax revenue across West Virginia and Pennsylvania in 2009; and $11.1 billion in annual output representing 8.1% of the region's economy and 100,000 jobs in the Barnett Shale in Texas in 2011. However, the review also identified the complexities and expense of the process that can lead to cost overruns, accidents and leakages, and concluded that the benefits of shale gas production are uncertain and conditional on the 'right' mix of technological systems; operating procedures, government regulations and corporate values at each locality. The variation in the literature highlighting the challenge of capturing accurate data on workers' place of residence has been noted together with concerns that increases in state and national employment may have little benefit to those localities faced with the costs of increased UNGD (Wrenn et al. 2015). This analysis of local employment in Pennsylvania combining a data set of local employment with a panel-data difference-in-difference-in-differences model reported that, while Marcellus activity had a positive effect on employment, it was only statistically significant for counties in which 90 or more wells were drilled in a given year, an impact which was halved when considering local employment.

Munasib and Rickman considered that, while unconventional shale gas and oil exploration increased energy sector employment, the impacts on other parts of local economies were poorly understood (Munasib and Rickman 2015). They examined the broader regional economic effects of the industry in three shale plays in Arkansas, North Dakota and Pennsylvania. The analysis included total employment, wage and salary employment, per-capita income, the poverty rate, population, and employment in accommodation and food services, construction and retail sectors. The synthetic control method was used to predict economic activity occurring in the absence of increased unconventional energy development. They reported large and significant positive effects for the oil and gas counties in North Dakota across all regional labour market metrics. However, they also found that significant positive effects in Arkansas were identified only in those counties with the most intensive shale gas production. This suggests a highly localised positive economic benefit. They considered the positive impacts of the employment effects on the local economy were smaller than those estimated in other analyses and noted the negative impact of rising local goods' prices and adverse effects on the local area quality of life. In addition, they found no significant positive effects in Pennsylvania. The study cautions against overestimating the potential of the industry to revive local economies and highlights that areas with significant levels of economic activity such as agriculture and tourism may be more likely to experience offsetting adverse economic effects. Modest increases in employment and income associated with increased UNGD had also previously been reported in an analysis of counties in Colorado, Texas and Wyoming (Weber 2012). This analysis of gas deposit and production data with economic data for 1998/1999 to 2007/2008 suggested the creation of fewer than 2.5 jobs per million dollars of gas production, an annual employment increase of 1.5% on pre-boom levels.

Rural North Dakota experienced an oil and UNGD boom in the 2010s estimated to have contributed over a billion dollars to the State's finances, creating 65,000 new jobs and leading to the lowest unemployment level in the USA. This region had seen previous oil-related booms in the 1950s and late 1970s which had led to housing shortages, more expensive public services and a legacy of costs for obsolete infrastructure. The benefits of this 5-year boom, the associated social challenges including impact on local housing, and potential solutions, were assessed through interviews with social workers and Directors of Social Care from across the state (Weber et al. 2014). The latter formed a primary focus group and the former a follow-up group of those working on the periphery of oil activity. The primary group of 20 self-selected participants from the State's 38 directors was interviewed using a semi-structured format. The follow-up group comprised 13 social workers serving the area around the state capital of Bismarck, the largest city on the margins of the energy boom. The authors noted housing as a recurrent theme. In particular, inadequate supply and high housing costs were reported, leading to 'gazumping', poor living conditions, increased homelessness, associated failure to recruit workers and the establishment of temporary accommodation (known in the USA as 'man camps'). Social Services Directors reported an increase in child protection issues, increasing day care shortage and a diminishing supply of foster homes. Data from the police service suggested 'troubling increases in domestic violence issues disproportionate to population'. Several benefits were also raised including economic development, partnerships with the industry and decreases in benefit support. However, these were regarded as 'mixed blessings at best' with some questioning whether local residents were directly benefiting at all as they endured multiple stresses related to the industry. One example cited recognised a major drop in the fuel assistance programme but an increased use of food banks due to higher rents. The authors prudently advise treating their findings with some caution recognising the limitations of this small cross-sectional study.

A part industry-funded statistical analysis of available reserves and the economics of conventional and unconventionally sourced natural gas found that the costs of producing gas from unconventional reservoirs were comparable to those of conventional gas in some cases (Aguilera et al. 2014). The authors concluded that the estimated available reserves can be accessed safely, cost-effectively and with less environmental damage than other fossil fuels, provided appropriate and effective regulation.

A wide range of environmental protection, public health, energy policy, land-use, economic, regulatory, political and climate change issues was reviewed in response to the proposal to introduce UNGD to NY State (Eaton 2013). A density of 3.5 or more wells per km^2 in highly productive areas was anticipated based on the experience of other shale gas-producing areas. The review considered that the quantification of all the costs and benefits associated with natural gas drilling in, or close to, New York City's drinking water sources might never be possible. A net benefit is dependent on both wider public acceptance of the process and effective enforcement. The latter was uncertain given the existing political and regulatory environments. While identifying potential benefits for the transition to a low-carbon economy Eaton cautions that these could be outweighed by highly significant environmental liabilities.

Local communities are understandably concerned about any effects a proposed UNGD may have on property values. The real or perceived impacts of shale gas development were examined using hedonic analysis, a technique that uses the trade-offs homebuyers make between property characteristics and price (Muehlenbachs et al. 2015). The researchers had access to a substantial property sales data set covering Pennsylvania and used both a triple-difference and a difference-in-differences-nearest-neighbour-matching technique, controlling for potential confounders, to estimate local effects while accounting for county-level macroeconomic impacts. The analyses show that the prices of homes dependent on groundwater are negatively affected by proximity to shale gas developments (up to −16.5% for those within 1 km). The value of homes on a mains supply showed a small increase. However, it is worth noting that the latter was only applicable to homes proximal to *producing* wells, which in the USA would provide homeowner royalty payments, and is dependent on the wells not being visible form the property.

The potential implications for UK property and investment were reviewed in a professional briefing note based on internet resources, albeit using largely respectable peer-reviewed papers and government and other agencies' research (Jones et al. 2014a). They suggest that the exploratory process in the UK is more expensive than in the USA at £6 million cf £2.4 million. The paper quotes one of the largest US insurance and financial services companies 'UNGD-related losses have never been a covered loss under personal or commercial policies', 'from an underwriting perspective we do not have a comfort level with the unique risks associated with the UNGD process to provide coverage at a reasonable price insurance' and risks potentially associated with UNGD 'are not part of our contracts and this is common across the industry'. The review also identifies emerging problems with obtaining mortgages and media sources suggesting some mortgage providers being unwilling to offer mortgages for dwellings within 300 ft of a site with shale gas rights. In England, a leading firm of surveyors considered that while it was too soon to confidently evaluate the impact on property values 'house prices could fall by as much as 30%'. Jones also highlights concerns that the government guidance provided for planning authorities in the UK is inadequate (Jones et al. 2014b). Witter's 2013 HIA reported a 15% reduction in property values in the vicinity of the site and postulated that anxiety and stress levels would be increased as a result of community concerns (Witter et al. 2013).

The effect of proximity to UNGD sites on willingness to purchase property compared four environment, viz. 'heavy' fracking sites (fracking 0.25 mile away, house supplied by well water and drill site visible), 'light' fracking sites (fracking one mile away not visible from the property, house served by well water), a business park development and a closed petrol station with leaking underground storage tanks (LUST) (Throupe et al. 2013). Of 194 Texan respondents, 26% were willing to offer a bid in the heavy fracking option. The maximum offer varied from 0.1 to 100% of their valuation (the former representing a 99.9% discounting) with a mean discounting of 34%. The average discount of the top 50% of potential bidders was 20%. A higher proportion of the 177 Gulf Coast Floridian respondents of 36% were prepared to bid but their discounts were larger: mean 50%, with 29% the average for the top 50%. A total of 183 Gulf Coast Floridians were also asked about their intentions for the light fracking option. Thirty-seven percentage confirmed they would make an offer with a discounting range of 0% to almost 100%, a mean of 41% for the whole sample, and 17% for the top half of the market. These discounts are approximately 10% less than for the heavy fracking scenario. Respondents had lower willingness to buy and higher discounts for both UNGD options than the business park option but higher willingness to pay and lower discounting compared to petrol stations with LUST. Interestingly, there were higher levels of discounting related to the UNGD options in areas unfamiliar with petroleum extraction, perhaps reflecting a stigma associated with the process.

While the impact on US property values has been under-researched, increased demand and costs of rental properties could be expected due to the demand created by transient workers (Barth 2013). The environmental risks associated with the process have led to some reports of 'a large and significant reduction in house prices' and difficulties in obtaining property insurance and a negative impact on future construction and economic development. In this wide-ranging review Barth also recognised that while the shale gas industry will generate some local and regional jobs and revenues, the levels of both are probably exaggerated in the industry-funded literature. Some studies have used inappropriate economic modelling, e.g. inter-industry coefficients to assess growth in local ancillary and other industries. The experience of a state such as Texas with its long-established extractive industry infrastructure cannot legitimately be applied to areas new to UNGD which would require the import of key skilled staff (who often send money home rather than spending it locally), materials and services. In addition, such areas are predominantly non-urban with smaller populations and lower economic diversity which will reduce any economic benefit. These areas' economies are often dependent on agriculture, tourism, organic farming, hunting, fishing, outdoor recreation, and wine and brewing, all of which are highly sensitive to large-scale industrialisation and potential water, air and land contamination. Large-scale UNGD imposes additional costs on local social, health and emergency services as well as the environmental costs such as traffic congestion and road damage. It is estimated, for example, that Marcellus UNGD-related heavy truck traffic caused up to between $13–23,000 of damage per well to state maintained roads in 2011 (Abramzon et al. 2014). These are stressors that such communities are less able to manage or mitigate and there are concerns that the same natural gas industry 'boom' that brings some benefits for rural communities also brings an influx of non-local workers; increased crime, housing costs and demand for public services; and additional burdens on local infrastructure (Haefele and Morton 2009).

The effect on agriculture was also examined following a study reporting a decline in cow numbers and milk production in drilled areas (Adams and Kelsey 2012). Milk production, number of cows and average milk production per cow in five Pennsylvania counties with the most unconventional drilling activity were compared to six neighbouring counties with fewer than 100 wells drilled from 1996 through 2011 with a particular focus on the period 2007 through 2011, a time of large-scale increase in UNGD activity (Finkel et al. 2013). The number of milk cows in the most fracked counties fell substantially (range −18.3 to −46.7%). Of the six comparison counties, there was an 11.5% increase in one, no change in two and a modest decline in three. Declining milk cows numbers were associated, unsurprisingly, with a corresponding decrease in total milk production. The authors recognise the weaknesses in this study and identified other plausible explanations but considered that further research was warranted given the importance of this industry in Pennsylvania.

The literature on green energy strongly suggests that households are willing to pay (WTP) a premium for electricity from green energy sources such as wind, solar and biomass (Popkin et al. 2013). The likely welfare impacts (using WTP as a proxy) of using natural gas extracted by hydraulic fracturing for household electricity were explored in an economic choice experiment (Popkin et al. 2013). The null hypothesis that the difference between mean WTP for New York State electricity produced from hydraulically fractured gas and a 'status quo' option of current electricity supply is zero was tested using data from an Internet survey of 515 households from nine New York counties within the Marcellus Shale region and 18 outside the shale region. New York City was excluded from the study given the scale and magnitude of population, and social and political differences compared to up-state counties. The analysis controlled for key variables including age, gender, educational attainment, place of residence and proximity to UNGD sites. A potential for non-response bias, not necessarily substantive, was noted. While there was variability in the impact with some predicted to gain, New York households were found to incur an estimated welfare loss from HVHF as the source of their electricity of 40–46% of average household electric bills in HVHF counties and 16–20% of bills in areas outside HVHF counties. This equates to respondents being willing to accept UNGD-derived electricity providing their monthly bills were reduced by between \$22 and \$48 (mean bill \$124) with the required discounting increasing with increased proximity to UNGD sites. Respondents generally expressed a preference to continue with the status quo (out of state fossil fuel and nuclear energy). This negative local perception of UNGD is also reflected in a contingent valuation study of a random sample of Susquehanna Valley Pennsylvania residents' ($n = 186$) WTP for eliminating the risks of water pollution due to hydraulic fracking (Bernstein et al. 2013). This found that residents were willing to pay up to \$10.50 a month for additional safety measures to protect local watersheds from shale gas extraction.

Climate change

The most important distal effect of UNGD is its potential contribution to climate change. Shale gas is promoted by the industry and its proponents as a clean source of energy and as a bridge towards a less carbon-dependent sector. However, the resource being extracted and distributed, methane, has a global warming potential 72 times greater than CO_2 over a 20-year period and its release during extraction and distribution has been documented which has important climate change implications.

Shale gas supplies also have powerful modifying impacts on energy markets and economies dependent on the volumes generated, relative cost, substitution for other fuels, advances in technology, and existing and emerging energy and climate change policies. There are concerns, for example, around the displacement of renewables, an associated increase in coal and oil use, and that future development is dependent on, as yet, uncertain technological breakthroughs in carbon-capture and storage technology to address climate change contribution (Sovacool 2014). The inter-relationship between these factors is complex, and the required careful analysis is hampered by the current uncertainty regarding the frequency and volume of these releases (Moore et al. 2014; Weber and Clavin 2012).

Comprehensive sources of UNGD activity data and associated emission factors are extremely limited. The majority of UNGD greenhouse gas (GHG) emission analyses rely on EPA well completion emission factors developed for the U.S. National GHG Inventory. Although a vital source of information, they have largely been derived from aggregated data (Tyner and Johnson 2014). Methane emissions at natural gas production well pads in routine production or in completion flowback were measured using a top-down wind tracer flux measurements method (Omara et al. 2016). This included 17 well pads with a total of 88 wells and 18 conventional sites with an average of one well per well pad. The average site-level methane emission rate for the well pad sites in routine production was 23 times greater than the mean for the conventional sites. The authors considered this difference to be due to the UNG facility size and higher production rate. Conversely, UNGD sites had much lower production-normalised methane rates which were attributed to better process management. The authors considered the Pennsylvania methane emissions inventory underestimated site-level emissions by up to 40 times for five of UNGD sites included in this study, a difference reflected in an estimate of total VOCs emitted from the oil and gas fields of Weld County Colorado, where the majority of wells produce wet gas, which was twice the state emissions inventory (Pétron et al. 2014). O'Sullivan and Paltsev estimated methane emissions from nearly 4000 hydraulically fractured US wells during 2010 assuming a variety of controls and concluded that the then current estimate widely used in analyses was exaggerated, particularly if flaring and 'green completions' were assumed (O'Sullivan and Paltsev 2012). Black carbon emission factors using data from 26 flares in North Dakota have been reported to be much lower than previous estimates (Weyant et al. 2016).

The impact of increasing natural gas operations during 1996–2013 was examined using ambient levels of ethane, a marker for fugitive natural gas emissions (Vinciguerra et al. 2015). The study accessed hourly data from two EPA Photochemical Assessment Monitoring Stations sited for the Marcellus Shale and a control site in Rockdale Georgia, an area with similar urban sources of pollution but no extensive natural gas production. They reported that daytime ethane concentrations had increased significantly for the former from c.7% of total measured non-methane organic carbon to c.15% from 2010 to 2013. This trend was not observed in the control area and was considered to be linked to the rapidly increasing natural gas production in neighbouring states, especially Pennsylvania and West Virginia. Although other sources of this trend cannot be definitively excluded, the authors conclude that the relationship was plausible and, in the absence of control measures, would continue. Allen examined direct measurements of methane emissions (from May 2012 through December 2012) at 150 production sites, 27 well completion flowbacks, nine well unloadings and four workovers in the US Gulf Coast, Midcontinent, Rocky Mountain and Appalachian production regions (Allen et al. 2013). The production sites contained 489 hydraulically fractured wells. Levels of methane were compared with the 2011 EPA National Emission Inventory. Results for well completion flowbacks were considerably lower than the Emission Inventory while levels for pneumatic pumps and controllers and equipment leaks were either comparable or higher. The study, funded by the Environment Defense League and several energy companies, acknowledged the uncertainties inherent in this type of analysis and calculated that, if the emission factors reported were representative, then total annual emissions from these sources were broadly similar to the national emission inventory. However, most assessments of emission inventories report substantial underestimates of methane releases with one analysis reporting average methane emissions at the wells up to 23 times greater than the upper range reported by Allen (Goetz et al. 2015). Fugitive methane emissions from oil and natural gas (ONG) operations in the Barnett Shale area were quantified using a mobile laboratory (Lan et al. 2015). Air samples were taken <1.2 km downwind from 152 ONG facilities, including 125 well pads, 13 compressor stations, 2 gas processing plants and 12 landfill sites. Samples were taken at the plume centre line although, given the density of the facilities, emission rates could only be calculated for 36% of the well pads. A more precise model was used where adequate information on emission sources was available. Results indicated that some compressor stations and gas processing plants were disproportionally higher emitters of methane. Modelling showed well pad emissions to be linearly correlated with gas production. While recognising the study limitations including quasi-random site selection, model uncertainties and short duration the authors suggest that the EP Greenhouse Gas Reporting Program (based on self-reported emissions by industry) underestimates emissions from compressor stations and processing plants by up to a factor of 10^4 and some were comparable to a large landfill site. Robust data on methane leakage rates are critical for estimating GHG impact (Allen DT 2014). A study funded by a sustainable shale advocacy foundation reviewed the evidence around methane leaks from North American natural gas systems (Brandt et al. 2014). This reported that official inventories consistently underestimate methane emissions and that a large proportion of leakage could be caused by a small number of 'super-emitters', a phenomenon that may skew emission estimates (Lavoie et al. 2015; Subramanian et al. 2015). However, they concluded that hydraulic fracturing is unlikely to be a 'dominant' source. In addition, while the natural gas sector was an important source of methane leakage, its contribution would not prevent the climate benefits of substitution for coal. Studies which use top-down measurements consistently report significantly higher leakage rates than those based on bottom-up estimates. Methane emissions from two of the fastest growing US unconventional oil and gas production regions during 2006–2008 and 2009–2011 were estimated using satellite observations and a mass-balance approach (Schneising et al. 2014). They estimated leakages (energy content) of 10.1 ± 7.3 and 9.1 ± 6.2% agreeing with Brandt that existing inventories underestimated fugitive releases, the level of which they considered seriously undermined claims of a climate benefit associated with shale. Aircraft-based monitoring over the Marcellus Shale region in 2012 reported a large regional methane flux (Caulton et al. 2014). The analyses also showed that the methane emission flux from the drilling phase was two to three orders of magnitude greater than inventory estimates for some well pads. The authors considered the emissions to be so 'surprisingly high' as to be a national issue. The uncertainty inherent in top-down and bottom-up estimates was reduced in a study using repeated mass-balance measurements, ethane as a fingerprint for source attribution, a more complete count of facilities and the integration of multiple ground-based measurement data sets (Zavala-Araiza et al. 2015a). This analysis from the Barnett Shale region reported that half of methane emissions were accounted for by just 2% of facilities with 90% of emissions due to 10% of sites. In addition, their estimates of methane emission releases were significantly higher than those based on public inventories. Acknowledging the importance of apportioning methane emissions from shale formations to the hydrocarbon products, Zavala-Araiza also used mass, energy and economic value basis allocation methods to assign emissions to the three main products of production activity: saleable natural gas, oil, and natural gas liquids (Zavala-Araiza et al. 2015b). This analysis, while identifying regional variability, apportioned c 85% of the emissions to natural gas including an allocation to salable (dry) natural gas about two to seven times lower than those commonly reported. A comprehensive review of the implications of shale gas development for climate change acknowledged that most evidence indicated that substituting natural gas for coal in electricity production and for electricity in buildings (dependent on the mix displaced) and gasoline in transport decreases GHG emissions (Newell and Raimi 2014). However, modelling suggests that without significant fuel policy changes, increased natural gas production will slightly increase overall energy use and stimulate fuel switching including from renewables. The implications of this for GHG are uncertain and dependent on upstream methane emissions. Lower natural gas prices, such as those experienced in the USA, encourage the substitution for coal but also the substitution away from low-carbon energy sources including nuclear and renewables, the latter concern shared by others (Sovacool 2014; Jackson et al. 2014), and also increases energy consumption. The beneficial GHG effect of natural gas is dependent on, firstly, its displacement of more coal and petroleum than low GHG technologies like nuclear, hydro and renewables, and, secondly, the control of methane emissions from gas systems which are not fully understood. While natural gas can help reduce the costs of achieving GHG reduction goals, the modest GHG reductions attributed to shale gas are not sufficient to substantially change the trajectory of global GHG concentrations. This requires stronger incentives to switch to natural gas, renewables, nuclear, and for carbon capture and sequestration for fossil fuels. The authors call for further research internationally into the likely magnitude of substitution of natural gas for coal against zero-carbon electricity. These themes are echoed in other studies.

An energy system optimisation model was employed to explore how trends in natural gas production could affect emissions of GHGs, VOCs and NOx based on variable inputs including gas extraction, distribution and use, and alternative policies for GHG controls (McLeod et al. 2014). Scenarios developed included: base case (EPA model); cheap gas (in which UNGD continues to grow); expensive gas; and reduced carbon scenarios included a fossil fuel cap; a GHG fee (reflecting social cost); coal retirements; and conventional natural gas-fuelled vehicles. GHG emissions were estimated to decrease by 1.4% from 2010 to 2050 in the costly gas model. However, emissions were modelled as increasing by 2–3% in both the base case and cheap gas scenarios. For the cheap gas model, a 20-year global warming potential (GWP) of methane of 72 produced an estimated 6% increase in overall energy system GHG emissions between 2010 and 2050 while a 100-year GWP of methane of 25 produced an estimated 3% increase by 2050. Neither the coal retirement nor GHG fee models led to a significant reduction in natural gas production due to exports to neighbouring states in the former, and the fee not being high enough to deter use of gas as an electricity fuel source in the latter. Modelled outputs suggested that variations in natural gas cost and abundance had little impact on overall GHG emissions from the US energy system, due to offsetting changes across sectors; e.g. in the 'costly gas' scenario, increased coal replaced natural gas electricity production. The greatest reductions in GHG emissions were found with the fossil cap scenario (reduction of proportion of fossil fuel generated electricity to 20% by 2050). Nevertheless, in each reduced carbon scenario the Rocky Mountain electricity mix shows greater reliance on wind. NOx emissions declined in all the scenarios considered. Increased VOC emissions from NG production offset part of the anticipated reductions from the transport sector. In the base, cheap gas and costly gas scenarios NOx and VOC emissions also decreased by varying amounts between 2010 and 2050.

Assuming an abundant natural gas supply, simulations from five integrated assessment models of energy–economy–climate systems were developed (McJeon et al. 2014). This analysis found that global expansion of UNGD could produce large volumes of economically competitive unconventional gas. However, this increase in global supply does not materially reduce the trajectory of GHG emissions or climate forcing. A projected additional natural gas consumption up to 170% by 2050, for example, would produce a modest effect on CO_2 emissions (from −2 to +11%), and most models reported a small increase in climate forcing (from −0.3 to +7%) associated with the increased use of abundant gas. The authors conclude that while the global use of abundant natural gas may substantially change the energy system, it will not necessarily be an effective substitute for policies to address climate change.

The Massachusetts Institute of Technology Emissions Prediction and Policy Analysis model, developed by consortia including industry bodies, has been used to address concerns about the economics of the US shale gas industry and the legitimacy of using large supply assumptions to frame future environmental policy (Jacoby and O'Sullivan 2012). The model used cost data from a variety of sources to explore the implications of shale gas for two GHG control strategies. Shale gas commercial viability generates contradictory effects both stimulating the national economy and providing the flexibility to cost-effectively meet GHG reduction targets while producing higher emissions than an uneconomic shale projection. While the authors emphasise that their results are illustrative, they conclude that the concerns are overstated. However, they recognise that the modelled regulatory policies used would stifle the market for the development and use of the low-emission technologies required for more ambitious GHG targets and that shale gas could effectively stymie this market altogether. They use an interesting analogy to articulate this concern 'while taking advantage of this gift in the short run, treating gas as a bridge to a low-carbon future, it is crucial not to allow the greater ease of the near-term task to erode efforts to prepare a landing at the other end of the bridge'.

Several studies have used life cycle analysis (LCA) to compare shale gas with conventional natural gas and coal. This is important as, while the methane content of conventional and unconventional gas is approximately the same (Hultman et al. 2011), the extraction techniques differ.

A LCA conducted on Marcellus Shale natural gas examined GHG emissions, energy and water consumption under both the then current (2011–2012) and previous (2007–2010) operating practices (Dale et al. 2013). Combustion-derived GHG emissions were similar to conventional natural gas, lower than conventional fossil fuels but higher than unconventional oil sources. Shale gas may represent a decrease in some emissions relative to coal, but it remains insufficient to meet scientific mitigation goals for global carbon emissions. This study emphasises the large uncertainties at various points of the shale gas life cycle and the need to collect data on other key potential issues. A meta-analysis of the available literature has been used to develop robust, consistent and contemporary comparisons of life cycle GHG emission estimates for electricity produced from shale gas, conventionally produced natural gas and coal (Heath et al. 2014). The median estimates of GHG emissions from shale gas-generated electricity on a per unit electrical output basis are similar to those for conventional natural gas, with both approximately half that of coal. However, shale gas life cycle GHG emissions could approach the range of best-performing coal-fired generation in some circumstances. Liquids unloading and estimated ultimate recovery (EUR) of wells were identified as having the largest impact on life cycle GHG emissions. The authors call for further monitoring and improved characterisation of EUR and production practices. Shale gas life cycle emissions were estimated to be 6% lower than conventional natural gas, 23% lower than gasoline and 33% lower than coal in a comparative LCA (Burnham et al. 2012). However, the range in values for shale and conventional gas overlap and the benefit of using natural gas can be significantly reduced by upstream methane leakage. While natural gas *combustion* produces significantly lower GHG emissions compared to coal and oil, LCA identifies statistical uncertainty as to whether *total* emissions are actually lower. Accordingly, the authors call for improved environmental management and reduced GHG emissions. The estimated life cycle impacts of UK shale gas, assuming its use for electricity generation, have been compared with fossil fuel alternatives and three low-carbon options, viz. nuclear, offshore wind and solar photovoltaics (Stamford and Azapagic 2014). This analysis demonstrates that potential variation of different parameters can result in a wide range of life cycle environmental impacts for shale gas. Some of these are favourable relative to conventional gas and other alternatives, others very unfavourable. The estimates for the GWP of electricity from UK shale gas are consistent with the literature from other countries. For GWP, shale gas is broadly comparable to conventional gas sources. A power plant with 52.5% efficiency (lower heating value (LHV) basis) fuelled by conventional gas has a GWP of 401–508 g CO_2-eq./kWh which overlaps the range for shale gas at 412–1102 g CO_2-eq./kWh. The combustion stage was identified as the most important factor, but the impact was estimated to be considerably worse depending on the amount of gas vented and the EUR per well (among other factors) as identified by Heath et al. (2014). The paper also considered the comparative impact of shale gas and coal, conventional gas, nuclear, wind and solar on a range of other issues including toxicity, abiotic effects and ozone depletion and creation. The results of this comparison are quite complex with little consistency. While shale gas was worse than coal for three impacts considered (photochemical oxidants, terrestrial ecotoxicity and ozone layer depletion) it was better than the renewable options for four (freshwater, marine and human toxicity, and abiotic depletion of elements). Shale gas also had the highest ecoterrestrial toxicity compared with any of the other technologies. The authors conclude that shale gas appears to be a sound option for the UK in terms of energy security, cost and climate change (despite some of the evidence it presents regarding the latter) providing it can be economically extracted but cautions that the large variations in potential impacts described and the prospect of other effects requires 'tight regulation' for it to be regarded a 'sound environmental option'. Hultman's estimate of the greenhouse footprint of shale gas used for electricity generation was around 11% higher than conventional gas but and 56% that of coal for standard assumptions (Hultman et al. 2011); similar results were reported in a LCA of Marcellus Shale gas (Jiang et al. 2011). Howarth's 2011 estimation of a shale gas GHG footprint at least 20% greater than coal (Howarth et al. 2011) is a significant outlier and has been challenged (Jenner and Lamadrid 2013; Laurenzi and Jersey 2013). The former compared the environmental and health impacts of coal, shale and natural gas recommending more shale and less coal. However, while the shale gas life cycle has a smaller GHG footprint than the coal lifecycle it is larger than that of the conventional gas lifecycle. The latter, of ExxonMobil Research and Engineering Company, conducted a LCA of Marcellus Shale gas in power generation using real production data including gas engine emissions and flowback flaring. Marcellus shale gas production and processing was estimated to contribute 1.2% of the total GHG emissions, statistically indistinguishable from conventional gas. The EUR of the well and the power plant efficiency were identified as the most important factors. Both the carbon footprint and freshwater consumption were around half that of coal, and the authors conclude replacing coal with shale gas for power generation could produce substantial GHG reductions and freshwater savings. Estimated 'well to wire' (WtW) emissions of shale gas when used for power generation were found to be considerably lower than for coal and broadly comparable (1.8–2.4% higher) with conventional gas (Stephenson et al. 2011). The authors' conclusions, all employees of Shell, are reassuring but they acknowledge that in extreme conditions shale gas WtW emissions could be up to 15% higher than conventional gas and this estimate presumes effective flaring and recovery measures. A review of Howarth's 2011 analysis also estimated that the long-term shale gas GHG impact was less than coal over long term once its higher power generation efficiency was taken into account (Wang et al. 2011). They considered that existing technologies could reduce the short-term impact to less than coal. In addition, there is potential for using depleted shale gas reservoirs to store CO_2 cost-effectively reducing GHG impact further. A probabilistic model was used to estimate the GHG footprint of shale gas together with a case study using data from the Montney and Horn River shale gas basins in Northern British Columbia (Shahriar et al. 2014). Their analysis reported a much smaller footprint than that of Barnett Shale (which was considered representative of US shale gas) due to regulatory flaring requirements. The authors also challenged Howarth's estimates.

However, atmospheric methane emission derived from three natural gas production regions which accounted for over 50% of the US unconventional shale gas and approximately 20% of all natural gas production found natural gas loss rates from the Haynesville, Fayetteville and Marcellus study regions as within the range of emissions estimated by Howarth (Peischl et al. 2015). This study used 1-day methane fluxes calculated for early summer 2013 based on measurements taken from a research aircraft. Other potential methane sources such as livestock and landfills were not considered significant. In addition, Howarth's (2014) review of subsequent research and the fifth IPCC assessment reported that the 2011 estimates of methane emissions from shale and natural gas were 'relatively robust' (Howarth 2014).

However, the fundamental positions of, on the one hand, a climate change benefit of natural gas replacing coal in electricity generation and, on the other, a climate change disbenefit of methane leakage from the UNGD process have both been challenged given carbon cycle and climate system timescales (Schrag 2012). In this analysis, the critical issues are cheap natural gas stimulating additional energy demand while suppressing investment in energy efficiency and low-carbon technologies including renewables.

Seismic

It has been known since the 1960s that earthquakes can be induced by fluid injection. The injection of fracking fluid into a fault zone in the UK Bowland Shale induced small but felt earthquakes in April and May 2011 (Marshall 2011). A numerical model developed to estimate the maximum magnitude of similarly induced events concluded they would be too small to cause damage (Baisch 2013), a similar conclusion to Westaway and Younger (2014).

An analysis of an earthquake in Alberta Canada in the vicinity of the Fox Creek UNGD concluded that, while more data were required to definitively link the earthquake with UNGD, there was a plausible association with local shale gas exploration (Wang et al. 2016). This was the third 'felt' event during the first 6 months of 2015 and occurred a month after hydraulic fracturing activity. Assessment of publicly available records revealed no other major industrial activities associated with oil recovery or wastewater disposal. A series of 116 earthquakes ranging in Richter local magnitude (ML) from 0.6 to 2.9 proximate to a well in Oklahoma during a UNGD operation have been evaluated (Holland 2013). No other earthquakes were identified prior to, or after, fracking. The first earthquake was recorded 24 h after hydraulic fracturing beginning, a delay consistent with the diffusion of pore pressure in the subsurface over a distance of c 2 km. The likelihood of an association is strengthened by the absence of earthquakes during a 2-day break in the fracking and a resumption following the process restarting.

While injection of wastewater will not be permitted in the UK, it is worth noting reported incidences of linked seismic activity in assessing geological plausibility. A total of 198 possible examples of induced seismicity from 66 published papers and reports were examined for evidence for, and mechanics of, faults being reactivated due to hydraulic fracturing (Davies et al. 2013). The review considered the following potential triggers: mine subsidence, oil and gas field depletion, fluid injection for secondary oil recovery, research-related projects, wastewater disposal, solution mining, enhanced geothermal systems operations, reservoir impoundment, groundwater extraction and hydraulic fracturing for recovery of hydrocarbons from shale. A number of plausible pathways for the latter were identified along with mechanisms for reactivating faults due to hydraulic fracturing including fracturing fluid or displaced pore fluid entering a fault, transmission of a pressure pulse and deformation or 'inflation' of the rock. The authors concluded that while the risk of induced seismicity could not be ruled out the magnitude of such activity was small compared to processes such as reservoir impoundment, conventional oil and gas field depletion, water injection for geothermal energy recovery, and wastewater injections. Dynamic triggering of seismic activity in natural settings has been linked to subsurface fluids (van der Elst et al. 2013). This paper described and suggested that increases in deep wastewater injection may have led to dramatically increased seismic activity in the

Midwestern US. The study considers the prospect of distant earthquakes triggering areas of induced seismicity. An initial search of the Advanced National Seismic System earthquake catalogue provided some evidence. While recognising that most injection wells are not associated with large earthquakes, at least half of the 4.5 moment magnitude scale (Mw) or larger earthquakes in the USA interior over the previous decade had been recorded in regions of potential injection-induced seismicity. Three sites were identified as being particularly sensitive: Prague, Oklahoma; Snyder, Texas; and Trinidad, Colorado. Sensitivity to remote triggering was found to be associated with a long delay between the start of fluid injection and the seismicity onset and in those regions experiencing moderate magnitude earthquakes within 6–20 months. The authors postulate that such triggering could be indicative of fluid injection compromising some critical threshold. This appeared to be dependent on decades of injection, the inherent likelihood of a moderate magnitude earthquake in the region and relatively low levels of seismicity within 10 km prior to the first triggering event. The authors emphasise the importance of improved seismic monitoring in areas of subsurface fluid injection. More than 109 small earthquakes (Mw 0.4–3.9) had been detected over 14 months close to a deep fluid injection well used for disposal of UNGD wastewater from Pennsylvania (Kim 2013). These occurred in an area with no known previous earthquakes. The first earthquake was recorded 13 days after injection started and the pattern of events appeared to be related to pressure build-up. Kim concluded that the earthquakes were induced by the fluid injection at a deep injection well due to increased pore pressure along the pre-existing subsurface faults located close to the wellbore.

Conclusion and recommendations

This review has considered 156 peer-reviewed published papers and general reviews on the public health impact of UNGD. This seems an extraordinarily small evidence base to inform decisions about an industry that has produced probably the most significant change in energy policy since the advent of the fossil fuel economy (Lave and Lutz 2014). This evidence base is very modest in terms of quality as well as size. There are no studies, for example, that rigorously integrate, analyse and interpret UNGD-related exposure *and* health outcome data. This is a major gap in our understanding. UNGD unequivocally presents an exposure hazard. The process uses and/or produces toxic chemicals at every stage of its development, operation and decommissioning, and there are well-understood mechanisms for, and occurrences of, the release of some of these chemicals. The distribution and combustion of the produced gas also inevitably releases chemicals to the environment. However, while there are some signals in the literature as Coram notes (Coram et al. 2014), there is a hugely important distinction between a hazard, the inherent danger of an adverse consequence, and a risk, the likelihood of that consequence actually occurring. There is a reliance in the literature on the modelling or attribution of exposures which inevitably introduces uncertainties although most of the studies reporting monitoring data related to HVHF operations suggest associated elevated levels of airborne pollutants including VOCs and silica, and waterborne pollutants such as VOCs although data on direct source apportionment are critically limited. In addition, where exposure data have been reported they have rarely included monitoring from the periods before, during and after operation. This lack of a serious portfolio of peer-reviewed data interpretation, analysis and characterisation covering appropriate temporal phases of the process, despite its operation on such a large scale for so many years, renders any confident judgment regarding the safety of UNGD extremely problematic. This applies to both air and water monitoring effectively precluding a credible risk assessment of either the direct impacts on the quality of these environmental media or as to their potential as pollutant pathways to human exposure. It is worth noting, however, that while the threat to water supplies could be much lower in the UK due to the commitments of the UK government and industry, the potential for population exposure to air pollutants may be greater than the USA as UNGD sites may well be in closer proximity to population centres given the relative sizes and population densities.

The majority of papers examining health effects report a link to UNGD, but this literature is, if anything, even weaker. Around half of the studies use derived hazard indices or self-reported symptoms, some subjects are self-referred or referred by activists, most involve very small sample sizes, a number of the symptoms are of questionable plausibility, and very few use a credible exposure measure. As a result this body of work is compromised by the real potential for exposure misclassification, bias, statistical unreliability and questionable spatial, temporal and biological plausibility. It is worth noting that four of the five studies which use clinically confirmed cases and large sample sizes do report associations between residential proximity to UNGD sites and increased risk of plausibly related adverse health outcomes including three studies strongly suggesting adverse reproductive outcomes. The latter particularly requires further research given the evidence of the developmental and reproductive toxicity of many of the chemicals associated with UNGD (Webb et al. 2014; Kassotis et al. 2014) The fifth study, examining local childhood cancer incidence before and after establishment of UNGD sites, reported elevated, albeit not significantly so, levels of all cancers and leukaemia, and an increase in CNS tumours of borderline significance following UNGD operation. The majority of the health-related research focuses on short-term outcomes and 'traditional' environmental media issues (Werner et al. 2015). The latter is an especially important criticism given the lack of research into the potential for serious public health nuisance impacts such as noise, 24-h lighting, dust, odours and traffic disruption. Adgate notes this as well as the potential for intra-community differences in the perception of risk and rewards leading to stress in some residents (Adgate et al. 2014). In a UK context, nuisance refers to a legal concept rather than simply an irritation and the significant body of law concerning nuisance going back to the nineteenth century was a fundamental catalyst for the public health movement and reflects the serious, sometimes deadly, impact of these issues.

The literature on the global warming impact of UNGD overwhelmingly reports that the combustion of shale gas for electricity and heating is a less climate damaging alternative to coal (although it is questionable whether coal is really an appropriate benchmark (Coram et al. 2014; Schrag 2012)) and better than, or broadly similar to, conventional gas. However, it is important to consider the *lifecycle* perspective in this context and here the evidence is concerning. There are clear uncertainties about the extent and volume of inevitable fugitive methane emissions during unconventional gas extraction and distribution which could have a powerful effect on its global warming potential. Again the lack of critical data militates against an informed judgment and is reflected in the calls for more monitoring and research which are consistent features of the literature. Shale gas has also routinely been described by its advocates as a 'bridge fuel' for the transition to less carbon-intensive fuel economy. The evidence for this is questionable given its dependence on the development of large-scale carbon-capture and sequestration technologies (Sovacool 2014; Jacoby and O'Sullivan 2012; Schrag 2012), the economic disincentives to do so that 'cheap' shale gas creates and its displacement of renewable energy sources and concerns that the span of this 'bridge' may be incompatible with the chronology and regulation of shale gas development (Jackson et al. 2014; Sovacool 2014; Howarth 2014; Levi 2013; Schrag 2012; Brown et al. 2009). The apparent 'orthodoxy' of seemingly dichotomous positions that shale gas development is either a climate change positive given its advantages compared to coal for electricity generation or a negative due to its associated fugitive methane emissions has been challenged given that its most important climate impact is potentially more likely to be the effects on energy consumption and the development and use of renewables and carbon-capture technologies (Schrag 2012). This analysis articulates a political case for environmentalists 'recruiting' the oil and gas industries in the drive to close coal-fired power stations and move towards a low-carbon economy in the USA. This is both interesting and contentious but is implausible for the UK given the respective chronologies of the current coal plant closures and production potential of shale. There is also some evidence from the USA that shale gas production has perversely led to more coal and oil use. The falling price of the gas has incentivised producers to use the UNGD technique to access the more profitable shale oil leading to the USA becoming the world's biggest producer of crude oil in 2013 (The Economist 2013). Although coal use in the USA has declined, this has been more than made up by the foreign export market meaning that more coal being burned in Europe and Asia (Parenteau and Barnes 2013).

The broader economic case for shale gas, even in the USA where the scale of production has seen major reductions in both energy costs and reliance on imported fuels, is not without its critics, especially in relation to the effects on local economies. Many of the jobs created either require expertise not found locally or are low-paid appealing to transient workers with a tradition of sending money home rather than spending it locally. In any case, local communities are faced with the major challenges associated with servicing the needs of these workers and the impact of the industry infrastructure on their environment and existing social networks. It has been noted that the majority of the supportive analyses have been industry-sponsored, not subject to peer-review, and have overestimated the benefits. Indeed, the consistent use of the term 'conservative estimates' in the industry-sponsored reportage is considered by some to be misleading and that the estimates are in fact likely to be 'overstated' (Kinnaman 2011) or even 'wildly optimistic' (Hughes 2013). A number of studies have concluded that UNGD may not actually be as profitable as suggested by advocates (Kinnaman 2011), particularly in some economic circumstances (Beaver 2014; Throupe et al. 2013), or indeed not at all once all the costs are taken into account (Sovacool 2014). One of these factors, largely absent from the industry analyses, is the additional social and economic costs imposed on the local communities in terms of property values, availability of mortgages and insurance, availability of safe and affordable housing, the establishment of temporary accommodation, increases in crime, increasing day care shortage, the costs of highway maintenance, and psychological stress (Weber et al. 2014; Barth 2013; Witter et al. 2013). These communities are currently predominantly rural or semi-rural in nature and will be largely such if UNGD proceeds in the UK. The disproportionate health burden of UNGD borne by these communities has been noted (Coram et al. 2014), and there are real concerns about the compatibility of such an industrial process with traditional local economic enterprises such as agriculture and tourism. The undoubted increased tax revenues for regional or national exchequers are of little consolation to these communities, and indeed, there is evidence from the experience of other extractive industries that this generates resentment and a loss of trust in both the industry and authorities (van der Voort and Vanclay 2015). The redistribution of the environmental injustices historically endured by 'national sacrifice zones' such as Appalachia to more affluent areas with no previous experience of such industry is creating 'profound social, cultural and economic shocks for middle class communities losing control over their environments' (Lave and Lutz 2014). It is critical that policy-makers considering UNGD proposals are aware of the lessons of history. The phenomena of the 'resource curse' and the boom-bust cycle associated with extractive industries are well documented, and there is emerging evidence from the long-established Barnett Shale that, relative to the rest of Texas, local unemployment has actually increased (Barth 2013). Reducing the likelihood of this requires a measured development of the process to enable the economy and society to adjust (Stevens 2003). It should be a fundamental principle that such resource extraction should only be undertaken when it is clear the local benefits outweigh those of leaving the fuel where it is (Perdue and Pavela 2012).

The economic implications of this industry for the UK are perhaps even less convincing. There is little reason to expect that the UK will be immune from the negative environmental and social impacts described elsewhere, and indeed, they may be more profound given the much smaller size of the nation. It is also accepted that shale gas production in the UK will not reduce the domestic price of energy given the level of reserves, the high cost of extraction and the nature of the European energy market (Stevens 2013). Indeed, there are legitimate concerns that UK shale production may not be economically viable at all (Acquah-Andoh 2015).

The literature on seismic effects is very limited and generally reassuring in a UK context, especially as injection of wastewater, will not be permitted but the experience from Groningen NL, albeit in relation to a conventional gas field, is instructive in terms of the importance of transparency, effective compensation schemes, perceived local benefits of the industry and confidence in regulation (van der Voort and Vanclay 2015). The latter is very important given that the paucity of independent data and research appears to have positioned the industry as the pivotal source of intelligence and expertise. Simplistic paeans to 'tight' or 'gold standard' regulation will very rapidly lose public, political and professional credibility in an era of extraordinary public service cost-cutting. Indeed, concerned communities will be highly sceptical about the need for such a 'high' standard of regulation when they are simultaneously being reassured that UNGD is inherently a safe process. There is only one metric for the quality of regulation, effectiveness, and that requires an adequate and assured level of resourcing, independence and local oversight. It is reassuring that both the UK regulators and nascent industry appear to have learned from some of the negative aspects of the US experience. Full disclosure of the chemicals used by UK operators will be required and storage of flowback water in open lagoons will not be permitted. The industry has committed to a community engagement charter and that sites will be located with access to mains water and close to the main gas distribution network to reduce the number of truck movements and the level of fugitive gas releases, respectively. All proposals will be subject to an Environmental Impact Assessment and, if approved, the industry body has agreed to environmental monitoring before, during and after operation, and to fund local and regional community projects (United Kingdom Onshore Operators Group 2016). While welcome, these controls and initiatives cannot fully address the real concerns about the environmental, health, economic and social impacts of UNGD given the fundamental hazards the process inevitably generates, the proposed scale of the industry and the lack of data and analysis currently available.

Policymakers, planners and investors are faced with a series of pernicious trade-offs and tough choices (Sovacool 2014), and while research is developing it is some way from being able to meaningfully inform those choices. The significance of this responsibly is heightened by the potential consequences of the industry scaling up after its introduction. There are serious gaps in our understanding of the potential impacts, many legitimate concerns derived from first principles, and some concerning signals in the literature which require addressing with a robust research investment (Shonkoff et al. 2014; Adgate et al. 2014; Finkel and Hays 2013; Mash et al. 2014). As Werner concludes 'the evidence (or lack thereof) is not sufficient to rule out possible health impacts' (Werner et al. 2015). This uncertainty is also reflected in the grey literature with some recent reviews expressing confidence in the safety of the process given sound operational practices and regulation (Task Force on Shale Gas 2015; The Royal Society and The Royal Academy of Engineering 2012; Public Health England 2014), some being more equivocal (Lightowlers 2015) while others highlight the level of risk (AEA Technology 2012; Maryland Institute for Applied Environmental Health School of Public Health 2014) or even call for a moratorium (New York State Department of Health; McCoy and Saunders 2015). What we do know is that natural gas has been in shale formations for millions of years and will be around for future generations (Finkel and Hays 2013). There is a fundamental requirement for high-quality epidemiological research incorporating real exposure measures covering the periods before, during and post-shale gas extraction, improved understanding of methane leakage throughout the UNGD process and a rigorous analysis of the social and economic impacts in a context of local democratic accountability and equity. In relation to the latter, it is to be hoped that the UK government takes note of the primacy of the decisions of local municipalities about proposed UNGD as, at the time of writing, it has announced its intention to rule on industry appeals against two local planning decisions at a ministerial level.

An 'a priori' programme routinely integrating environmental hazard, exposure and health outcome data across large spatial areas would provide valuable data on plausible associations between a range of potential environmental health insults (not simply UNGD) and health effects, direct public health resources more efficiently, and reassure the public that 'something is being done' to proactively protect them. It is more than unfortunate that despite repeated calls for such a tracking system over many years (Finkel et al. 2015; Middleton and Saunders 2015; Penning et al. 2014; Finkel and Hays 2013; Saunders et al. 2012) and the required tools and expertise already readily being available that such a programme has not already been established. It is clearly better as Goldstein said 'to anticipate the potential for harm, and then act proactively, to prevent it' (Mitka 2012). There will undoubtedly be other novel technologies in the future that challenge the existing knowledge base and an environmental public health tracking programme would provide policymakers, regulators and public health practitioners with essential data and analysis to inform decisions and actions.

As the available evidence does not enable a definitive public health judgment, a position shared by the US Centers for Disease Control (Centers for Disease Control and Prevention), we have a duty to pursue and assess that evidence while ensuring that, in the meantime, communities are not exposed to unacceptable risks. Several countries and North American states have banned, or imposed moratoria on, hydraulic fracturing including France, Bulgaria, Germany, Scotland, Wales, New York, Nova Scotia, Newfoundland, Quebec and New Brunswick (Finkel et al. 2015). The Wingspread Declaration on the Precautionary Principle counsels that 'When an activity raises threats of harm to human health or the environment, precautionary measures should be taken even if some cause and effect relationships are not established scientifically. In this context the proponent of the activity, rather than the public, should bear the burden of proof' (Science and Environmental Health Network 2016). Considering the uncertainties surrounding the health, environmental, social, global warming potential and economic implications of unconventional gas within this internationally recognised framework, it would seem prudent to incentivise further research across all the domains of UNGD-related impact and delay any proposed developments until the products of this investment have been peer-reviewed and assessed. It is recognised that the decision to allow UNGD in the UK will have a major political dimension which is reflected in the UK government reserving the final planning appeal decision to central government rather than the local planning inspector. If UNGD is permitted in the UK local agencies must be adequately resourced to respond to the environmental, social and economic effects, and the commitments by the UK government and industry described above must be rigorously applied together with the establishment of a comprehensive environmental public health tracking system to monitor any emerging risks and focus interventions most effectively.

Appendix 1: Glossary/acronyms

AMCV	Air monitoring comparison values
ATSDR	Agency for Toxic Substances and Disease Registry
BTEX	Benzene, toluene, ethylbenzene and xylene
CHD	Coronary heart defects
CIs	Confidence intervals
CNS	Central nervous system
CO	Carbon monoxide
CS_2	Carbon disulphide
DBP	Disinfection by-products
DEP	Department of Environmental Protection
EDC	Endocrine disrupting chemical
EPA	Environmental Protection Agency
EUR	Estimated ultimate recovery
FPH	Faculty of Public Health
GHG	Greenhouse gas
GI	Gastrointestinal
GIS	Geographic information system
GWP	Global warming potential
H_2S	Hydrogen sulphide
HAPs	Hazardous air pollutants
HI	Hazard index
HVHF	High-volume hydraulic fracturing
IRIS	Integrated risk information system
LCA	Life cycle analysis
LHV	Lower heating value
LUST	Leaking underground storage tanks
MCL	Maximum content level
ML	Local magnitude
Mw	Magnitude scale
NIOSH	National Institute for Occupational Safety and Health
NMHCs	Non-methane hydrocarbons
NORM	Naturally occurring radioactive materials
NOx	Oxides of nitrogen
NTD	Neural tube defects
OEL	Occupational exposure limit
OSHA	Occupational Safety and Health Administration
ONG	Oil and natural gas
PAHs	Polycyclic aromatic hydrocarbons
PEL	Permissible exposure limit
PM	Particulate matter
PSE Healthy Energy	Physicians, Scientists and Engineers for Healthy Energy
PSM	Propensity score matching
REL	Recommended exposure limit sure limit
SGA	Small for gestational age
SIRs	Standardised incidence ratios
SO_2	Sulphur dioxide
TCEQ	Texas Commission on Environmental Quality

TLV	Threshold limit value
UOG	Unconventional oil and gas extraction
VOCs	Volatile organic compounds
WTP	Willing to pay
WtW	Well to wire
WWTP	Wastewater treatment plant

Appendix 2: Search strategy

1. UNGD: Shale gas, shale gas development, shale gas drill$, shale gas exploration, shale gas industry, shale gas production, unconventional gas, unconventional gas extraction, frack$, hydraulic fracturing, fracturing, high volume hydraulic fracturing, HVHF
2. Exposure: Air quality, pollution, water, land, contamination, toxin$, PAH$, benzene, methane, metal$, diesel fume$, VOC$, endocrine disrupt$, PM, particulate matter, particulate$, naturally occurring radioactive mat$, fume$
3. Health: Public health, cancer$, neurological, neurobehavioral, reproductive, Low birth weight, birth outcome$, congenital heart defect$, neural tube defect$, oral cleft$, pre term birth$, stress, occupational health, mental health, mental well-being, conception, infertility
4. Nuisance: Noise, dust, odour$, odor$, light, traffic, congestion
5. Climate change: Climate change, green house gas$, GHGs, methane, energy policy, fuel policy, energy security
6. Economic: Econom$, local economy, water sustainability, income, employment, disposable income, fuel poverty, rural economy$
7. Seismicity: Seism$, earthquake$, tremor$

1 and 2, 1 and 3, 1 and 4, 1 and 5, 1 and 6, 1 and 7.

Databases

The following databases were searched:

Ovid Medline, Economic and Social Research Council, Centre for Economic Policy Research.

Citation searches

Reference lists were examined for papers not identified in searches.

Grey literature/internet/key informants

Includes advice from recognised experts in the field and domestic and international government and key institutional websites.

Inclusion/exclusion

Inclusion:

All: English language, no year restrictions, international, national, regional or local effects, exclusively or significantly related to, or specifically considers HVHF and any associated infrastructure, development, operation or legacy activities/impacts.

Exposure: human, all environmental media, measure of exposure (direct or indirect).

Health: clinically diagnosed and self-reported symptoms.

Nuisance/economic: direct or indirect economic, environmental, nuisance and/or social impacts.

Climate change/policy: all GHGs, impact on compliance with fuel/energy and climate change policies and commitments.

Exclusion: animal studies, non-English, anonymous pieces, studies of UNGD technology, environmental exposures based on estimates with no measured data, levels of contamination in waste products with no assessment or estimation of exposure potential, traffic-related accidents (the UK industry will not require the level of heavy vehicle support reported in the USA and elsewhere), non-peer-reviewed commentaries, opinions, editorials, letters to the editor.

Paper review and data extraction

Data extracted to a pre-defined data extraction table. A 10% sample of included papers independently assessed by two reviewers and unresolved anomalies referred to the other authors for resolution.

Appendix 3: Excluded papers

	Paper	Reason for rejection
1.	Abrahams LS et al. Life Cycle Greenhouse Gas Emissions From U.S. Liquefied Natural Gas Exports: Implications for End Uses. *Environ. Sci. Technol.*, **2015**, *49* (5), pp 3237–3245	LNG exports
2.	Ahmadov R, McKeen S, Trainer M, Banta R, Brewer A, Brown S, et al. 2015. Understanding high wintertime ozone pollution events in an oil- and natural gas-producing region of the western US. Atmos. Chem. Phys. 15:411–429	Oil and gas—no distinction of dominant source
3.	Albertson JD et al. A Mobile Sensing Approach for Regional Surveillance of Fugitive Methane Emissions in Oil and Gas Production. *Environ. Sci. Technol.*, **2016**, *50* (5), pp 2487–249	Describes method for detecting methane
4.	Alexander BM et al. The Development and Testing of a Prototype Mini-Baghouse to Control the Release of Respirable Crystalline Silica from Sand Movers. J Occup Environ Hyg. 2016, 13(8):628–38	Testing emission control
5.	Allard DJ. Pennsylvania's technologically enhanced, naturally occurring radioactive material experiences and studies of the oil and gas industry. Health Phys 2015;108(2):178	Presentation
6.	Allen DT et al. Methane Emissions from Process Equipment at Natural Gas Production Sites in the United States: Pneumatic Controllers *Environ. Sci. Technol.*, **2015**, *49* (1), pp 633–640	Principally natural gas but includes conventional and unconventional and oil. No distinction of dominant source
7.	Alvarez, Ramón A, et al. Greater Focus Needed on Methane Leakage from Natural Gas Infrastructure. Proceedings of the National Academy of Sciences 109 (2012): 6435–6440	Examines changes to vehicle fleet as well as use for electricity
8.	Asche F et al. *Energy Policy*, 2012, vol. 47, issue C, pages 117–124	Not an issue for UK
9.	Aucott ML and Melillo JM. A Preliminary Energy Return on Investment Analysis of Natural Gas from the Marcellus Shale. Journal of Industrial Ecology, 17: 668–679	Doesn't address economic (dis)benefits
10.	Bern CR, Clark ML, Schmidt TS, Holloway JM, McDougal RR. 2015. Soil disturbance as a driver of increased stream salinity in a semiarid watershed undergoing energy development. J. Hydrol. 524:123–136; doi:10.1016/j.jhydrol.2015.02.020	Website link. Refers to soil disturbance of any type
11.	Binnion, M. 2012. How the technical differences between shale gas and conventional gas projects lead to a new business model being required to be successful. Marine and Petroleum Geology. 31(1): 3–7	Doesn't address economic (dis)benefits
12.	Birdsell DT, Rajaram H, Dempsey D, Viswanathan HS. 2015. Hydraulic fracturing fluid migration in the subsurface: A review and expanded modeling results. Water Resour. Res. 51:7159–7188; doi:10.1002/2015WR017810	Simulation
13.	Bolden AL et al. New Look at BTEX: Are Ambient Levels a Problem? *Environ. Sci. Technol.*, **2015**, *49* (9), pp 5261–5276	Review of non-cancer health effects of BTEX
14.	Boothroyd IM et al. Fugitive emissions of methane from abandoned, decommissioned oil and gas wells. Sci Total Environ. 2016 Mar 15;547:461–9	Abandoned-not relevant to UK
15.	Bowen, Z. H., et al. (2015), Assessment of surface water chloride and conductivity trends in areas of unconventional oil and gas development—Why existing national data sets cannot tell us what we would like to know, Water Resour. Res., 51, 704–71	Oil and gas—no distinction of dominant source
16.	Boyle MD, Payne-Sturges DC, Sangaramoorthy T, Wilson S, Nachman KE, Babik K, et al. (2016) Hazard Ranking Methodology for Assessing Health Impacts of Unconventional Natural Gas Development and Production: The Maryland Case Study. PLoS ONE 11(1): e0145368. doi:10.1371/journal.pone.0145368	Methodological and hypothetical examples
17.	Brantley HL, Thoma ED, Eisele AP. 2015. Assessment of volatile organic compound and hazardous air pollutant emissions from oil and natural gas well pads using mobile remote and on-site direct measurements. Journal of the Air & Waste Management Association 65:1072–1082	Oil and gas—no distinction of dominant source

	Paper	Reason for rejection
18.	Brantley SL, Yoxtheimer D, Arjmand S, Grieve P, Vidic R, Pollak J, et al. 2014. Water resource impacts during unconventional shale gas development: The Pennsylvania experience. International Journal of Coal Geology; doi:10.1016/j.coal.2013.12.017	Shortcomings of monitoring of contraventions
19.	British Columbia Oil and Gas Commission 2012	Not peer-reviewed
20.	Brown D, Weinberger B, Lewis C, Bonaparte H. 2014. Understanding exposure from natural gas drilling puts current air standards to the test. Rev Environ Health 29:277–292; doi:10.1515/reveh-2014-0002	Inadequacy of air quality standards
21.	Brown DR, Lewis C, Weinberger BI. 2015. Human exposure to unconventional natural gas development: A public health demonstration of periodic high exposure to chemical mixtures in ambient air. Journal of Environmental Science and Health, Part A 50: 460–472	Hypothetical
22.	Brown SPA et al. Resources for the Future. Natural gas: a bridge to a low-carbon future? Resources 2009;Issue Brief 09-11	Think tank briefing
23.	Busch C and Gimon E. 2014. Natural Gas versus Coal: Is Natural Gas Better for the Climate? The Electricity Journal, 27 (7): 97–111	Natural gas in general
24.	Burkhart 2013 Potential radon release during fracturing in Colorado. Proceedings of the 2013 International AARST Symposium	Conference proceedings
25.	Carlton AG, Little E, Moeller M, Odoyo S, Shepson PB. 2014. The Data Gap: Can a Lack of Monitors Obscure Loss of Clean Air Act Benefits in Fracking Areas? Environ. Sci. Technol. 48:893–894; doi:10.1021/es405672t	Methodological
26.	Cathles LM et al. A commentary on "The greenhouse-gas footprint of natural gas in shale formations" by R.W. Howarth, R. Santoro, and Anthony Ingraffea. Climatic Change, DOI 10.1007/s10584-011-0333-0	Commentary
27.	Cathles, L. M. (2012), Assessing the greenhouse impact of natural gas, Geochem. Geophys. Geosyst., 13, Q06013, doi:10.1029/2012GC004032	Natural gas in general
28.	Caulton DR et al.Methane Destruction Efficiency of Natural Gas Flares Associated with Shale Formation Wells. *Environ. Sci. Technol.*, **2014**, *48* (16), pp 9548–9554	Efficiency of flaring
29.	Chabudzinski L, Chmiel S, Michalczyk Z. 2015. Metal content in the waters of the upper Sanna River catchment (SE Poland): condition associated with drilling of a shale gas exploration wellbore. Environ. Earth Sci. 74:6681–6691; doi:10.1007/s12665-015-4668-0	Exploratory borewell
30.	Craddock,H. Shale gas in Europe: The chemical challenge. Materials World. 2014 22 2:41	Magazine article
31.	Darbouche H. MENA's Growing Natural Gas Deficit and the Issue of Domestic Prices", *Energy Strategy Reviews*, 2013, 2 (1): 116–121	Not an issue in the UK
32.	de Melo-Martin I et al. The role of ethics in shale gas policies. Sci Total Environ 2014 (470–471) 1114	Ethics
33.	Edwards PM et al. High winter ozone pollution from carbonyl photolysis in an oil and gas basin. Nature. 2014, 514(7522):351–4	Letter
34.	Edwards PM et al. Ozone photochemistry in an oil and natural gas extraction region during winter: simulations of a snow-free season in the Uintah Basin, Utah. Atmos. Chem. Phys., 13, 8955–8971, doi:10.5194/acp-13-8955-2013, 2013	Simulation
35.	Elliot TR and Celia MA. Potential Restrictions for CO2 Sequestration Sites Due to Shale and Tight Gas Production. *Environ. Sci. Technol.*, **2012**, *46* (7), pp 4223–4227	Identifies sites suitable for carbon storage and overlap with shale areas that might be developed-hypothetical
36.	Entrekin SA, Maloney KO, Kapo KE, Walters AW, Evans-White MA, Klemow KM. 2015. Stream Vulnerability to Widespread and Emergent Stressors: A Focus on Unconventional Oil and Gas. PLoS ONE 10:e0137416; doi:10.1371/journal.pone.0137416	Indices to describe watershed vulnerability

	Paper	Reason for rejection
37.	Fanchi JR et al. Probabilistic Decline Curve Analysis of Barnett, Fayetteville, Haynesville, and Woodford Gas Shales. Journal of Petroleum Science and Engineering 2013, 50 109:308–311	Production modelling
38.	Fedak F et al. Birth Outcomes and Natural Gas Development: Methodological Limitations http://dx.doi.org/10.1289/ehp.1408647 volume 122 I number 9 I September 2014	Letter
39.	Field RA et al. Air quality concerns of unconventional oil and natural gas production. Environmental Science. Processes and Impacts 2014;16(5):954–969	Theoretical
40.	Field RA, Soltis J, McCarthy MC, Murphy S, Montague DC. 2015. Influence of oil and gas field operations on spatial and temporal distributions of atmospheric non-methane hydrocarbons and their effect on ozone formation in winter. Atmos. Chem. Phys. 15:3527–3542	Oil and gas—no distinction of dominant source
41.	Finkel ML and Law A. The rush to drill for natural gas: a public health cautionary tale. 2011 101, 5: 784–785	Commentary
42.	Franco B, Bader W, Toon GC, Bray C, Perrin A, Fischer EV, et al. 2015. Retrieval of ethane from ground-based FTIR solar spectra using improved spectroscopy: Recent burden increase above Jungfraujoch. Journal of Quantitative Spectroscopy and Radiative Transfer 160:36–49; doi:10.1016/j.jqsrt.2015.03.017	Not HVHF
43.	Freeman CM et al. A numerical study of performance for tight gas and shale gas reservoir systems Journal of Petroleum Science and Engineering 108: 22–39	Doesn't address economic (dis)benefits
44.	Gallagher ME et al. Natural Gas Pipeline Replacement Programs Reduce Methane Leaks and Improve Consumer Safety. *Environ. Sci. Technol. Lett.*, **2015**, *2* (10), pp 286–291	Remedial action
45.	Gao J and Fengqi U - Shale Gas Supply Chain Design and Operations toward Better Economic and Life Cycle Environmental Performance: MINLP Model and Global Optimization Algorithm. *ACS Sustainable Chem. Eng.*, **2015**, *3* (7), pp 1282–1291	Describes LCA model development-no comparison with other energy sources
46.	Gassiat C et al. 2013. Hydraulic fracturing in faulted sedimentary basins: Numerical simulation of potential contamination of shallow aquifers over long time scales. Water Resour. Res. 49:8310–8327; doi:10.1002/2013WR014287	Model to identify conditions needed for slow migration
47.	Gentner DR et al. Emissions of organic carbon and methane from petroleum and dairy operations in California's San Joaquin Valley. Emissions of organic carbon and methane from petroleum and dairy operations in California's San Joaquin Valley, Atmos. Chem. Phys., 14, 4955–4978, doi:10.5194/acp-14-4955-2014, 2014	Not HVHF
48.	Gilmore K et al. Transport of Hydraulic Fracturing Water and Wastes in the Susquehanna River Basin, Pennsylvania. 2013, Transport of Hydraulic Fracturing Water and Wastes in the Susquehanna River Basin, Pennsylvania." *J. Environ. Eng.*, 10.1061/(ASCE)EE.1943-7870.0000810, B4013002	Estimates GHG contribution of transport in a specific area and transport of fracturing water not relevant to UK
49.	Goldstein BD The importance of public health agency independence: Marcellus shale gas drilling in Pennsylvania. Am J Public Health. 2014,104(2):e13–5	Lack of public health input to risk assessment
50.	Goldstein BD Kriesky J and Pavliakova B Environ Health Perspect. 2012 Apr; 120(4): 483–486	Review of expertise on advisory panels
51.	Goodwin S; Carlson K; Knox K; Douglas C; Rein L. Water intensity assessment of shale gas resources in the Wattenberg field in northeastern Colorado. Environmental Science & Technology. 48(10):5991–5, 2014	Efficient water usage-not relevant to UK
52.	Gracceva F and Zeniewski P. Exploring the uncertainty around potential shale gas development – A global energy system analysis based on TIAM (TIMES Integrated Assessment Model) Energy 2013, 57:443–457	Doesn't address economic (dis)benefits

	Paper	Reason for rejection
53.	Graham J, Irving J, Tang X, Sellers S, Crisp J, Horwitz D, et al. 2015. Increased traffic accident rates associated with shale gas drilling in Pennsylvania. Accident Analysis & Prevention 74:203–209; doi:10.1016/j.aap.2014.11.003	Traffic accidents
54.	Hammes, U et al. Unconventional reservoir potential of the upper Permian Zechstein Group: a slope to basin sequence stratigraphic and sedimentological evaluation of carbonates and organic-rich mudrocks, Northern Germany. Environ Earth Sci 2013, 70: 3797. doi:10.1007/s12665-013-2724-1	Resource estimates
55.	Harriss R et al. Using Multi-Scale Measurements to Improve Methane Emission Estimates from Oil and Gas Operations in the Barnett Shale Region, Texas. *Environ. Sci. Technol.*, **2015**, *49* (13), pp 7524–7526	Viewpoint: oil and gas
56.	Heilweil VM, Stolp BJ, Kimball BA, Susong DD, Marston TM, Gardner PM. 2013. A Stream-Based Methane Monitoring Approach for Evaluating Groundwater Impacts Associated with Unconventional Gas Development. Groundwater 51:511–524; doi:10.1111/gwat.12079	Sampling method
57.	Helmig - Highly Elevated Atmospheric Levels of Volatile Organic Compounds in the Uintah Basin, Utah *Environ. Sci. Technol.*, 2014, *48* (9), pp 4707–4715	Gas field but no reference to HVHF
58.	Hibbard PJ and Shatzki. The Interdependence of Electricity and Natural Gas: Current Factors and Future Prospects. The Electricity Journal 2012, 25(4):6–17	Not relevant
59.	Holahan R and Arnold G. An institutional theory of hydraulic fracturing policy. Ecological Economics 2013, 94 127–134	Doesn't address economic (dis)benefits
60.	Howard T et al. Sensor transition failure in the high flow sampler: Implications for methane emission inventories of natural gas infrastructure. J Air Waste Manag Assoc. 2015 65(7):856–62	Implications of sensor failure
61.	Howarth, R.W., Santoro, R. & Ingraffea, A. Climatic Change (2012) 113: 537. doi:10.1007/s10584-012-0401-0	Response to Cathles paper
62.	Ikonnikova S et al. Factors influencing shale gas production forecasting: Empirical studies of Barnett, Fayetteville, Haynesville, and Marcellus Shale plays. 2015, Factors influencing shale gas production forecasting: Empirical studies of Barnett, Fayetteville, Haynesville, and Marcellus Shale plays. Economics of Energy & Environmental Policy 2015, 4, (1): 19–35	Doesn't address economic (dis)benefits
63.	Jeong S et al. Spatially Explicit Methane Emissions from Petroleum Production and the Natural Gas System in California. *Environ. Sci. Technol.*, **2014**, *48* (10): 5982–5990	Not HVHF focused
64.	Johnson Dr et al. Methane Emissions from Leak and Loss Audits of Natural Gas Compressor Stations and Storage Facilities. *Environ. Sci. Technol.*, **2015**, *49* (13): 8132–8138	Compares UNG wells with CVNG wells
65.	Kahrilas,G. A.Blotevogel,J. Stewart,P. S. Borch,T. Biocides in hydraulic fracturing fluids: A critical review of their usage, mobility, degradation, and toxicity 2015 49 (1) 16–32	Review of considerations in selecting biocides
66.	Kaiser MJ. Haynesville shale play economic analysis. Journal of Petroleum Science and Engineering 2012, 82–83:75–89	Economic viability of this play
67.	Kaiser MJ. Profitability assessment of Haynesville shale gas well. Energy 2012, 50 38(1):315–330	Doesn't address economic (dis)benefits
68.	Kaktins - Drilling the Marcellus shale for natural gas: environmental health issues for nursing The Pennsylvania nurse react-text: 44 66(1):4–8; quiz 8-9/react-text react-text: 47/react-text react-text: 48 March 2011	General overview for nurses
69.	Kang M et al. Direct measurements of methane emissions from abandoned oil and gas wells in Pennsylvania. PNAS 2014, 111(51):18173–18177	Abandoned sites

	Paper	Reason for rejection
70.	Kang M, Baik E, Miller AR, Bandilla KW, Celia MK. 2015. Effective Permeabilities of Abandoned Oil and Gas Wells: Analysis of Data from Pennsylvania. Environ. Sci. Technol. 49:4757–4764; doi:10.1021/acs.est.5b00132	Abandoned oil and gas wells
71.	Karion A et al. Aircraft-Based Estimate of Total Methane Emissions from the Barnett Shale Region. *Environ. Sci. Technol.*, **2015**, *49* (13): 8124–813	Differentiates between oil/gas-related emissions and other sources but specifically states no attribution to HVHF
72.	Karion A et al. 2015 - Methane emissions estimate from airborne measurements over a western United States natural gas field. Geophysical Research Letters 2013, 40(16):4393–4397	Oil and gas—no distinction of dominant source
73.	Kerschke DI and Schulz H. The shale gas potential of Tournaisian, Visean, and Namurian black shales in North Germany: baseline parameters in a geological context. Environ Earth Sci 2013, 70: 3817. doi:10.1007/s12665-013-2745-9	Doesn't address economic (dis)benefits
74.	Kopald, D. E. The Conference on Corporate Interference with Science and Health: fracking, food and wireless: genesis, rationale, and results. 2013 28 (4):145–158	Conference proceedings
75.	Korfmacher KS et al. Public health and high volume hydraulic fracturing. New Solut. 2013;23(1):13–31. doi: 10.2190/NS.23.1.c	Public health policy discussion
76.	Kort EA et al. Four corners: The largest US methane anomaly viewed from space. Geophysical Research Letters 2014, 41(19): 6898–6903	Gas, coal and coalbed methane
77.	Koss AR, de Gouw J, Warneke C, Gilman JB, Lerner BM, Graus M, et al. 2015. Photochemical aging of volatile organic compounds associated with oil and natural gas extraction in the Uintah Basin, UT, during a wintertime ozone formation event. Atmos. Chem. Phys. 15:5727–5741; doi:10.5194/acp-15-5727-2015	Oil and gas—no distinction of dominant source
78.	Kovats S et al. The health implications of fracking. The Lancet 2014, 383 (9919): 757–758	Commentary on conference
79.	Krzyzanowski - Environmental pathways of potential impacts to human health from oil and gas development in northeast British Columbia, Canada *Environmental Reviews*, 2012, 20(2): 122–134, 10	Oil and gas—no distinction of dominant source
80.	Lamb BK et al. Direct Measurements Show Decreasing Methane Emissions from Natural Gas Local Distribution Systems in the United States. *Environ. Sci. Technol.*, **2015**, *49* (8): 5161–5169	Distribution systems—all gas doesn't specify UNG
81.	Lan X, Talbot R, Laine P, Torres A, Lefer B, Flynn J. 2015. Atmospheric Mercury in the Barnett Shale Area, Texas: Implications for Emissions from Oil and Gas Processing. Environ. Sci. Technol. 49:10692–10700	Oil and gas—no distinction of dominant source
82.	Lauver LS Environmental health advocacy: an overview of natural gas drilling in northeast Pennsylvania and implications for pediatric nursing J Pediatr Nurs. 2012 Aug;27(4):383–9	Guidance for nurses on evaluating issue
83.	Law A et al. Public Health England's draft report on shale gas extraction. *BMJ* 2014;348:g2728	Editorial
84.	Lee J. The regional economic impact of oil and gas extraction in Texas. Energy Policy, 2015, (56) 87:60–71	University briefing paper
85.	Lee, L., Wooldridge, P. J., deGouw, J., Brown, S. S., Bates, T. S., Quinn, P. K., and Cohen, R. C.: Particulate organic nitrates observed in an oil and natural gas production region during wintertime, Atmos. Chem. Phys., 15, 9313–9325	Oil and gas—no distinction of dominant source
86.	Lipscomb,C. A. Wang,Y. Kilpatrick,S. J. Unconventional shale gas development and real estate valuation issues. 2012 42 (2): 161–175	Unavailable

	Paper	Reason for rejection
87.	Llewellyn GT, Dorman F, Westland JL, Yoxtheimer D, Grieve P, Sowers T, et al. 2015. Evaluating a groundwater supply contamination incident attributed to Marcellus Shale gas development. PNAS 201420279; doi:10.1073/pnas.1420279112	Pre-drilling salinisation sources
88.	Lu X. Implications of the Recent Reductions in Natural Gas Prices for Emissions of CO2 from the US Power Sector. *Environ. Sci. Technol.*, **2012**, *46* (5): 3014–3021	US gas prices-not relevant to UK
89.	Lyon DR et al. Constructing a Spatially Resolved Methane Emission Inventory for the Barnett Shale Region. *Environ. Sci. Technol.*, **2015**, *49* (13): 8147–8157	Oil and gas inventory estimates
90.	Mackie P, Johnman C, Sim F. 2013. Hydraulic fracturing: a new public health problem 138 years in the making? Public Health 127:887–888	Editorial
91.	Macy TR et al. Carbon Footprint Analysis of Source Water for Hydraulic Fracturing: A Case Study of Mine Water Versus Freshwater. Water Environ 2015, 34: 20	Not relevant to UK
92.	Marchese AJ et al. Methane Emissions from United States Natural Gas Gathering and Processing. *Environ. Sci. Technol.*, **2015**, *49* (17): 10718–10727	All natural gas
93.	McCarron GP, King D. 2014. Unconventional natural gas development: economic salvation or looming public health disaster? Australian and New Zealand Journal of Public Health 38:108–109	Commentary
94.	McCawley M. Air Contaminants Associated with Potential Respiratory Effects from Unconventional Resource Development Activities. Semin Respir Crit Care Med. 2015, 36(3):379–87	No measures and uses traffic volumes as metric
95.	McCubbin DR et al. Quantifying the health and environmental benefits of wind power to natural gas. Energy Policy 2013, 53: 429–441	Reject-wind power
96.	McCubbin –D and Sovacool BK. The Hidden Factors That Make Wind Energy Cheaper than Natural Gas in the United States. Electricity Journal, 24 (9): 84–95	Wind energy
97.	McDermott-Levy R, Kaktins N, Sattler B. Fracking, the environment, and health. 2013 113 (6): 45–51	General implications for nursing
98.	McGlade C et al. Unconventional gas – A review of regional and global resource estimates. Energy 2013, 55: 571–584.	Resource estimates
99.	McKain K et al. Methane emissions from natural gas infrastructure and use in the urban region of Boston, Massachusetts. PNAS 2015 Feb, 112(7):1941–6	NG infrastructure and use and not UNG focused
100.	Melikoglu M. Shale gas: Analysis of its role in the global energy market. Renewable and Sustainable Energy Reviews 2014, 37: 460–468	Doesn't address economic (dis)benefits
101.	Meng, Q. Spatial analysis of environment and population at risk of natural gas fracking in the state of Pennsylvania, USA. Sci Total Environ 2015, 515–516: 198–206	Uses GIS to map 'risk' defined simply as proximity. No exposure measures or estimates and no health data
102.	Miller SM et al. Anthropogenic emissions of methane in the United States. PNAS 2013, 110(50): 20018–20022	General assessment of methane sources
103.	Mitchell AL and Casman EA. Economic Incentives and Regulatory Framework for Shale Gas Well Site Reclamation in Pennsylvania. *Environ. Sci. Technol.*, **2011**, *45* (22): 9506–9514	Doesn't address economic (dis)benefits
104.	Mitchell AL et al. Measurements of Methane Emissions from Natural Gas Gathering Facilities and Processing Plants: Measurement Results. *Environ. Sci. Technol.*, **2015**, *49* (5): 219–3227	All natural gas
105.	Moitra, S. Puri, R. Paul, D. Huang, Y.-C T. Global perspectives of emerging occupational and environmental lung diseases. 2015 21 (2): 114–120	General review of potential sentinel occupational diseases

	Paper	Reason for rejection
106.	Myhrvold NP and Caldeira K. Greenhouse gases, climate change and the transition from coal to low-carbon electricity. Environmental Research Letters Journal 2012, 7(1)	No specific consideration of HVHF
107.	Nathan BJ et al. Near-Field Characterization of Methane Emission Variability from a Compressor Station Using a Model Aircraft. *Environ. Sci. Technol.*, **2015**, *49* (13): 7896–7903	Compressor station
108.	Oglend - Shale Gas Boom Affecting the Relationship Between LPG and Oil Prices	Not an issue in the UK
109.	Ogneva-Himmelberger Y, Huang L. 2015. Spatial distribution of unconventional gas wells and human populations in the Marcellus Shale in the United States: Vulnerability analysis. Applied Geography 60:165–174	Analysis of spatial relationship between socio-economic factors and UNGD sites
110.	Olaguer EP et al. Updated methods for assessing the impacts of nearby gas drilling and production on neighborhood air quality and human health. J Air Waste Manag Assoc. 2016, 66(2):173–83	Methodological
111.	Olaguer EP. 2012. The potential near-source ozone impacts of upstream oil and gas industry emissions. J Air Waste Manag Assoc 62: 966–977	Hypothetical
112.	Oltmans S et al. Anatomy of wintertime ozone associated with oil and natural gas extraction activity in Wyoming and Utah. Elementa: Science of the Anthropocene, 2. 000024	Meteorological
113.	Pacsi AP, Alhajeri NS, Zavala-Araiza D, Webster MD, Allen DT. 2013. Regional air quality impacts of increased natural gas production and use in Texas. Environ. Sci. Technol. 47:3521–3527; doi:10.1021/es3044714	Production estimated
114.	Pacsi AP, Kimura Y, McGaughey G, Mcdonald-Buller EC, Allen DT. 2015. Regional ozone impacts of increased natural gas use in the Texas power sector and development in the Eagle Ford shale. Environ. Sci. Technol.; doi:10.1021/es5055012	Natural gas use
115.	Parker KM, Zeng T, Harkness J, Vengosh A, Mitch WA. 2014. Enhanced Formation of Disinfection By-Products in Shale Gas Wastewater-Impacted Drinking Water Supplies. Environ. Sci. Technol.; doi:10.1021/es5028184	Experimental
116.	Patzek TW et al. Gas production in the Barnett Shale obeys a simple scaling theory. PNAS 2013, 110(49): 19731–19736	Doesn't address economic (dis)benefits
117.	Peischel J et al. Quantifying sources of methane using light alkanes in the Los Angeles basin, California. Journal of Geophysical Research: Atmospheres 2013;118(10):4974–4990	Not focused on shale
118.	Pekney NJ et al. Measurement of atmospheric pollutants associated with oil and natural gas exploration and production activity in Pennsylvania's Allegheny National Forest. J Air Waste Manag Assoc. 2014, 64(9):1062–72	Oil and gas—no distinction of dominant source
119.	Penning TM, Breysse PN, Gray K, Howarth M, Yan B. 2014. Environmental health research recommendations from the Inter-Environmental Health Sciences Core Center Working Group on Unconventional Natural Gas Drilling Operations. Environ Health Perspect 122:1155–1159	Working group research recommendations
120.	Perry, S. L. Using ethnography to monitor the community health implications of onshore unconventional oil and gas developments: examples from Pennsylvania's Marcellus Shale. 2013 23 (1) 33-53	Methodological
121.	Pétron G, Frost G, Miller BR, Hirsch AI, Montzka SA, Karion A, et al. 2012. Hydrocarbon emissions characterization in the Colorado Front Range: A pilot study. J. Geophys. Res. 117:D04304	Pilot study-oil, gas and other sources
122.	Pétron G, Karion A, Sweeney C, Miller BR, Montzka SA, Frost G, et al. 2014. A new look at methane and non-methane hydrocarbon emissions from oil and natural gas operations in the Colorado Denver-Julesburg Basin. J. Geophys. Res. Atmos	Oil and gas—no distinction of dominant source

	Paper	Reason for rejection
123.	Phillips NG et al. Mapping urban pipeline leaks: Methane leaks across Boston. Environ Pollut. 2013, 173:1–4	Urban pipeline leaks
124.	Powers M, Saberi P, Pepino R, Strupp E, Bugos E, Cannuscio CC. 2015. Popular Epidemiology and "Fracking": Citizens' Concerns Regarding the Economic, Environmental, Health and Social Impacts of Unconventional Natural Gas Drilling Operations. J. Community Health 40:534–541	Analysis of letters to local newspaper
125.	Pratson LF et al. Fuel Prices, Emission Standards, and Generation Costs for Coal vs Natural Gas Power Plants. Environ Sci Technol. 2013, 47(9):4926–33	Relates to power stations
126.	Prenni - Oil and gas impacts on air quality in federal lands in the Bakken region: an overview of the Bakken Air Quality Study and first results. *Environ. Sci. Technol.*, **2013**, *47* (9), 4926–4933	Fossil fuel
127.	Rafferty MA, Limonik E. 2013. Is shale gas drilling an energy solution or public health crisis? Public Health Nurs 30:454–462	Call for nursing research and hia
128.	Rahm BG, Bates JT, Bertoia LR, Galford AE, Yoxtheimer DA, Riha SJ. Wastewater management and Marcellus Shale gas development: Trends, drivers, and planning implications. J Environ Manage 2013, 120:105–113	Trends in wastewater use and policies
129.	Rappenglück B, Ackermann L, Alvarez S, Golovko J, Buhr M, Field RA, et al. 2014. Strong wintertime ozone events in the Upper Green River basin, Wyoming. Atmos. Chem. Phys. 14:4909–4934; doi:10.5194/acp-14-4909-2014	Fossil fuel exploration
130.	Reagan MT, Moridis GJ, Keen ND, Johnson JN. 2015. Numerical simulation of the environmental impact of hydraulic fracturing of tight/shale gas reservoirs on near-surface groundwater: Background, base cases, shallow reservoirs, short-term gas, and water transport. Water Resour. Res. 51:2543–2573; doi:10.1002/2014WR016086	Hypothetical
131.	Rella CW et al. Measuring Emissions from Oil and Natural Gas Well Pads Using the Mobile Flux Plane Technique. *Environ. Sci. Technol.*, **2015**, *49* (7): 4742–4748	Proportion of emissions by well pad
132.	Rich,A Grover,J. Sattler,M. Hunt,A. Holbrook,J. Howard,J. T1 - Air emissions from natural gas exploration and mining in the Barnett shale geologic reservoir. 2012 1 116–133. Proceedings of the Air and Waste Management Association's Annual Conference and Exhibition, AWMA	Conference proceedings-published in included paper from JAWMA
133.	Ritter K et al. Industry experience in deriving updated emission factors to characterize methane emissions for select emission sources in natural gas systems. Carbon Management 2014, 5(5–6): 107	Review of industry efforts to characterise emissions
134.	Rodriguez MA, Barna MG, Moore T. 2009. Regional impacts of oil and gas development on ozone formation in the western United States. J Air Waste Manag Assoc 59: 1111–1118	Oil and gas—no distinction of dominant source
135.	Rutter AP, Griffin RJ, Cevik BK, Shakya KM, Gong L, Kim S, et al. 2015. Sources of air pollution in a region of oil and gas exploration downwind of a large city. Atmospheric Environment 120:89–99; doi:10.1016/j.atmosenv.2015.08.073	Oil and gas—no distinction of dominant source
136.	Sanchez N. and Mays DC. Effect of methane leakage on the greenhouse gas footprint of electricity generation. Climatic Change 2015, 133: 169. doi:10.1007/s10584-015-1471-6	Hypothetical model to identify leakage level required to eliminate advantage over coal
137.	Sang W, Stoof CR, Zhang W, Morales VL, Gao B, Kay RW, et al. 2014. Effect of Hydrofracking Fluid on Colloid Transport in the Unsaturated Zone. Environ. Sci. Technol.; doi:10.1021/es501441e	Colloid transport
138.	Schmidt CW. Blind Rush? Shale Gas Boom Proceeds Amid Human Health Questions. Environ Health Perspect 2011, 119:a348–a353	Environews article-subject to internal editing
139.	Schnell RC, Oltmans SJ, Neely RR, Endres MS, Molenar JV, White AB. 2009. Rapid photochemical production of ozone at high concentrations in a rural site during winter. Nature Geosci 2:120–122; doi:10.1038/ngeo415	Letter

	Paper	Reason for rejection
140.	Schwartz MO. 2014. Modelling the hypothetical methane-leakage in a shale-gas project and the impact on groundwater quality. Environ Earth Sci 73:4619–4632; doi:10.1007/s12665-014-3787-3	Hypothetical
141.	Schwietzke - Natural gas fugitive emissions rates constrained by global atmospheric methane and ethane. *Environ. Sci. Technol.*, 2014, *48* (14), pp 7714–7722	All natural gas no distinction of dominant source
142.	Shearer - The effect of natural gas supply on US renewable energy and CO2 emissions. Environ. Res. Lett. 9 (2014) 094008 (8 pp)	All natural gas no distinction of dominant source
143.	Skalak KJ, Engle MA, Rowan EL, Jolly GD, Conko KM, Benthem AJ, et al. 2014. Surface disposal of produced waters in western and southwestern Pennsylvania: Potential for accumulation of alkali-earth elements in sediments. International Journal of Coal Geology 126:162–170; doi:10.1016/j.coal.2013.12.001	Surface disposal of produced water (not relevant to UK)
144.	States S, Cyprych G, Stoner M, Wydra F, Kuchta J, Monnell J, et al. 2013. Brominated THMs in Drinking Water: A Possible Link to Marcellus Shale and Other Wastewaters. Journal - American Water Works Association 105:E432–E448; doi:10.5942/jawwa.2013.105.0093	Wastes associated with sources including non-HVHF
145.	Stephenson E et al. Greenwashing gas: Might a 'transition fuel' label legitimize carbon-intensive natural gas development? Energy Policy 2012, 46: 452–459	General discussion of uncertainties
146.	Subramanian R et al. Methane Emissions from Natural Gas Compressor Stations in the Transmission and Storage Sector: Measurements and Comparisons with the EPA Greenhouse Gas Reporting Program Protocol. *Environmental Science and Technology* 2015, 49(5): 3252–3261	Identification of super-emitters and comparison of emissions with EPA emissions
147.	Tao Z and Clarens A. Estimating the Carbon Sequestration Capacity of Shale Formations Using Methane Production Rates. *Environ. Sci. Technol.*, **2013**, *47* (19):11318–11325	Relates to carbon-capture capacity
148.	Teasdale CJ et al. Ground Gas Monitoring: Implications for Hydraulic Fracturing and CO2 Storage. Environ Sci Technol 2014, 48(23):13610–13616	Technical assessment of ground-level monitoring techniques
149.	Thompson CR, Hueber J, Helmig D. 2014. Influence of oil and gas emissions on ambient atmospheric non-methane hydrocarbons in residential areas of Northeastern Colorado. Elementa: Science of the Anthropocene 2:000035	Oil and gas—no distinction of dominant source
150.	Townsend-Small A et al. Integrating Source Apportionment Tracers into a Bottom-up Inventory of Methane Emissions in the Barnett Shale Hydraulic Fracturing Region. *Environ. Sci. Technol.*, **2015**, *49* (13): 8175–8182	Methods of source apportionment
151.	Tyner DR and Johnson MR. Emission Factors for Hydraulically Fractured Gas Wells Derived Using Well- and Battery-level Reported Data for Alberta, Canada. Environ Sci Technol. 2014, 48(24):14772–81	Relative contribution of differing phases but no analysis of overall significance of UNGD
152.	Venkatesh A et al. Uncertainty in life cycle greenhouse gas emissions from United States natural gas end-uses and its effects on policy. *Environ. Sci. Technol.*, **2011**, *45* (19): 8182–8189	Domestic and imported natural gas
153.	Wakamatsu H and Aruga K. The impact of the shale gas revolution on the U.S. and Japanese natural gas markets. *Energy Policy* 2013, 62 (C): 1002–1009	Changes in US and Japanese natural gas market structures
154.	Walters K, Jacobson J, Kroening Z, Pierce C. 2015. PM2.5 Airborne Particulates Near Frac Sand Operations. J. Environ. Health 78: 8–12	Not HVHF
155.	Walton J and Woocay A. Environmental issues related to enhanced production of natural gas by hydraulic fracturing. 2013 8 (1) 62–71	Non-peer-reviewed section of journal
156.	Warneke C et al. PTR-QMS versus PTR-TOF comparison in a region with oil and natural gas extraction industry in the Uintah Basin in 2013. Atmos. Meas. Tech 2015, 8: 411–420	Methodological

	Paper	Reason for rejection
157.	Warneke C, Gseleger F, Edwards PM, Dube W, Pétron G, Kofler J, et al. Volatile organic compound emissions from the oil and natural gas industry in the Uinta Basin, Utah: point sources compared to ambient air composition. Atmos. Chem. Phys. Discuss 2014, 14:11895–11927; doi:10.5194/acpd-14-11895-2014	Differentiates between the composition of emissions from oil and gas wells but no discussion of significance in terms of exposure/GHG
158.	Warner NR, Darrah TH, Jackson RB, Millot R, Kloppmann W, Vengosh A. 2014. New Tracers Identify Hydraulic Fracturing Fluids and Accidental Releases from Oil and Gas Operations. Environ. Sci. Technol.; doi:10.1021/es5032135	Methodological
159.	Weber - A decade of natural gas development: The makings of a resource curse? Selected Paper prepared for presentation at the Agricultural & Applied Economics Association's 2013 AAEA & CAES Joint Annual Meeting, Washington, DC, August 4–6, 2013	Paper prepared for presentation at meeting and single author's own views
160.	Weijermars R. Economic appraisal of shale gas plays in Continental Europe. Applied Energy 2013,106:100–115	Economics of the process not impacts
161.	Weijermars R. US shale gas production outlook based on well roll-out rate scenarios. *Applied Energy*, 2014, 124 (C): 283–297	Doesn't address economic (dis)benefits
162.	Weinhold B. 2012. The Future of Fracking: New Rules Target Air Emissions for Cleaner Natural Gas Production. Environ Health Perspect 120:a272–a279	Discussion of revised regulation
163.	Wennberg - On the Sources of Methane to the Los Angeles Atmosphere. Environ. Sci. Technol., 2012, 46 (17), pp 9282–9289	Fossil fuel emissions—no distinction of HVHF
164.	Wigley TML. Coal to gas: the influence of methane leakage. Climatic Change 2011, 108: 601. doi:10.1007/s10584-011-0217-3	Theoretical, letter
165.	Williams JF, Lundy JB, Chung KK, Chan RK, King BT, Renz EM, et al. 2014. Traumatic Injuries Incidental to Hydraulic Well Fracturing: A Case Series. Journal of Burn Care & Research 1; doi:10.1097/BCR.0000000000000219	Not available-relates to occupational burn injuries
166.	Witter RZ Tenney L Clark S Newman LS. Occupational exposures in the oil and gas extraction industry: State of the science and research recommendations. 2014 57 (7):847–856. American Journal of Industrial Medicine Volume 57, Issue 7, pages 847–856	Review of oil and gas industry-hvhf papers already identified
167.	Yacovitch TI et al. Mobile Laboratory Observations of Methane Emissions in the Barnett Shale Region. *Environ. Sci. Technol.*, **2015**, *49* (13): 7889–7895	Assesses utility of monitoring method—no assessment of overall GHG impact of UNGD
168.	Yao Y et al. Understanding variability to reduce the energy and GHG footprints of U.S. ethylene production. *Environ. Sci. Technol.*, **2015**, *49* (24): 14704–14716	Ethylene
169.	Yao Y, Chen T, Shen SS, Niu Y, DesMarais TL, Linn R, et al. 2015. Malignant human cell transformation of Marcellus Shale gas drilling flow back water. Toxicology and Applied Pharmacology 288:121–30; doi:10.1016/j.taap.2015.07.011	Oil and gas—no distinction of dominant source
170.	Yuan B et al. Airborne flux measurements of methane and volatile organic compounds over the Haynesville and Marcellus shale gas production regions. Journal of Geophysical Research: Atmospheres, 2015, 120(12): 6271–6289	Assessment of analytical method
171.	Zavala-Araiza D et al. Toward a Functional Definition of Methane Super-Emitters: Application to Natural Gas Production Sites. *Environ. Sci. Technol.*, **2015**, *49* (13): 8167–8174	Definition of super emitter
172.	Zhang L, Anderson N, Dilmore R, Soeder DJ, Bromhal G. 2014. Leakage detection of Marcellus Shale natural gas at an Upper Devonian gas monitoring well: a 3-D numerical modeling approach. Environ. Sci. Technol.; doi:10.1021/es501997p	Hypothetical: effectiveness of leakage detection
173.	Zhang L, Soeder DJ. 2015. Modeling of Methane Migration in Shallow Aquifers from Shale Gas Well Drilling. Ground Water; doi:10.1111/gwat.12361	Hypothetical

Paper	Reason for rejection
174. Zimmerle DJ et al. Methane Emissions from the Natural Gas Transmission and Storage System in the United States *Environ. Sci. Technol.*, 2015, *49* (15), pp 9374–9383	Covers all natural gas—no distinction of dominant source
175. Zou C et al. Geological characteristics and resource potential of shale gas in China. Petroleum Exploration and Development 2010, 37(6):641–653	Not OECD

References

Abramzon, S., Samaras, C., Curtright, A., Litovitz, A., & Burger, N. (2014). Estimating the consumptive use costs of shale natural gas extraction on pennsylvania roadways. *Journal of Infrastructure Systems, 20*(3), 06014001-1–06014001-5.

Acquah-Andoh, E. (2015). Economic evaluation of bowland shale gas wells development in the UK. *World Academy of Science, Engineering and Technology International Journal of Social, Behavioral, Educational, Economic, Business and Industrial Engineering, 9*(7), 2577–2585.

Adams, R., & Kelsey, L. (2012). *Pennsylvania dairy farms and marcellus shale, 2007–2010*. Penn State Cooperative Extension: Pennsylvania State University.

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

AEA Technology. (2012). Support to the identification of potential risks for the environment and human health arising from hydrocarbons operations involving hydraulic fracturing in Europe ED57281- Issue Number 17c.

Aguilera, R., Aguilera, R. F., & Ripple, R. D. (2014). Link between endowments, economics and environment in conventional and unconventional gas reservoirs. *Fuel, 126*, 224–238.

Ahmadi, M., & John, K. (2015). Statistical evaluation of the impact of shale gas activities on ozone pollution in North Texas. *Science of the Total Environment, 536*, 457–467.

Alawattegama, S. K., Kondratyuk, T., Krynock, R., Bricker, M., Rutter, J. K., Bain, D. J., et al. (2015). Well water contamination in a rural community in southwestern Pennsylvania near unconventional shale gas extraction. *Journal of Environmental Science and Health Part A, 50*(5), 516–528.

Allen, D. T. (2014). Atmospheric emissions and air quality impacts from natural gas production and use. *Annual Review of Chemical and Biomolecular Engineering, 5*, 55–75.

Allen, D. T., Torres, V. M., Thomas, J., Sullivan, D. W., Harrison, M., Hendler, A., et al. (2013). Measurements of methane emissions at natural gas production sites in the United States. *Proceedings of the National Academy of Science, 110*(44), 17768–17773.

Baisch, S. (2013). Seismic hazard associated with shale-gas-fracking? The bowland shale case study. 75th EAGE Conference and Exhibition Incorporating SPE EUROPEC. WS03 Frontiers of Shale Gas Extraction and Microseismic Monitoring.

Bamberger, M., & Oswald, R. E. (2012). Impacts of gas drilling on human and animal health. *New Solutions, 22*(1), 51–77.

Bamberger, M., & Oswald, R. E. (2015). Long-term impacts of unconventional drilling operations on human and animal health. *Journal of Environmental Science and Health, Part A, 50*(5), 447–459.

Barth, J. M. (2013). The economic impact of shale gas development on state and local economies: Benefits, costs, and uncertainties. *New Solutions, 23*(1), 85–101.

Beaver, W. (2014). Environmental concerns in the Marcellus Shale. *Business and Society Review, 119*(1), 125–146.

Bergmann, A., Weber, F.-A., Meiners, H. G., & Müller, F. (2014). Potential water-related environmental risks of hydraulic fracturing employed in exploration and exploitation of unconventional natural gas reservoirs in Germany. *Environmental Sciences Europe, 26*(1), 1.

Bernstein, P., Kinnaman, T. C., & Wu, M. (2013). Estimating willingness to pay for river amenities and safety measures associated with shale gas extraction. *Eastern Economic Journal, 39*(1), 28–44.

Bloomdahl, R., Abualfaraj, N., Olson, M., & Gurian, P. L. (2014). Assessing worker exposure to inhaled volatile organic compounds from Marcellus Shale flowback pits. *Journal of Natural Gas Science and Engineering, 11*(21), 348–356.

Brandt, A. R., Heath, G. A., Kort, E. A., O'Sullivan, F., Pétron, G., Jordaan, S. M., et al. (2014). methane leaks from North American Natural Gas Systems. *Science, 343*(6172), 733–735.

Brown, S. P. A., Krupnick, A., & Walls, M. A. (2009). *Natural gas: a bridge to a low-carbon future? RFF Issue Brief 09–11*. Washington, DC: Resources for the Future.

Bunch, A. G., Perry, C. S., Abraham, L., Wikoff, D. S., Tachovsky, J. A., Hixon, J. G., et al. (2014). Evaluation of impact of shale gas operations in the Barnett Shale region on volatile organic compounds in air and potential human health risks. *Science of the Total Environment, 468–469*, 832–842.

Burnham, A., Han, J., Clark, C. E., Wang, M., Dunn, J. B., & Palou-Rivera, I. (2012). Life-cycle greenhouse gas emissions of shale gas, natural gas, coal, and petroleum. *Environmental Science and Technology, 46*(2), 619–627.

Casey, J. A., Ogburn, E. L., Rasmussen, S. G., Irving, J. K., Pollak, J., Locke, P. A., et al. (2015). Predictors of indoor radon concentrations in Pennsylvania, 1989–2013. *Environmental Health Perspectives, 123*(11), 1130–1137.

Casey, J. A., Savitz, D. A., Rasmussen, S. G., Ogburn, E. L., Pollak, J., Mercer, D. G., et al. (2016). Unconventional natural gas development and birth outcomes in Pennsylvania, USA. *Epidemiology, 27*(2), 163–172.

Caulton, D. R., Shepson, P. B., Santoro, R. L., Sparks, J. P., Howarth, R. W., Ingraffea, A. R., et al. (2014). Toward a better understanding and quantification of methane emissions from shale gas development. *Proceedings of the National Academy of Sciences, 111*(17), 6237–6242.

Centers for Disease Control and Prevention. CDC/ATSDR Hydraulic Fracturing Statement. https://www.cdc.gov/media/releases/2012/s0503_hydraulic_fracturing.html. Accessed 10 Aug 2016.

Chalupka, S. (2012). Occupational silica exposure in hydraulic fracturing. *Workplace Health and Safety, 60*(10), 460.

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

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

Coram, A., Moss, J., & Blashki, G. (2014). Harms unknown: health uncertainties cast doubt on the role of unconventional gas in Australia's energy future. *The Medical Journal of Australia, 200*(4), 210–213.

Dale, A. T., Khanna, V., Vidic, R. D., & Bilec, M. M. (2013). Process based life-cycle assessment of natural gas from the Marcellus Shale. *Environmental Science and Technology, 47*(10), 5459–5466.

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

Davies, R. J. (2011). Methane contamination of drinking water caused by hydraulic fracturing remains unproven. *Proceedings of the National Academy of Sciences, 108*(43), E871.

Davies, R. J., Almond, S., Ward, R. S., Jackson, R. B., Adams, C., Worrall, F., et al. (2014). Oil and gas wells and their integrity: Implications for shale and unconventional resource exploitation. *Marine and Petroleum Geology, 9*(56), 239–254.

Davies, R., Foulger, G., Bindley, A., & Styles, P. (2013). Induced seismicity and hydraulic fracturing for the recovery of hydrocarbons. *Marine and Petroleum Geology, 8*(45), 171–185.

Drollette, B. D., Hoelzer, K., Warner, N. R., Darrah, T. H., Karatum, O., O'Connor, M. P., et al. (2015). Elevated levels of diesel range organic compounds in groundwater near Marcellus gas operations are derived from surface activities. *Proceedings of the National Academy of Sciences, 112*(43), 13184–13189.

Eapi, G. R., Sabnis, M. S., & Sattler, M. L. (2014). Mobile measurement of methane and hydrogen sulfide at natural gas production site fence lines in the Texas Barnett Shale. *Journal of the Air and Waste Management Association, 64*(8), 927–944.

Eaton, T. T. (2013). Science-based decision-making on complex issues: Marcellus shale gas hydrofracking and New York City water supply. *Science of the Total Environment, 461–462*, 158–169.

Elliott, E., Ettinger, A., Leaderer, B., Bracken, M., & Deziel, N. (2016). A systematic evaluation of chemicals in hydraulic-fracturing fluids and wastewater for reproductive and developmental toxicity. *Journal of Exposure Science & Environmental Epidemiology*,. doi:10.1038/jes.2015.81.

Engelder, T., Cathles, L. M., & Bryndzia, L. T. (2014). The fate of residual treatment water in gas shale. *Journal of Unconventional Oil and Gas Resources, 9*(7), 33–48.

Esswein, E. J., Breitenstein, M., Snawder, J., Kiefer, M., & Sieber, W. K. (2013). Occupational exposures to respirable crystalline silica during hydraulic fracturing. *Journal of Occupational and Environmental Hygiene, 10*(7), 347–356.

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

Ethridge, S., Bredfeldt, T., Sheedy, K., Shirley, S., Lopez, G., & Honeycutt, M. (2015). The Barnett Shale: From problem formulation to risk management. *Journal of Unconventional Oil and Gas Resources, 9*(11), 95–110.

Ferrar, K. J., Kriesky, J., Christen, C. L., Marshall, L. P., Malone, S. L., Sharma, R. K., et al. (2013a). Assessment and longitudinal analysis of health impacts and stressors perceived to result from unconventional shale gas development in the Marcellus Shale region. *International Journal of Occupational and Environmental Health, 19*(2), 104–112.

Ferrar, K. J., Michanowicz, D. R., Christen, C. L., Mulcahy, N., Malone, S. L., & Sharma, R. K. (2013b). Assessment of effluent contaminants from three facilities discharging Marcellus Shale wastewater to surface waters in Pennsylvania". *Environmental Science and Technology, 47*(7), 3472–3481.

Field, R. A., Soltis, J., McCarthy, M. C., Murphy, S., & Montague, D. C. (2015). Influence of oil and gas field operations on spatial and temporal distributions of atmospheric non-methane hydrocarbons and their effect on ozone formation in winter. *Atmospheric Chemistry and Physics, 15*(6), 3527–3542.

Finkel, M. L., & Hays, J. (2013). The implications of unconventional drilling for natural gas: A global public health concern. *Public Health, 127*(10), 889–893.

Finkel, M., Hays, J., & Law, A. (2015). Unconventional natural gas development and human health: Thoughts from the United States. *The Medical Journal of Australia, 203*(7), 294–296.

Finkel, M. L., Selegean, J., Hays, J., & Kondamudi, N. (2013). Marcellus Shale Drilling's Impact on the Dairy Industry in Pennsylvania: A descriptive report. *New Solutions: A Journal of Environmental and Occupational Health Policy, 23*(1), 189–201.

Flewelling, S. A., & Sharma, M. (2014). Constraints on upward migration of hydraulic fracturing fluid and brine. *Groundwater, 52*(1), 9–19.

Flewelling, S. A., Tymchak, M. P., & Warpinski, N. (2013). Hydraulic fracture height limits and fault interactions in tight oil and gas formations. *Geophysical Research Letters, 40*(14), 3602–3606.

Fontenot, B. E., Hunt, L. R., Hildenbrand, Z. L., Carlton, D. D., Jr., Oka, H., Walton, J. L., et al. (2013). An evaluation of water quality in private drinking water wells near natural gas extraction sites in the barnett shale formation. *Environmental Science and Technology, 47*(17), 10032–10040.

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

Gilman, J. B., Lerner, B. M., Kuster, W. C., & de Gouw, J. A. (2013). Source signature of volatile organic compounds from oil and natural gas operations in Northeastern Colorado. *Environmental Science and Technology, 47*(3), 1297–1305.

Goetz, J. D., Floerchinger, C., Fortner, E. C., Wormhoudt, J., Massoli, P., Knighton, W. B., et al. (2015). Atmospheric emission characterization of marcellus shale natural gas development sites. *Environmental Science and Technology, 49*(11), 7012–7020.

Goldstein, B., & Malone, S. (2013). Obfuscation does not provide comfort: response to the article by Fryzek et al. on hydraulic fracturing and childhood cancer. *Journal of Occupational and Environmental Medicine, 55*(11), 1376–1378.

Gross, S. A., Avens, H. J., Banducci, A. M., Sahmel, J., Panko, J. M., & Tvermoes, B. E. (2013). Analysis of BTEX groundwater concentrations from surface spills associated with hydraulic fracturing operations. *Journal of the Air and Waste Management Association, 63*(4), 424–432.

Haefele, M., & Morton, P. (2009). The influence of the pace and scale of energy development on communities: Lessons from the natural gas drilling boom in the rocky mountains. *Western Economics Forum, 8*(2), 1–42.

Hays, J., & Shonkoff, S. B. C. (2016). Toward an understanding of the environmental and public health impacts of unconventional natural gas development: a categorical assessment of the peer-reviewed scientific literature, 2009–2015. *PLoS ONE, 11*(4), e0154164.

Heath, G. A., O'Donoughue, P., Arent, D. J., & Bazilian, M. (2014). Harmonization of initial estimates of shale gas life cycle greenhouse gas emissions for electric power generation. *Proceedings of the National Academy of Sciences, 111*(31), E3167–E3176.

Heilweil, V. M., Grieve, P. L., Hynek, S. A., Brantley, S. L., Solomon, D. K., & Risser, D. W. (2015). Stream measurements locate thermogenic methane fluxes in groundwater discharge in an area of shale-gas development. *Environmental Science and Technology, 49*(7), 4057–4065.

Hildenbrand, Z. L., Carlton, D. D., Fontenot, B. E., Meik, J. M., Walton, J. L., Taylor, J. T., et al. (2015). A comprehensive analysis of groundwater quality in the Barnett Shale region. *Environmental Science and Technology, 49*(13), 8254–8262.

Hladik, M. L., Focazio, M. J., & Engle, M. (2014). Discharges of produced waters from oil and gas extraction via wastewater treatment plants are sources of disinfection by-products to receiving streams. *Science of the Total Environment, 466–467*, 1085–1093.

Holland, A. A. (2013). Earthquakes triggered by hydraulic fracturing in south-central Oklahoma. *Bulletin of the Seismology Society of America, 103*, 1784.

Howarth, R. W. (2014). A bridge to nowhere: Methane emissions and the greenhouse gas footprint of natural gas. *Energy Science and Engineering, 2*(2), 47–60.

Howarth, R. W., Ingraffea, A., & Engelder, T. (2011). Natural gas: Should fracking stop? *Nature, 477*(7364), 271–275.

Hughes, J. D. (2013). Energy: A reality check on the shale revolution. *Nature, 494*(7437), 307–308.

Hultman, N., Rebois, D., Scholten, M., & Ramig, C. (2011). The greenhouse impact of unconventional gas for electricity generation. *Environmental Research Letters, 6*(4), 044008.

Ingraffea, A. R., Wells, M. T., Santoro, R. L., & Shonkoff, S. B. C. (2014). Assessment and risk analysis of casing and cement impairment in oil and gas wells in Pennsylvania, 2000–2012. *Proceedings of the National Academy of Sciences, 111*(30), 10955–10960.

Jackson, R. E., Gorody, A. W., Mayer, B., Roy, J. W., Ryan, M. C., & Van Stempvoort, D. R. (2013a). Groundwater protection and unconventional gas extraction: The critical need for field-based hydrogeological research. *Groundwater, 51*(4), 488–510.

Jackson, R. B., Vengosh, A., Carey, J. W., Davies, R. J., Darrah, T. H., O'Sullivan, F., et al. (2014). The environmental costs and benefits of fracking. *Annual Review of Environment and Resources, 39*, 327–362.

Jackson, R. B., Vengosh, A., Darrah, T. H., Warner, N. R., Down, A., Poreda, R. J., et al. (2013b). Increased stray gas abundance in a subset of drinking water wells near Marcellus shale gas extraction. *Proceedings of the National Academy of Sciences, 110*(28), 11250–11255.

Jacoby, H. D., & O'Sullivan, F. M. (2012). The influence of shale gas on US Energy and Environmental Policy. *Economics of Energy and Environmental Policy, 1*(1), 37.

Jemielita, T., Gerton, G. L., Neidell, M., Chillrud, S., Yan, B., Stute, M., et al. (2015). Unconventional gas and oil drilling is associated with increased hospital utilization rates. *PLoS ONE, 10*(7), e0131093.

Jenner, S., & Lamadrid, A. J. (2013). 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. *Energy Policy, 53*, 442.

Jiang, M., Michael Griffin, W. M., Hendrickson, C., Jaramillo, P., VanBriesen, J., & Venkatesh, A. (2011). Life cycle greenhouse gas emissions of Marcellus shale gas. *Environmental Research Letters, 6*(3), 034014.

Jones, P., Comfort, D., & Hillier, D. (2014a). Fracking for shale gas in the UK: Property and investment issues. *Journal of Property Investment and Finance, 32*(5), 505–517.

Jones, P., Hillier, D., & Comfort, D. (2014b). Fracking in the UK: Planning and property issues. *Property Management, 32*(4), 352–361.

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

Kemball-Cook, S., Bar-Ilan, A., Grant, J., Parker, L., Jung, J., Santamaria, W., et al. (2010). Ozone impacts of natural gas development in the Haynesville Shale. *Environmental Science and Technology, 44*(24), 9357–9363.

Kim, W. Y. (2013). Induced seismicity associated with fluid injection into a deep well in Youngstown, Ohio. *Journal of Geophysical Research, 118*(7), 3518.

Kinnaman, T. C. (2011). The economic impact of shale gas extraction: A review of existing studies. *Ecological Economics, 70*(7), 1243–1249.

Kohl, C. A. K., Capo, R. C., Stewart, B. W., Wall, A. J., Schroeder, K. T., Hammack, R. W., et al. (2014). Strontium isotopes test long-term zonal isolation of injected and marcellus formation water after hydraulic fracturing. *Environmental Science and Technology, 48*(16), 9867–9873.

Lampe, D. J., & Stolz, J. F. (2015). Current perspectives on unconventional shale gas extraction in the Appalachian Basin. *Journal of Environmental Science and Health, Part A, 50*(5), 434–446.

Lan, X., Talbot, R., Laine, P., & Torres, A. (2015). Characterizing fugitive methane emissions in the barnett shale area using a mobile laboratory. *Environmental Science and Technology, 49*(13), 8139–8146.

Laurenzi, I. J., & Jersey, G. R. (2013). Life cycle greenhouse gas emissions and freshwater consumption of marcellus shale gas. *Environmental Science and Technology, 47*(9), 4896–4903.

Lave, R., & Lutz, B. (2014). Hydraulic fracturing: A critical physical geography review. *Geography Compass, 8*(10), 739–754.

Lavoie, T. N., Shepson, P. B., Cambaliza, M. O. L., Stirm, B. H., Karion, A., Sweeney, C., et al. (2015). Aircraft-based measurements of point source methane emissions in the Barnett Shale basin. *Environmental Science and Technology, 49*(13), 7904–7913.

Levi, M. (2013). Climate consequences of natural gas as a bridge fuel. *Climate Change, 118*(3), 609–623.

Li, H., & Carlson, K. H. (2014). Distribution and origin of groundwater methane in the wattenberg oil and gas field of Northern Colorado. *Environmental Science and Technology, 48*(3), 1484–1491.

Lightowlers, P. (2015). *Chemical pollution from fracking*. London: CHEM Trust.

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

Llewellyn, G. T., Dorman, F., Westland, J. L., Yoxtheimer, D., Grieve, P., Sowers, T., et al. (2015). Evaluating a groundwater supply contamination incident attributed to Marcellus Shale gas development. *Proceedings of the National Academy of Sciences, 112*(20), 6325–6330.

Macey, G., Breech, R., Chernaik, M., Cox, C., Larson, D., Thomas, D., et al. (2014). Air concentrations of volatile compounds near oil and gas production: A community-based exploratory study. *Environmental Health, 13*(1), 82.

Marshall, M. (2011). How fracking caused earthquakes in the UK. *New Scientist* 2nd November.

Maryland Institute for Applied Environmental Health School of Public Health. (2014). *Potential public health impacts of natural gas development and production in the marcellus shale in Western Maryland*. College Park: University of Maryland.

Mash, R., Minnaar, J., & Mash, B. (2014). Health and fracking: Should the medical profession be concerned? *South African Medical Journal, 104*, 332–335.

McCoy, D., & Saunders, P. (2015). *Health and fracking: The impacts and opportunity costs*. London: Medact.

McJeon, H., Edmonds, J., Bauer, N., Clarke, L., Fisher, B., Flannery, B. P., et al. (2014). Limited impact on decadal-scale climate change from increased use of natural gas. *Nature, 514*(7523), 482–485.

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

McKenzie, L. M., Witter, R. Z., Newman, L. S., & Adgate, J. L. (2012). Human health risk assessment of air emissions from development of unconventional natural gas resources. *Science of the Total Environment, 1*(424), 79–87.

McLeod, J. D., Brinkman, G. L., & Milford, J. B. (2014). Emissions Implications of future natural gas production and use in the U.S. and in the Rocky Mountain Region. *Environmental Science and Technology, 48*(22), 13036–13044.

Middleton, J., & Saunders, P. (2015). 20 years of local ecological public health: the experience of Sandwell in the English West Midlands. *Public Health, 129*, 1344–1352.

Mitka, M. (2012). Rigorous evidence slim for determining health risks from natural gas fracking. *Journal of the American Medical Association, 307*(20), 2135–2136.

Molofsky, L. J., Connor, J. A., Wylie, A. S., Wagner, T., & Farhat, S. K. (2013). Evaluation of methane sources in groundwater in northeastern Pennsylvania. *Ground Water, 2013*(3), 333–349.

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

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

Munasib, A., & Rickman, D. S. (2015). Regional economic impacts of the shale gas and tight oil boom: A synthetic control analysis. *Regional Science and Urban Economics, 1*(50), 1–17.

Myers, T. (2012). Potential contaminant pathways from hydraulically fractured shale to aquifers. *Groundwater, 50*(6), 872–882.

Nelson, A. W., Knight, A. W., Eitrheim, E. S., & Schultz, M. K. (2015). Monitoring radionuclides in subsurface drinking water sources near unconventional drilling operations: a pilot study. *Journal of Environmental Radioactivity, 4*(142), 24–28.

New York State Department of Environmental Conservation. (2011). Chapter 5: Natural gas development activities and high-volume hydraulic fracturing. Supplemental Generic Environmental Impact Statement 2011.

New York State Department of Health. (2014). A Public health review of high volume hydraulic fracturing for shale gas development.

Newell, R. G., & Raimi, D. (2014). Implications of shale gas development for climate change. *Environmental Science and Technology, 48*(15), 8360–8368.

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

Olmstead, S. M., Muehlenbachs, L. A., Shih, J., Chu, Z., & Krupnick, A. J. (2013). Shale gas development impacts on surface water quality in Pennsylvania. *Proceedings of the National Academy of Sciences, 110*(13), 4962–4967.

Omara, M., Sullivan, M. R., Li, X., Subramanian, R., Robinson, A. L., & Presto, A. A. (2016). Methane emissions from conventional and unconventional natural gas production sites in the Marcellus Shale Basin. *Environmental Science and Technology, 250*(4), 2099–2107.

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

Paredes, D., Komarek, T., & Loveridge, S. (2015). Income and employment effects of shale gas extraction windfalls: Evidence from the Marcellus region. *Energy Economics, 47*, 112–120.

Parenteau, P., & Barnes, A. (2013). A bridge too far: Building off-ramps on the shale gas superhighway. *Idaho Law Review, 49*, 325–366.

Paulik, L. B., Donald, C. E., Smith, B. W., Tidwell, L. G., Hobbie, K. A., Kincl, L., et al. (2015). Impact of natural gas extraction on PAH levels in ambient air. *Environmental Science and Technology, 49*(8), 5203–5210.

Peischl, J., Ryerson, T. B., Aikin, K. C., de Gouw, J. A., Gilman, J. B., Holloway, J. S., et al. (2015). Quantifying atmospheric methane emissions from the Haynesville, Fayetteville, and northeastern Marcellus shale gas production regions. *Journal of Geophysical Research: Atmospheres, 120*(5), 2119–2213.

Pelak, A. J., & Sharma, S. (2014). Surface water geochemical and isotopic variations in an area of accelerating Marcellus Shale gas development. *Environmental Pollution, 195*, 91–100.

Penning, T. M., Breysse, P. N., Gray, K., Howarth, M., & Yan, B. (2014). Environmental health research recommendations from the Inter-Environmental Health Sciences Core Center Working Group on Unconventional Natural Gas Drilling Operations. *Environmental Health Perspectives, 122*, 1155–1159.

Perdue, R. T., & Pavela, G. (2012). Addictive economies and coal dependency: Methods of extraction and socioeconomic outcomes in West Virginia, 1997–2009. *Organization and Environment, 25*(4), 368–384.

Pétron, G., Karion, A., Sweeney, C., Miller, B. R., Montzka, S. A., Frost, G. J., et al. (2014). A new look at methane and nonmethane hydrocarbon emissions from oil and natural gas operations in the Colorado Denver-Julesburg Basin. *Journal of Geophysical Research: Atmospheres, 119*(11), 6836–6852.

Popkin, J. H., Duke, J. M., Borchers, A. M., & Ilvento, T. (2013). Social costs from proximity to hydraulic fracturing in New York state. *Energy Policy, 62*, 62–69.

Public Health England. (2014). *Review of the potential public health impacts of exposures to chemical and radioactive pollutants as a result of the shale gas extraction process CRCE 009*. Chilton: PHE.

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

Rahm, B. G., & Riha, S. J. (2014). Evolving shale gas management: Water resource risks, impacts, and lessons learned. *Environmental Science Processes and Impacts, 16*(6), 1400–1412.

Rahm, B. G., Vedachalam, S., Bertoia, L. R., Mehta, D., Vanka, V. S., & Riha, S. J. (2015). Shale gas operator violations in the Marcellus and what they tell us about water resource risks. *Energy Policy, 7*(82), 1–11.

Reilly, D., Singer, D., Jefferson, A., & Eckstein, Y. (2015). Identification of local groundwater pollution in northeastern Pennsylvania: Marcellus flowback or not? *Environmental Earth Sciences, 73*(12), 8097–8109.

Rich, A., Grover, J. P., & Sattler, M. L. (2014). An exploratory study of air emissions associated with shale gas development and production in the Barnett Shale. *Journal of the Air and Waste Management Association, 64*(1), 61–72.

Rosenman, K. D. (2014). Hydraulic fracturing and the risk of silicosis. *Clinical Pulmonary Medicine, 21*(4), 167–172.

Roy, A. A., Adams, P. J., & Robinson, A. L. (2014). Air pollutant emissions from the development, production, and processing of Marcellus Shale natural gas. *Journal of the Air and Waste Management Association, 64*(1), 19–37.

Rozell, D. J., & Reaven, S. J. (2012). Water pollution risk associated with natural gas extraction from the Marcellus Shale. *Risk Analysis: An International Journal, 32*(8), 1382–1393.

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

Saunders, P. J., Stewart, A., & Karim, T. (2012). Establishing an environmental public health tracking system in the UK. In Andrius Kavaliunas (Ed.) *Proceedings of the 12th World Congress on Environmental Health, Vilnius May 22–27, 2012* (pp. 27–32). Bologna: Medimond International Proceedings Division.

Schneising, O., Burrows, J. P., Dickerson, R. R., Buchwitz, M., Reuter, M., & Bovensmann, H. (2014). Remote sensing of fugitive methane emissions from oil and gas production in North American tight geologic formations. *Earth's Future, 2*(10), 548–558.

Schon, S. C. (2011). Hydraulic fracturing not responsible for methane migration. *Proceedings of the National Academy of Sciences, 108*(37), E664–E664.

Schrag, D. P. (2012). Is shale gas good for climate change? *Daedalus, 141*(2), 72–80.

Science and Environmental Health Network. (2016). Wingspread conference on the precautionary principle. http://www.sehn.org/wing.html. Accessed 10 Aug 2016.

Seaton, A., MacNee, W., Donaldson, K., & Godden, D. (1995). Particulate air pollution and acute health effects. *The Lancet, 345*(8943), 176–178.

Shahriar, A., Sadiq, R., & Tesfamariam, S. (2014). Life cycle greenhouse gas footprint of shale gas: A probabilistic approach. *Stochastic Environmental Research and Risk Assessment, 28*(8), 2185–2204.

Sharma, S., Bowman, L., Schroeder, K., & Hammack, R. (2015). Assessing changes in gas migration pathways at a hydraulic fracturing site: Example from Greene County, Pennsylvania, USA. *Applied Geochemistry, 9*(60), 51–58.

Shonkoff, S. B., Hays, J., & Finkel, M. L. (2014). Environmental public health dimensions of shale and tight gas development. *Environmental Health Perspectives, 122*(8), 787–795.

Siegel, D. I., Azzolina, N. A., Smith, B. J., Perry, A. E., & Bothun, R. L. (2015). Methane concentrations in water wells unrelated to proximity to existing oil and gas wells in Northeastern Pennsylvania. *Environmental Science and Technology, 49*(7), 4106–4112.

Sovacool, B. K. (2014). Cornucopia or curse? Reviewing the costs and benefits of shale gas hydraulic fracturing (fracking). *Renewable and Sustainable Energy Reviews, 37*, 249–264.

Stacy, S. L., Brink, L. L., Larkin, J. C., Sadovsky, Y., Goldstein, B. D., Pitt, B. R., et al. (2015). Perinatal outcomes and unconventional natural gas operations in Southwest Pennsylvania. *PLoS ONE, 10*(6), e0126425.

Stamford, L., & Azapagic, A. (2014). Life cycle environmental impacts of UK shale gas. *Applied Energy, 134*, 506–518.

Steinzor, N., Subra, W., & Sumi, L. (2013). Investigating links between shale gas development and health impacts through a community survey project in Pennsylvania. *New Solutions, 23*(1), 55–83.

Stephenson, T., Valle, J. E., & Riera-Palou, X. (2011). Modeling the relative GHG emissions of conventional and shale gas production. *Environmental Science and Technology, 45*(24), 10757–10764.

Stevens, P. (2003). Resource impact: curse or blessing? A literature survey. *Journal of Energy Literature, 9*(1), 3–42.

Stevens, P. (2013). *Shale gas in the United Kingdom*. London: Chatham House Royal Institute of International Affairs.

Subramanian, R., Williams, L. L., Vaughn, T. L., Zimmerle, D., Roscioli, J. R., Herndon, S. C., et al. (2015). Methane emissions from natural gas compressor stations in the transmission and storage sector: Measurements and comparisons with the EPA Greenhouse Gas Reporting Program Protocol. *Environmental Science and Technology, 49*(5), 3252–3261.

Swarthout, R. F., Russo, R. S., Zhou, Y., Hart, A. H., & Sive, B. C. (2013). Volatile organic compound distributions during the NACHTT campaign at the Boulder Atmospheric Observatory: Influence of urban and natural gas sources. *Journal of Geophysical Research: Atmospheres, 118*(18), 10614–10637.

Swarthout, R. F., Russo, R. S., Zhou, Y., Miller, B. M., Mitchell, B., Horsman, E., et al. (2015). Impact of Marcellus shale natural gas development in Southwest Pennsylvania on volatile organic compound emissions and regional air quality. *Environmental Science and Technology, 49*(5), 3175–3184.

Task Force on Shale Gas. (2015). Final conclusions and recommendations. London: Task Force on Shale Gas2.

The Economist (2013) Deep sigh of relief. The shale gas and oil bonanza is transforming America's energy outlook and boosting its economy. London: The Economist Newspaper Limited.

The Royal Society and The Royal Academy of Engineering. (2012). *Shale gas extraction in the UK: a review of hydraulic fracturing*. London: The Royal Society and The Royal Academy of Engineering.

The UK's Faculty of Public Health. (2016). http://www.fph.org.uk/what_is_public_health. Accessed 9 Aug 2016.

Thompson, C., Hueber, J., & Helmig, D. (2014). Influence of oil and gas emissions on ambient atmospheric non-methane hydrocarbons in residential areas of Northeastern Colorado. *Elementa: Science of the Anthropocene, 2*, 000035. doi:10.12952/journal.elementa.000035.

Throupe, R., Simons, R. A., & Mao, X. (2013). A review of hydro "fracking" and its potential effects on real estate. *Journal of Real Estate Literature, 21*(2), 205–232.

Tyner, D. R., & Johnson, M. R. (2014). Emission factors for hydraulically fractured gas wells derived using well- and battery-level reported data for Alberta, Canada. *Environmental Science and Technology, 48*(24), 14772–14781.

United Kingdom Onshore Operators Group. (2016). Community engagement charter oil and gas from unconventional reservoirs. http://www.ukoog.org.uk/images/ukoog/pdfs/communityengagementcharterversion6.pdf. Accessed 10 Aug 2016.

van der Elst, N. J., Savage, H. M., Keranen, K. M., & Abers, G. A. (2013). Enhanced remote earthquake triggering at fluid-injection sites in the Midwestern United States. *Science, 341*, 164–167.

van der Voort, N., & Vanclay, F. (2015). Social impacts of earthquakes caused by gas extraction in the Province of Groningen, The Netherlands. *Environmental Impact Assessment Review, 50*, 1–15.

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

Vidic, R. D., Brantley, S. L., Vandenbossche, J. M., Yoxtheimer, D., & Abad, J. D. (2013). Impact of shale gas development on regional water quality. *Science, 340*(6134), 1235009.

Vinciguerra, T., Yao, S., Dadzie, J., Chittams, A., Deskins, T., Ehrman, S., et al. (2015). Regional air quality impacts of hydraulic fracturing and shale natural gas activity: Evidence from ambient VOC observations. *Atmospheric Environment, 2015*(110), 144–150.

Wang, R., Gu, Y. J., Schultz, R., Kim, A., & Atkinson, G. (2016). Source analysis of a potential hydraulic-fracturing-induced earthquake near Fox Creek. *Alberta. Geophysical Research Letters, 43*(2), 564–573.

Wang, J., Ryan, D., & Anthony, E. (2011). Reducing the greenhouse gas footprint of shale gas. *Energy Policy, 39*, 8196–8199.

Warner, N. R., Christie, C. A., Jackson, R. B., & Vengosh, A. (2013a). Impacts of shale gas wastewater disposal on water quality in Western Pennsylvania. *Environmental Science and Technology, 47*(20), 11849–11857.

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

Warner, N. R., Kresse, T. M., Hays, P. D., Down, A., Karr, J. D., Jackson, R. B., et al. (2013b). Geochemical and isotopic variations in shallow groundwater in areas of the Fayetteville Shale development, north-central Arkansas. *Applied Geochemistry, 35*, 207–220.

Wattenberg, E. V., Bielicki, J. M., Suchomel, A. E., Sweet, J. T., Vold, E. M., & Ramachandran, G. (2015). Assessment of the acute and chronic health hazards of hydraulic fracturing fluids. *Journal of Occupational and Environmental Hygiene, 12*(9), 611–624.

Webb, E., Bushkin-Bedient, S., Cheng, A., Kassotis, C., Balise, V., & Nagel, S. (2014). Developmental and reproductive effects of chemicals associated with unconventional oil and natural gas operations. *Reviews on Environmental Health, 29*(4), 307–318.

Weber, J. (2012). The effects of a natural gas boom on employment and income in Colorado, Texas, and Wyoming. *Energy Economics, 34*(5), 1580–1588.

Weber, C. L., & Clavin, C. (2012). Life cycle carbon footprint of shale gas: Review of evidence and implications. *Environmental Science and Technology, 46*(11), 5688–5695.

Weber, B. A., Geigle, J., & Barkdull, C. (2014). Rural North Dakota's oil boom and its impact on social services. *Social Work, 59*(1), 62–72.

Werner, A. K., Vink, S., Watt, K., & Jagals, P. (2015). Environmental health impacts of unconventional natural gas development: A review of the current strength of evidence. *Science of the Total Environment, 505*, 1127–1141.

Westaway, R., & Younger, P. L. (2014). Quantification of potential macroseismic effects of the induced seismicity that might result from hydraulic fracturing for shale gas exploitation in the UK. *Quarterly Journal of Engineering Geology and Hydrogeology, 47*(4), 333–350.

Weyant, C. L., Shepson, P. B., Subramanian, R., Cambaliza, M. O. L., Heimburger, A., McCabe, D., et al. (2016). Black carbon emissions from associated natural gas flaring. *Environmental Science and Technology, 50*(4), 2075–2081.

Witter, R. Z., McKenzie, L., Stinson, K. E., Scott, K., Newman, L. S., & Adgate, J. (2013). The use of health impact assessment for a community undergoing natural gas development. *American Journal of Public Health, 103*(6), 1002–1010.

Wrenn, D., Kelsey, T., & Jaenicke, E. (2015). Resident vs. nonresident employment associated with Marcellus Shale development. *Agricultural and Resource Economics Review, 44*(2), 1–19.

Zavala-Araiza, D., Allen, D. T., Harrison, M., George, F. C., & Jersey, G. R. (2015a). Allocating methane emissions to natural gas and oil production from shale formations. *ACS Sustainable Chemistry and Engineering, 3*(3), 492–498.

Zavala-Araiza, D., Lyon, D. R., Alvarez, R. A., Davis, K. J., Harriss, R., Herndon, S. C., et al. (2015b). Reconciling divergent estimates of oil and gas methane emissions. *Proceedings of the National Academy of Sciences, 112*(51), 15597–15602.

Zavala-Araiza, D., Sullivan, D. W., & Allen, D. T. (2014). Atmospheric hydrocarbon emissions and concentrations in the barnett shale natural gas production region. *Environmental Science and Technology, 48*(9), 5314–5321.

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

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

Ziemkiewicz, P. F., Quaranta, J. D., Darnell, A., & Wise, R. (2014). Exposure pathways related to shale gas development and procedures for reducing environmental and public risk. *Journal of Natural Gas Science and Engineering, 1*(i6), 77–84.

Environmental Science & Technology

Critical Review

pubs.acs.org/est

Potential Public Health Hazards, Exposures and Health Effects from Unconventional Natural Gas Development

John L. Adgate,*,[†] Bernard D. Goldstein,[‡] and Lisa M. McKenzie[†]

[†]Colorado School of Public Health, University of Colorado Denver, 13001 E. 17th Place, Campus Box B119, Aurora, Colorado 80045, United States

[‡]Graduate School of Public Health, University of Pittsburgh, 130 DeSoto Street, A710 Crabtree Hall, Pittsburgh, Pennsylvania 15261, United States

ABSTRACT: The rapid increase in unconventional natural gas (UNG) development in the United States during the past decade has brought wells and related infrastructure closer to population centers. This review evaluates risks to public health from chemical and nonchemical stressors associated with UNG, describes likely exposure pathways and potential health effects, and identifies major uncertainties to address with future research. The most important occupational stressors include mortality, exposure to hazardous materials and increased risk of industrial accidents. For communities near development and production sites the major stressors are air pollutants, ground and surface water contamination, truck traffic and noise pollution, accidents and malfunctions, and psychosocial stress associated with community change. Despite broad public concern, no comprehensive population-based studies of the public health effects of UNG operations exist. Major uncertainties are the unknown frequency and duration of human exposure, future extent of development, potential emission control and mitigation strategies, and a paucity of baseline data to enable substantive before and after comparisons for affected populations and environmental media. Overall, the current literature suggests that research needs to address these uncertainties before we can reasonably quantify the likelihood of occurrence or magnitude of adverse health effects associated with UNG production in workers and communities.

I. INTRODUCTION

The U.S. holds large reserves of on-shore natural gas in many regions, including but not limited to the Barnett Shale in Texas, the Denver-Julesberg Basin in Colorado, and the Marcellus Shale in the northeast.[1,2] Technological advances in directional and horizontal drilling and hydraulic fracturing (referred to herein as unconventional natural gas, UNG) have eased access to shale and tight gas reserves that were previously uneconomical to recover, resulting in a "shale gas boom" at the beginning of the 21st century.[3,4] In the U.S., the number of UNG wells rose from 18 485 in 2004 to 25 145 in 2007 and it is estimated that over 11 000 wells are hydraulically fractured each year.[5,6] As of 2011, 95% of the natural gas consumed in the U.S. was produced domestically and production is projected to increase from 23 trillion cubic feet in 2011 to 33.1 trillion cubic feet in 2040, with almost all the projected growth in UNG production.[7] The most recent worldwide estimates of natural gas reserves are 2.6–5.7 times greater than what was estimated in the 1990s.[8]

As UNG development grows, it is expected to become more common near where people live and work, increasing the likelihood of human exposure to associated pollutants and related chemical and nonchemical stressors as well as transport of pollutants to nearby cities.[1,9−13] With any fossil fuel development, there is a potential for release of air and water pollutants, physical and public safety hazards, and a range of psychosocial stressors. At present the potential risks from UNG development are more uncertain than risks from conventional natural gas development.[1,6,10,12−19] This is because hydraulic fracturing fluid contains potentially hazardous chemicals, well fracturing requires large volumes of water and sand, and the overall process creates air pollution and large volumes of wastewater containing dissolved chemicals and contaminants of subterranean origin.[4] While unconventional technologies allow for consolidation of several wells on one well pad, multiwell pads focuses an intense industrial activity in one area for several months.[3,12] To maintain gas flows, wells may also be fractured more than once.[3,20] Because UNG development is a recent phenomena, relatively little peer-reviewed public health research exists. Nonetheless, there are potential health risks because production is rising and increasingly occurring near where people live and development is transforming both the population and character of nearby communities.[1,10,12,21] The lack of research on population health effects has led to broad public concern about the potential consequences of the UNG development process.

Special Issue: Understanding the Risks of Unconventional Shale Gas Development

Received: October 15, 2013
Revised: February 4, 2014
Accepted: February 10, 2014
Published: February 24, 2014

dx.doi.org/10.1021/es404621d | *Environ. Sci. Technol.* 2014, 48, 8307−8320

Table 1. Relationships between Sources, Processes and Hazards That May Lead to Human Exposure, Health Effects or Population Health Effects[a]

		chemical hazards					
source	process	air	ground water	surface water soil/ sediments	physical hazards	safety hazards	water scarcity hazard
large trucks	all	DE			noise, vibration	spills and accidents	
heavy equipment	well pad construction, drilling, and well abandonment	DE			noise, vibration	spills and accidents	
dust	well pad construction, well abandonment	PM					
drilling mud	drilling	DMV	DM	DM			
fracturing fluid	hydraulic fracturing, flowback	Silica, FFV	FF	FF		spills	removes water from hydrological cycle
generators	drilling, hydraulic fracturing	DE			noise		
produced water	drilling and construction, flowback	DMV, PHC	DM, PHC, IN	DM, PHC, IN		spills	
drill cuttings	drilling and construction	PM, DMV, PHC	DM, PHC, IN	DM, PHC, IN		spills	
flowback water	flowback	FFV, PHC	FF, PHC, IN	FF, PHC, IN			
deep injection	flowback				seismic activity		
gas venting	drilling, flowback, production	CH_4, H_2S, PHC				accidents	
gas flaring	drilling, flowback,	NO_X, CO_2,			noise		
pigging[b]	production						
	production	CH_4, PHC				accidents	
pipelines	production	CH_4, PHC				accidents	
condensate tanks	production	CH_4, PHC					

[a] **CH_4**: methane; **CO_2**: carbon dioxide; **DE**: diesel emissions, including particulate matter (**PM**), nitrogen oxides (NO_x), polyaromatic, aliphatic, and aromatic hydrocarbons, aldehydes, and sulfur dioxides (SOx); **DM**: drilling muds, e.g., boric acid, borate salts, rubber-based oil, synthetic oil; **DMV**: drilling Muds, Volatile, e.g., rubber-based oil, synthetic oil, aluminum tristearate, choline chloride; **FF**: fracturing fluids, e.g., lauryl sulfate, guar gum and others (see Table 2); **FFV**: fracturing fluids, volatile: e.g., glutaraldehyde, ethylene glycol, methanol,, petroleum distillate; **H_2S**: hydrogen sulfide; **IN**: inorganic chemicals; barium, strontium, bromine, heavy metals, salts and NORM (naturally occurring radioactive materials); **NO_X**: nitrogen oxides; **PHC**: aromatic and aliphatic petroleum hydrocarbons. Refs: King, G.E., Hydraulic Fracturing 101: What Every Representative, Environmentalist, Regulator, Reporter, Investor, University Researcher, Neighbor and Engineer Should Know About Estimating Frac Risk and Improving Frac Performance in Unconventional Gas and Oil Wells. *SPE Hydraulic Fracturing Technology*; Woodlands, TX, 2012; Jiang, M., et al. Life cycle greenhouse gas emissions of Marcellus shale gas. *Environ. Res. Lett.*. 2011. 6(3); United States Department of Energy, *Modern Shale Gas Development in the United States: A Primer*; Oklahoma City, OK, 2009. [b]The process of using gauges to perform maintenance on gas lines without stopping the flow of gas in the pipe line.

This review takes a systems approach to exploring main sources, hazards, exposures, and potential population health effects associated with UNG development in the US. We summarize the strengths and limitations of the existing literature on exposure pathways, environmental media concentrations, and potential risks for workers and communities as well as evaluate existing and potential approaches for assessing population health effects. We also identify risk mitigation strategies and related public health research needs.

II. HAZARDS AND SCALE OF EXPOSURES

As with any complex industrial process, UNG development is a series of steps best viewed as a system: (1) well pad and infrastructure preparation; (2) drilling and construction of well pipelines and facilities; (3) hydraulic fracturing; (4) "flow back" of gas, fracturing fluids, and produced water during well completion; and (5) subsequent connection of the well to the natural gas distribution system.[3] During the 20−30 year production life of a well petroleum byproducts are collected for sale and wastes (e.g., drilling cuttings, flowback and produced water) are treated, recycled and/or disposed offsite. Table 1 summarizes the relationship between major sources, development processes and hazards that may lead to human exposures and health effects. In addition to the chemical, physical, and safety hazards specified in Table 1, Figure 1 outlines the major psychosocial stressors associated with UNG development that may affect the health of nearby populations.

Chemical and nonchemical stressors found in and around UNG development sites may affect both workers and communities. The overall effect of these stressors on population health depends on the hazards, exposure pathways, and temporal and spatial reach of each stressor and its impacts, which may range from the well pad to local, regional, and global scales. The key exposure pathways and health effects are governed by the rate of release, fate and transport, persistence, and frequency and duration of human contact with each stressor, as well as the human behavioral factors that increase or decrease the likelihood of exposure (Figure 1). At the well site itself, the most imminent potential public health effects are accidents and injuries to workers who may also be exposed to acute (e.g., H_2S) and chronic (e.g., silica) stressors.[6,22] Stressors that exert their impacts at the local scale include chemical

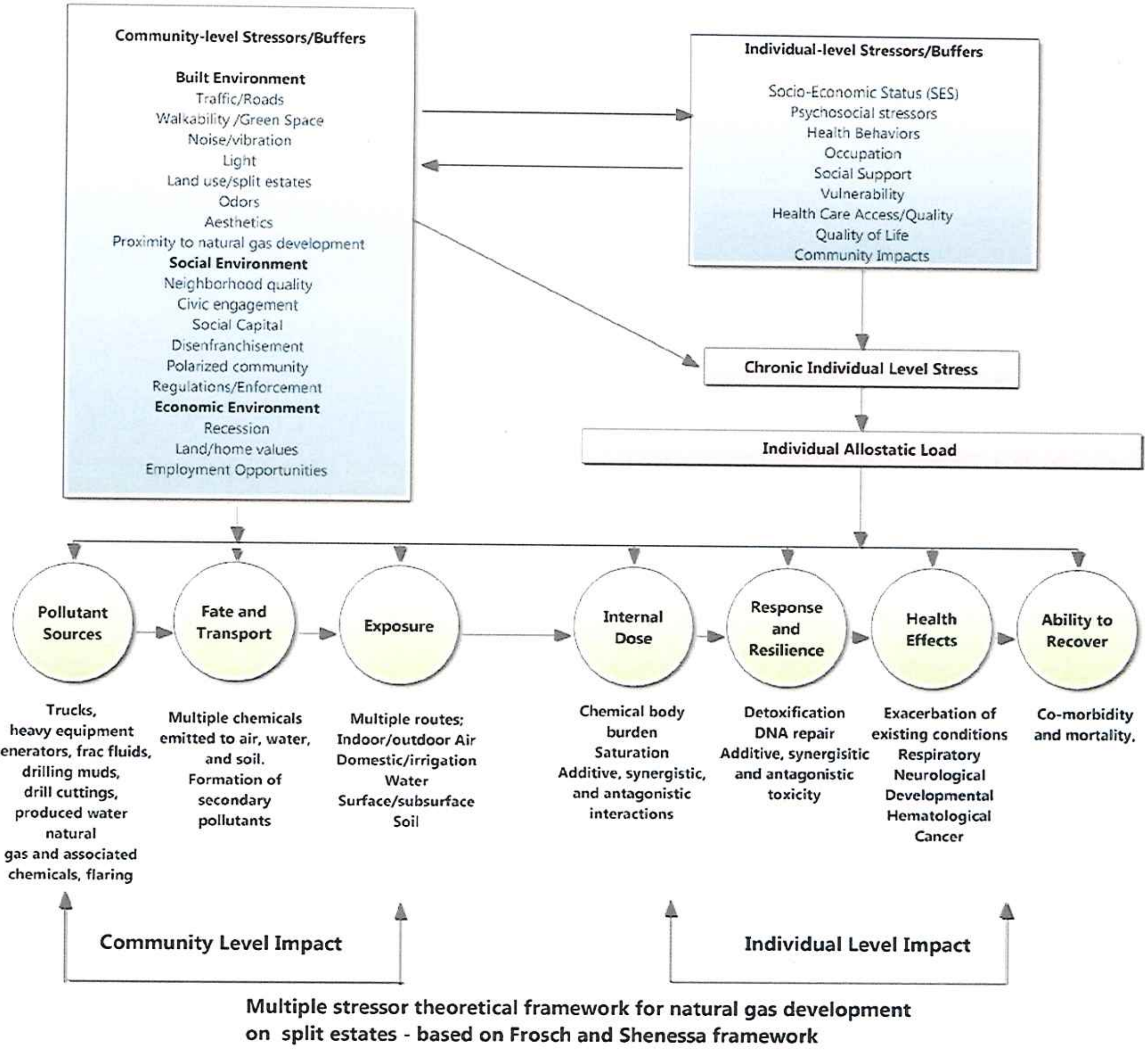

Figure 1. Allostatic load conceptual model describing community and individual level stressors and their relationship with psychosocial stress.

hazards transported offsite, such as volatile organic compounds (VOCs), diesel exhaust, fracturing fluids, and drilling and hydraulic fracturing wastes that migrate offsite through spills, leaks, or accidents (Table 1). Though there are potentially mitigating factors, such as increased tax revenue or income for leaseholders, nearby residents may complain of odors, noise, light, or psychosocial stress from declining land values or decreased housing availability.[10,23,24] The development of intracommunity differences in the perception of risk and rewards may also lead to stress in some residents.[25] Some local stressors may also be regional issues, such as water availability, ground level ozone, and water quality. At the global scale, the contribution of UNG development to methane and carbon dioxide levels in the atmosphere has broad implications for population health.[26,27]

The following sections describe existing mortality and morbidity outcomes that may stem from the major chemical, physical and psychosocial stressors that exist in and around UNG development as well as the pathways by which these stressors may affect workers and communities.

III. EXPOSURE PATHWAYS AND HEALTH EFFECTS

A. Occupational. *1. Fatalities and Injuries.* Industrial incidents, malfunctions, and worksite and traffic accidents put workers at increased risk of exposure to fires, explosions, and uncontrolled chemical releases. While there are no data specific to UNG production, data on the oil and gas industry indicate that it has a high occupational fatality rate. Between 2005 and 2009, the fatality rate was two and a half times the rate in the construction industry and 7-fold higher than the general industry rate.[22,28] Bureau of Labor Statistics data indicate that the fatality rate for oil and gas workers was more than 8-fold higher than in other occupations.[28] Nearly a third of the deaths were due to traffic accidents and single-vehicle rollovers were the most common accident type. Mortality rates are also related to the size of the company, with smaller companies having higher fatality rates compared to medium and large-sized operators.[29] Although the mortality rate data are aggregated across petroleum and natural gas workers, state-level data collected in Wyoming during the recent gas production boom suggest that the recent increase in natural gas development had a major impact on mortality trends. Between 2001 and 2008, Wyoming had 32 fatalities from drill rig accidents and 25 transportation-related fatalities in the oil and gas sector.[30] Wyoming also had the highest workplace fatality rate in the country in five of the six years between 2003 and 2008, and in 2010 its occupational fatality rate was three and half times the national average.[30,31] In contrast to worksite fatalities, nationwide rates of reportable injuries in the oil and gas industry were ~3 folder lower than in the construction industry, though this may be a result of under-reporting.[16,22,28] Under-reporting would be consistent with the findings of Mendeloff and Burns (2012), who found an unexpected negative correlation between reported fatalities and nonfatal injuries in the similarly decentralized construction industry, which the authors suggest was due to under-reporting of nonfatal injuries when fatalities were high.[32]

2. Air Pollution. Unconventional natural gas development and production workers are at risk from air pollution exposure because they work in and around major emission sources. Air pollution from UNG development originates from (1) direct and fugitive emissions of methane and nonmethane hydrocarbons from the well and associated infrastructure (e.g., production tanks, valves, pipelines, and collection and processing facilities); (2) diesel engines that power equipment, trucks, and generators; (3) drilling muds, fracturing fluids, and flowback water; and (4) deliberate venting and flaring of gas and related petroleum products.

Hydrogen sulfide (H_2S), which is naturally occurring in natural gas reserves, is an explosion risk and is arguably the greatest acute toxicity hazard for natural gas workers.[33−35] Significant irritant and other central nervous system health effects occur at or above 100 ppm, and these effects gradually increase in severity with duration of exposure, with immediate death occurring at ~1000 ppm.[34] Little data exist on the frequency of occupational exposure to H_2S, but many companies require use of alarmed personal monitors to prevent fatalities.[16,22]

Among the hundreds of chemicals used to drill and fracture wells, silica is the most common additive to the process. Silica is also one of the key occupational hazards for workers because mechanical handing of crystalline silica, which is used as a proppant during hydraulic fracturing, creates large clouds of respirable dust.[16,36] Esswein et al.'s recent study of workers in Colorado, Texas, North Dakota, Arkansas, and Pennsylvania found that 8 h time weighted average breathing zone silica concentrations in 111 samples ranged from 0.007 mg/m^3 to 2.76 mg/m^3.[37] Nintey-three (84%) of the samples exceeded the American Conference of Industrial Hygienists threshold limit value (TLV) of 0.025 mg/m^3, 76 (68%) exceeded the National Institute of Occupational Safety and Health (NIOSH) recommended exposure limit (REL) of 0.05 mg/m^3, and 57 (51%) exceeded the Occupational and Safety Health Administration's (OSHA) current permissible exposure limit (PEL) for respirable silica-containing dust. Increasing evidence of the toxicity of silica has led OSHA to recently propose dropping its PEL to match the NIOSH REL.[38] Respirable silica can cause silicosis and lung cancer and has been associated with tuberculosis, chronic obstructive pulmonary disease (COPD), kidney disease, and autoimmune disease.[16] Exposure to silica dust also poses a hazard to workers in industries supporting shale gas development, such as sand mining and transport.[39]

Workers also may be exposed to petroleum hydrocarbons, such as aromatics (e.g., benzene, toluene, ethyl benzene, and xylenes; hereafter BTEX) and aliphatic compounds during well development and production.[27] The health effects most often associated with benzene include acute and chronic nonlymphocytic leukemia, acute myeloid leukemia, chronic lymphocytic leukemia, non-Hodgkins lymphoma, anemia and other blood disorders and immunological effects.[40,41] Occupational exposure to petroleum compounds is also associated with increased risk of eye irritation and headaches, asthma symptoms, and multiple myeloma and non-Hodgkins lymphoma.[42−47] Many of the common petroleum hydrocarbons measured in and around UNG sites, such as BTEX, have robust toxicity databases and health-based standards, while toxicity information for others, such as heptane, octane, and diethylbenzene, is more limited, thereby hampering the assessment of risks for these compounds.[48]

We found no published studies on exposures of UNG workers to other compounds used on site, though there are potential exposures from vaporization or aerosolization of drilling muds and hydraulic fracturing fluids that contain a range of neurological, respiratory and skin toxicants.[14,49−51] Workers are also exposed to diesel exhaust emitted from trucks and generators used to power operations. While diesel exhaust emissions vary by engine type and controls, exposure to diesel exhaust in other industries is associated with respiratory and cardiovascular disease.[52−54] The International Agency for Research on Cancer has classified diesel exhaust as a human carcinogen, while U.S. EPA classifies it as likely to be carcinogenic in humans.[41,55]

There is relatively little published research on other occupational stressors associated with UNG development, such as particulate matter from diesel engines or other combustion sources. Noise exposure is a significant hazard due to the presence of multiple sources, including heavy equipment, compressors, and diesel powered generators. Loud continuous noise has health effects in working populations.[56] It is likely that exposure to noise is substantial for many workers, and this is potentially important for health because drilling and servicing operations are exempt from some sections of the OSHA noise standard.[22] In addition to these direct exposures, peri-occupational issues, such as incidents of childhood lead poisoning from "take home" exposure to pipe dope on work clothes, increased rates of sexually transmitted infections, and steep increases in the demand for and price of rental housing are all adverse outcomes related to the rapid increase in the workforce in locales where development is occurring.[10,23,51] These work and life issues are addressed in greater depth in the Community effects section.

B. Community. While workers may be exposed to a wide range of hazards during well development, residents and community members living, attending school and working adjacent to UNG development sites may experience many of the same chemical or physical exposures. Although concentrations in the environment are likely lower further from development sites, the round-the-clock development cycle means that cumulative exposures may be of concern for people living near UNG development activities.

1. Accidents and Injuries. Reports to state agencies indicate that traffic and industrial accidents occur in the course of UNG development and operations.[23,57,58] Increased truck traffic in residential areas raises the likelihood for traffic accidents and may decrease residents walking and exercising in areas of development.[12] The average multistage well can require hundreds to more than a 1000 truck round trips to deliver equipment (e.g., bulldozers, graders, pipe), chemicals, sand, and water needed for well development and fracturing.[13,59] Truck counts in Bradford County, PA, for example, were approximately 40% higher than a comparable 5-year average prior to UNG development, with a proportional increase in accidents involving large trucks. [59] Preliminary analysis of data from the Pennsylvania Department of Transportation's Crash Reporting System indicates a significant increase in the number of total accidents and accidents involving heavy trucks between 1997 and 2011 in counties with a relatively large degree of shale gas development compared to counties with no development.[58] Similarly, the Texas Department of Transportation noted a 40% increase in reported fatal motor vehicle accidents from 2008 to 2011 in 20 Eagle Ford Shale counties.[57] Additional research on the impact of increased truck traffic on residential accident and fatality rates is needed.

While not extensively addressed in the peer-reviewed literature, industrial accidents and natural disasters involving well infrastructure and pipelines may put nearby residents at increased risk of exposure to fires, explosions and hazardous chemicals, which is a concern in many communities.[23] The September 2013 catastrophic flood in northeastern Colorado, for example, resulted in 13 notable releases of oil, totaling 43 134 gallons, and 17 releases of produced water, totaling 26 385 gallons.[60] The limited monitoring conducted after the flood indicated that the releases were extensively diluted to concentrations below detection limits by the large volumes of floodwater, and that bacterial contamination of water supplies due to nonfunctional water treatment plants was likely a bigger public health concern than spills originating from petroleum development infrastructure.[61]

2. Air Pollution. Increased traffic from industrial operations can degrade air quality due to diesel exhaust, road dust, and nitrogen oxides (NOx) (Table 1). In addition to traffic-related pollutants, people living near UNG development sites may be exposed to VOCs, silica, and other chemicals used during fracturing and well completion as well as fugitive emissions of VOCs from pipes and valves. While there are few studies characterizing the emission and distribution of pollutants from well pads, there are many documented instances of odor complaints and increased air concentrations of VOCs and other compounds at or near well pads during development.[25,62,63] People living within $^1/_2$ mile of a multiwell pad complained of odors during well completions in Garfield County, CO, and 81% of respondents to a self-reporting survey in active shale gas development areas in Pennsylvania reported odors.[15,62] Hydrogen sulfide has a very low odor threshold and a 10 h half-life, so it may be responsible for some odor complaints.[34]

Pilot studies in Colorado's Piceance Basin, Pennsylvania's Marcellus, and Texas's Barnett Shale indicate that VOCs, including C2–C8 alkanes, aromatic hydrocarbons, methyl mercaptan, and carbon disulfide, are emitted during well completions as well as from compressors, condensate storage tanks and related infrastructure.[17,64–66] Natural gas development may be the primary source of ambient benzene concentrations in the Dallas Fort Worth Area and Garfield County, CO.[17,67] One of the few community pollution studies with near-well pad measurements during well completion found that VOCs were detected more often and at higher concentrations compared to regional ambient air samples.[15] In that study, benzene concentrations ranged from 0.94 to 69 $\mu g/m^3$ and C_5 to C_8 aliphatic hydrocarbon concentrations ranged from 24 to 2700 $\mu g/m^3$ in 24 samples collected 130 to 500 feet from the center of five well pads in western Colorado during the high-emission period of uncontrolled flowback. A second study in western Colorado collected 24 h integrated air samples 0.7 miles from a well pad and found that emissions were higher during drilling compared to levels found during a closed loop ("green") completion.[36] A study in eastern Colorado collected 36, 3 h integrated air samples during morning hours at 850 and 1650 feet from a well pad during a green completion.[68] Benzene concentrations ranged from 0.73 to 2.06 $\mu g/m^3$, and the highest toluene and speciated nonmethane organic carbon concentrations were observed when multiple trucks were at the well pad.[69] In addition to these three studies, regional scale air quality studies suggest that oil and gas operations are a significant source of ambient benzene and alkanes on the northern Colorado Front Range.[70,71]

Studies in Texas, Oklahoma, and Colorado have attributed emissions of light alkanes from oil and gas development to the formation and transport of ozone to nearby urban areas.[70–72] Ground level ozone concentrations in the Haynesville Shale region of East Texas and Louisiana are projected to increase by up to 9 and 17 ppb under low- and high-emission scenarios, respectively. The area affected by high ozone levels under the high-emission scenario is twice that of the low-emission scenario.[73] Increases in ozone levels in either scenario are sufficient to push some counties in the study area beyond the current U.S. EPA 8 h National Ambient Air Quality Standard (NAAQS) for ozone (75 ppb). Monitoring in the Dallas Fort Worth area indicates that decreases in mean annual 8 h ozone concentrations from 1997 to 2011, which coincided with dramatic increases in the number of shale gas wells after about 2007.[65] Additional study is needed to determine if this trend is attributable to decreasing emissions from unconventional gas development or if controls on other sources of VOCs are responsible for the observed change.[74,75] A modeling study of the Barnett Shale region of Texas predicts that VOC emissions associated with compressor engines and NOx emissions from flaring natural gas could increase peak 1 h ozone concentrations by up to 3 ppb and 8 h concentrations by several ppb.[76] A group at Rand Corporation has developed estimates of air emissions from operations related to the shale gas industry in Pennsylvania and utilized an EPA model to monetize estimated health effects. Their region-wide estimate of damages was \$7.2–35 million in 2011. Of note is that aggregate NOx emissions in some counties were 20–40 times higher than allowable for a single minor source.[77] Researchers in Colorado are conducting comprehensive studies designed to characterize shale gas emissions, with results expected in 2014 and 2015.[78]

Winter ozone concentrations above the 8 h NAAQS were observed in relatively remote areas in Utah's Uintah Basin and Wyoming's Upper Green River Basin in recent years.[79–81] Peak ozone concentrations reached 149 ppb and 8 h averages reached 134.6 ppb in the Uintah basin, and emissions inventories indicate that oil and gas operations were responsible for 98–99% of the VOCs and 57–61% of the NOx ozone precursors.[82] In the Upper Green River Basin, photolytic ozone production resulted in peak ozone concentrations >140 ppb when NOx and VOCs from the production of UNG become trapped at the surface by intense, shallow temperature inversions.[80] A modeling study indicates that wintertime ozone production in this region is most sensitive to VOC emissions, suggesting that emission controls on UNG development will likely play an important part in addressing concerns about elevated ozone.[83]

The recent Allen et al. study examining methane releases during the drilling cycle of cooperating industries in different areas of the United States is also pertinent to community air pollution.[84] The study observed a very wide range of total methane emissions as well as a wide range in the rate of release for wells right next to each other that were developed by the same company. Methane emissions during the flowback period ranged from 0.01 to 17 Mg, and the rate of methane emissions during an uploading event varied by about 100-fold. While the authors did not measure BTEX or other VOCs, it is likely that the same degree of variability would be expected for these compounds assuming they are emitted with the measured methane. The work of Allen et al. suggests that local hot spots of both methane and possibly nonmethane air pollutants exist. As not all companies or production areas have cooperated with methane emission measurements, and as emission control practices vary across the industry, there is legitimate concern that local air pollution may produce adverse effects in individuals who live near the high emitting sites or processes.[85]

Apart from the direct effects of these pollutants on human health, UNG development also has the potential to positively or negatively affect global climate. Burning natural gas is far more energy-efficient than burning other fossil fuels, particularly coal, and results in lower emissions of carbon dioxide.[86] Methane itself is a potent greenhouse gas and any released to the atmosphere that otherwise would be locked up underground contributes to global climate change. Direct methane emissions occur during drilling and well completion, and fugitive methane emissions occur along pipelines, valves, and other related infrastructure. Although controversial, the emerging consensus in the scientific literature is that the advantage conferred by burning natural gas is a net benefit compared to burning coal, even considering methane losses to the atmosphere from UNG production.[70,84,87−93] Any further reduction in direct and fugitive methane emissions would be a further net benefit if natural gas permanently replaces coal that otherwise would be produced and burned.

3. Water Pollution. Intense public interest has been focused on possible contamination of drinking water sources with hydraulic fracturing chemicals and other pollutants associated with drilling and production (Tables 1 and 2). Potential pathways of surface and groundwater contamination from UNG development are transportation spills, well casing leaks, migration through fractured rock, abandoned wells, drilling site discharge, and wastewater disposal. [94]

The existing scientific literature has limited information indicating that UNG development may contaminate domestic ground or surface water supplies for individuals or communities.[19,95] Direct attribution of contamination from the fracturing process is hindered by lack of baseline data, the widespread presence of methane and petroleum byproducts in many gas-bearing basins, and nondisclosure agreements that limit the reporting of contamination after legal settlements.[1,3,96] Current scientific consensus is that accidents and malfunctions, such as well blowouts, leaking casings, and spills of drilling fluids or wastewater, are more likely to contaminate surface and groundwater supplies than the process of high-volume hydraulic fracturing itself.[19,94]

Table 2. Types of Additive, Example Chemicals, And Their Purpose in the Hydraulic Fracturing Process[a]

additive	example chemical	purpose
acid	hydrochloric or muriatic acid	helps dissolve minerals and initiate cracks in the rock
antibacterial agent	glutaraldehyde	eliminates bacteria in the water that produces corrosive byproducts
breaker	ammonium persulfate	allows a delayed break down of the fracturing gel
clay stabilizer	potassium chloride	brine carrier fluid
corrosion inhibitor	n,n-dimethyl formamide	prevents corrosion of pipes
cross-linker	borate salts	maintains fluid viscosity
defoamer	polyglycol	lowers surface tension and allows gas escape
foamer	acetic acid (with NH_4 and $NaNO_2$)	reduces fluid volume and improves proppant carrying capacity
friction reducer	petroleum distillate	minimizes friction in pipes
gel guar gum	hydroxyethyl cellulose	helps suspend the sand in water
iron control	citric acid	prevents precipitation of metal oxides
oxygen scavenger	ammonium bisulfate	maintains integrity of steel casing of wellbore; protects pipes from corrosion by removing oxygen from fluid
pH adjusting agent	sodium or potassium carbonate	adjusts and controls pH of the fluid
proppant	silica, sometimes ceramic particles	holds open (props) fractures to allow gas to escape from shale
scale inhibitor	ethylene glycol	reduces scale deposits in pipe
solvents	stoddard solvent, various aromatic hydrocarbons	improve fluid wettability or ability to maintain contact between the fluid and the pipes
surfactant	isopropanol	increases viscosity of the fracturing fluids and prevents emulsions

[a] Sources: Colborn, T., et al. Natural Gas Operations from a Public Health Perspective. *Human and Ecological Risk Assessment: An International Journal.* 2011. 17(5): p. 1039−1056; Earthworks. *Hydraulic Fracturing 101.* 2011 [cited 2012 Jan 11] Available from: http://www.earthworksaction.org/issues/detail/hydraulic_fracturing_101; Encana Corporation. Chemical use. [cited 2013 Sep 25] Available from: http://www.encana.com/environment/water/fracturing/chemical-use.html; EnergyIndustryPhotos. What is Hydraulic Fracturing and What is it Used for? . 2008 [cited 2012 Jan 11] Available from: http://www.energyindustryphotos.com/what_is_hydraulic_fracturing.htm; King, G.E., Hydraulic Fracturing 101: What Every Representative, Environmentalist, Regulator, Reporter, Investor, University Researcher, Neighbor and Engineer Should Know About Estimating Frac Risk and Improving Frac Performance in Unconventional Gas and Oil Wells. *SPE Hydraulic Fracturing Technology*; Woodlands, TX, 2012; Jiang, M., et al. Life cycle greenhouse gas emissions of Marcellus shale gas. *Environ. Res. Lett.*. 2011. 6(3); United States Department of Energy, *Modern Shale Gas Development in the United States: A Primer*; Oklahoma City, OK, 2009.

Aside from accidents and malfunctions, the evidence for contamination of groundwater wells with methane, fracturing chemicals, or other process wastes is mixed.[97−100] EPA studies in Pavilion, Wyoming, and Dimmick, Pennsylvania that have suggested associations between UNG development and drinking water contamination are controversial because of uncertainties about whether the chemicals present in these aquifers are there as a result of the hydraulic fracturing process.[96,101,102] Residents of both towns have been provided replacement drinking water by authorities.[101] An extensive report by the Ground Water Protection Council exploring drinking water contamination from UNG development in Texas and Ohio found evidence of leakage from orphaned wells and disposal pits, but no evidence of contamination from site preparation or the well stimulation process.[85] Osborn et al. used a convenience sampling approach to explore water quality in 60 samples collected in areas of active drilling in the Marcellus Shale.[18] While they did not find evidence of hydraulic fracturing chemicals in their samples, they did find that methane levels were higher in drinking water wells closer to UNG wells. Similarly, analysis of private well water quality in aquifers overlying the Barnett Shale has revealed that arsenic, selenium, strontium and total dissolved solids (TDS) exceeded the EPA's maximum contamination limit (MCL) in some samples located within 3 km of active natural gas wells.[103] Overall, the existing peer-reviewed literature lacks studies with substantive comparisons of water quality before and after natural gas development due to a lack of baseline data on water quality prior to the advent of UNG development. There is at least one documented case of contamination of water supplies from abandoned natural gas wells, but a comprehensive analysis of the effect of plugged or abandoned wells as a potential exposure pathway is a research need.[104]

Produced water is the largest component of the UNG development waste stream and is distinct from flowback water, which is primarily fracturing fluids that come out after immediately after well stimulation.[105,106] Produced water is water present in gas-bearing formations that comes to the surface over the life of the well . Given the high pressure and temperature in the underlying strata, both flowback and produced waters have the potential to contain transformation products that originate from the drilling muds and fracturing chemicals as well as methane, petroleum condensate, salts, metals, and, depending on the formation, naturally occurring radioactive materials (NORM). Flowback and produced water is stored in surface pits or sealed tanks prior to reuse and/or disposal.[87] Studies assessing composition of Marcellus Shale produced water found that most metals and salt ion concentrations increased with time after fracturing and were correlated with the composition of the underlying strata.[107,108] Current evidence suggests that wastewater is more effectively treated onsite because effluents discharged to publicly owned treatment plants may not be able to provide sufficient treatment for this waste stream.[109,110]

Potential for groundwater contamination from surface spills at wastewater storage and treatment facilities at active well sites has received increased attention. From July 2010 to July 2011, Gross et al. noted 77 reported surface spills (~0.5% of active wells in the region) impacting the groundwater in Weld County, CO.[111] Measurements of BTEX exceeded EPA maximum contaminant limits in most cases, and actions taken to remediate the spills were effective at reducing BTEX levels.[111]

C. Potential Health Effects and Population-Based Studies. At present, there are no population-based studies of health effects from water contamination, and relatively few studies exploring the impact of airborne exposures. Nonetheless, the potential for health effects can be inferred for specific chemicals from known health effects of contaminants if data exist on their potential potency that can then be linked to measured or estimated human exposure.

Exposure to ozone is associated with several adverse health effects, including respiratory, cardiovascular, and total mortality as well as decreased lung function, asthma exacerbation, COPD, cardiovascular effects and adverse birth outcomes.[112] People with asthma, children, and the elderly are at increased risk, and adverse health outcomes have been observed at concentrations as low as 41 ppb.[112] The overall relationship between ozone concentration and response to multiple outcomes appears to be linear with no indication of a threshold.[112] While there are many studies documenting the health effects of ozone exposures and several studies that suggest an association between unconventional oil and gas development and ground level ozone production, we found only one population-based study on ozone- and health effects in a UNG development region. That study found that between 2008 and 2011, Sublette County, Wyoming observed a 3% increase in the number of clinic visits for adverse respiratory-related effects for every 10 ppb increase in the 8 h ozone concentration the previous day.[113]

Populations living near UNG operations report odors and, in some cases, upper respiratory, neurological, and dermatological symptoms.[1,23,62,114] While these studies lack scientific rigor because they are volunteer or convenience samples of the local population, these effects are consistent with known health effects associated with petroleum hydrocarbons exposure. For example, inhalation of trimethylbenzenes and xylenes can irritate the respiratory system with effects ranging from eye, nose, and throat irritation to difficulty in breathing and impaired lung function.[115,116] Inhalation of xylenes, benzene, and aliphatic hydrocarbons can adversely affect the nervous system with effects ranging from dizziness, headaches, fatigue, and limb numbness to a lack of muscle coordination, tremors, temporary limb paralysis, and unconsciousness at high levels.[40,115−119] Maternal exposure to ambient levels of benzene has been associated with an increase in birth prevalence of neural tube defects.[120]

There is a growing epidemiological literature on the health effects associated with UNG development. A retrospective study of 124 862 births in rural Colorado indicated an association between maternal proximity to natural gas well sites and birth prevalence of congenital heart defects and neural tube defects, but no association with oral clefts, term low birth weight or preterm birth.[121] A working paper exploring 1 069 699 births in Pennsylvania reported increased prevalence of low birthweight and small for gestational age births, as well as reduced appearance, pulse, grimace, activity, respiration (APGAR) scores in infants born to mothers living within 2.5 km of a natural gas well compared to infants born to mothers living further than 2.5 km from a well.[122] While these preliminary epidemiological studies are hindered by a lack of spatial and temporal specificity in exposure and individual level risk factors, they underscore the need for a better understanding of exposures and health effects in populations living in UNG development and production areas. Another study compared standardized incidence rates (SIRs) for childhood cancer in Pennsylvania counties, but found no difference in SIRs for all cancer types except central nervous system (CNS) tumors, which the authors attributed to a large number of excess tumors in counties with the fewest wells.[123] The scientific validity of this ecological study is questionable because it chose before and after comparison periods that are not relevant to current concerns about UNG development.[124] It is also limited by lack of an individual level assessment of relevant confounders and the assumption that individual exposures to hydraulic fracturing are uniform within a county or confined by county boundaries. Additional epidemiological studies are needed to shed light on the existence and nature of disease patterns that might be associated with UNG development.

D. Socioeconomic Impacts, Psychosocial Effects and Human Health. In addition to the potential for public health benefits from lower regional and global air pollution levels resulting from replacing coal with natural gas in power plants, there are potential economic benefits that could contribute to the overall health of a community.[125] Natural gas development may bring economic growth through increased employment. Though estimates are uncertain, unconventional oil and natural gas development is estimated to employ up to 1.7 million people in the U.S. and is projected to support nearly 3 million jobs by 2020.[126] Various reports and a leading industry association, America's Natural Gas Alliance (ANGA), state that the benefits of natural gas include local infusion of funds to leaseholders, jobholders, and the providers of ancillary services, as well as the economic value to the general public of lower prices of natural gas and electricity.[86,126−128]

There are also negative economic effects, however, which often fall on community members least able to bear the loss. A substantial body of literature indicates negative social effects from energy extraction in small "boomtowns" during the 1970s and 1980s that are similar to the 21st century UNG boom.[10]

Studies in Colorado and Canada finding increases in crime, substance abuse, and sexually transmitted infections corresponding to periods of increased natural gas development activity substantiate these concerns.[10,12,23,129] The influx of UNG industry workers has led to rapid rental price increases, particularly in rural counties with low populations and limited housing stock.[130] The effect has been greatest on low and fixed income individuals who can no longer pay for their homes. As a result, local social services, including the need to develop homeless shelters, may be strained.[131] Community resilience, defined as the ability of a community to sustainably utilize available resources to withstand, respond to, and/or recover from adverse events, may be affected by UNG development, as was evident when social services were further strained by a major storm in central Pennsylvania in 2011.[130] The economic value of lost ecosystem services in areas that rely on tourism and second homes has not been fully assessed, although one estimate suggests a loss of between $11 and $27 million per year in Pennsylvania.[132] A study in Washington County, PA, a semirural area, has reported at least a transitory loss in property values in areas immediately surrounding shale gas drilling sites.[130] In view of the broad social effects and the community divisiveness that has attended UNG development, health effects attributable to stress are not surprising and are consistent with previous studies of boomtowns.[10,127,133−136]

Many of the nonspecific symptoms associated with UNG development may reflect psychosocial stress. Contributing to this stress is a lack of trust and transparency concerning industry and government action. Ferrar et al. (2013) noted that those who believe their health has been affected report higher stress levels due to loss of trust and perceived lack of transparency. More than half these subjects report they have been denied or provided with false information (79%), that their concerns/complaints have been ignored (58%), and that they are being taken advantage of (52%).[25] It is notable that these psychosocial stressors are reported more frequently than physical stressors such as noise (45%) and odors (13%). Perceived secrecy about hydraulic fracturing agents and the makeup of produced water are contributing to this lack of trust.[130] Social amplification of risk perception is commonly noted in situations in which there is a lack of trust.[137,138] A recent review of the many factors involved in risk perception found that the two major determinants were familiarity and trust; with other factors, such as gender, age, media coverage, and socioeconomic status being far less important.[139]

IV. HEALTH RISKS FROM SHALE GAS DEVELOPMENT

To date observational studies exploring the association between human health and UNG development have had a number of scientific limitations, including self-selected populations, small sample sizes, relatively short follow-up times and unclear loss to follow-up rates, limited exposure measurements and/or lack of access to relevant exposure data, and lack of consistently collected health data, particularly for noncancer health effects. Given these limitations, the lack of observational studies and the public's demand for answers, it is likely that human health risk assessments will be needed to provide projections of potential future harm for both short-term catastrophic and long-term human health risks.

Risk Governance, Risk Estimates, and Cumulative Risk. Natural gas development is governed by a mix of federal, state, and local laws and regulations.[1,13] The Federal government has relatively little direct authority over natural gas development and production, as the permitting authority lies with states and, in some cases, local authorities.[13] Companion papers in this volume address the key risk governance issues around UNG development, so we focus on the current estimates of public health risk and related issues and research needs.

Human health risk assessments published to date have focused on risks to communities from only air exposure. McKenzie et al.'s screening-level human health risk assessment is the only study to utilize measurements collected near well pads during the high emission well completion process, and found that residents living nearest to the well pad were at increased risk of acute and subchronic respiratory, neurological and reproductive effects.[15] They also estimated lifetime excess cancer risks, which were in the range of concern but below the range where action is typically taken. Other risk assessments conducted to date are largely in agreement with these observations, indicating slightly elevated excess lifetime cancer risks driven by benzene, some indication of acute or subchronic noncancer risks for those living closest to well sites, and little indication of chronic noncancer risks.[69,96,140−143] Few studies have attempted to use biomonitoring to explore risks from shale gas-related pollutants. Blood and urine samples collected from 28 adults living in Dish, Texas, a town with large numbers of gas wells, storage tanks, and compressor stations near residences, found no indication of community wide-exposure to VOCs.[144] These results likely reflect the multiple potential sources and the short half-lives of most VOCs in urine and blood, especially since the sampling did not coincide with known or perceived exposures, and concurrent air samples were not collected for study subjects.

This limited collection of risk studies underscores the overall lack of and need for substantive research on the human health effects stemming from UNG development. Given the broad range of chemical and nonchemical stressors present in and around UNG development sites and public demand for explication of the real and perceived risks, more substantive cumulative risk research is needed to address public concerns about the effects of UNG development on human and ecosystem health.[145,146] Figure 1 outlines a potential cumulative risk assessment approach that incorporates chemical, physical, and psychosocial stressors that contribute to stress-related health effects in populations living near UNG development sites. This cumulative risk approach uses an allostatic load conceptual model to incorporate the various stressors and buffers that act on individuals and communities.[145,147] Additional research is needed to both produce cumulative risk estimates and judge their utility for local, state, and federal decision-makers.

V. PUBLIC HEALTH RESEARCH NEEDS

The major uncertainties that should be addressed in future research on the effects of UNG development are the magnitude and duration of human exposure to stressors as well as the lack of baseline data to enable substantive before and after comparisons in affected populations and environmental media.[13] Additional process uncertainties include the location and extent of future UNG development as well as the cost, feasibility, and success of future emission control and mitigation strategies. Overall, the current scientific literature suggests that there are both substantial public concerns and major uncertainties to address before we can reasonably quantify the likelihood of occurrence or magnitude of adverse health effects in workers and communities where UNG development will likely occur.

Occupational health and safety research needs include both disease surveillance and exposure characterization. This includes tracking of fatalities, injuries, and health effects data in a defined population of unconventional resource workers, with particular focus on benzene, toluene, and silica related disease, hearing loss, and other traffic and worksite safety issues as well as health-based standards for poorly characterized compounds, such as aliphatic hydrocarbons.[22,29] Exposure data is also needed in workers to characterize the magnitude, frequency, duration of exposure to the wide range of chemical and physical stressors present at the worksite. Measurements should focus on continuous exposure monitoring to characterize acute and chronic worker exposure to aliphatic and aromatic hydrocarbons, diesel exhaust, fracturing chemicals, silica, produced water, H_2S, NORM, and noise over the wide range of UNG development activities.

Given the lack of systematic tracking of exposure and health effects in communities, there are little data to inform risk mitigation and risk management activities. For air quality, key unknowns include characterization of baseline air quality prior to development in new areas as well as characterization of the variability in exposure during high emissions processes, specifically drilling, hydraulic fracturing, and well completion activities. For water quality, unknowns include characterization of baseline water quality and impacts during each of the process steps that use water, that is, chemical mixing, hydraulic fracturing, flowback, and storage of flowback and produced water and wastewater treatment and disposal. Research on other stressors, including noise and light, traffic, and other safety hazards needs to be conducted in the context of understanding the overall effect of the mixture of these chemical and physical stressors. The interaction with the stress created by rapid change and community disruption is a key research need for characterizing health effects in locales where development is encroaching. Better understanding of cumulative risk issues will help inform UGD control policies and mitigate adverse community effects.[148]

At present, relatively little funding for independent research is available from federal, state, foundations, industry, or public-private partnerships to address these public health research needs. Given the high level of mistrust observed between citizens and the natural gas development industry it is important that research is designed and conducted by scientists that are not perceived as biased in favor of or against the industry.[95] Public-private partnerships (e.g., the Health Effects Institute) that solicit and fund rigorous research are a model that has worked for contentious public health issues in the past and may be effective in the future.

AUTHOR INFORMATION

Corresponding Author

*Phone: 303.724.4692; fax: 303.724.4495; e-mail: John.Adgate@ucdenver.edu.

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

Drs. Adgate and McKenzie were supported, in part, by funds from the National Science Foundation (NSF CBET-1240584), Research Partnership to Secure Energy for America/Department of Energy (EFDTIP2-TIP213), and the Colorado School of Public Health. We thank Nathan De Jong for his support in developing the manuscript.

LIST OF ACRONYMS

APGAR	appearance, pulse, grimace, activity, respiration
BTEX	benzene, toluene, ethyl benzene, xylenes
CNS	central nervous system
COPD	Chronic obstructive pulmonary disease
H_2S	hydrogen sulfide
MCL	maximum contamination limit
Mg	megagram
NAAQS	National Ambient Air Quality Standard
NIOSH	National Institute of Occupational Safety and Health
REL	recommended exposure limit
NOx	nitrogen oxides
NORM	naturally occurring radioactive materials
OSHA	Occupational and Safety Health Administration
PEL	permissible exposure limit
SIR	standardized incidence rate
TDS	total dissolved solids
TLV	threshold limit value
UNG	unconventional natural gas
U.S. EPA	United States Environmental Protection Agency
VOC	volatile organic compound

REFERENCES

(1) Goldstein, B. D.; 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* (4), 483–6, DOI: 10.1289/ehp.1104594.

(2) *Review of Emerging Resources: U.S. Shale Gas and Shale Oil Plays*; U.S. Energy Information Administration: Washington DC, 2011; http://www.eia.gov/analysis/studies/usshalegas/pdf/usshaleplays.pdf.

(3) King, G. E. *Hydraulic Fracturing 101: What Every Representative, Environmentalist, Regulator, Reporter, Investor, University Researcher, Neighbor and Engineer Should Know About Estimating Frac Risk and Improving Frac Performance in Unconventional Gas and Oil Wells*; Woodlands, TX, 2012; DOI 10.2118/152596-MS.

(4) *What is Shale Gas and Why Is It Important?*; U.S. Energy Information Administration: Washington DC, 2012; http://www.eia.gov/energy_in_brief/article/about_shale_gas.cfm.

(5) Vidas, H.; Hugman, B. *Availability, Economics, and Production Potential of North American Unconventional Natural Gas Supplies*; ICF International, 2008. http://www.ingaa.org/cms/31/7306/7628/7833.aspx.

(6) *Overview of Final Amendments to Air Regulations for the Oil and Gas Industry Fact Sheet*; U.S. Environmental Protection Agency: Washington DC, 2012; http://www.epa.gov/airquality/oilandgas/pdfs/20120417fs.pdf.

(7) *Annual Energy Outllook for 2013*; U.S. Energy Information Administration: Washington DC, 2013; http://www.eia.gov/forecasts/aeo/.

(8) Dong, Z.; Holditch, S. A.; McVay, D. A.; Ayers, W. B. Global unconventional gas resource assessment. *SPE Econ. Manage.* **2012**, *4* (4), 222−234, DOI: 10.2118/148365-PA.

(9) Finkel, M. L.; Law, A. The rush to drill for natural gas: a public health cautionary tale. *Am. J. Public Health* **2011**, *101* (5), 784−5, DOI: 10.2105/ajph.2010.300089.

(10) Jacquet, J. Energy boomtowns and natural gas: Implications for Marcellus Shale local governments and rural communities; The Northeast Regional Center for Rural Development: University Park, PA, 2009; http://aese.psu.edu/nercrd/publications/rdp/rdp43/view.

(11) Korfmacher, K. S.; Jones, W. A.; Malone, S. L.; Vinci, L. F. Public health and high volume hydraulic fracturing. *New Solutions* **2013**, *23* (1), 13−31, DOI: 10.2190/NS.23.1.c.

(12) Witter, R. Z.; McKenzie, L.; Stinson, K. E.; Scott, K.; Newman, L. S.; Adgate, J. The use of health impact assessment for a community undergoing natural gas development. *Am. J. Public Health* **2013**, *103* (6), 1002−10, DOI: 10.2105/AJPH.2012.301017.

(13) *Oil and Gas: Information on Shale Resources, Development, and Environmental and Public Health Risks*, GAO-12-735; U.S. Government Accountability Office: Wasington, DC, 2012; http://www.gao.gov/assets/650/647791.pdf.

(14) Colborn, T.; Kwiatkowski, C.; Schultz, K.; Bachran, M. Natural gas operations from a public health perspective. *Hum. Ecol. Risk Assess.: Int. J.* **2011**, *17* (5), 1039−1056, DOI: 10.1080/10807039.2011.605662.

(15) McKenzie, L. M.; Witter, R. Z.; Newman, L. S.; Adgate, J. L. Human health risk assessment of air emissions from development of unconventional natural gas resources. *Sci. Total Environ.* **2012**, *424*, 79−87, DOI: 10.1016/j.scitotenv.2012.02.018.

(16) *Worker Exposure to Silica during Hydraulic Fracturing Hazard Alert*; National Institute for Occupational Safety and Health: Washington DC, 2012; http://www.osha.gov/dts/hazardalerts/hydraulic_frac_hazard_alert.html.

(17) Zielinska, B.; Fujita, B.; Campbell, B. *Monitoring of Emissions from Barnett Shale Natural Gas Production Facilities for Population Exposure Assessment*; Desert Research Institute,: Houston, TX, 2011; https://sph.uth.edu/mleland/attachments/Barnett%20Shale%20Study%20Final%20Report.pdf.

(18) Osborn, S. G.; Vengosh, A.; Warner, N. R.; Jackson, R. B. Methane contamination of drinking water accompanying gas-well drilling and hydraulic fracturing. *Proc. Natl. Acad. Sci.* **2011**, *108* (20), 8172−8176, DOI: 10.1073/pnas.1100682108.

(19) Vidic, R. D.; Brantley, S. L.; Vandenbossche, J. M.; Yoxtheimer, D.; Abad, J. D. Impact of shale gas development on regional water quality. *Science.* **2013**, *340*, (6134); DOI 10.1126/science.1235009.

(20) Curtright, A. E.; Giglio, K. Feasibility and Challenges of Using Acid Mine Drainage for Marcellus Shale Natural Gas Extraction. In *Coal Mine Drainage for Amrcellus Shale Natural Gas Extraction: Proceedings and Recommendations from a Roundtable on Feasibility and Challenges*; RAND Corporation: Pittsburgh, PA, 2011; http://www.rand.org/pubs/conf_proceedings/CF300.html.

(21) 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), 14−17, DOI: 10.1088/1748-9326/8/1/014017.

(22) Witter, R. Z.; Tenney, L.; Clark, S.; Newman, L. Occupational exposures in the oil and gas extraction industry: state of the science and research recommendations. *Am. J. Ind. Med.* **2014**, in press.

(23) Witter, R. Z.; McKenzie, L. M.; Towle, M.; Stinson, K.; Scott, K.; Newman, L.; Adgate, J. L. *Health Impact Assessment for Battlement Mesa, Garfield County Colorado*; Colorado School of Public Health, 2011. http://www.garfield-county.com/public-health/documents/1%20%20%20Complete%20HIA%20without%20Appendix%20D.pdf

(24) Adair, S. K.; Pearson, B. R.; Monast, J.; Vengosh, A.; Jackson, R. B. Considering shale gas extraction in North Carolina: Lessons from other states. *Duke Environmental Law & Policy Forum* **2012**, *22*, 257−385, http://scholarship.law.duke.edu/delpf/vol22/iss2/2/.

(25) Ferrar, K. J.; Kriesky, J.; Christen, C. L.; Marshall, L. P.; Malone, S. L.; Sharma, R. K.; Michanowicz, D. R.; Goldstein, B. D. Assessment and longitudinal analysis of health impacts and stressors perceived to result from unconventional shale gas development in the Marcellus Shale region. *Int. J. Occup. Environ. Health* **2013**, *19* (2), 104−12, DOI: 10.1179/2049396713y.0000000024.

(26) Intergovernmental Panel on Climate Change. *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation: Special Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: New York, NY, 2012; http://ipcc-wg2.gov/SREX/.

(27) Hendler, A.; Nunn, J.; Lundeen, J. *VOC Emissions from Oil and Condensate Storage Tanks*, Final Report; Texas Environmental Research Consortium: Woodlands, TX, 2006; http://startelegram.typepad.com/barnett_shale/files/environmental_h051cfinalreport.pdf.

(28) Bureau of Labor Statistics. *Census of Fatal Occupational Injuries*, Restricted Data under NIOSH MOU; Washington, D.C., 2009; http://www.bls.gov/iif/oshcfoi1.htm.

(29) Retzer, K. D.; Hill, R. D.; Pratt, S. G. Motor vehicle fatalities among oil and gas extraction workers. *Accid.; Anal. Prevent.* **2013**, *51*, 168−74, DOI: 10.1016/j.aap.2012.11.005.

(30) Ryan, T. Interoffice Memorandum: Occupational Fatality Recommendations. 2011, http://wyofile.com/wp-content/uploads/2012/01/RYAN-Recomendations-OCCUPATIONAL-FATALITY.pdf.

(31) Frosch, D. *Report Blames Safety Lapses for an Epidemic of Deaths at Wyoming Job Sites*; New York Times, January 12, 2012; http://www.nytimes.com/2012/01/13/us/report-blames-safety-lapses-for-deaths-at-wyoming-job-sites.html?_r=0.

(32) Mendeloff, J.; Burns, R. States with low non-fatal injury rates have high fatality rates and vice-versa. *Am. J. Ind. Med.* **2012**, *56* (5), 509−519, DOI: 10.1002/ajim.22047.

(33) Hendrickson, R. G.; Chang, A.; Hamilton, R. J. Co-worker fatalities from hydrogen sulfide. *Am. J. Ind. Med.* **2004**, *45* (4), 346−350, DOI: 10.1002/ajim.10355.

(34) Guidotti, T. L. Hydrogen sulfide advances in understanding human toxicity. *Int. J. Toxicol.* **2010**, *29* (6), 569−581, DOI: 10.1177/1091581810384882.

(35) *OSHA Fact Sheet: Hydrogen Sulfide*; Occupational Safety and Health Administration: Washington DC, 2005; https://www.osha.gov/OshDoc/data_Hurricane_Facts/hydrogen_sulfide_fact.pdf.

(36) Colborn, T.; Schultz, K.; Herrick, L.; Kwiatkowski, C. An exploratory study of air quality near natural gas operations. *Hum. Ecol. Risk Assess.: Int. J.* **2013**, *20*, 86−105, DOI: 10.1080/10807039.2012.749447.

(37) Esswein, E. J.; Breitenstein, M.; Snawder, J.; Kiefer, M.; Sieber, W. K. Occupational exposures to respirable crystalline silica during hydraulic fracturing. *J. Occup. Environ. Hyg.* **2013**, *10* (7), 347−56, DOI: 10.1080/15459624.2013.788352.

(38) *OSHA's Proposed Crystalline Silica Rule: Overview*, Occupational Safety and Health Administration; U.S. Department of Labor: Washington DC, 2012; https://www.osha.gov/silica/factsheets/OSHA_FS-3683_Silica_Overview.html.

(39) Zdunczyk, M. J. Hydraulic fracturing sand (frac sand). *Min. Eng.* **2013**, *65* (7), 68−70.

(40) *Toxicological profile for Benzene*, Agency for Toxic Substances and Disease Registry; U.S. Deparment of Health and Human Services: Atlanta, GA, 2007; http://www.atsdr.cdc.gov/toxprofiles/tp.asp?id=40&tid=14.

(41) *Diesel Engine Exhaust*, Integrated Risk Information System; U.S. Environmental Protection Agency, 2003; http://www.epa.gov/iris/subst/0642.htm.

(42) Glass, D. C.; Gray, C. N.; Jolley, D. J.; Gibbons, C.; Sim, M. R.; Fritschi, L.; Adams, G. G.; Bisby, J. A.; Manuell, R. Leukemia risk associated with low-level benzene exposure. *Epidemiology* **2003**, *14* (5), 569−577, http://www.jstor.org/stable/3703314.

(43) Kirkeleit, J.; Riise, T.; Bråtveit, M.; Moen, B. Increased risk of acute myelogenous leukemia and multiple myeloma in a historical cohort of upstream petroleum workers exposed to crude oil. *Cancer, Causes Control* **2008**, *19* (1), 13−23, DOI: 10.1007/s10552-007-9065-x.

(44) Brosselin, P.; Rudant, J.; Orsi, L.; Leverger, G.; Baruchel, A.; Bertrand, Y.; Nelken, B.; Robert, A.; Michel, G.; Margueritte, G.; Perel, Y.; Mechinaud, F.; Bordigoni, P.; Hemon, D.; Clavel, J. Acute childhood leukaemia and residence next to petrol stations and automotive repair garages: the ESCALE study (SFCE). *Occup. Environ. Med.* **2009**, *66* (9), 598−606, DOI: 10.1136/oem.2008.042432.

(45) Kim, B. M.; Park, E. K.; LeeAn, S. Y.; Ha, M.; Kim, E. J.; Kwon, H.; Hong, Y. C.; Jeong, W. C.; Hur, J.; Cheong, H. K.; Yi, J.; Kim, J. H.; Lee, B. E.; Seo, J. H.; Chang, M. H.; Ha, E. H. BTEX exposure and its health effects in pregnant women following the Hebei Spirit oil spill. *J. Prev. Med. Pub. Health* **2009**, *42* (2), 96−103, DOI: 10.3961/jpmph.2009.42.2.96.

(46) White, N.; teWaterNaude, J.; van der Walt, A.; Ravenscroft, G.; Roberts, W.; Ehrlich, R. Meteorologically estimated exposure but not distance predicts asthma symptoms in schoolchildren in the environs of a petrochemical refinery: A cross-sectional study. *Environ. Health* **2009**, *8* (1), 45 DOI: 10.1186/1476-069X-8-45.

(47) Goldstein, B. D. Benzene as a cause of lymphoproliferative disorders. *Chem.-Biol. Interact.* **2010**, *184* (1−2), 147−150, http://dx.doi.org/10.1016/j.cbi.200912.021.

(48) U.S. Environmental Protection Agency. Integrated Risk Information System. 2011; http://www.epa.gov/IRIS/.

(49) Searl, A.; Galea, K. Toxicological review of the possible effects associated with inhalation and dermal exposure to drilling fluids production streams. *Inst. Med.*. **2011**; http://www.iom-world.org/pubs/IOM_TM1104.pdf.

(50) 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* (8), 710−719, http://www.maxwellsci.com/print/rjaset/v2-710-719.pdf.

(51) Khan, F. Take home lead exposure in children of oil field workers. *J. Okla. State Med. Assoc.* **2011**, *104* (6), 252 http://www.ncbi.nlm.nih.gov/pubmed/21888039.

(52) Hart, J. E.; Rimm, E. B.; Rexrode, K. M.; Laden, F. Changes in Traffic Exposure and the Risk of Incident Myocardial Infarction and All-Cause Mortality. *Epidemiology* **2013**, *24* (5), 734−742, DOI: 10.1097/EDE.0b013e31829d5dae.

(53) Hart, J. E.; Laden, F.; Schenker, M. B.; Garshick, E. Chronic Obstructive Pulmonary Disease Mortality in Diesel-Exposed Railroad Workers. *Environ. Health Perspect.* **2006**, *114* (7), 1013−1017, DOI: 10.2307/3651770.

(54) Hesterberg, T. W.; Long, C. M.; Bunn, W. B.; Sax, S. N.; Lapin, C. A.; Valberg, P. A. Non-cancer health effects of diesel exhaust: A critical assessment of recent human and animal toxicological literature. *Crit. Rev. Toxicol.* **2009**, *39* (3), 195−227, DOI: 10.1080/10408440802220603.

(55) Wong, O.; Harris, F.; Armstrong, T. W.; Hua, F. A hospital-based case-control study of non-Hodgkin lymphoid neoplasms in Shanghai: analysis of environmental and occupational risk factors by subtypes of the WHO classification. *Chem. Biol. Interact.* **2010**, *184* (1−2), 129−46, DOI: 10.1016/j.cbi.2009.10.016.

(56) Levy, B. S.; Wegman, D. H.; Baron, S. L.; Sokas, R. K. *Occupational and Environmental Health: Recognizing and Preventing Disease and Injury*, 6th ed.; Oxford University Press: New York, NY, 2011;

(57) *Increased Traffic, Crashes Prompt New Campaign to Promote Safe Driving on Roadways Near Oil, Gas Work Areas;* Texas Department of Transportation: Austin, TX, 2013; http://www.txdot.gov/driver/share-road/be-safe-drive-smart.html.

(58) Muehlenbachs, L.; Krupnick, A. J. Shale gas development linked to traffic accidents in Pennsylvania. Common Resources. 2013; http://common-resources.org/2013/shale-gas-development-linked-to-traffic-accidents-in-pennsylvania/ (accessed September 27, 2013).

(59) New York State Department of Environmental Conservation. *Revised Draft SGEIS on the Oil, Gas and Solution Mining Regulatory Program: Well Permit Issuance for Horizontal Drilling and High Volume Hydraulic Fracturing in the Marcellus Shale and Other Low Permeability Gas Reserviors;* New York State, 2011; http://www.dec.ny.gov/energy/75370.html.

(60) Colorado Oil and Gas Conservation Commission. COGCC Flood Information. 2013; http://cogcc.state.co.us/Announcements/Hot_Topics/Flood2013/Flood.htm (accessed October 10, 2013).

(61) *Water sampling of Flood-Affected Rivers and Streams Shows No Pollutants Associated with Oil and Gas Spills;* Colorado Department of Public Health and Environment: Denver, CO, 2013; http://www.colorado.gov/cs/Satellite/CDPHE-Main/CBON/1251646839607.

(62) Steinzor, N.; Subra, W.; Sumi, L. Investigating links between shale gas development and health impacts through a community survey project in Pennsylvania. *New Solutions* **2013**, *23* (1), 55−83, DOI: 10.2190/NS.23.1.e.

(63) Ethridge, S. Interoffice Memorandum: Texas Commision on Environmental Quality. *Health Effects Review of Ambient Air Monitoring Data Collected by Wolf Eagle Environmental Engineers and Consultants for DISH, TX,* **2009**, http://www.barnettshalenews.com/documents/ntxairstudy/Wolf%20Eagle%20Report%20%20Evaluation%20for%20DISH%20TX%20by%20TCEQ%2010-27-2009.pdf.

(64) *Analysis of Data Obtained for the Garfield County Air Toxics Study Summer 2008;* Frazier, A., Ed.; Air Pollution Control Division; Rifle Denver, CO, 2009; http://www.garfieldcountyaq.net/default_new.aspx.

(65) Honeycutt, M. *Air Quality Impacts of Natural Gas Operations in Texas;* Texas Commision on Environmental Quality, 2012; http://www.iom.edu/~/media/Files/Activity%20Files/Environment/EnvironmentalHealthRT/2012-04-30/Honeycutt.pdf.

(66) *Southwestern Pennsylvania Marcellus Shale Short-Term Ambient Air Sampling Report;* Pennsylvania Department of Environmental Protection: Bureau of Air Quality; 2010; http://www.dep.state.pa.us/dep/deputate/airwaste/aq/aqm/docs/Marcellus_SW_11-01-10.pdf.

(67) *Garfield County Emissions Inventory;* Colorado Department of Public Health and Environment: Air Pollution Control Division, 2009; http://www.garfield-county.com/air-quality/documents/airquality/Garfield_County_Emissions_Inventory-2009.pdf.

(68) *Air Emissions Case Study Related to Oil and Gas Development in Erie, Colorado;* Colorado Department of Public Health and Environment: Air Pollution Control Division, 2012; http://www.colorado.gov/airquality/tech_doc_repository.aspx?action=open&file=Erie_Air_Emissions_Case_Study_2012.pdf.

(69) *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);* Colorado Department of Public Health and Environment: Disease Control and Environmental Epidemiology Division: Rifle, CO, 2007; http://www.garfield-county.com/public-health/documents/Working%20Draft%20CDPHE%20Screeing%20Level%20Risk%20Air%20Toxics%20Assessment%2012%2020%2007.pdf.

(70) Pétron, G.; Frost, G.; Miller, B. R.; Hirsch, A. I.; Montzka, S. A.; Karion, A.; Trainer, M.; Sweeney, C.; Andrews, A. E.; Miller, L.; Kofler, J.; Bar-Ilan, A.; Dlugokencky, E. J.; Patrick, L.; Moore, C. T.; Ryerson, T. B.; Siso, C.; Kolodzey, W.; Lang, P. M.; Conway, T.; Novelli, P.; Masarie, K.; Hall, B.; Guenther, D.; Kitzis, D.; Miller, J.; Welsh, D.; Wolfe, D.; Neff, W.; Tans, P. Hydrocarbon emissions characterization in the Colorado Front Range: A pilot study. *J. Geophys. Res.: Atmos.* **2012**, *117* (D4), D04304 DOI: 10.1029/2011JD016360.

(71) Gilman, J. B.; Lerner, B. M.; Kuster, W. C.; de Gouw, J. A. Source signature of volatile organic compounds from oil and natural gas operations in northeastern Colorado. *Environ. Sci. Technol.* **2013**, *47* (3), 1297−1305, DOI: 10.1021/es304119a.

(72) Katzenstein, A. S.; Doezema, L. A.; Simpson, I. J.; Blake, D. R.; Rowland, F. S. Extensive regional atmospheric hydrocarbon pollution in the southwestern United States. *Proc. Natl. Acad. Sci.* **2003**, *100* (21), 11975−11979, DOI: 10.1073/pnas.1635258100.

(73) Kemball-Cook, S.; Bar-Ilan, A.; Grant, J.; Parker, L.; Jung, J.; Santamaria, W.; Mathews, J.; Yarwood, G. Ozone impacts of natural gas development in the Haynesville Shale. *Environ. Sci. Technol.* **2010**, *44* (24), 9357−63, DOI: 10.1021/es1021137.

(74) U. S. Environmental Protection Agency. Tier 2 Vehicle and Gasoline Sulfur Program: Cars and Light Trucks. http://www.epa.gov/tier2/ (accessed October 14, 2013).

(75) U. S. Environmental Protection Agency. Tier 3 Vehicle Emission and Fuel Standards Program: Cars and Light trucks. http://www.epa.gov/otaq/tier3.htm (accessed October 14, 2013).

(76) Olaguer, E. P. The potential near-source ozone impacts of upstream oil and gas industry emissions. *J. Air Waste Manage. Assoc.* **2012**, *62* (8), 966−977, DOI: 10.1080/10962247.2012.688923.

(77) Curtright, A. E. The Environmental Costs of Emissions from Shale Gas Extraction, 2013. http://www.rand.org/blog/2013/02/the-environmental-costs-of-emissions-from-shale-gas.html.

(78) Collett, J. L. Garfield County Gas Emissions Study Persentation. http://www.garfield-county.com/news/administration-documents/Powerpoint_proposal_from_CSU_to_characterize_air_emissions_from_natural_gas_drilling.pdf (accessed October 14, 2013).

(79) Martin, R.; Moore, K.; Mansfield, M.; Hill, S.; Harper, K.; Shorthill, H. *Final Report: Uinta Basin Winter Ozone and Air Quality Study December 2010−March 2011*; Energy Dynamics Laboratory, Utah State University Research Foundation, 2011; http://rd.usu.edu/files/uploads/ubos_2010-11_final_report.pdf.

(80) Schnell, R. C.; Oltmans, S. J.; Neely, R. R.; Endres, M. S.; Molenar, J. V.; White, A. B. Rapid photochemical production of ozone at high concentrations in a rural site during winter. *Nat. Geosci.* **2009**, 2 (2), 120−122, http://dx.doi.org/10.1038/ngeo415.

(81) Carter, W. P. L.; Seinfeld, J. H. Winter ozone formation and VOC incremental reactivities in the Upper Green River Basin of Wyoming. *Atmos. Environ.* **2012**, *50*, 255−266, http://dx.doi.org/10.1016/j.atmosenv.2011.12.025.

(82) Utah Department of Environmental Quality. Final Report: 2012 Unitah Basin Winter Ozone & Air Study. *Uintah Basin Winter Ozone Study*. 2013; http://rd.usu.edu/files/uploads/ubos_2011-12_final_report.pdf

(83) Edwards, P. M.; Young, C. J.; Aikin, K.; deGouw, J. A.; DubÃŠ, W. P.; Geiger, F.; Gilman, J. B.; Helmig, D.; Holloway, J. S.; Kercher, J. Ozone photochemistry in an oil and natural gas extraction region during winter: simulations of a snow-free season in the Uintah Basin, Utah. *Atmos. Chem. Physi. Discuss.* **2013**, *13* (3), 7503−7552, DOI: 10.5194/acpd-13-7503-2013.

(84) Allen, D. T.; Torres, V. M.; Thomas, J.; Sullivan, D. W.; Harrison, M.; Hendler, A.; Herndon, S. C.; Kolb, C. E.; Fraser, M. P.; Hill, A. D.; Lamb, B. K.; Miskimins, J.; Sawyer, R. F.; Seinfeld, J. H. Measurements of methane emissions at natural gas production sites in the United States. *Proc. Natl. Acad. Sci.* **2013**, DOI: 10.1073/pnas.1304880110.

(85) Nash, J. Assessing the potential for self-regulation in the shale gas industry. In *Workshop on Governance of Risks of Shale Gas Development*, Washington DC, 2013; http://sites.nationalacademies.org/DBASSE/BECS/DBASSE_083520.

(86) Logan, J.; Heath, G.; Macknick, J.; Paranhos, E.; Boyd, W.; Carlson, K. *Natural Gas and the Transformation of the US Energy Sector: Electricity*; Joint Institute for Strategic Energy Analysis, 2012; http://www.nrel.gov/docs/fy13osti/55538.pdf.

(87) Jiang, M.; Griffin, W. M.; Hendrickson, C.; Jaramillo, P.; VanBriesen, J.; Venkatesh, A. Life cycle greenhouse gas emissions of Marcellus shale gas. *Environ. Res. Lett.* **2011**, *6* (3), 034014 DOI: 10.1088/1748-9326/6/3/034014.

(88) Karion, A.; Sweeney, C.; Pétron, G.; Frost, G.; Hardesty, R. M.; Kofler, J.; Miller, B. R.; Newberger, T.; Wolter, S.; Banta, R.; Brewer, A.; Dlugokencky, E.; Lang, P.; Montzka, S. A.; Schnell, R.; Tans, P.; Trainer, M.; Zamora, R.; Conley, S. Methane emissions estimate from airborne measurements over a western United States natural gas field. *Geophys. Res. Lett.* **2013**, *40* (16), 4393−4397, DOI: 10.1002/grl.50811.

(89) Laurenzi, I. J.; Jersey, G. R. Life cycle greenhouse gas emissions and freshwater consumption of Marcellus Shale gas. *Environ. Sci. Technol.* **2013**, *47* (9), 4896−4903, DOI: 10.1021/es305162w.

(90) Stephenson, T.; Valle, J. E.; Riera-Palou, X. Modeling the relative GHG emissions of conventional and shale gas production. *Environ. Sci. Technol.* **2011**, *45* (24), 10757−64, DOI: 10.1021/es2024115.

(91) Howarth, R. W.; Santoro, R.; Ingraffea, A. Methane and the greenhouse-gas footprint of natural gas from shale formations. *Clim. Change* **2011**, *106* (4), 679−690, DOI: 10.1007/s10584-011-0061-5.

(92) Alvarez, R. A.; Pacala, S. W.; Winebrake, J. J.; Chameides, W. L.; Hamburg, S. P. Greater focus needed on methane leakage from natural gas infrastructure. *Proc. Natil. Acad. Sci.* **2012**, DOI: 10.1073/pnas.1202407109.

(93) Tollefson, J. Oil boom raises burning issues. *Nature* **2013**, *495* (7441), 290−1, DOI: 10.1038/495290a.

(94) Rozell, D. J.; Reaven, S. J. Water pollution risk associated with natural gas extraction from the Marcellus Shale. *Risk Anal.* **2011**, *32* (8), 1382−1393, DOI: 10.1111/j.1539-6924.2011.01757.x.

(95) Goldstein, B. D.; Bjerke, E. F.; Kriesky, J. K. Challenges of unconventional shale gas development: so what's the rush? *Notre Dame J. Law Ethics Public Policy* **2013**, *27* (1), 149−186.

(96) Agency for Toxic Substances and Disease Registry. *Health Consultation: Evaluation of Contaminants in Private Residential Well Water Pavillion*, Wyoming, 2010. http://www.atsdr.cdc.gov/hac/PHA/Pavillion/Pavillion_HC_Well_Water_08312010.pdf.

(97) Jackson, R. B.; Vengosh, A.; Darrah, T. H.; Warner, N. R.; Down, A.; Poreda, R. J.; Osborn, S. G.; Zhao, K.; Karr, J. D. Increased stray gas abundance in a subset of drinking water wells near Marcellus Shale gas extraction. *Proc. Natl. Acad. Sci. U.S.A.* **2013**, DOI: 10.1073/pnas.1221635110.

(98) Davies, R. J. Methane contamination of drinking water caused by hydraulic fracturing remains unproven. *Proc. Natl. Acad. Sci.* **2011**, *108* (43), E871 DOI: 10.1073/pnas.1113299108.

(99) Saba, T.; Orzechowski, M. Lack of data to support a relationship between methane contamination of drinking water wells and hydraulic fracturing. *Proc. Natl. Acad. Sci.* **2011**, *108* (37), E663 DOI: 10.1073/pnas.1108435108.

(100) Schon, S. C. Hydraulic fracturing not responsible for methane migration. *Proc. Natl. Acad. Sci.* **2011**, *108* (37), E664−E664.

(101) U.S. Environmental Protection Agency. EPA Completes Drinking Water Sampling in Dimock, PA. http://yosemite.epa.gov/opa/admpress.nsf/0/1A6E49D193E1007585257A46005B61AD (accessed May 16, 2013).

(102) Encana. Why Encana refutes U.S. EPA Pavillion ground water report. http://www.encana.com/news-stories/news-releases/details.html?release=632327 (accessed October 14, 2013).

(103) Fontenot, B. E.; Hunt, L. R.; Hildenbrand, Z. L.; Carlton, D. D.; Oka, H.; Walton, J. L.; Hopkins, D.; Osorio, A.; Bjorndal, B.; Hu, Q.; Schug, K. A. 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* (17), 10032−10040, DOI: 10.1021/es4011724.

(104) *Report to Congress: Management of Wastes from the Exploration, Development, and Production of Crude Oil, Natural Gas, and Geothermal Energy*, EP AJ53().SW-as.oo3 U.S. Environmental Protection Agency; Office of Solid Waste and Emergency Response: Washington D.C., 1987.

(105) Veil, J. A.; Puder, M. G.; Elcock, D.; Redweik Jr., R. J. A white paper describing produced water from production of crude oil, natural gas, and coal bed methane. *Prepared by Argonne National Laboratory for the US Department of Energy, National Energy Technology*

Laboratory, January. 2004. http://netldev.netl.doe.gov/research/energy-analysis/publications/details?pub=2061f020-2f50-4c65-b464-779f0e23a628.

(106) Lutz, B. D.; Lewis, A. N.; Doyle, M. W. Generation, transport, and disposal of wastewater associated with Marcellus Shale gas development. *Water Resour. Res.* **2013**, *49* (2), 647−656, DOI: 10.1002/wrcr.20096.

(107) Barbot, E.; Vidic, N. S.; Gregory, K. B.; Vidic, R. D. Spatial and temporal correlation of water quality parameters of produced waters from devonian-age shale following hydraulic fracturing. *Environ. Sci. Technol.* **2013**, *47* (6), 2562−2569, DOI: 10.1021/es304638h.

(108) Haluszczak, L. O.; Rose, A. W.; Kump, L. R. Geochemical evaluation of flowback brine from Marcellus gas wells in Pennsylvania, USA. *Appl. Geochem.* **2013**, *28* (0), 55−61, http://dx.doi.org/10.1016/j.apgeochem.2012.10.002.

(109) Ferrar, K. J.; Michanowicz, D. R.; Christen, C. L.; Mulcahy, N.; Malone, S. L.; Sharma, R. K. Assessment of effluent contaminants from three facilities discharging Marcellus Shale wastewater to surface waters in Pennsylvania. *Environ. Sci. Technol.* **2013**, *47* (7), 3472−3481, DOI: 10.1021/es301411q.

(110) Wilson, J. M.; VanBriesen, J. M. Oil and gas produced water management and surface drinking water sources in Pennsylvania. *Environ. Pract.* **2012**, *14* (04), 288−300, DOI: 10.1017/S1466046612000427.

(111) Gross, S. A.; Avens, H. J.; Banducci, A. M.; Sahmel, J.; Panko, J. M.; Tvermoes, B. E. Analysis of BTEX groundwater concentrations from surface spills associated with hydraulic fracturing operations. *J. Air Waste Manage. Assoc. (1995)* **2013**, *63* (4), 424−32, DOI: 10.1080/10962247.2012.759166.

(112) *Air Quality Criteria for Ozone and Related Photochemicaloxidants*, EPA/600/R-05/004aF-cF; U.S. Environmental Protection Agency: National Center for Environmental Assessment-Office of Research and Development: Research Triangle Park, NC, 2006; http://cfpub.epa.gov/ncea/cfm/recordisplay.cfm?deid=149923.

(113) *Associations of Short-Term Exposure to Ozone and Respiratory Outpatient Clinic Visits - Sublette County, Wyoming, 2008−2011*; Pride, K., Peel, J., Robinson, B., Busacker, A., Grandpre, J., Yip, F., Murphy, T.; State of Wyoming Department of Health: Cheyenne, WY, 2013; https://cste.confex.com/cste/2013/webprogram/Paper1219.html.

(114) Saberi, P. Navigating Medical Issues in Shale Territory. *New Solutions* **2013**, *23* (1), 209−221, http://dx.doi.org/10.2190/NS.23.1.m.

(115) *Toxicological Profile for Xylenes*, Agency for Toxic Substances and Disease Registry; U.S Department of Health and Human Services; Atlanta, GA, 2007; http://www.atsdr.cdc.gov/toxprofiles/tp.asp?id=296&tid=53.

(116) *Chemicals in the Environment: 1,2,4-Trimethylbenzene (C.A.S. No. 95-63-6)*; EPA 749-F-94-022; U.S. Environmental Protection Agency: Office of Pollution Prevention and Toxics; Washington, DC, 1994; http://www.epa.gov/chemfact/f_trimet.txt.

(117) Carpenter, C. P.; Geary, D. L.; Myers, R. C.; Nachreiner, D. J.; Sullivan, L. J.; King, J. M. Petroleum hydrocarbons toxicity studies XVII. Animal responses to n-nonane vapor. *Toxicol. Appl. Pharmacol.* **1978**, *44*, 53−61.

(118) Nilsen, O. G.; Haugen, O. A.; Zahisen, K.; Halgunset, J.; Helseth, H.; Aarset, A.; Eide, I. Toxicity of n-C9 to n-C13 alkanes in the rat on short term inhalation. *Pharmacol. Toxicol.* **1988**, *62*, 259−266.

(119) Galvin, J. B.; Marashi, F. n-Pentane. *J. Toxicol. Environ. Health, Part A* **1999**, *58*, 35−56.

(120) Lupo, P.; Symanski, E.; Waller, D.; Chan, W.; Langlosi, P.; Canfield, M.; Mitchell, L. Maternal exposure to ambient levels of benzene and neural tube defects among offspring, Texas 1999−2004. *Environ. Health Perspect.* **2010**, *119* (3), 397−402, DOI: 10.1289/ehp.1002212.

(121) McKenzie, L. M.; Guo, R.; Witter, R. Z.; Satvitz, D. A.; Newman, L. S.; Adgate, J. L. Maternal residential proximity to natural gas development and adverse birth outcomes in rural Colorado. *Environ. Health Perspect.* **2014**, DOI: 10.1289/ehp.1306722.

(122) Hill, E. Unconventional Natural Gas Development and Infant Health: Evidence from Pennsylvania. Cornell University: Working Paper, Charles Dyson School of Applied Economics and Management, 2012. www.dyson.cornell.edu/research/researchpdf/wp/.../Cornell-Dyson-wp1212.pdf.

(123) Fryzek, J.; Pastula, S.; Jiang, X.; Garabrant, D. H. Childhood cancer incidence in Pennsylvania counties in relation to living in counties with hydraulic fracturing sites. *J. Occup. Environ. Med.* **2013**, *55* (7), 796−801, DOI: 10.1097/JOM.0b013e318289ee02.

(124) Goldstein, B. D.; Malone, S. Obfuscation does not provide comfort. *J. Occup. Environ. Med.* **2013**, *55* (11), 1376−1378, DOI: 10.1097/JOM.0000000000000014.

(125) Adler, N. E.; Newman, K. Socioeconomic Disparities In Health: Pathways And Policies. *Health Affairs* **2002**, *21* (2), 60−76, DOI: 10.1377/hlthaff.21.2.60.

(126) IHS. *The Economic and Employment Contribution of Unconventional Gas Development in State Economies*; Washington D.C., 2012. http://marcelluscoalition.org/wp-content/uploads/2012/06/State_Unconv_Gas_Economic_Contribution_Main.pdf.

(127) Christopherson, S.; Rightor, N. *How Should We Think About the Economic Consequences of Shale Gas Drilling*; Cornell University, 2011. http://www.greenchoices.cornell.edu/downloads/development/shale/marcellus/Thinking_about_Economic_Consequences.pdf.

(128) America's Natural Gas Alliance. U.S. Shale Gas Benefits. American Natural Gas Association. http://anga.us/issues-and-policy/jobs/us-shale-gas-benefits#.UlyEY9jD-cw (accessed October 14, 2013).

(129) Goldenberg, S.; Shoveller, J.; Koehoorn, M.; Ostry, A. Barriers to STI testing among youth in a Canadian oil and gas community. *Health Place* **2008**, *14* (4), 718−729, http://dx.doi.org/10.1016/j.healthplace.2007.11.005.

(130) Williamson, J.; Kolb, B. Marcellus Natural Gas Development's Effect on Housing in Pennsylvania. *Center for the Study of Community and the Economy.* **2011**; http://www.marcellus.psu.edu/resources/PDFs/housingreport.pdf

(131) Perry, S. L. Using ethnography to monitor the community health implications of onshore unconventional oil and gas developments: Examples from Pennsylvania's Marcellus Shale. *New Solutions* **2013**, *23*, 33−53, http://dx.doi.org/10.2190/NS.23.1.d.

(132) Dutzik, T.; Ridlington, E.; Rumpler, J. The costs of fracking: The price tag of dirty drilling's environmental damage. *Environment Ohio Research & Policy Center*, 2012. http://www.ourenergypolicy.org/the-cost-of-fracking-the-price-tag-of-dirty-drillings-environmental-damage/

(133) Perry, S. L. Energy Consequences and Conflicts across the Global Countryside: *North American Agricultural Perspectives*, 2012. http://forumonpublicpolicy.com/vol2011.no2/archivevol2011.no2/perry.pdf.

(134) Jacquet, J. B. Landowner attitudes toward natural gas and wind farm development in northern Pennsylvania. *Energy Policy.* **2012**; http://www.sciencedirect.com/science/article/pii/S0301421512006702

(135) Jacquet, J. B.; Stedman, R. C. The risk of social-psychological disruption as an impact of energy development and environmental change. *J. Environ. Plann. Manage.* **2013**, 1−20, DOI: 10.1080/09640568.2013.820174.

(136) Brasier, K.; Filteau, M.; McLaughlin, D.; Jacquet, J.; Stedman, R.; Kelsey, T.; Goetz, S. Residents' perceptions of community and environmental impacts from development of natural gas in the Marcellus Shale: A comparison of Pennsylvania and New York cases. *J. Rural Social Sci.* **2011**, *26* (1), 32−61, http://ag.auburn.edu/auxiliary/srsa/pages/Articles/JRSS%202011%2026%201%2032-61.pdf.

(137) Kasperson, R. E.; Renn, O.; Slovic, P.; Brown, H. S.; Emel, J.; Goble, R.; Kasperson, J. X.; Ratick, S. The social amplification of risk: A conceptual framework. *Risk Anal.* **1988**, *8* (2), 177−187, DOI: 10.1111/j.1539-6924.1988.tb01168.x.

(138) Slovic, P. Perception of risk. *Science* **1987**, *236* (4799), 280−285, DOI: 10.1126/science.3563507.

(139) Wachinger, G.; Renn, O.; Begg, C.; Kuhlicke, C. The risk perception paradox—Implications for governance and communication of natural hazards. *Risk Anal.* **2013**, *33* (6), 1049−1065, DOI: 10.1111/j.1539-6924.2012.01942.x.

(140) *Garfield County Air Toxics Inhalation Screening Level Human Health Risk Assessment: Inhalation of Volatile Organic Compounds Measured In 2008 Air Quality Monitoring Study*. Colorado Department of Public Health and Environment: Disease Control and Environmental Epidemiology Division; Rifle, CO, 2010. http://www.garfield-county.com/public-health/documents/6%2030%2010%20%20RisK%20Assessment%20for%20Garfield%20County%20based%20on%202008%20air%20monitoring.pdf.

(141) Sierra Research Inc. *Screening Health Risk Assessment Sublette County, Wyoming*; SR2011-01-03; Sierra Research, Inc.,: Pinedale, WY, 2011. http://www.pinedaleonline.com/pdfs/healthriskassessmentfeb2011.pdf.

(142) Bunch, A. G.; Perry, C. S.; Abraham, L.; Wikoff, D. S.; Tachovsky, J. A.; Hixon, J. G.; Urban, J. D.; Harris, M. A.; Haws, L. C. Evaluation of impact of shale gas operations in the Barnett Shale region on volatile organic compounds in air and potential human health risks. *Sci. Tot. Environ.* **2014**, *468*, 832−842, http://www.sciencedirect.com/science/article/pii/S0048969713010073.

(143) *Health Consultation: Public Health Implications of Ambient Air Exposures to Volatile Organic Compounds as Measured in Rural, Urban, and Oil & Gas Development Areas Garfield County, Colorado*, Agency for Toxic Substances and Disease Registry; U.S Department of Health and Human Services Agency; Atlanta, GA, 2008; http://www.atsdr.cdc.gov/HAC/pha/Garfield_County_HC_3-13-08/Garfield_County_HC_3-13-08.pdf.

(144) *DISH, Texas Exposure Investigation*; Texas Department of State Health Services: Dish, Denton County, TX, 2010; www.dshs.state.tx.us/epitox/consults/dish_ei_2010.pdf.

(145) Sexton, K.; Linder, S. H. Cumulative Risk Assessment for Combined Health Effects From Chemical and Nonchemical Stressors. *Am. J. Public Health* **2011**, *101* (S1), S81−S88, DOI: 10.2105/ajph.2011.300118.

(146) Brittingham, M. *Ecological Risks of Shale Gas Development. Risks of Unconventional Shale Gas Development*; Washington DC, 2013; http://sites.nationalacademies.org/DBASSE/BECS/DBASSE_083187.

(147) Morello-Frosch, R.; Shenassa, E. D. The environmental "riskscape" and social inequality: Implications for explaining maternal and child health disparities. *Environ. Health Perspect.* **2006**, *114* (8), 1150−1153, DOI: 10.1289/ehp.8930.

(148) Fry, M. Urban gas drilling and distance ordinances in the Texas Barnett Shale. *Energy Policy* **2013**, *62*, 79−89, http://dx.doi.org/10.1016/j.enpol.2013.07.107.