Working Paper

12-2014
Revision January 2015

Toward an understanding of the environmental and public health impacts of shale gas development: an analysis of the peer-reviewed scientific literature, 2009-2014

Jake Hays[1], Seth B.C. Shonkoff[2,3,4]

1 PSE Healthy Energy, New York, NY
2 PSE Healthy Energy, Oakland, CA
3 Department of Environmental Science, Policy and Management
University of California, Berkeley, CA
4 Lawrence Berkeley National Laboratory, Berkeley, CA

1. Introduction

Conversations on the environmental and public health impacts of shale gas development enabled by hydraulic fracturing continue to play out in the media, in policy discussions, and among the general public. But what does the science actually say? While research continues to lag behind the rapid scaling of unconventional forms of oil and gas development, there has been a surge of peer-reviewed scientific papers published in recent years (Figure 1). In fact, of all the available literature on the impacts of shale gas development, over 75% has been published since January 1, 2013. What this tells us is that the scientific community is only now beginning to understand the environmental and public health implications. Numerous hazards and risks have been identified, but many data gaps remain. While there is now a far more substantive body of science than there was several years ago, there is still a notable dearth of quantitative epidemiology that assesses associations between risk factors and human health outcomes among populations.

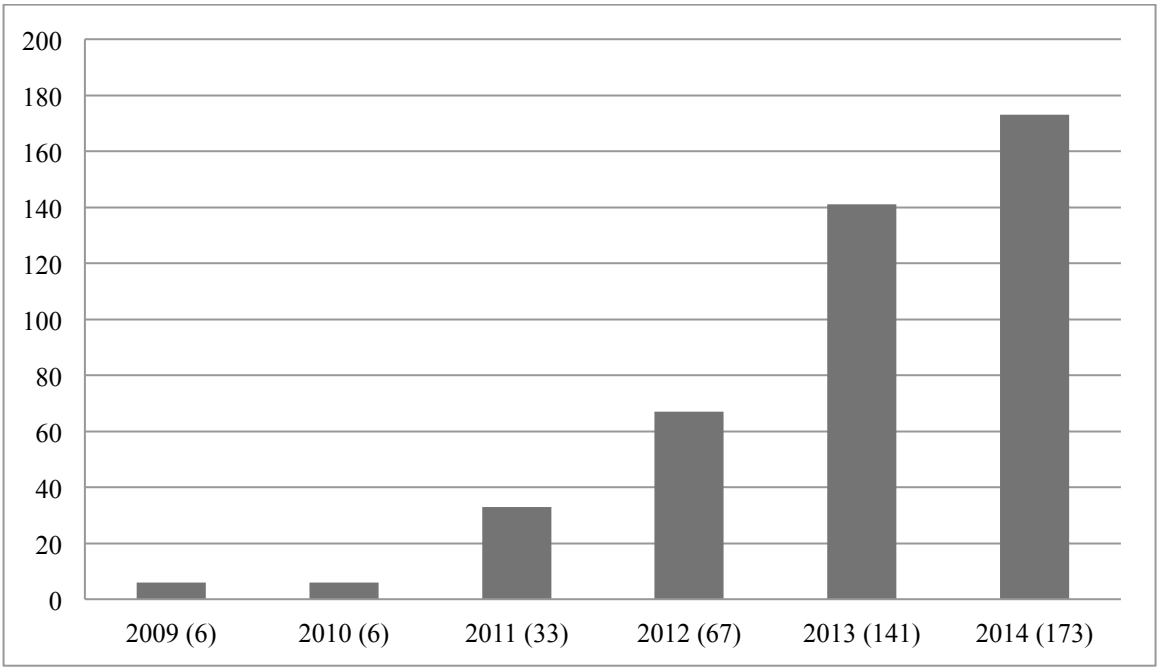

Figure 1. Number of publications that assess the impacts of shale or tight gas development by year, 2009-2014

In this analysis we provide an overview of current scientific knowledge regarding these potential impacts. We include only published peer-reviewed literature available on the subject. Specifically, we analyze studies relevant to near-term and long-term environmental public health among communities in proximity to shale gas development.

As shale gas activities continue to expand, states and countries are in a unique position to learn from experiences and scientific assessment in areas where development is already underway, including parts of Pennsylvania, Texas, and Colorado. While energy policy requires more than empirical data, legislative and regulatory bodies should account for the emerging body of science on the environmental and public health implications of shale gas development. This analysis is an attempt to summarize this emerging body of science from the available peer-reviewed literature.

There are many limitations to our analysis and it provides just a snapshot of the empirical knowledge on the public health hazards, risks, and impacts associated with shale gas development. For a more nuanced discussion please refer to our review article (Shonkoff et al. 2014) published in *Environmental Health Perspectives* (http://ehp.niehs.nih.gov/wp-content/uploads/122/8/ehp.1307866.pdf). Furthermore, as a working paper, this document is preliminary and has not yet been subjected to external peer review. Nonetheless, it provides readers with a general sense of the direction in which the existing body of scientific literature points in terms of identified and potential environmental and public health impacts.

2. Methods

A. Database assemblage and review

This analysis was conducted using the PSE Shale and Tight Gas Study Citation Database (available at: http://psehealthyenergy.org/site/view/1180). This near exhaustive collection of peer-reviewed literature on shale gas development is divided into 12 topics that attempt to organize the papers in a useful and coherent fashion. These topics include air quality, climate, community, ecology, economics, general (comment/review), health, regulation, seismicity, waste/fluids, water quality, and water usage. This study database has been assembled over several years using a number of different search strategies, including the following:

- Systematic searches in scientific databases across multiple disciplines: PubMed (http://www.ncbi.nlm.nih.gov/pubmed/), Web of Science (http://www.webofknowledge.com), and ScienceDirect (http://www.sciencedirect.com)
- Searches in existing collections of scientific literature on shale gas development, such as the Marcellus Shale Initiative Publications Database at Bucknell University (http://www.bucknell.edu/script/environmentalcenter/marcellus), complemented by Google (http://www.google.com) and Google Scholar (http://scholar.google.com)
- Manual searches (hand-searches) of references included in peer-reviewed studies that pertain directly to shale gas development.

For science literature search engines we used a combination of Medical Subject Headings

(MeSH)-based and keyword strategies, which included the following terms as well as relevant combinations thereof:

> shale gas, shale, hydraulic fracturing, fracking, drilling, natural gas, air pollution, methane, water pollution, public health, water contamination, fugitive emissions, air quality, climate, seismicity, waste, fluids, economics, ecology, water usage, regulation, community, epidemiology, Marcellus, Barnett, Denver-Julesberg Basin, unconventional gas development, and environmental pathways.

This database and subsequent analysis excluded technical papers on shale gas development not applicable to determining potential environmental and public health impacts. Examples include papers on optimal drilling strategies, reservoir evaluations, estimation algorithms of absorption capacity, patent analyses, and fracture models designed to inform stimulation techniques. Because this collection is limited to papers subjected to external peer-review in the scientific community, it does not include government reports, environmental impact statements, policy briefs, white papers, law review articles, or other grey literature. Nor does it include studies on coalbed methane, coal seam gas, tar sands or other forms of fossil fuel extraction (offshore drilling, etc.).

We have tried to include all literature that meets our criteria in our collection of the peer-reviewed science; however, it is possible that some papers may have gone undetected. Thus, we refer to the collection as *near* exhaustive. We are sure, however, that the most seminal studies on the environmental public health dimensions of shale gas development in leading scientific journals are accounted for.

The PSE Healthy Energy database has been used and reviewed by academics, experts, and government officials throughout the U.S. and internationally and has been subjected to public and professional scrutiny before and after this analysis. It represents the most comprehensive public collection of peer-reviewed scientific literature on shale and tight gas development in the world and has been accessed by thousands of people. Again, many of the publications in this database through 1 February 2014 are discussed in greater detail in Shonkoff et al. (2014).

B. Scope of analysis

1. Definitions:

There has been great confusion about the environmental dimensions of shale and tight gas development (often termed “fracking”) because of the lack of uniform, well-defined terminology and boundaries of analysis. The public and the media use the term fracking as an umbrella term to refer to the entirety of shale gas development, including processes ranging from land clearing to well stimulation, to hydrocarbon development, to waste disposal. On the other hand, the oil and gas industry and many in the scientific

community generally use the term as shorthand for one particular type of well stimulation method used to enhance the production of oil and natural gas – hydraulic fracturing.

The PSE Healthy Energy database and this analysis are both concerned with shale gas development in its entirety, enabled by hydraulic fracturing, and not just the method of well stimulation. Environmental and public health analyses that include only the latter should have a limited role in policy discussions. If we are to understand the social, environmental, and public health dimensions of shale gas development we must look beyond just the process of hydraulic fracturing, especially when the scientific literature indicates other aspects of the overall process warrant concern. Thus, this project should be viewed as an analysis of the scientific literature on hydraulic fracturing *and* its associated operations and ancillary infrastructure that comprise the development of shale and tight gas.

2. Inclusion and exclusion criteria:

The temporal focus of this analysis is, first and foremost, on the primary research on shale gas development published between 1 January 2009 and 31 December 2014. The reason for starting this analysis in 2009 is that research on modern, unconventional forms of natural gas development did not appear until around that time. We only include papers that evaluate environmental and public health impacts of shale gas development. As such, not all publications in the PSE Healthy Energy database were used in this analysis. We have excluded the following topics: climate, community, ecology, economics, regulation, seismicity, waste/fluids, and water usage.

We have also not included all papers that fall under the three topics (health, water quality, and air quality) used in this analysis. For instance, with the exception of public health papers, for which there has been very little primary research, we have excluded commentaries and review articles. Further, we have excluded those papers that provide baseline data or address research methods that do not assess impacts. We have also excluded letters to the editors of scientific journals that critique a particular study or the subsequent response of the author(s).

As previously mentioned, we have restricted the studies included in this analysis to those published from 2009 through 2014. There are some studies in the database on conventional forms of oil and natural gas development that are relevant to shale gas, but to maintain greater consistency we have decided to exclude those prior to 2009 from the analysis. For instance, we excluded a study published in *The Lancet* that examined the association between testicular cancer and employment in agriculture and oil and gas development published in 1986 (Sewell et al. 1986). Relatedly, some of the studies included in this analysis may be broader than shale gas development and could potentially include other forms of both conventional and unconventional oil and gas development. This is true for some of the top-down, field based air pollutant emissions studies that gauge leakage rates and emission factors in Western oil and gas fields. Where

studies are not specifically related to shale gas development we included them only when the findings were both recent and substantially relevant.

Again, it is important to note that scientists are only beginning to understand the environmental and public health dimensions of these rapidly expanding industrial practices. Our analysis represents a survey of the existing science to date in an attempt to determine the direction in which scientific consensus is headed and to achieve a better understanding of the environmental and public health impacts of this form of energy development.

C. Categorical framework

We have created categories for each topic in an attempt to identify and group studies in ways that are both useful and intuitive. Clearly, there are limitations to this approach and many studies are nuanced or incommensurable in ways that may not be appropriate for this type of analysis. Further, some studies may properly belong in multiple topics. For instance, a few studies that contain data that are relevant to both air quality and public health have been included in both of these topics (Bunch et al. 2014; Colborn et al. 2014; Macey et al. 2014). Nonetheless, in order to glean some kind of emerging scientific consensus on the environmental public health dimensions of shale gas development we strived to create the most simple and accurate approach possible. Please refer to the tables included in the appendix for the citations and categorization of the studies, which are listed alphabetically by author.

Topics	Categories
Health	• Indication of potential public health risks or actual adverse health outcomes • No indication of public health risks or actual adverse health outcomes
Water Quality	• Indication of potential, positive association, or actual incidence of water contamination • Indication of minimal potential, negative association, or rare incidence of water contamination
Air Quality	• Indication of elevated air pollutant emissions and/or atmospheric concentrations • No indication of significantly elevated air pollutant emissions and/or atmospheric concentrations

1. Health

Health outcome studies and epidemiologic investigations continue to be particularly limited and most of the peer-reviewed papers to date are commentaries and reviews. Accordingly, we have also separately analyzed peer-reviewed scientific commentaries and review articles ("all papers") for this topic. Although commentaries should essentially be acknowledged as opinions, they are the opinions of experts formed from the available literature and have also been subjected to peer review.

We have included in this topic papers that consider the question of public health in the context of shale gas development. Of course, research findings in other categories such as air quality and water quality are relevant to public health, but here we only include those studies that *directly* consider the health of individuals and human populations. We only consider research to be original if it measures health outcomes or complaints (i.e., not health research that only attempts to determine public opinion or consider methods for future research agendas).

2. Water Quality

Papers on water quality are more nuanced in that some rely on empirical field measurements, while others explore mechanisms for contamination or use modeled data to determine water quality risks. Further, some of these studies explore only one aspect of shale gas development, such as the well stimulation process enabled by hydraulic fracturing. Thus, these studies do not indicate whether or not shale gas development as a whole is associated with water contamination and are therefore limited in their utility for gauging water quality impacts. Nonetheless, we have included all original research, including modeling studies. We have excluded studies that explore only evaluative methodology or baseline assessments as well papers that simply comment on or review previous studies. Here we are only concerned with actual findings in the field or modeling studies that specifically address the risk or occurrence of water contamination.

3. Air Quality

Air quality is a more complex, subjective measure that beckons comparison to other forms of energy development or industrial processes. Yet a review and analysis of the air quality data is still useful and relevant to health outcomes. Although methane is a precursor to tropospheric ozone we have excluded studies that focus exclusively on methane emissions from this topic. However, studies that address methane *and* non-methane volatile organic compound (VOC) emissions have been included, given the health-damaging dimensions of a number of VOCs (i.e., benzene, toluene, ethylbenzene, xylene, etc.) and the role of VOCs in the production of tropospheric ozone, a strong respiratory irritant. The few studies that have explored the health implications of air pollution emissions and exposure levels are included in both this category and the public health category. The papers in this topic are those that specifically address air emissions

and air quality from well stimulation-enabled oil and gas development (i.e., unconventional oil and gas development) at either a local or regional scale. These include local and regional measurements of non-methane volatile organic compounds and tropospheric ozone.

3. Results

Health

Based on our criteria, we included 16 original research studies relevant to questions involving associations between shale gas development and public health outcomes. Of these 16 studies, 14 (87%) identified potential public health risks or actual observed poor public health outcomes and 2 (13%) found no indication of significant public health risks or actual adverse health outcomes (Figure 2). When we included commentaries and review papers in the analysis, 47 of 49 (96%) indicated potential or actual public health hazards or risks (Figure 3). The vast majority of all papers in this topic indicate the need for additional study, particularly large-scale, quantitative epidemiologic research.

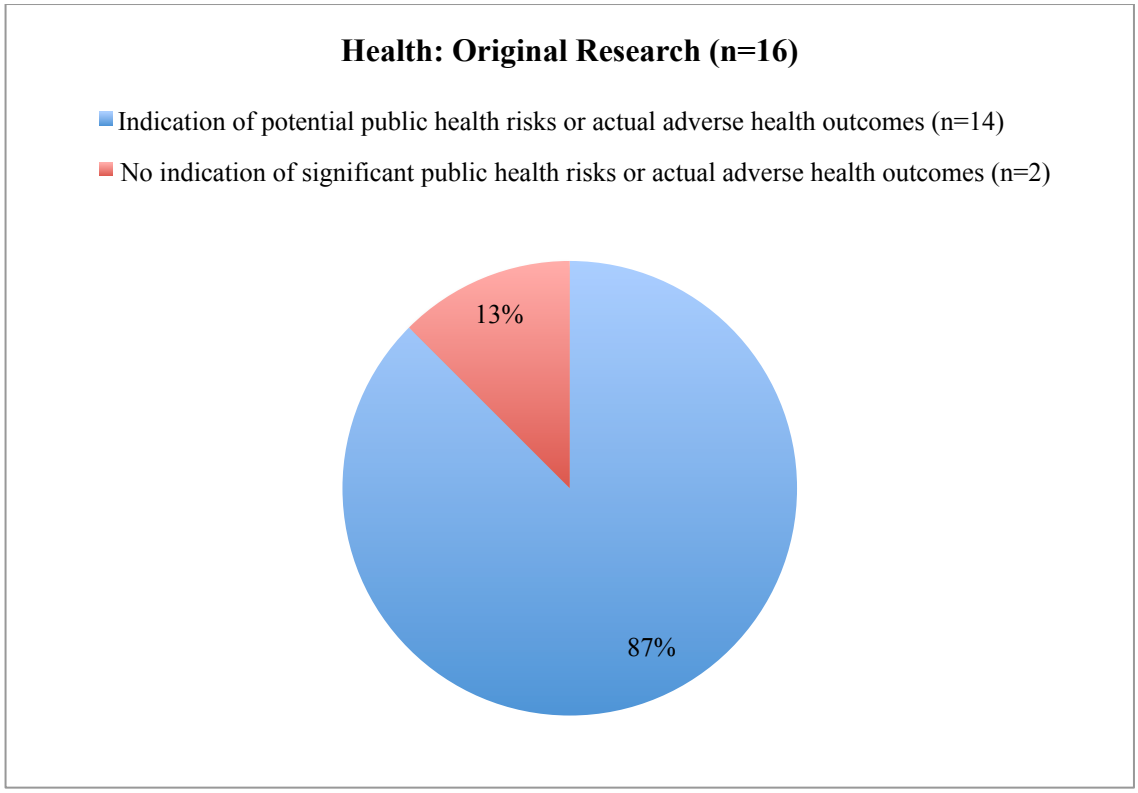

Figure 2. Peer-reviewed publications on the human health dimensions of shale gas development (original research)

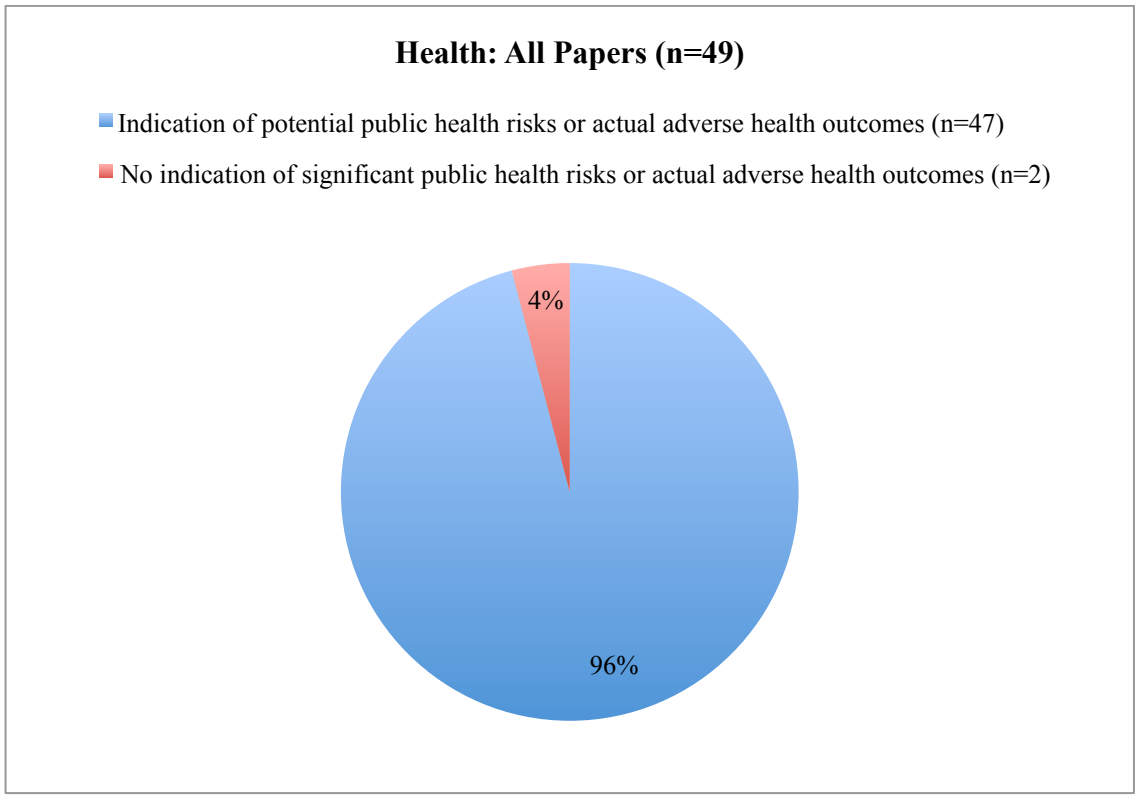

Figure 3. Peer-reviewed publications on the human health dimensions of shale gas development (original research, commentaries, and reviews)

Water Quality

Based on our criteria, we included 30 original research studies relevant to shale gas development and water contamination. Of these 30 studies, 22 (73%) showed indication of potential, positive association, or actual incidence of water contamination associated with shale gas development, while 8 (27%) showed indication of minimal potential, negative association, or rare incidence of water contamination (Figure 4).

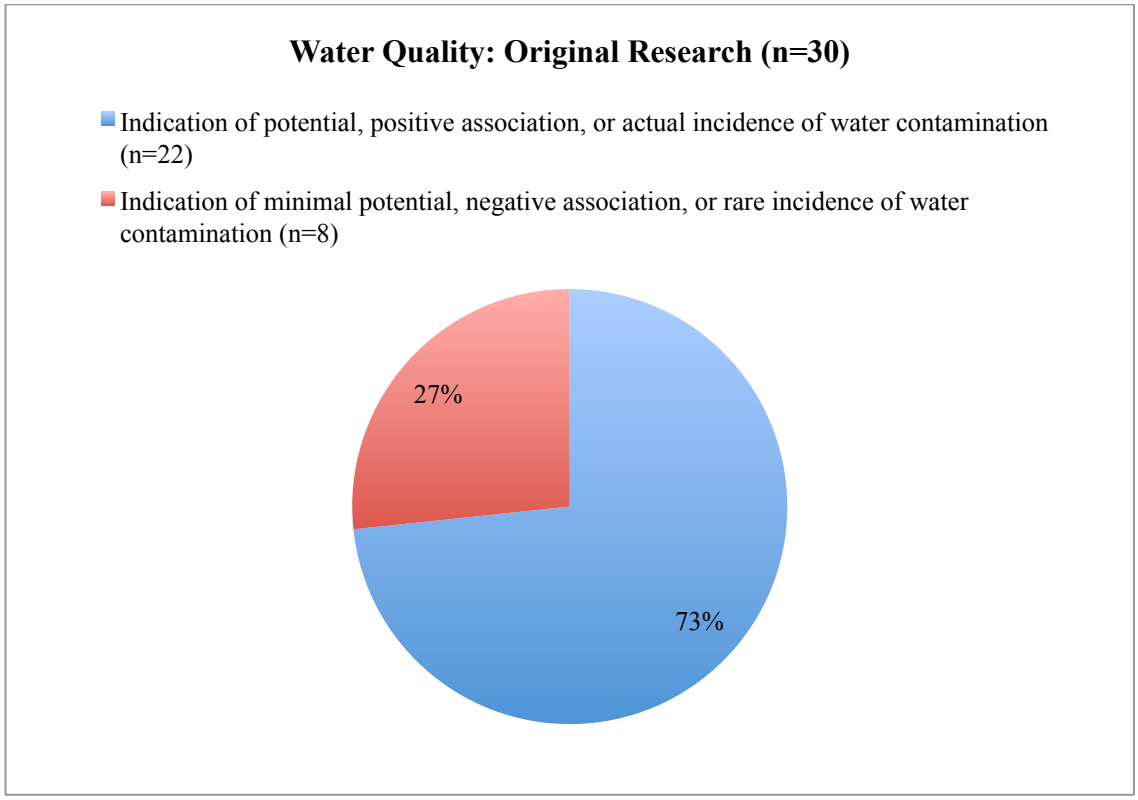

Figure 4. Peer-reviewed publications on shale gas development and water quality contamination (original research)

Air Quality

Based on our criteria, we included 23 original research studies relevant to questions involving associations between shale and tight gas development and air pollutant emissions and atmospheric air pollutant concentrations. Of these 26 studies, 24 (92%) showed indications of elevated air pollutant emissions and/or atmospheric concentrations, while 2 (8%) of the studies showed no indication of significantly elevated air pollutant emissions and/or atmospheric concentrations (Figure 5).

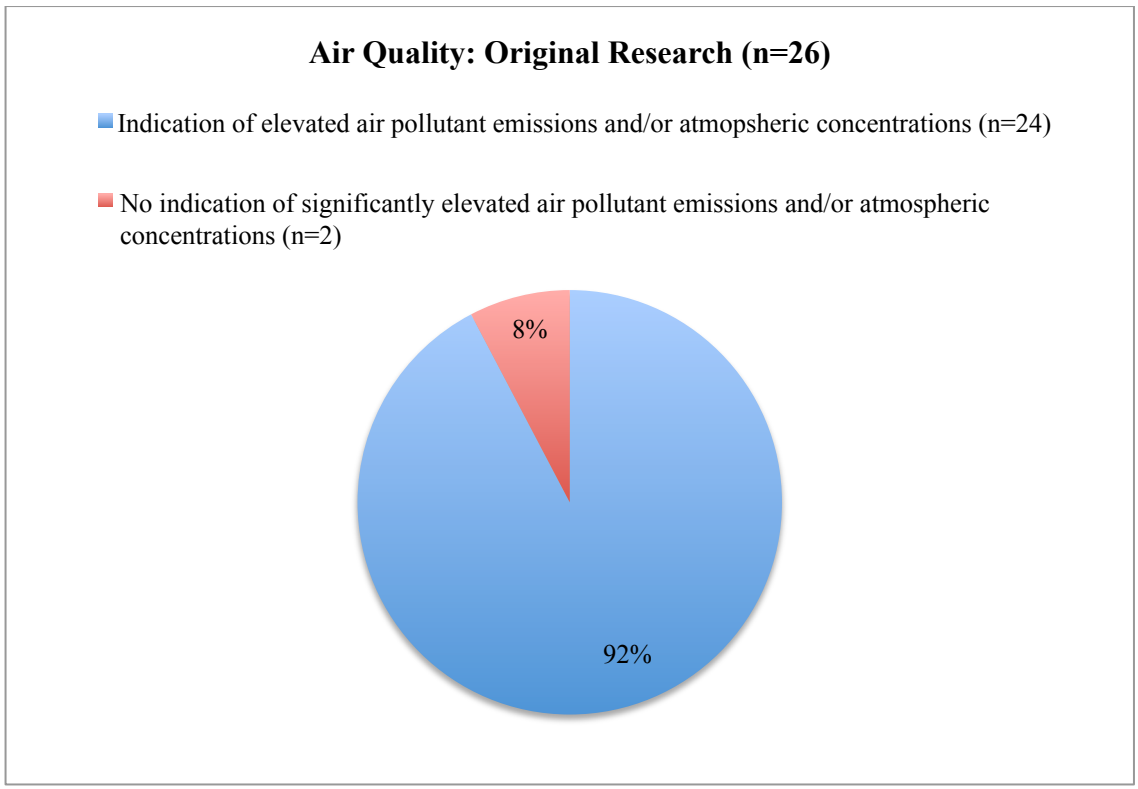

Figure 5. Peer-reviewed publications on shale and tight gas development and air pollutant emissions/air quality degradation (original research)

4. Discussion

In this analysis, we reviewed the direction of findings among papers that assessed the association between shale and tight gas development and air, water, and public health impacts. In each subject area, we found that the majority of studies indicated negative impacts of shale and/or tight gas development on the outcome of interest. Scientific consensus is not yet achievable given comparison limitations due to differences in geological, geographic, engineering, and other attributes, as well as methodological differences between studies. However, these results indicate that shale and tight gas development has known environmental and public health hazards and risks. Regulators, policy makers, and others who are charged with determining how, where, when, and if the development of shale gas should be deployed in their jurisdictional boundaries should take these findings into account.

There are clear limitations to this analysis. It provides just an overview of existing scientific studies based on the world's experience with shale gas development from 1 January 2009 to 31 December 2014. While our database is to our best estimation exhaustive, our literature search may not have captured all relevant scientific literature. Additionally, differences in geography may render some studies less relevant when interpreted across geographic and geological space.

Despite the inherent limitations, our analysis provides a general idea of the weight of the scientific evidence of possible impacts arising from shale gas development. It is important to note that this analysis only concerns itself with current empirical evidence and does not take into account developments that could potentially influence environmental and public health outcomes in positive or negative ways under different regulatory regimes. For instance, technological improvements may mitigate some existing problems, but as development continues, well pad intensities increase, and novel geologies and practices are encountered, impacts may increase.

Finally, all forms of energy production and industrial processing have environmental impacts. This report is only focused on reviewing and presenting the available science on some of the most salient environmental and public health concerns associated with shale gas development. We make no claims about the level of impacts that should be tolerated by society – these are ultimately questions of value.

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Appendix

Health: Original Research (n=16)

- *Indication of potential public health risks or actual adverse health outcomes (n=14)*

1. Bamberger M, Oswald RE. 2012. Impacts of Gas Drilling on Human and Animal Health. NEW SOLUTIONS: A Journal of Environmental and Occupational Health Policy 22:51–77; doi:10.2190/NS.22.1.e.
2. 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 17:1039–1056; doi:10.1080/10807039.2011.605662.
3. 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 0:null; doi:10.1080/10807039.2012.749447.
4. Esswein EJ, Breitenstein M, Snawder J, Kiefer M, Sieber WK. 2013. Occupational exposures to respirable crystalline silica during hydraulic fracturing. J Occup Environ Hyg 10:347–356; doi:10.1080/15459624.2013.788352.
5. Esswein EJ, 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:D174–D184; doi:10.1080/15459624.2014.933960.
6. Ferrar KJ, Kriesky J, Christen CL, Marshall LP, Malone SL, Sharma RK, et al. 2013. Assessment and longitudinal analysis of health impacts and stressors perceived to result from unconventional shale gas development in the Marcellus Shale region. International Journal of Occupational and Environmental Health 19:104–112; doi:10.1179/2049396713Y.0000000024.
7. Kassotis CD, Tillitt DE, Davis JW, Hormann AM, Nagel SC. 2013. Estrogen and Androgen Receptor Activities of Hydraulic Fracturing Chemicals and Surface and Ground Water in a Drilling-Dense Region. Endocrinology 155:897–907; doi:10.1210/en.2013-1697.
8. Macey GP, 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 13:82; doi:10.1186/1476-069X-13-82.
9. McKenzie LM, Guo R, Witter RZ, Savitz DA, Newman LS, Adgate JL. 2014. Birth Outcomes and Maternal Residential Proximity to Natural Gas Development in Rural Colorado. Environmental Health Perspectives 122; doi:10.1289/ehp.1306722.
10. McKenzie LM, Witter RZ, Newman LS, Adgate JL. 2012. Human health risk assessment of air emissions from development of unconventional natural gas resources. Sci. Total Environ. 424:79–87; doi:10.1016/j.scitotenv.2012.02.018.
11. Rabinowitz PM, Slizovskiy IB, Lamers V, Trufan SJ, Holford TR, Dziura JD, et al. 2014. Proximity to Natural Gas Wells and Reported Health Status: Results of a Household Survey in Washington County, Pennsylvania. Environmental Health Perspectives; doi:10.1289/ehp.1307732.
12. Saberi P, Propert KJ, Powers M, Emmett E, Green-McKenzie J. 2014. Field Survey of Health Perception and Complaints of Pennsylvania Residents in the Marcellus Shale Region. Int J Environ Res Public Health 11:6517–6527; doi:10.3390/ijerph110606517.
13. 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: A Journal of Environmental and Occupational Health Policy 23:55–83; doi:10.2190/NS.23.1.e.
14. 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.

- *No indication of significant public health risks or actual adverse health outcomes (n = 2)*

1. Bunch AG, Perry CS, Abraham L, Wikoff DS, Tachovsky JA, Hixon JG, 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; doi:10.1016/j.scitotenv.2013.08.080.
2. Fryzek J, Pastula S, Jiang X, Garabrant DH. 2013. Childhood cancer incidence in pennsylvania counties in relation to living in counties with hydraulic fracturing sites. J. Occup. Environ. Med. 55:796–801; doi:10.1097/JOM.0b013e318289ee02.

Health: All Papers (n=49)

- *Indication of potential public health risks or actual adverse health outcomes (n=47)*

1. Adgate JL, Goldstein BD, McKenzie LM. 2014. Potential Public Health Hazards, Exposures and Health Effects from Unconventional Natural Gas Development. Environ. Sci. Technol. 48:8307–8320; doi:10.1021/es404621d.
2. Bamberger M, Oswald RE. 2012. Impacts of Gas Drilling on Human and Animal Health. NEW SOLUTIONS: A Journal of Environmental and Occupational Health Policy 22:51–77; doi:10.2190/NS.22.1.e.
3. Bamberger M, Oswald RE. 2014. Unconventional oil and gas extraction and animal health. Environ. Sci.: Processes Impacts; doi:10.1039/C4EM00150H.
4. Chalupka S. 2012. Occupational silica exposure in hydraulic fracturing. Workplace Health Saf 60:460; doi:10.3928/21650799-20120926-70.
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12. Finkel M, Hays J, Law A. 2013a. The Shale Gas Boom and the Need for Rational Policy. American Journal of Public Health e1–e3; doi:10.2105/AJPH.2013.301285.
13. Finkel ML, Hays J. 2013. The implications of unconventional drilling for natural gas: a global public health concern. Public Health 127:889–893; doi:10.1016/j.puhe.2013.07.005.
14. Finkel ML, Hays J, Law A. 2013b. Modern Natural Gas Development and Harm to Health: The Need for Proactive Public Health Policies. ISRN Public Health; doi:http://dx.doi.org/10.1155/2013/408658.
15. Finkel ML, Law A. 2011. The rush to drill for natural gas: a public health cautionary tale. Am J Public Health 101:784–785; doi:10.2105/AJPH.2010.300089.
16. Goldstein BD. 2014. The importance of public health agency independence: marcellus shale gas drilling in pennsylvania. Am J Public Health 104:e13–15; doi:10.2105/AJPH.2013.301755.
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18. Hill M. 2014. Shale gas regulation in the UK and health implications of fracking. The Lancet 383:2211–2212; doi:10.1016/S0140-6736(14)60888-6.
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24. Lauver LS. 2012. Environmental health advocacy: an overview of natural gas drilling in northeast Pennsylvania and implications for pediatric nursing. J Pediatr Nurs 27:383–389; doi:10.1016/j.pedn.2011.07.012.
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30. McDermott-Levy R, Kaktins N. 2012. Preserving health in the Marcellus region. Pa Nurse 67: 4–10; quiz 11–12.
31. McKenzie LM, Guo R, Witter RZ, Savitz DA, Newman LS, Adgate JL. 2014. Birth Outcomes and Maternal Residential Proximity to Natural Gas Development in Rural Colorado. Environmental Health Perspectives 122; doi:10.1289/ehp.1306722.
32. McKenzie LM, Witter RZ, Newman LS, Adgate JL. 2012. Human health risk assessment of air emissions from development of unconventional natural gas resources. Sci. Total Environ. 424:79–87; doi:10.1016/j.scitotenv.2012.02.018.
33. Penning TM, Breysse PN, Gray K, Howarth M, Yan B. 2014. Environmental Health Research

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- *No indication of significant public health risks or actual adverse health outcomes (n=2)*

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- *Indication of elevated air pollutant emissions and/or atmospheric concentrations (n=24)*

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- *No indication of significantly elevated air pollutant emissions and/or atmospheric concentrations (n=2)*

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