RFF REPORT

Health Impacts of Unconventional Oil and Gas Development

Alan J. Krupnick and Isabel Echarte

This report was produced as part of **The Community Impacts of Shale Gas and Oil Development***, an RFF initiative.*

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Summary

This report reviews the academic literature analyzing the effect of unconventional oil and gas development on health outcomes—i.e., for a study to be reviewed, it must link unconventional oil and gas development to some measure of health impact or risk. We classify the literature according to methodologies used—epidemiological, health impact assessments, community based participatory research, occupational health, and hypothesis-generating studies. We chose to focus the majority of our analysis on epidemiological studies, as these studies directly address associations between health outcomes and oil and gas development. We do not include toxicological studies analyzing health effects on animals. The health impacts literature reviews are additionally accompanied by a "span chart," which summarizes the literature along a key dimension: which elements of the damage function model (which links oil and gas activities to burdens, concentrations, exposures, and impacts) are covered by a given study. In all, 32 studies were reviewed, covering the following health impacts: birth outcomes, cancer, asthma, and other health effects such as migraines and hospitalization. Occupational health studies also addressed exposure to certain pollutants (such as silica and volatile organic compounds), and a number of hypothesis-generating studies analyzed burdens and concentrations (such as water and air samples) in order to assess the potential for health impacts. The literature is furthermore summarized (by impact) in the health section of the Risk-Benefit Matrix[1] below, indicating the relationship between this impact, as reported across the literature, and unconventional oil and gas development as well as the quality of the body of research assessing that impact.

- We found that though many epidemiological studies used robust statistical methods to estimate changes in health outcomes associated with unconventional oil and gas development, all had shortcomings that were most often significant.
- These studies furthermore reported contradictory results for each impact. Some studies, for example, found increases in preterm birth, while others found decreases or no association. As is illustrated by the Community Risk-Benefit Matrix, all impacts had inconsisting findings across the literature for that outcome. Where the results of these studies did not contradict each other, the impact was only analyzed by a single study.
- Furthermore, only one study spans the full range of damage function elements—due to the nature of the data and research methodologies, the studies are unable to assess the mechanisms of any health impacts (i.e., whether a certain impact is caused by air pollution, stress, water pollution, or another burden). Those that do assess burdens or concentrations do not measure changes in health outcomes or assess the potential for such changes (save for one study). (See the span chart for more details).
- As a result, even where good evidence is offered for a link between unconventional oil and gas development and health, the causal factor(s) driving this association are unclear.

Though we do not see strong evidence of changes in outcomes associated with unconventional oil and gas development in the literature, a lack of data or a lack of rigorous

[1] The Risk-Benefit Matrix also summarizes the findings of our literature reviews on local public finance issues (including education and truck traffic), economic outcomes, seismicity, and housing values.

studies does not rule out the potential for these effects.

Community Risk-Benefit Matrix

The Community Risk-Benefit Matrix identifies specific areas of concern related to impacts addressed by the team's literature review (left column of the matrix), as well as impacts for which RFF experts have conducted original research and analysis. (See the section of the matrix related to this review, on the health impacts of unconventional oil and gas development, on the following two pages.)

The matrix indicates the quality of the literature for each impact, judged subjectively with the color indicating whether we find the studies analyzing an impact to be, on average, of a certain quality. Impacts may be assessed by multiple low-quality studies and a medium-quality study, for example, and we would consider this body of literature to be low quality. A high-quality classification indicates that we trust the results of such studies, including the accuracy, magnitude, and direction of the results—meaning, in a practical sense, that it has no serious or fatal flaws (such as inadequate methodologies) that would lead us to question the results. A study is considered low quality if we believe we cannot trust the results because the study has multiple, serious flaws (e.g., methodology, data, focus, or study design are inadequate to reliably estimate outcomes). A study is considered medium quality if it does not fit in the other two categories. A study is therefore medium quality if it has any such major flaw or if either the methodology, data, focus, or study design lead to questionable results for a number of reasons. Generally, we find the magnitude and direction of these results to be informative, but question the precision.

Lastly, we summarize the findings reported by the literature for each impact—whether the studies as a whole report increases, decreases, or no relationship between the impact and an increase in unconventional oil and gas development. The "heterogeneous" classification indicates that the literature reports different outcomes across areas. The "inconsistent" classification indicates that the literature reports contradictory results (i.e., two studies find an increase or decrease for a certain impact in the same context).

View or download the entire matrix, including all sections that correspond with each of the literature reviews by topic produced as part of this initiative:

WHIMBY (What's Happening in My Backyard?): A Community Risk-Benefit Matrix of Unconventional Gas and Oil Development

COMMUNITY RISK-BENEFIT MATRIX LITERATURE REVIEW: HEALTH IMPACTS OFUNCONVENTIONAL OIL AND GAS DEVELOPMENT

Birth Outcomes

Impact	Findings	Results
Birthweight	~	Studies of mixed quality find positive, negative, and null associations with birthweight.
Low APGAR	~	One study finds a positive association, while a high-quality study finds no association.
Preterm birth	~	Several studies report no association with development, while one higher-quality study and another lower-quality study find an increase in premature births.
Small for gestational age	~	Two studies report an increase in babies who are small for their gestational age, while another higher-quality study reports no association.
Birth defects	↑	One flawed study finds evidence of an increase in some birth defects, but no association with one defect.

Cancer

Impact	Findings	Results
CNS Tumors	↑	One study finds evidence of positive association.
Childhood cancers	Ø	One lower quality study finds no association.
Leukemia and lymphoma	~	Studies report evidence of an increase or no association. One risk assessment finds an elevated risk of leukemia and other cancers based on air measurements of benzene, though another study finds air measurements of pollutants to be below a threshold of concern.

KEY

(green)	Higher quality: The majority of studies reviewed for an impact are of higher quality. Where there is one study of higher quality, it is marked as such.
(blue)	Medium quality: The majority of studies reviewed for an impact are of medium quality. Where there is one study of medium quality, it is marked as such.
(orange)	Lower quality: The majority of studies reviewed for an impact are of lower quality. Where there is one study of lower quality, it is marked as such.
(light grey)	Not reviewed: Research on an impact was not reviewed.
↑	Increase: Studies show a positive, robust association with an impact (an increase in incidence or magnitude).
↓	Decrease: Studies show a negative, robust association with an impact (a decrease in incidence or magnitude).
↑↓	Heterogeneous: Across regions or areas, studies report robust results that differ.
Ø	No association: Studies report results that showed no association.
~	Inconsistent: Studies report differing (contradictory) results.

Community Risk-Benefit Matrix Literature Review: Health Impacts of Unconventional Oil and Gas Development (continued)

Other Health

Impact	Findings	Results
Asthma	↑ (medium quality)	One study reports increases in asthma hospitalizations, ER visits, and prescriptions for asthma medications.
Hospitalization	↑ (lower quality)	One study finds an increase in hospital rates for some types of inpatient cases, but no associations for most cases.
Migraines	~ (medium quality)	Two medium-quality studies report no association, while one lower-quality study reports an increase; all are self-reported symptoms.
Multiple symptoms	↑ (lower quality)	One study finds positive and no associations for different types of self-reported symptoms.

Key

(green)	Higher quality: The majority of studies reviewed for an impact are of higher quality. Where there is one study of higher quality, it is marked as such.
(blue)	Medium quality: The majority of studies reviewed for an impact are of medium quality. Where there is one study of medium quality, it is marked as such.
(orange)	Lower quality: The majority of studies reviewed for an impact are of lower quality. Where there is one study of lower quality, it is marked as such.
(grey)	Not reviewed: Research on an impact was not reviewed.
↑	Increase: Studies show a positive, robust association with an impact (an increase in incidence or magnitude).
↓	Decrease: Studies show a negative, robust association with an impact (a decrease in incidence or magnitude).
↑↓	Heterogeneous: Across regions or areas, studies report robust results that differ.
Ø	No association: Studies report results that showed no association.
~	Inconsistent: Studies report differing (contradictory) results.

1. Introduction

Literature studying the impacts of unconventional oil and gas development on health outcomes is largely inconclusive regarding not only the size and significance of the health effects but also the potential mechanisms, such as air pollution or stress. Several studies find some evidence of health impacts related to unconventional oil and gas development, such as an elevated incidence of preterm birth near oil and gas development, but these studies face data-related and measurement issues. Some health impacts, such as cancers, are difficult to study because they have long latency periods, meaning the impacts might not be known for many years

Studies that have conducted literature reviews include Werner et al. (2015), Shonkoff et al. (2014), Finkel and Hays (2013), and Adgate et al. (2014). Some discuss known stressors as well as uncertainties that remain (Adgate et al. 2014), while others highlight the lack of epidemiological studies definitively able to establish cause and effect (Finkel and Hays 2013, 2015). Werner et al. (2015) finds that much of the literature focuses on impacts on water and air, with “health impacts inferred rather than evidenced,” and that most of the scientific evidence lacks methodological rigor (1127). All highlight the data gaps and the need for more epidemiological studies to assess associations between unconventional oil and gas development and risk factors as well as establishing causation for any health impacts. This review finds that similar gaps persist in the literature, despite the publication of several more epidemiological studies, an issue discussed below.

This review first considers epidemiological studies, which are divided into two groups: studies using data reported to institutions (such as hospitals) and studies with self-reported symptoms. Within those two groups, studies are further categorized by the health impact being analyzed, such as birth outcomes or hospitalization rates. Next, health impact assessments (HIAs), most often used to assess potential health concerns ex ante, are addressed. Community-based participatory research (CBPR) studies, using community resources and residents to conduct data collection, are in a separate category because of the direct participation of residents in data collection.

We also give a brief overview of the occupational health literature related to unconventional oil and gas development, though we do not go into detail given that our focus here is on community impacts, and worker exposure patterns are quite different than a community’s. Finally, we discuss studies that analyze risk factors and are largely hypothesis-generating. These studies range from surveys gauging people’s perception of health risks to studies sampling air or water quality and inferring health impacts. Other studies simply assess chemicals or pollutants known to be associated with unconventional oil and gas development and analyze the risks and the potential for health impacts of the associated chemicals and emissions. There are many hypothesis-generating studies, but we focus on a handful to provide a sample of the type of literature; thus that section is not comprehensive.

We chose to concentrate on epidemiological studies, as they directly address associations between health outcomes and oil and gas development. We do not include toxicological studies analyzing health effects on animals. These studies, while they may have indirect implications for human health and may guide further research, are outside of the scope of this literature review.[2]

[2] Kassotis et al. (2015, 2016), for example, analyze developmental and reproductive health outcomes in

Furthermore, we do not discuss nonacademic studies or issue briefs published by various interest groups, though some have been influential in public discourse on the health impacts of oil and gas development.[3]

Table 1 summarizes the studies in each section, and the study span chart and accompanying text at the end of this paper provide further insights into this literature. All but five studies (Hill 2013a; McKenzie et al. 2014; Macey et al. 2014; Elliott et al. 2017; Hays et al. 2016) focus their analysis on unconventional natural gas, or shale, development. The studies that do not often include other types of energy development, such as conventional natural gas or oil, are indicated in the table below.

2. Epidemiological Studies

Few epidemiological studies are able to provide quantifiable evidence of the relationship between unconventional oil and gas development practices and health outcomes, a finding confirmed by a literature review and a summary of issues in unconventional oil and gas development health literature (Finkel and Hays 2015; Shonkoff et al. 2014). Several factors contribute to the difficulty of conducting a study that can rigorously quantify a cause-and-effect relationship between unconventional oil and gas development environmental risk factors and health outcomes. The lack of information regarding the extent of pollution from fracking sites, often due to a lack of air and water monitoring near such sites, hinders attempts to establish exposure among individuals in local communities. Finding extensive information regarding the chemicals used in fracking fluid, for example, is not straightforward, as the industry is not required by any national regulation to report such information, and states differ in their requirements and stringency, though recently many have moved to require the use of FracFocus for reporting this information.

Many companies do, however, report these chemicals voluntarily to the Groundwater Protection Council and the Interstate Oil and Gas Compact Commission's FracFocus website. Further, the lack of widespread monitoring of emissions, ambient air quality, and water quality throughout diverse geographies and regions adds to the lack of clarity, particularly as air quality monitors generally target urban areas (Macey et al. 2014). Even when establishing exposure potential, it is difficult to assess the potential for health impacts, as "an undetermined number of the chemical compounds used in the drilling and fracturing processes lack scientifically based maximum contaminant levels" (Finkel and Hays 2015, 1). Moreover, the fracking boom is relatively recent, meaning that any long-term health impacts, such as cancers, may not occur for quite some time. Despite these impediments, a few studies do provide evidence for negative health impacts from unconventional oil and gas development.

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mice, which may indicate potential health concerns for humans.

[3] Fleischman et al. (2016) is one such study. The authors look at counties at high risk of cancer or respiratory impacts based on the US Environmental Protection Agency's (EPA's) 2011 National Air Toxics Assessment (NATA), which is meant to "inform national and local data collection and policy efforts" and is not a "measure of actual risk in specific locations" (6). They then state that these high-risk areas "are generally located in states with the largest amount of oil and gas infrastructure." Such a study is hypothesis-generating, and the correlation between state-wide oil and gas infrastructure and county-level risk does not indicate causation, as is implied throughout the study.

TABLE 1. ORGANIZATION OF LITERATURE REVIEW

Study Type	Subcategory	Study Name and Topic
Epidemiological studies	Hospital-reported data	*Birth outcomes*: Hill (2013a, 2013b),* Casey et al. (2016), McKenzie et al. (2014),† Stacy et al. (2015) *Asthma*: Rasmussen et al. (2016) *Hospitalization rates*: Jemielita et al. (2015) *Cancer*: McKenzie et al. (2017),** Fryzek et al. (2013)
	Self- reported health effects	*Multiple symptoms*: Tustin et al. (2017), Rabinowitz et al. (2015).
Health impact assessments and risk assessments	N/A	*Battlement Mesa, CO, HIA*: Witter et al. (2013) *Cancer risk analysis for Battlement Mesa HIA:* McKenzie et al. (2012)
Community-based participatory research	N/A	*Multistate air pollution*: Macey et al. (2014)‡ *Symptoms and air quality*: Steinzor et al. (2013)
Occupational health	N/A	*Silica exposure*: Esswein et al. (2013) *Volatile organic compound exposure*: Esswein et al. (2014), Bloomdahl et al. (2014) *Cancer risk:* Durant et al. (2016) *Fatalities and accidents*: Harrison et al. (2016), Mason et al. (2015)
Risk factors and hypothesis-generating studies	Sampling and modeling	*Fracking-related pollutants:* Elliott et al. (2017), ‡ Aminto and Olson (2012), Colborn et al. (2011) *Radon levels*: Casey et al. (2015), Mitchell et al. (2016)
	Inferring impacts	*Air samples*: Colborn et al. (2014), Bunch et al. (2014) *Water samples*: Kassotis et al. (2013) *Noise impacts*: Hays et al. (2016)‡
	Surveys	*Perceptions of health effects*: Saberi et al. (2014), Ferrar et al. (2013)

* Oil, shale gas, conventional natural gas, and coal bed methane
** Oil and gas
† Natural gas (conventional or shale)
‡ Unconventional oil and gas

2.1. Proxies for Exposure

These papers are often forced to use proximity to wells and the intensity of nearby oil and gas development as proxies for exposure because of the data limitations and to capture multiple exposure pathways. The downside to this method is that the effects of a particular exposure pathway cannot be tested and identified, though data limitations would prevent such analysis in any event. Additionally, proxies in the literature surveyed here are unable to account for topography, which may have a large effect on the potential for exposure, particularly in hilly or mountainous areas. Several studies measure thresholds (e.g., comparison of impacts within 2.5 kilometers [km] of an existing shale well and those within 2.5 km of a permitted but undeveloped well site in Hill 2013b); others include the intensity of nearby shale gas development using inverse distance weighted (IDW) measures (e.g., McKenzie et al. 2014).[4]

[4] IDW accounts for the number of wells within a certain radius (in this case, 10 miles) and also the distance from those wells to the point of interest (in this case, the maternal residence). According to McKenzie et al. (2014, 413), "An IDW well count of 125 wells/mile could be computed from 125 wells each located 1 mile from the maternal residence or 25 wells each located 0.2 miles from the maternal residence."

Other studies use even more complicated metrics to account for other aspects of oil and gas development, such as production phases (drilling, fracking, producing) and their durations (e.g., Casey et al. 2016). The results for studies using such metrics are more difficult to interpret. Authors generally construct quartiles to compare lowest levels of exposure in the first quartile with highest levels of exposure in the fourth quartile. Such proxies may be more accurate in measuring exposure, though the trade-off is that they are more difficult to interpret. The suitability of the proxy for exposure is an issue for all the studies and is unresolvable until researchers can identify and test for an agent that could cause the hypothesized effect.

2.2. Hospital-Reported Data

Birth Outcomes

The proxy issue applies with particular force to the intriguing literature on birth outcomes. Two working papers by Hill (2013a, 2013b) study infant health outcomes for mothers living near shale activity in Colorado and Pennsylvania, respectively, using what have become standard quantitative methods. Both studies find that the proximity of the mothers' residences to wells increases the prevalence of negative health outcomes for infants, such as low birth weight, though these working papers have received critical reviews and are not yet published in peer-reviewed journals.

In Pennsylvania, studying singleton births to mothers from 2003 to 2010, Hill (2013b) finds that living within 2.5 km of a shale gas well increased the incidence of low birth weight by 25 percent and "small for gestational age" (the 10th percentile of weight distribution for gestational week of birth) by 18 percent. Apgar scores below 8, which predicts the need for respiratory support, increased by 26 percent. The prevalence of low birth weights persisted up to 5 km from a well head, with the effects not attributable to existing trends. Hill (2013a), studying Colorado births between 2000 and 2011, found remarkably similar results: residences within 1 km of a well (oil, shale gas, conventional natural gas, and coal bed methane wells) saw an increase in the incidence of low birth weight by 31 percent and premature birth by 33 percent, as well as reduced gestational periods, though these results do not persist beyond a 2 km threshold. The author states that though these effects are large, they are "biologically plausible" given the results found in other literature on the effects of air pollution or maternal stress on birth outcomes.

Both papers conclude that the results do not differ across water sources for the households, meaning the mechanism is less likely to be water related. With a conservative, back-of-the-envelope calculation, Hill founds that with 2011 well estimates, these impacts could cost Pennsylvania $30 million and Colorado $8.5 million as a result of the hospital costs, decreased lifetime earnings, and special services associated with low birth weight and premature infants.

What is notable about these studies is that they not only provide evidence for a link between shale activities and negative health outcomes, but they did so across two states. These findings imply that there may be a systemic mechanism through which oil and gas activities can affect birth outcomes and infant health. Addressing whatever mechanism causes these issues, however, would require further study.

The studies, however, have received criticism concerning their methodology. The most important is that they relied on the assumption that mothers who live near a permitted well and mothers who live near a drilled or producing well have similar characteristics—that their socioeconomic characteristics, which may also influence birth outcomes, do not change between the time a well is permitted and when that well begins producing (Revkin 2012). This is an important issue, as mothers who are more well-off may move away from oil and gas development, or mothers who are less well-off may take advantage of decreased home prices. Muehlenbachs et al. (2015) find that housing prices of groundwater-dependent homes near active shale well sites sell at a discount. Hill (2013b) shows evidence of this issue: within 2.5 km of a well in Pennsylvania, the population of mothers after drilling showed statistically significantly higher levels of Medicaid and Women, Infants, and Children (WIC, a low-income nutritional program) status—5.5 and 3.1 percentage points higher, respectively, than before drilling. Hill (2013a) does not report results for Medicaid or WIC status but finds a larger share of teen mothers post-drilling within 5 km of a well in Colorado.

Stacy et al. (2015) conducted a similar study of over 15,000 live births in southwest Pennsylvania from 2007 to 2010. The study uses the IDW metric, as defined above, and breaks this number down into quartiles, with the least exposed quartiles having an IDW well count of less than 0.87 wells per mile and the most exposed quartile having 6 wells or greater per mile. And like McKenzie et al. (2014), discussed below, this study uses a 10-mile radius surrounding a well to limit its analysis. The study finds that infants in the highest exposure quartile weighed on average almost 22 grams less than those in the lowest. The study also found that infants in the highest exposure category had 34 percent greater odds of being small for gestational age (SGA) than those in the lowest,[5] with the lowest exposure quartile showing a 4.8 percent prevalence rate of SGA and the highest exposure quartile a 6.5 percent SGA rate. The study did not find any significant effects of well density on premature births, except for a higher average birth weight and a lower share of premature infants born to mothers living in the second exposure quartile—an odd result. The study also uses a 10-mile radius, larger than many other studies, for analysis, which makes it difficult to control for variation within that area of interest. This large radius means the results could reflect differences in health outcomes due to socioeconomic status, for example, rather than proximity to natural gas development.

McKenzie et al. (2014), also using an IDW count of wells within a 10-mile radius, finds evidence of birth defects related to natural gas development in rural Colorado over the 1996–2009 period, though the study also finds a *decreased* risk of preterm birth and term low birth weight. Flaws in this study include that it counts any well that is “existing” within the registry used for data during the entire birth year of the infant; this means the well could be of various types (shale or conventional), it could be active or inactive, and the timing of a well’s drilling or activity may not match the timing of the pregnancy necessary for potential exposure (Fedak et al. 2014). Also, the study relied on cross-sectional data in

[5] Stacy et al. (2015), Casey et al. (2016), McKenzie et al. (2014), Rasmussen et al. (2016), Tustin et al. (2017), and Rabinowitz et al. (2015) report some or all results in terms of odds ratios (ORs). An OR is the ratio of the odds of an event in a treatment group (here, the highest exposure quartile) to the odds of an event in the control group (the lowest exposure quartile). For a detailed discussion of the calculation of an OR and comparison to a risk ratio, see the appendix.

addition to using a 10-mile radius, as did Stacy et al. (2015), which presents issues as discussed in the paragraph above. Fedak et al. (2014), in a published critique of the study, also took issue with the study's hypothesis that benzene is the mechanism through which the defects occur, as the study provides little evidence to support this claim.

More recently, Casey et al. (2016) conducted a similar study analyzing Pennsylvania birth outcomes from 2009 to 2013. This study not only looks at post-2010 shale gas development (when development began to spread even more) but also improves on the proxy for exposure by accounting for production intensity and construction phase duration of well pad development as well as the overall intensity of drilling activities in these areas. The authors state that this metric means that "a woman living close to several well pads under development, but far from any producing wells, could have a similar index as a woman living near only producing wells" (5). Those in the first quartile of exposure live within in 20 miles of an average of 6 wells and a median of 0. Those in the fourth quartile of exposure live within 20 miles of an average of 124 wells and a median of 8. These numbers show a large difference in exposure intensity between the quartiles, supporting the author's use of this metric as a proxy (the third type discussed above).

The study found that the odds of a preterm birth were 40 percent greater for those in the most exposed quartile than for those in the least exposed category, or an odds ratio of 1.4 in this quartile. Because of the complexity of the exposure metric, however, it is difficult to interpret these results in a more meaningful way or compare them with Hill's results. The authors found no correlation of unconventional natural gas activity with Apgar score, SGA, or term birth weight. Cox (2016) critiques the study, primarily on the issue of using proxies to estimate exposure (an issue present in most studies). The problem with the methodology of the study is that Casey et al. (2016) have addressed only for mothers in 2010 and 2013 yet analyze 2009 through 2013. Between those two years, almost 80 percent had the same address, with 6 percent moving within 1,500 meters (m) and another 10 percent moving 1,500 m to 16 km from their original addresses. This discrepancy has the potential to introduce some error into the estimates—particularly those from 2009.

While many of these birth outcome studies have some level of issues with methodology, they also present results that are suggestive of serious health impacts. Thus we strongly suggest that further study of these relationships is warranted. Future studies need to posit specific hypotheses about the agent or agents causing such outcomes and then construct exposure metrics that are consistent with those hypotheses so that policy is able to address the source of such impacts.

Asthma

Rasmussen et al. (2016), analyzing asthma exacerbation related to shale development, expands the IDW metric used in Stacy et al. (2015) to four IDW metrics, each specifically addressing a different phase of shale development. The authors analyze the relationship of shale development and asthma exacerbation in Pennsylvania from 2005 to 2012. The study uses four different IDW exposure metrics: one for the IDW number of well pads being prepared, a second IDW for the number of wells being spudded, a third IDW for the stimulation metric controlling for number of wells and well depth as a surrogate for truck traffic, and a fourth IDW for number of wells and gas production volume as a surrogate for fugitive emissions. Each of the four exposure metrics is divided into four quartiles ranging from very low to high.

The study finds that the odds of asthma hospitalizations are 74 percent greater for high levels of exposure to production activities than for very low levels. The odds of emergency department visits were 119 percent greater for high levels of production than for very low levels. The odds of hospitalizations and emergency room visits were 66 and 71 percent, respectively, greater for high levels of well stimulation; 64 and 57 percent, respectively, greater for high levels of exposure to spudded wells; and 45 and 37 percent, respectively, greater for high levels of pad development. Additionally, the authors found a large difference in the odds of prescriptions for an oral corticosteroid (OCS), a medication for asthma—over three times higher—for high levels of production exposure than for very low levels and somewhat lower differences for well stimulation, spudded wells, and well pad development.

With its four exposure proxy measures, this study is unique in that it begins to address the potential mechanisms for these health impacts. Further study of the stressors (physical and mental) that populations might be exposed to during the production and stimulation phases, for example, could work to illuminate or establish the mechanism through which shale development exacerbates asthma.

Even so, the exposure proxy can be questioned. Patients in the highest exposed group for the spud metric lived a median of 19 km from the closest well, while those in the lowest exposure group lived a median of 63 km from the closest well. Though the difference in distance between the two exposure groups is large, a 19 km median distance for the highest exposed group might not be small or accurate enough for the shale activity metric to be considered a robust proxy for exposure. The populations in control and case groups also differed in a few ways across the three categories of asthma exacerbation analyzed (new OCS, ER visit, and hospitalization); the study, however, did not report the characteristics of populations within each exposure quartile, and it is therefore difficult to assess whether the results are credible.

Hospitalization

Jemielita et al. (2015) conducted a hospitalization study with a broader focus, assessing hospital utilization rates for a variety of symptoms and health impacts in three counties in Pennsylvania from 2007 to 2011, and finds that shale gas wells (by total wells and average density for a given zip code) were associated with increased cardiology inpatient rates within that zip code. The study conducts a field experiment between Bradford and Susquehanna Counties, which saw increased fracking activity, and Wayne County, which saw no fracking activity between 2007 and 2011. The authors report the results in terms of risk ratios (RRs), which differ from ORs.[6] Only cardiology inpatient cases were statistically significant for both the well count and well density analyses—each additional well raises cardiology inpatient rates per zip code by 0.07 percent. Cardiology and neurology were also significantly associated with well density, with 27 and 18.8 percent higher risk in zip codes in the highest quantiles of well density (0.79 wells/km^2) than in zip codes with no wells per kilometer

[6] Though these terms are often used interchangeably to describe statistical results, “risk” and “odds” indicate different types of measurements. An RR is the ratio of the risk of an event occurring in the treatment group (those living near high quartiles of well density, for example) to the risk of the event in the control group (those living near the lowest quartile of well density). See footnote 4 for an explanation of ORs. A detailed discussion of the difference between the two measurements can be found in the appendix.

squared. The issue with this analysis—simply comparing zip codes with and without wells—is that a number of unobservable differences may bias the results, meaning zip codes that have drilling might be different than zip codes that do not have drilling in a way that affects the prevalence of inpatient cardiology or neurology rates. Additionally, this level of analysis likely is not able to address within–zip code variation in exposure.

Cancer

Studies focusing on the impacts of oil and gas development on cancer face data-related issues, making their findings less reliable. One study, McKenzie et al. (2017), does find increased incidences of leukemia in rural Colorado among a small sample of cases, though Fryzek et al. (2013) does not. Casey et al. (2015) and Mitchell et al. (2016) address the issue more indirectly, through changes in radon levels in homes due to the use of Marcellus shale gas or shale development, discussed in a later section.

McKenzie et al. (2017) studies cases of acute lymphocytic leukemia (ALL) and non-Hodgkin lymphoma (NHL) in 0- to 24-year-olds between 2001 and 2013. The study compares these cases with the IDW counts of all active oil and gas wells within 16.1 km of the person's home at the time of diagnosis (including but not limited to unconventional development). Because the study used the Colorado Central Cancer Registry for its data, the control groups are people with other types of cancer. While this may present issues in measurement, as the control group is not the average rural population, this issue would likely bias the results downward. The study finds that ALL cases in the age 5–24 group were 4.3 times as likely to live in the highest tertile of IDW well counts compared with controls (other rural residents in the cancer database). No association was found for children 0–4 years old, consistent with the issue of latency in cancer cases.

Because the authors chose to restrict observations to rural areas to avoid other sources of exposure (such as traffic or industrial activity), the sample size is small (87 cases compared with 528 controls). Additionally, the study uses well counts from the Colorado Oil and Gas Conservation Commission, which defines the dates of an active well as those between the "spud-in" date and the permanent plugging of a well. The issue with such a definition is that wells may be temporarily shut in or inactive for a period of time (Ho et al. 2016). Another issue is that the authors use the address at the time of diagnosis for the analysis and do not have the address histories—meaning the results could be biased unless a large majority of the study population had not moved in the decade or so before diagnosis. Finally, the authors are unable to control for smoking during pregnancy, as this information is missing for almost 60 percent of the study population. There are many issues that might bias the results of the study. The big impact found in these results, however, indicates that this issue warrants further study.

Fryzek et al. (2013), a widely criticized study, analyze childhood cancer incidence before and after fracking in Pennsylvania counties. The study concludes that cancer did not increase following hydraulic fracturing. There are a number of issues with this study, however. First, the authors analyze cancer incidence between 1995 and 2009, which was mostly before the fracking "boom" in the state, and the study also ignores the issue of latency with cancer, as fracking began in the state just one to two years before the end point of this study (Goldstein and Malone 2013). Second, the study uses a very crude metric for exposure—a county's cancer rates related to its extent of shale development, a very large unit of observation that makes it difficult to both proxy exposure and account for within-county variation. The results of the study should not be considered conclusive because of the many issues present.

2.3. Self-Reported Health Effects

Several studies look for links between health effects and unconventional oil and gas development by collecting information on self-identified health effects. Some epidemiological studies combine surveys with econometric analysis to assess the relationship between exposure to unconventional development and reported or perceived health outcomes. Self-reported symptoms are potentially subject to more bias, as those living near shale development may know about the potential for health effects and may therefore be more attuned to their own symptoms. Additionally, those who choose to respond to a survey about health may be more likely to be experiencing symptoms. Because the following two studies do not mention shale development, however, there is less potential for bias. Two other surveys were conducted; these are discussed in the section titled Risk Factors and Hypothesis-Generating Studies, as they are more indicative of public perception regarding the health impacts of shale development and are not epidemiological studies.

Multiple Symptoms

Tustin et al. (2017) is perhaps the most rigorous of the survey-based studies discussed here, analyzing chronic rhinosinusitis (CRS), migraine, and fatigue. The authors sent surveys to a random sample of individuals using data from the Geisinger Health System in Pennsylvania, a representative sample of the population. About one-third, or 7,847, responded to the 2014 survey, which made no mention of shale gas development. Using data on natural gas development, the authors construct quartiles of natural gas development exposure, like Stacy et al. (2015) and Casey et al. (2016), and find associations between shale development and each of the three aforementioned health outcomes or a combination thereof. The study finds a threshold for the presence of symptoms, as the associations were present for only the fourth quartile of shale development. Comparing the lowest and highest activity quartiles (using ORs), the odds of respondents reporting CRS were 11 percent greater. The odds of reporting migraine and fatigue were 43 and 47 percent greater in the highest activity quartile than in the lowest, and the odds of reporting a combination of those symptoms were more than 80 percent greater. Each of these symptoms can be caused by multiple factors, such as stress, sleep deprivation, noise, odors, hormonal issues, toxins, allergens, and more. Though too much weight should not be placed on the results, because of the aforementioned issues with bias in self-reporting symptoms and with exposure proxies, it is suggestive of a relationship between natural gas activity and health effects. Like many of the studies discussed in this section, however, the mechanism for such effects is not able to be ascertained.

Rabinowitz et al. (2015) conducted a similar study, surveying the self-reported health symptoms of 492 people in 180 randomly selected groundwater-dependent households in Washington County, Pennsylvania. This survey also does not mention shale gas activity, though its exposure metric compares households within 1 km of a gas well and those either 1–2 km from a well or greater than 2 km from a well—a less complicated exposure metric than that of Tustin et al. (2017) and similar to that of Hill (2013a, 2013b). The study finds that upper respiratory symptoms were more frequently reported by households within 1 km of a gas well than by households farther away, and a similar result was found for skin conditions, though no correlation was found with reported neurological, cardiovascular, or gastrointestinal conditions. The study states that these findings are "hypothesis-generating," as it finds the potential for a relationship.

3. Health Impact Assessments and Risk Assessments

Because of the limitations of epidemiological studies, some research seeks to assess potential effects through other methods. Though these studies are less precise than ex post epidemiological research, they do aid in filling gaps that exist because of data-related or temporal limitations. Such studies can be informative for communities and residents weighing decisions about permitting shale development.

Importantly, the Colorado Department of Public Health and Environment conducted a health risk assessment using more than 10,000 air samples from oil and gas producing regions of Colorado to estimate potential air exposures for those living 500 feet or more from a production site (McMullin et al. 2017). The study finds that concentrations were below the short- and long-term "safe" levels for exposure for noncancer risks, and the cancer risk of these substances was within EPA's "acceptable risk" range. The authors state that these findings indicate low levels of risk of health effects from the combined exposure to all of these substances, though benzene, acetaldehyde, and formaldehyde had the highest estimated risk levels and are priorities for monitoring.

3.1. Battlement Mesa, CO, Health Impact Assessment

Health impact assessments (HIAs) can provide information regarding the potential for health effects and exposures before shale development, using expert analysis, scientific information, and stakeholder input (Institute of Medicine of the National Academies 2014). According to a workshop summary from the Institute of Medicine of the National Academies, while HIAs are mostly qualitative in nature, they differ from risk assessments and policy critiques in that they are more formal, usually conducted in a six-step process,[7] and meant to inform societal decisions and options for managing health by conducting assessments and offering recommendations.

Witter et al. (2013) is an HIA assessing the public health aspects of future shale gas development in Battlement Mesa, Colorado, conducted after the community petitioned for a health assessment before any permits were issued to operators. The study concludes that drinking water contamination likely would not be an issue, as the proposed well locations were downstream of the intake point from the Colorado River. The HIA therefore did not conduct analysis of any potential health effects from water contamination, as exposure through this channel is unlikely in the first place. Using EPA risk assessment methods, however, the study finds a short-term nonchronic increase of noncancer health effects and a small lifetime excess cancer risk for those living closer to wells based on the study conducted by McKenzie et al. (2012) to inform this HIA (see below). When discussing potential changes to the community, such as school enrollment, sexually transmitted diseases, and crime, the study finds that

[7] This six-step process is described in the National Academies Workshop Summary. The first is screening, in which stakeholders decided whether an HIA should be done and whether it would add information. The second is deciding on the scope and identifying the important health impacts and most affected populations. The third is assessment, in which researchers analyze the baseline conditions present and the characteristics of the population. The fourth is developing a set of health-based recommendations, as well as a feasible plan accompanying them and indicators for monitoring. The fifth step is developing a report for dissemination. The last step is monitoring and evaluation, including analysis of whether the HIA was beneficial.

measures of these indices had increased in the previous years. But then the authors assume that this is due to natural gas development near Battlement Mesa, though any number of factors could influence such changes.

3.2. Cancer Risk Analysis for Battlement Mesa HIA

McKenzie et al. (2012) estimates potential air emissions exposure in Garfield County, Colorado—the county in which Battlement Mesa is located—to inform the previous health impact assessment for the area. The study estimates noncancer health effects and excess lifetime cancer risks for residential exposure scenarios for the Battlement Mesa project using ambient air quality data in Garfield County from 2008 to 2010. The samples were collected every six days from a fixed monitoring station as well as near well pads, located within a mile of Interstate 70. The study, however, relies on the assumption that any pollutants found in the samples can be attributed solely to shale development. The authors use EPA methods for creating the exposure scenarios comparing residents within half a mile of wells and those more than half a mile away from wells.

The results of the study show elevated subchronic (less than 20-month) noncancer hazards, such as neurological, respiratory, and hematologic effects. Those closer to wells are estimated to see a slightly elevated cancer risk, mainly due to benzene and ethyl benzene. Because of the narrow geological focus and rigor of this study, a more informative analysis of air quality changes from shale development was possible. McKenzie et al. (2012) is the only study of those discussed in this literature review to establish a connection to shale gas development, a burden (air pollution), a concentration (measures of ambient air), exposure (through modeling), and the impacts of chronic and subchronic health outcomes using EPA methods (see Study Span Chart at the end of this paper). Though this study is not ex post and therefore does not measure realized impacts, it is the most useful from a policy perspective in that policymakers can require, for example, technology that mitigates air emissions of benzene and ethyl benzene to reduce cancer risks if such impacts are, in fact, occurring. Taking into account the exact shale development plans as well as nearby impacts of shale development, residents and policymakers in the Battlement Mesa community and communities nationwide would be better informed as to the risks of living near shale development, despite the lack of ex post data.

While HIAs are able to provide a site-specific overview of potential exposure and health impact pathways before development, the conclusions drawn are often at best suggestive, save for the quantitative research conducted in McKenzie et al. (2012) used to inform Witter et al. (2013). Finkel and Hays (2013) highlights the importance of hypothesis-generating studies: “It should not be concluded that an absence of data implies that no harm is being done” (889). Such studies contribute to the literature by exposing gaps of knowledge as well as highlighting important areas for future research. And as epidemiological studies often cannot be conducted until issues—such as cancer, which has years- to decades-long latency periods—appear, HIAs provide some indication of potential risk until epidemiological studies can be conducted to test these hypotheses.

4. Community-Based Methods

Community-based participatory research (CBPR) is another method of identifying pollution and exposure risks from shale development. In these studies, residents of communities being studied participate directly in the study and collect data, such as ambient air quality samples. According to Steinzor et al. (2013), some of the core principles of CBPR include "an emphasis on community engagement, use of strengths and resources within communities, application of findings to help bring about change, and belief in the research relevance and validity of community knowledge" (58).

4.1. Multistate Air Pollution

Macey et al. (2014), for example, conducted a multistate study—including Arkansas, Colorado, Ohio, Pennsylvania, and Wyoming—focused on unconventional oil and gas development, in which a company trained residents in the methods, site selection, and community monitoring necessary to collect data. The residents were instructed to collect ambient air samples at locations of community concern when the conditions would have led them to file a complaint with authorities. This study differs from HIAs and epidemiological studies in that the residents participate in and make active decisions in how data are collected.

The study identifies eight volatile compounds that exceeded US Agency for Toxic Substances and Disease Registry (ATSDR) minimal risk levels[8] and EPA Integrated Risk Information System (IRIS) cancer risk levels[9]—mainly hydrogen sulfide, formaldehyde, and benzene. This study is useful in that it is able to show that state monitoring studies are incomplete, as existing data are often limited, with a focus on a small number of air contaminants in areas of high population density, and few states have requirements for baseline air and water quality testing (Steinzor et al. 2013). CBPR or similar methods may also be more useful in elucidating episodic—as opposed to systemic—hazards and providing more clarity as to what is occurring when residents experience certain impacts. As shale development pollution and air quality impacts fluctuate greatly with various phases of development, such methods should be considered for monitoring purposes. Furthermore, this study shows that setback distances are possibly insufficient to reduce health risks, as it finds high concentrations of volatile compounds at distances greater than the 150- to 500-foot setback distances used in many states.

4.2. Symptoms and Air Quality

Steinzor et al. (2013) is similarly able to establish health and environmental concerns that warrant further investigation through a combination of self-reported surveys and environmental testing. This CBPR study differs from HIAs or surveys alone in that the authors "selected areas for investigation based in part on the observations of change in environmental conditions by long-time residents" (58). Conducted between August 2011 and July 2012, the survey covers 108 residents in 14 Pennsylvania counties. It finds that over 80 percent of respondents experienced odors sometimes or constantly, about 5 reported existing health symptoms worsening after shale development, and participants in 22 households also reported several symptoms in pets or livestock. Environmental testing detected a total of 19 volatile organic compounds (VOCs) in ambient air samples outside of homes. Symptoms, such as throat irritation, were more prevalent closer to facilities. The issue with such a survey is its limited sample size and the fact that it was not randomly distributed, as participants passed on the survey to other participants. Self-reporting health effects presents further issues in measurement and bias. Additionally, air tests

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[8] See the ATSDR Toxic Substances Portal for more information (https://www.atsdr.cdc.gov/mrls/).

[9] See the EPA IRIS site for more information (https://www.epa.gov/iris).

were not randomly sampled. The study is a step toward bridging the knowledge gap in its ability to identify further areas for research as well as providing an indication of public perceptions of health effects, though it is far from conclusive regarding any definite health effects or mechanisms.

CBPR studies in general are most useful in "identifying linkages and considerations that can be used to develop protocols for additional research and policy measures" (Steinzor et al. 2013, 58). Their methodologies prevent statistical analysis and cannot necessarily establish causation. These studies, however, point to potential mechanisms for certain health effects, which can be further analyzed.

5. Occupational Health Studies

A number of studies look at the impacts of unconventional oil and gas development on employees working on site. These impacts are expected to be greater than what communities face given the relatively close proximity of workers to burdens and possibly their increased levels of exertion (which would matter, for example, for air pollution). This review does not go into detail on these studies, as they do not measure community impacts, the focus of this exercise. These studies are worth briefly considering, nonetheless, because they often directly measure exposures, unlike the majority of studies reviewed here. These studies measure exposure through breathing zone samples, urine samples, modeling and estimation of concentrations and exposures, and more.

5.1. Silica Exposure

Esswein et al. (2013) assesses exposure to silica during fracking operations using breathing zone and air samples. The study, collecting 111 breathing zone samples at 11 sites in five states from 2010 to 2011, finds that levels of respirable crystalline silica (present in the sand used to hold open fissures created by the fracking process) exceeded occupational health criteria at each of the sites, sometimes by more than 10 times the limit. The study identifies seven sources of dust generation, such as sand handling machinery.

5.2. Volatile Organic Compound Exposure

Bloomdahl et al. (2014) and Esswein et al. (2014) model VOC exposures and measure chemical exposures, respectively, during flowback operations. Esswein et al. (2014) examines flowback operations specifically in Colorado and Wyoming in 2013 to assess potential chemical exposures. Analyzing urine and air samples at six flowback sites, the study finds that airborne concentrations of benzene exceeded some criteria near point sources, such as tank gauging activities. The authors state that these findings are preliminary, and further research would be needed to fully understand exposures and hazards during flowback operations. Bloomdahl et al. (2014) uses a different approach, modeling concentrations and estimating worker exposure to 12 VOCs present in flowback water. The study finds the potential for subchronic health impacts but does not find exposure concentrations exceeding the range of acceptable risk (surpassing an excess lifetime cancer risk value of one in a million) for any of the VOCs.

5.3. Cancer Risk

Durant et al. (2016) assesses cancer risk from dermal exposure to flowback fluid. This study conducted an analysis similar to the Bloomdahl et al. (2014) model. The study finds that cancer risks exceeded a target lifetime risk of 10^{-6} (one in a million) only for two specific compounds, assuming the worker's full hand was exposed to flowback water not removed from skin for three hours (or one event per week for four years), defined by the authors as "an extreme scenario"

(Durant et al. 2016, 974). The authors state that these findings indicate more concern regarding risk than Bloomdahl et al. (2014); however, the dermal pathway of exposure depends on some sort of safety failure occurring, whereas inhalation of VOCs or silica is a concern during several stages of shale development.

5.4. Fatalities and Accidents

Finally, a number of articles (such as Harrison et al. 2016; Mason et al. 2015) discuss media reports and databases of fatal work injuries to analyze the number and cause of oil and gas worker fatalities, though they do not differentiate between conventional and unconventional oil and gas operations and often do not use statistical analysis.

6. Risk Factors and Hypothesis-Generating Studies

A large number of studies addressing the health impacts of unconventional oil and gas development often look at the potential for health effects or human exposure, most often through qualitative analysis listing and characterizing the chemicals used in fracking or the air pollutants associated with certain operations. Additionally, some surveys sample air or water and infer the potential for health impacts by characterizing the chemicals and pollutants reported. Other studies addressing public perceptions regarding the health impacts of unconventional oil and gas development can be indicative of community concerns that further research and policy should address. Such studies are beneficial in that they are able to generate hypotheses and direct future research, but they do not measure actual emissions, chemical levels, exposure, or health effects. As discussed in the introduction, the list of studies below is not intended to be comprehensive—it is intended to provide an understanding of various types of hypothesis-generating studies and analyses of risk factors.

6.1. Sampling and Modeling

Fracking-Related Pollutants

Elliott et al. (2017) analyzes the carcinogenicity of water contaminants and air pollutants related to unconventional oil and gas development. The study mainly uses a list of chemicals in fracking fluids and wastewater from EPA and compiles a list of air pollutants from various studies using International Agency for Research on Cancer (IARC) assessments to classify the risk level of leukemia and lymphoma for each chemical or pollutant. The majority (80 percent) have not been evaluated by the IARC for carcinogenicity. Aminto and Olson (2012) actually model spill scenarios in water and soil for 12 hazardous components found in fracking fluids. Though the study does not model exposure, it does model the potential concentration of these components and “can serve as a screening tool to identify contaminants of concern … to be considered for full risk assessment” (20). Colborn et al. (2011) similarly analyzes the potential health effects of 632 chemicals used in hydraulic fracturing operations. These three studies provide evidence of the potential for health effects due to shale development; it may, however, be the case that these chemicals do not reach communities or are not present in large enough quantities or for long enough periods of time to affect local populations. Such a question can be answered only by establishing exposure and health effects through studies such as those discussed earlier.

Radon Levels

Casey et al. (2015) looks at radon levels—the second-leading cause of lung cancer globally—in Pennsylvania buildings. Because Pennsylvania is known to have some of the highest indoor radon levels in the United States, the element has been measured by the Pennsylvania Department of Environmental

Protection for several decades. The authors use these data, as well as metrics for well drilling and well production, to identify a relationship. They find that each additional drilled well per square kilometer surrounding a building is associated with levels of radon that are 2.8 percent higher on the first floor of the building, with positive but weak effects on basement-level radon. An additional 100 m^3 of gas production per day is associated with 1.3 percent higher indoor concentrations of radon.

Mitchell et al. (2016), however, does not estimate detectable changes in lung cancer death rates, using a different methodology. Measuring the amount of radon in Marcellus gas (rather than in Pennsylvania homes), the study finds it unlikely that exposure from natural gas cooking would exceed less than 1 percent of EPA’s action level. And individuals using unvented gas appliances for primary heating may face lifetime risks of lung cancer of 0.0039. It is important to note that these studies are addressing different questions: drilling may impact radon in Pennsylvania homes in ways other than the indoor use of natural gas from the Marcellus shale. This study is not able to study actual exposures and does not quantify the increased potential for exposures; the authors are able to show that the presence of a cancer-causing element has increased with natural gas development. Because of the latency of many cancers, future studies like this one may be more informative regarding any cancer-related impacts of shale development.

6.2. Inferring Impacts

Air Sampling

In the same vein, some studies conduct air and water sampling to collect a list of pollutants to classify in terms of health risk, again generating hypotheses related to potential health effects. Colborn et al. (2014), for example, conducted weekly air sampling in rural Colorado between 2010 and 2011 and finds that the number of nonmethane hydrocarbons and their concentrations were greatest during the drilling stage of unconventional gas development. Methane, ethane, propane, and other alkanes, which the authors state are likely to come from shale development activities, had the highest concentrations. The study then uses health literature to assess the implications of the chemicals. It notes that polycyclic aromatic hydrocarbons were found at concentrations for which the literature finds effects (lower developmental and IQ scores) for prenatally exposed children. The study also finds one toxic solvent in the majority of samples that are reported in products used for shale development. The findings may not necessarily be attributable to shale development, as air samples are measured near oil and gas operations that occur near residential areas, but its findings are important in hypothesis building.

Making use of an existing air monitoring network in the Barnett Shale region, Bunch et al. (2014) evaluates community-wide exposures to shale gas activities from seven monitors at six locations in the Dallas–Fort Worth area with high densities of wells and low levels of urban source impacts between 2000 and 2011. The study finds that no VOC concentrations exceeded state health-based air comparison values (HBACVs) and, analyzing annual average concentrations, finds that the samples are below levels of concern using a deterministic risk assessment and probabilistic risk assessment according to EPA methodology. While these results are useful in that they indicate potentially low risk of exposure to VOCs for larger communities, more studies are needed to rule out the possibility of more localized or sporadic VOC concentrations given the small number of locations analyzed.

Water Samples

Kassotis et al. (2013) samples surface water and groundwater to assess endocrine-disrupting chemicals in Garfield County, Colorado, and finds the majority of the 39 water samples exhibiting estrogenic activity and almost half exhibiting antiestrogenic and antiandrogenic activities. Though the study does find that these sampled sites exhibited higher levels of these health-related activities in drilling dense regions than in reference sites with "limited nearby" operations, the small sample size makes attribution specifically to shale development more difficult. Again, like Colborn et al. (2014), this study is useful in generating testable hypotheses and directing future research, though it is not conclusive regarding local health effects.

Noise Impacts

And finally, Hays et al. (2016) reviews literature on the health impacts of noise exposure due to unconventional oil and gas development and compares the findings with some samples of noise measurements from a few sources, finding that unconventional oil and gas activities create noise at levels that might increase the risk of health issues, including sleep disturbance, hypertension, and cardiovascular diseases. More such studies are needed.

6.3. Surveys

Perceptions of Health Effects

Some studies conduct surveys of public perceptions surrounding the health impacts of shale development. Saberi et al. (2014), for example, conducted a survey of 72 Pennsylvania adults with existing medical conditions, asking about their levels of concern with shale gas development exposure as well as whether they attributed any symptoms to such development. There are a number of issues with such a survey when discussing health impacts: focusing on adults with existing medical conditions provides an inherently biased sample, and the small sample size and questions focusing on shale development may further bias results. Such a study is useful, however, in that it contributes to the study of public perceptions of the health effects of shale development in the region and can identify potential areas for further research.

Ferrar et al. (2013) is a slightly more rigorous survey of Pennsylvania residents living near Marcellus Shale gas development with two sets of interviews, one conducted in 2010 with 533 residents and the second in 2012 with 520 residents. Like Saberi et al. (2014), this study contributes to understanding public perceptions of health impacts and elucidates areas for further research. Additionally, the study is able to measure a change over time in the amounts of reported health impacts and stressors—or other concerns, such as odors or ignored complaints—comparing data longitudinally by participant. The study finds that perceived health impacts increased over time, while the number of stressors reported remained constant. Surveys are important in that they provide evidence of community concerns and priority areas for both policy and research to address.

7. Conclusion

Overall, we find that the literature does not provide strong evidence regarding specific health impacts and is largely unable to establish mechanisms for any potential health effects. More study is therefore needed to properly inform communities of risks and also inform policymakers and oil and gas operators of methods for reducing these impacts on communities.

These studies, particularly the epidemiological studies, are indicative of potential impacts. The Colorado Department of Public Health and Environment, in its review of the literature, likewise concludes that "at this time, results from exposure and health effect studies do not indicate the need for immediate public health action, but rather indicate the need for more detailed exposure monitoring and systematic analyses of health effects of residents living near oil and gas operations" (McMullin et al. 2017, iii). A lack of data and a lack of quality studies do not indicate a lack of health impacts. Rather, in order to confirm or reject evidence of health impacts, more rigorous and high-quality studies are needed. Furthermore, both establishing causation and elucidating the mechanism through which unconventional oil and gas development may cause these specific health impacts are necessary so that policymakers can mitigate health risks effectively and at relatively low cost.

8. Appendix

8.1. Odds Ratios and Risk Ratios

The everyday usage of words such as *odds*, *risk*, and *probability* is often imprecise, as the words are frequently used interchangeably. In terms of quantitative methodology, however, the words indicate very different types of calculations. Most of the epidemiological studies discussed in this review use odds ratios (ORs).

As Szumilas (2010) explains, "The OR represents the odds that an outcome will occur given a particular exposure, compared to the odds of the outcome occurring in the absence of that exposure." To describe how this ratio functions mathematically, we use a simple example related to the studies above. We define an outcome here as an infant born small for gestational age (SGA), a binary variable in which the infant is either SGA or not. Exposure in this example is the mother living within 2 km of a shale gas well (see Table 2).

Here, the following equation describes the odds that an infant will be SGA when the mother lives within 2 km of a well compared with the odds that an infant will be SGA when the mother lives more than 2 km away from a well:

$$OR = \frac{odds\ of\ outcome\ in\ exposure\ group}{odds\ of\ outcome\ in\ control\ group} = \frac{(a/b)}{(c/d)}$$

The risk ratio (RR), used in Jemielita et al. (2015), differs from the odds ratio in a key way that might not be evident in the colloquial use of these two words. While the numerator, odds of an outcome in the exposure group, in the OR compares *a* with *b*, the numerator in RR, the risk of an event in the treatment group, compares *a* with the total number of those in the exposure group (*a* + *b*) (Schnell, n.d.).

TABLE 2. OUTCOMES AND EXPOSURE

	Outcome *(SGA)*	***No Outcome*** *(not SGA)*
Exposure *(within 2 km of well)*	*a*	*b*
Control *(>2 km away from well)*	*c*	*d*

Where:

a = # of SGA infants within 2 km of a well

b = # of non-SGA infants within 2 km of a well

c = # of SGA infants more than 2 km from a well

d = # of non-SGA infants more than 2 km from a well

Source: Adapted from Szumilas (2010).

The risk ratio (RR), used in Jemielita et al. (2015), differs from the odds ratio in a key way that might not be evident in the colloquial use of these two words. While the numerator, odds of an outcome in the exposure group, in the OR compares *a* with *b*, the numerator in RR, the risk of an event in the treatment group, compares *a* with the total number of those in the exposure group (*a* + *b*) (Schnell, n.d.).

$$RR = \frac{risk\ of\ event\ in\ treatment\ group}{risk\ of\ event\ in\ control\ group} = (\frac{a}{a+b})/(\frac{c}{c+d})$$

Both measures are frequently used in epidemiological studies to measure the relationship between exposures and outcomes (Szumilas 2010), and the majority of epidemiological studies analyzed in this review made use of such metrics.

8.2. Study Span Chart

Studies of the impact of unconventional oil and gas development are often reviewed and used by decision makers. But in general, these reviews require a high level of expertise and decoding. To increase accessibility, we have created a study span chart to increase comprehension among those without formal training in these subject areas.

We recognize two dimensions of usefulness: study quality and span. Study quality has multiple aspects, such as sampling strategy, sample size, statistical analysis, and many other elements. Study *span*, however, can be easily summarized diagrammatically.

The study span chart below is built around the damage function or impact pathway model (Krupnick et al. 2014). This model links the *activities* of interest (in this case, oil and gas development) to *burdens* produced, to *concentrations* of those burdens in the environment, to *exposure* of "receptors" that are affected by these burdens (e.g., humans and animals), and to the physical (and mental) *impacts* those burdens cause in receptors. Almost all studies of interest feature two or more of these pathway *elements*. The more elements of the impact pathway model that a study includes, in general, the more useful the study for researchers and for policymakers, although this is not always the case. Since the concern is ultimately with impacts of unconventional oil and gas development), studies that are not linked directly to unconventional oil and gas development are less useful than those that are. Studies that stop short of measuring and linking to impacts are likewise less useful. Also, studies that measure *only* activities and impacts (a large fraction of studies) cannot determine causal effects but can be suggestive of an impact that needs further research.

8.3. Impact Pathway Model Elements

Activities

Activities can include site preparation, truck traffic, drilling, fracturing, well completion, and the various methods of storage or disposal of fracturing fluids and flowback, such as pit or pond storage, treatment by municipal plants, and use of industrial wastewater treatment plants. This element can also mean the general presence of oil and gas development in a community rather than specific activities or processes.

Burdens

Burdens are the initial consequences of the above activities, such as emissions caused by diesel pumps in a fracking operation, chemicals leaking from wastewater stored in pits or ponds, a truck trip to deliver freshwater, or the occurrence of induced seismicity from oil and gas development.

Concentration

Concentration is the amount of the above burdens present in the environment, usually measured as concentrations of pollutants, such as the ambient air quality in a neighborhood near a site or the chemicals present in surface water.

Exposure

Exposure measures the amount of a substance or other type of burden that enters the body or the amount and intensity of earthquakes a region might be exposed to over a given time period. Exposure can also include the element of dose or cover a measure of the number of people or animals exposed to a burden.

Impacts

Impacts include both physical and mental outcomes that affect human or animal populations, such as increased preterm birth or aboveground damage to dwellings from induced seismicity.

8.4. Description of the Chart

The top of the chart contains a representation of the impact pathway elements. All studies in a given literature (e.g., health or seismicity) are then placed on this chart. The elements included in the study are shown by the boxes to the right of the study that are colored in. To the left of this chart, studies are grouped by type (e.g., epidemiological studies, health impact assessments). Below, we include a discussion of this chart.

We found 32 health studies during our literature review. The fact that only one study (McKenzie et al. 2012) attempts to include all five impact pathway elements illustrates the knowledge gap that exists regarding the health effects of unconventional oil and gas development and the mechanism through which such effects materialize in communities.

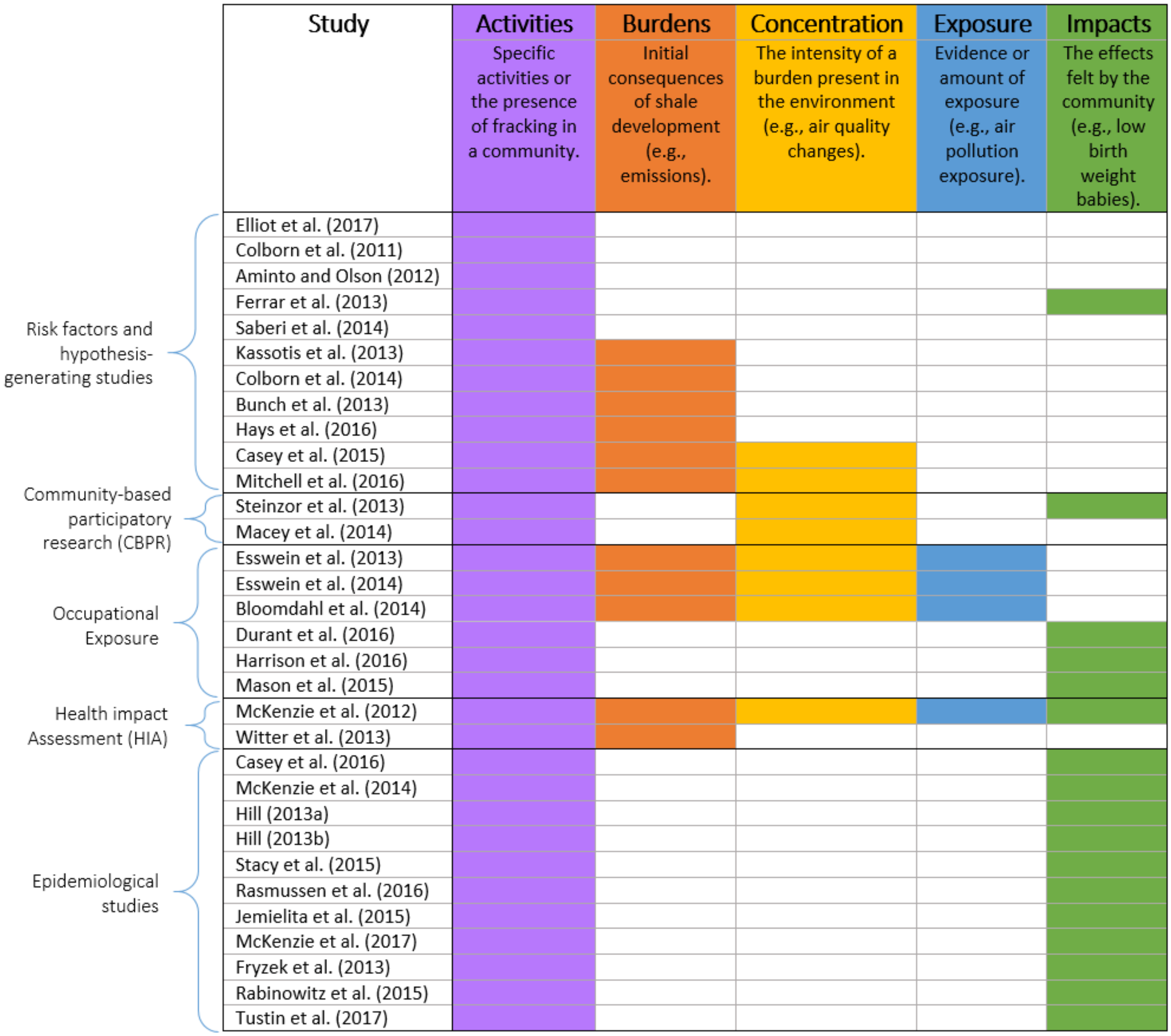
Out of the 17 studies on this chart that do address or estimate impacts, most studies simply establish that an impact is related to unconventional oil and gas development (the "Activity") without addressing the specific mechanism through which an impact occurs. The epidemiological studies, for example, are indicative of potential impacts on birth outcomes from unconventional oil and gas development exposure in general, without isolating the specific mechanism of the impact—the cause of these impacts could be anything from chemical emissions to maternal stress (Casey et al. 2016, McKenzie et al. 2014, Hill 2013a, Hill 2013b, Stacey et al. 2015).

Two of the studies that address impacts are additionally based on community-collected information (CBPR)—though these studies can provide information about areas of community concern and episodic instances of air pollution, they are likewise not definitive (Steinzor et al. 2013, Macey et al. 2014).

Only four other studies are able to address four of the five elements, leaving out the impacts element (Durant et al. 2016, Esswein et al. 2013, Esswein et al. 2014, Bloomdahl et al. 2014). All of these studies are occupational studies and use direct measurement or an estimate of exposure. Though such exposures might be limited to workers and not affect neighboring communities, the studies are suggestive of the type (but not the magnitude) of risks related to unconventional oil and gas development. Two additional studies (Harrison et al. 2016 and Mason et al. 2015) address work accidents and fatalities in the oil and gas industry.

Furthermore, three hypothesis-generating studies infer health impacts based on analysis or measurement of certain burdens (Kassotis et al. 2013, Colborn et al. 2014, Bunch et al. 2013, Hays et al. 2016). These studies do not have a color in the "Impacts" column on the chart because they do not measure or provide evidence about these impacts in any way—rather they highlight data gaps or future areas for study.

STUDY SPAN CHART: HEALTH IMPACTS LITERATURE



The chart does not portray elements that would determine study quality. As our literature review notes, Casey et al. (2016) and the studies below it on the chart are more rigorous epidemiological studies that are better able to address the potential for correlations (and perhaps causation) than studies addressing potential impacts or simple relationships between an observed impact and exposure or proximity to unconventional oil and gas development. Other studies, such as health impact assessments and community based participatory research, are also helpful in addressing the potential for some impacts from unconventional oil and gas development, particularly where data gaps exist. These studies are particularly helpful in situations or time frames where ex-post epidemiological studies are not possible—for example, as a community decides whether to allow fracking. Taken as a whole, this literature demonstrates that there is a need for further research to understand and identify the causes of these impacts.

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