RFF REPORT

Pathways to Dialogue

What the Experts Say about the Environmental Risks of Shale Gas Development

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PATHWAYS TO DIALOGUE:
WHAT THE EXPERTS SAY ABOUT THE ENVIRONMENTAL RISKS OF SHALE GAS DEVELOPMENT

Alan Krupnick, Hal Gordon, and Sheila Olmstead[1]

1. Introduction

The national debate over shale gas development in the United States is characterized by a seeming lack of consensus over its environmental, economic, and social implications. On the one hand, shale gas offers great promise as a low-cost source of electricity, industrial feedstocks, residential and commercial energy, and even transportation fuel. On the other hand, public fears about the environmental effects of shale gas development threaten to dim or eliminate these prospects.

Our understanding of this issue is hindered by many factors, including its complexity, a lack of data, and differing values surrounding how society should balance uncertainty over the risks of action with the risks of inaction.

The result is a policy landscape dominated by strong and contradictory opinions. Shale gas detractors have been blamed for performing biased, inaccurate, and misleading studies. When the US Environmental Protection Agency has moved to regulate or even study risks, critics have accused the agency of wanting to shut down the industry. And attempts by the Bureau of Land Management to write new regulations for drilling on federal land are derided as being so onerous and bureaucratic as to stymie all such development. Meanwhile, environmental groups eye academic supporters of shale gas development with suspicion and claim that they and some state regulators are captured by industry.

Experts at Resources for the Future's (RFF's) Center for Energy Economics and Policy have been working to find common ground among the parties to create "pathways to dialogue." This report is the first survey-based, statistical analysis of experts in government, industry, universities, and nongovernmental organizations (NGOs) to identify the priority environmental risks related to shale gas development—those for which the experts believe government regulation and/or voluntary industry practices are currently inadequate to protect the public or the environment.

The 215 experts who responded to the survey questions were asked to choose from a total of 264 "risk pathways" that link specific shale gas development activities—from site development to well abandonment—to burdens such as air pollution, noise, or groundwater contamination. They were also

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given the opportunity to choose from 14 potential accidents and provide their qualitative assessment of the probability that these accidents could happen and how severe they might be.

The results stand in sharp contrast to the rhetoric of much of the public debate. For example, a key finding is the *high degree of consensus among experts* about the specific risks to mitigate. These "consensus risks" are those that survey respondents from all four expert groups most frequently identified as needing further regulatory or voluntary action.

Several of the consensus risks pertain to impacts that have received less attention in the popular debate than others. For example, the experts frequently identified the potential impacts on lakes, rivers, and streams (surface water) as a priority, and less frequently identified potential risks to underground aquifers (groundwater). In fact, only 2 of the 12 consensus risks identified by the experts are unique to the shale gas development process, and both have potential impacts on surface water. The remaining 10 consensus risks relate to practices common to gas and oil development in general, such as the construction of roads, well pads, and pipelines and concerns about leaky casing and cementing. Note that this survey did not ask about the strength or urgency of these pathways. The absence of a pathway in the consensus does not mean that it is unimportant. In the interest of identifying pathways that are important *and* for which progress toward dialogue and action seems most probable, we urge the targeting of the consensus pathways.

In Section 2 of this report, we describe (a) the process used to develop the risk matrix that formed the basis for survey development and (b) the design of the survey itself. Section 3 outlines our approach to data cleaning and statistical analysis of survey data. Section 4 presents results and is supported by further detail in the appendix. We summarize the study findings in Section 5.

2. Our Approach

To identify the priority risk pathways, we first had to determine the full set of possible pathways. We defined two types: plausible risks from routine, everyday operations and possible risks arising from accidents.

2.1 Routine Risks

We characterized the first set of risks—routine risk pathways—through the creation of a risk matrix (see the complete matrix in the appendix, Table A1, and online at www.rff.org/shalematrix). The risk matrix illustrates how the activities associated with the development of a shale gas well can create burdens that might impact "intermediate" endpoints that people care about—such as groundwater, soil quality, and local communities.[2] It identifies the potential risks to be considered when developing a well, examining impacts from widespread drilling activities. It is important to note that rather than tally impacts that have occurred, the matrix shows all those that could plausibly occur under normal or unusual operating conditions.

The list of activities and burdens was developed in consultation with academic experts Mukul Sharma, a professor of petroleum engineering at the University of Texas; James Saiers, a professor of hydrology at Yale University; and Karlis Muehlenbachs, a professor of geology at the University of Alberta. We also used information garnered from visits to shale gas development sites; discussions with stakeholders, including industry experts, regulatory experts, NGOs, and academics; and reviews

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[2] We also developed links to "final" endpoints, such as human mortality and morbidity, but these are not part of the survey or the risk matrix on the web.

of the academic and other literatures on the potential impacts of the process. The risk matrix itself does not make any judgment regarding the severity or importance of each burden or impact, a task left to survey respondents.

As shown in Table A1 in the appendix, the rows of the matrix list specific activities that comprise the shale gas development process, under six major categories that range from well pad preparation to upstream and downstream activities. Each activity is a potential source of risk. The columns identify six aspects of the environment that could be affected by each activity, including air quality, groundwater, and habitat. In the individual cells at the intersections of the rows (activities) and the columns (impacts) are the burdens that could be created by an activity and would have potential impacts that people care about. The risk matrix in Table A1 defines 264 distinct risk pathways (cells). Table A2 provides the full list of potential burdens, only some of which are relevant to each activity–impact pair.

To summarize, Table 1 displays the number of pathways that we presented in the survey for the six shale gas development activity categories and six risk pathways.

Table 1. Distribution of Pathways in the Matrix

	Groundwater	Surface water	Soil quality	Air quality	Habitat distribution	Community disruption	Totals
Site development and drilling preparation	0	4	1	3	4	6	18
Drilling activities	10	8	4	11	5	7	45
Fracking[a] and completion	11	12	4	14	11	10	62
Well production and operation	2	2	2	10	1	4	21
Fluid storage and disposal	18	19	8	7	9	19	80
Other activities	11	8	8	8	1	2	38
Totals	52	53	27	53	31	48	264

[a] In this report we use the popular term “fracking” instead of the technical term “fracing” of the long form “hydraulic fracturing.”

In defining the potential risk pathways in Table 1, we realized that respondents might view some risks as negligible under typical geological, hydrological, or other conditions but more significant when wells are challenging to complete, operator behavior is less than state-of-the-art, regulations are not well enforced, or vulnerable ecosystems and communities are in close proximity. These cases could make the consequences of any burden release particularly significant. Accordingly, we defined two types of priority risk pathways: typical and tail-end.

This matrix does not take into account accidents or other extreme events, which could potentially occur, but rather risks that may occur from routine operations either in typical or challenging (tail-end) environments. Furthermore, this matrix does not extend to the final impacts of each burden outlined. Each burden may have final impacts on human health, markets, ecosystems, climate change, and/or quality of life. The survey does not incorporate the links between burdens and final impacts because the expertise needed to identify priority cells is different from that needed to assess final impacts.

2.2 Risks from Accidents

We also developed 14 accident categories, given below:

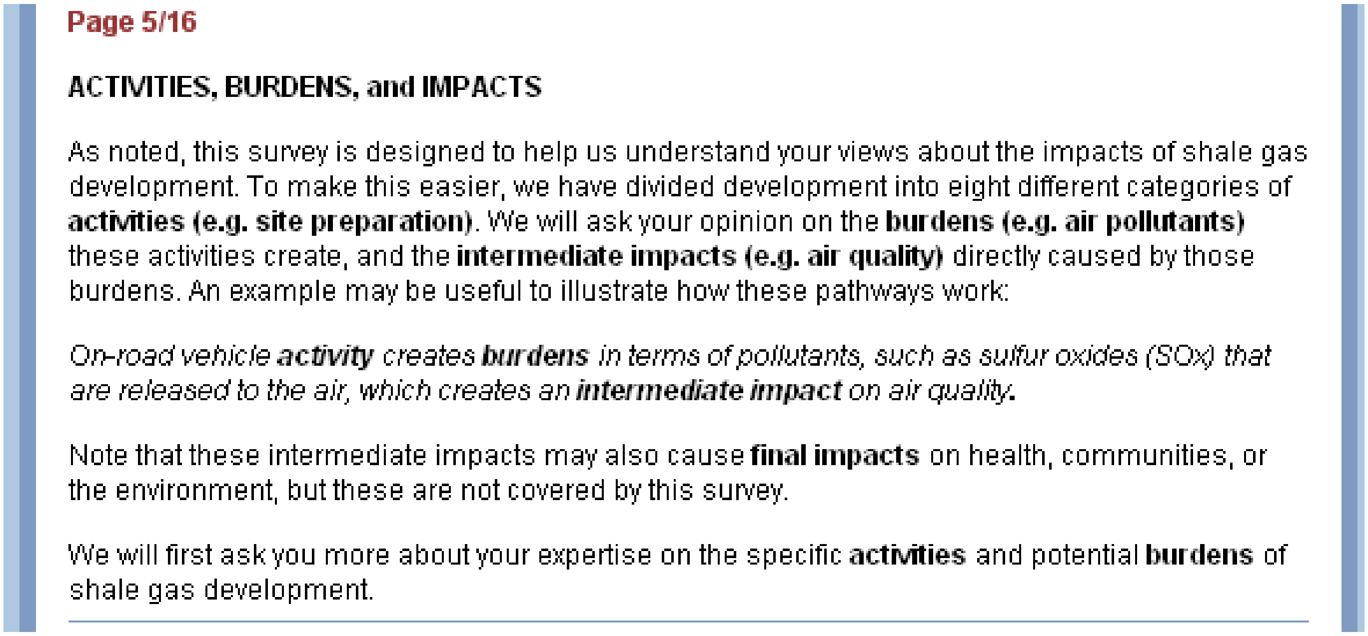
- truck accident
- casing failure
- cement failure
- surface blowout
- underground blowout
- surface valve failure
- hose burst
- impoundment failure
- storage tank spill
- pipeline rupture
- underground well communication
- other accident resulting in spill
- other accident resulting in fire or explosion
- other accident with consequence not listed here

In addition to asking respondents to choose their priorities for further regulatory or voluntary action to reduce accident risks, we also assessed respondents' judgment regarding both their likely probability and the magnitude of potential consequences, conditional on an accident occurring. Given uncertainty, the thin literature on these issues, and the subjective nature of such an assessment, we grouped probabilities and consequences into categories and treated combined responses as notional descriptions of expected value—expected value because the typical approach is to multiply probability by consequence to obtain expected values, but notional because these are qualitative categories, not hard and fast numbers.

2.3 Survey Design

The next step was to design a survey instrument that allowed respondents to identify the pathways that were their priorities for further government or industry action. The survey has five parts. The first identified respondents' characteristics: their education (degrees and field of study), current employer, years in their current job, years of experience in oil and gas as well as the specific activities and impacts associated with shale gas development, and their knowledge of various US shale gas plays.

The second part introduced the concept of risk pathways. Quoting from the survey:



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ACTIVITIES, BURDENS, and IMPACTS

As noted, this survey is designed to help us understand your views about the impacts of shale gas development. To make this easier, we have divided development into eight different categories of **activities (e.g. site preparation)**. We will ask your opinion on the **burdens (e.g. air pollutants)** these activities create, and the **intermediate impacts (e.g. air quality)** directly caused by those burdens. An example may be useful to illustrate how these pathways work:

*On-road vehicle **activity** creates **burdens** in terms of pollutants, such as sulfur oxides (SOx) that are released to the air, which creates an **intermediate impact** on air quality.*

Note that these intermediate impacts may also cause **final impacts** on health, communities, or the environment, but these are not covered by this survey.

We will first ask you more about your expertise on the specific **activities** and potential **burdens** of shale gas development.

This concept was then married to our definition of "priority" to categorize certain risk pathways.[3] Because we defined priority in terms of further actions to be taken by *either* government or industry, we also asked respondents up front if, in general, they think government or industry should have primary authority to mitigate these risks or if authority should be shared. Later in the survey, we came back to this issue, using a random sample of the priority risk pathways respondents identified, to assess whether a specific pathway should, in their view, be addressed by the government (via regulation) or by industry (via voluntary action).

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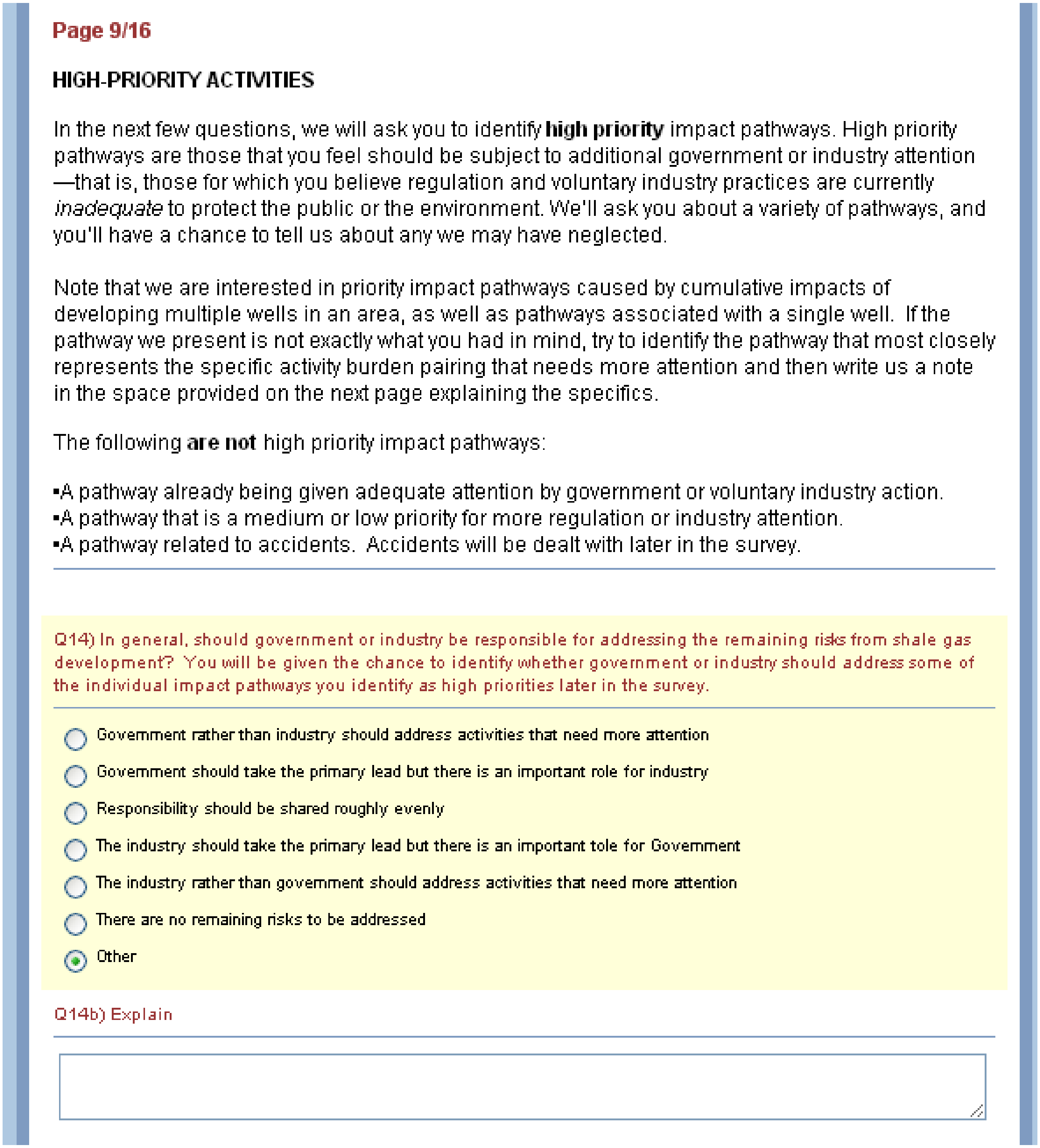
[3] In this report, we use the term "risk pathways," but the survey used the somewhat more technical term "impact pathways." Readers should treat these as synonyms.



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HIGH-PRIORITY ACTIVITIES

In the next few questions, we will ask you to identify **high priority** impact pathways. High priority pathways are those that you feel should be subject to additional government or industry attention—that is, those for which you believe regulation and voluntary industry practices are currently *inadequate* to protect the public or the environment. We'll ask you about a variety of pathways, and you'll have a chance to tell us about any we may have neglected.

Note that we are interested in priority impact pathways caused by cumulative impacts of developing multiple wells in an area, as well as pathways associated with a single well. If the pathway we present is not exactly what you had in mind, try to identify the pathway that most closely represents the specific activity burden pairing that needs more attention and then write us a note in the space provided on the next page explaining the specifics.

The following **are not** high priority impact pathways:

- A pathway already being given adequate attention by government or voluntary industry action.
- A pathway that is a medium or low priority for more regulation or industry attention.
- A pathway related to accidents. Accidents will be dealt with later in the survey.

Q14) In general, should government or industry be responsible for addressing the remaining risks from shale gas development? You will be given the chance to identify whether government or industry should address some of the individual impact pathways you identify as high priorities later in the survey.

○ Government rather than industry should address activities that need more attention
○ Government should take the primary lead but there is an important role for industry
○ Responsibility should be shared roughly evenly
○ The industry should take the primary lead but there is an important tole for Government
○ The industry rather than government should address activities that need more attention
○ There are no remaining risks to be addressed
● Other

Q14b) Explain

We next defined the two types of priority risk pathways: “typical” and “tail-end.” When respondents were asked to identify their priority routine risk pathways, they were offered different mechanisms for highlighting pathways of concern for the typical case and those only of concern in a tail-end case. Here is the language:

We want to know about high priority risks in two cases:

Typical-Routine cases are those in which operators make standard, typical operating choices, regulations are in effect and reasonably enforced, the wells operate under typical geological and hydrological conditions, and have typical proximity to other wells, vulnerable ecosystems and communities.

Tai-end Routine cases are those in which operating conditions are challenging, operator behavior is less than state of the art, regulations are not well enforced, or vulnerable ecosystems and communities are in close proximity to shale gas development. Note that tail-end cases need not be the most extreme situations you can imagine—instead, consider conditions reasonably foreseeable in routine operations at the 5% of wells of greatest concern.

Note also that we will ask you later about risks of accidents. Here we are only interested in burdens occurring under routine conditions.

Filling out the Table

The table below lists activities by rows, impacts by column, and burdens in the body of the table (called cells). To indicate an impact pathway is a high priority, click on the relevant cell. If you click once, the cell will turn green. **Green indicated you believe the impact pathway is a high priority in both the typical and tail-end cases.** If you click a second time, the cell will turn red. **Red indicates you believe the impact pathway is only a high priority in the tail-end case.** If you click a third time, the cell will return to its original state. (the "x"s and check marks are meaningless, so ignore them)

Green=high priority in both typical and tail-end cases
Red=high priority only in tail-end cases

If the cell at the intersection of a row and a column doesn't have a color, this means you do not believe the impact pathway represented by that cell is a high priority.

Once respondents identified their priority pathways using the matrix, we used their responses to inform two subsequent questions seeking additional detail. To reduce complexity and survey length, these follow-up questions asked about a subset of each respondent's priority pathways, rather than the full set.4 The first question asked whether information about that pathway was sufficient to support regulatory or voluntary action, or whether further research was needed. The second asked whether the authority for addressing the risks should rest more with government (through regulation) or with industry (through voluntary action).

After the risk matrix follow-up questions, we asked a general question about whether respondents feel that the net effect of the boomtowns that have been created by rapid shale gas growth has been positive or negative. We also asked whether their identified priority risk pathways, as a whole, apply to all shale plays with which the respondent listed having experience, or a subset. Because this

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[4] The sample was drawn by activity category according to a fraction of the total number of pathways offered (site development: 3/18; drilling: 6/45; fracturing: 9/62; well production: 3/21; fracturing fluid: 11/80; other: 5/38). No matter how many pathways were chosen in each activity category, the questions would follow up on a maximum of 15 percent of the original offered.

treatment of plays is so coarsely grained, we then invited respondents to provide written elaboration on this point.

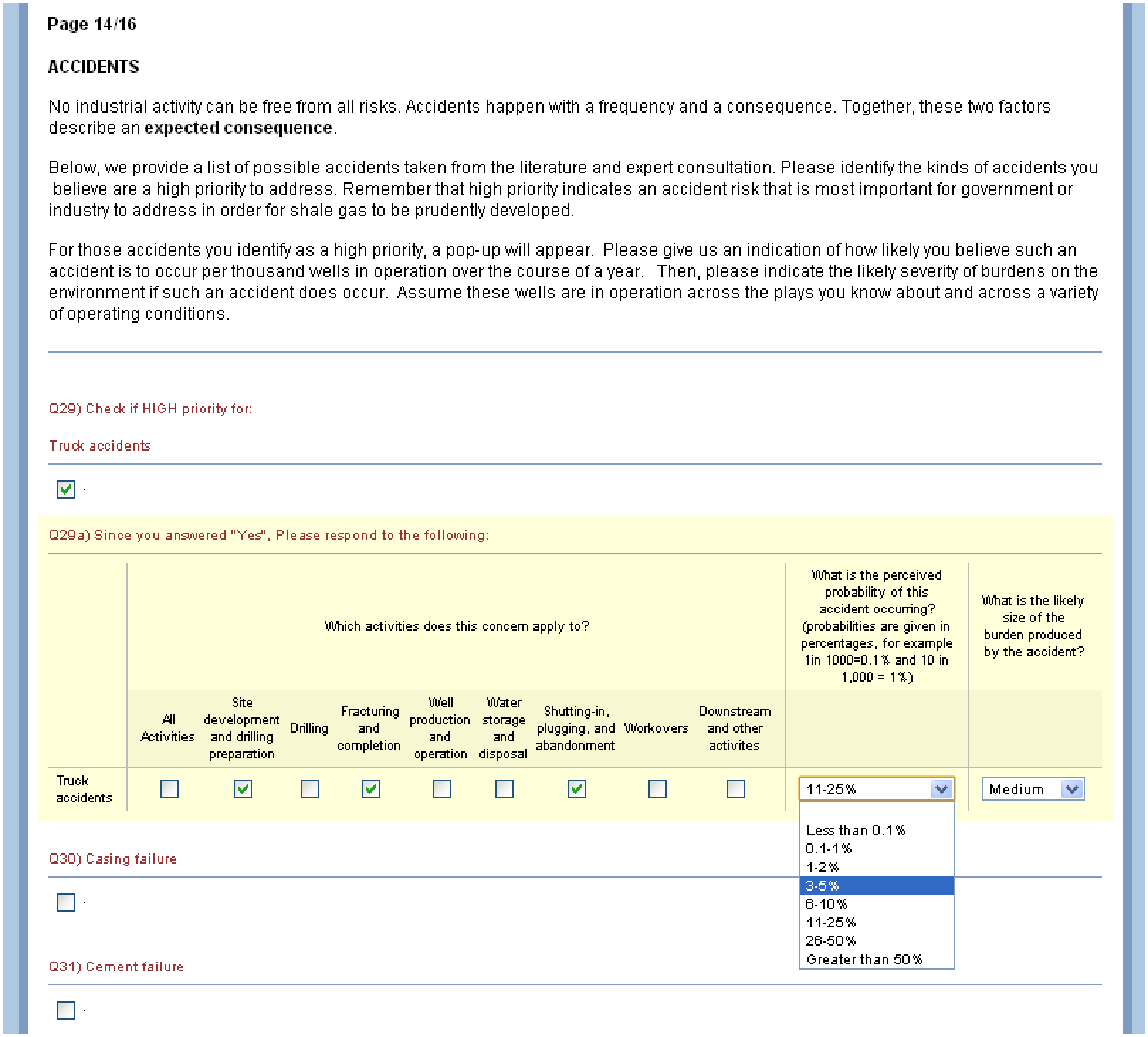
Finally, this section asked for more detail about burdens. Respondents were asked to identify the burden characteristics that drove them to choose one typical and one tail-end pathway as a high priority. They could pick from the following characteristics:

- location of wells near vulnerable ecosystems
- location of wells near communities
- geology
- hydrology
- well characteristics
- operator technologies
- operator practices
- regulatory gaps
- lax enforcement/reporting
- other

The survey's fourth section asked respondents to identify priority potential accidents for either regulatory or industry action, from among the 14 categories listed earlier. For each chosen as a priority, respondents were asked what its likely frequency of occurrence per 1,000 wells would be and, conditional on an occurrence, the accident's likely severity. Potential probabilities were given in percentages, with the lowest category less than 0.1 percent (or less than 1 in 1,000) per year. To gauge severity, we asked respondents to choose the likely size of the burden from five qualitative categories, ranging from very small to very large. The language is on the following page.

We do not advise readers to put any faith in the probability as a number. Rather, these choices should be treated qualitatively and interpreted in relative rather than absolute terms—that is, the lowest-probability choice is ranked lower than the next lowest, and so forth.

The fifth part of the survey shifted again to a focus on burdens. It showed respondents the burden list in Table A2, allowed them to choose specific burdens of particular concern, and asked them to explain their choices. In this part of the survey, respondents were also given the opportunity to comment on risk pathways, impacts, activities, or burdens we omitted—or to say anything else about the survey. We ended the survey with two final questions. First, we asked respondents if their answers should be viewed as their personal opinions or the official views of their institutions. Second, we asked whether they previously had seen our risk matrix, which had been publicized at an RFF event in Washington, DC, in November 2011 and had been posted on RFF's website since June 2012.



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ACCIDENTS

No industrial activity can be free from all risks. Accidents happen with a frequency and a consequence. Together, these two factors describe an **expected consequence**.

Below, we provide a list of possible accidents taken from the literature and expert consultation. Please identify the kinds of accidents you believe are a high priority to address. Remember that high priority indicates an accident risk that is most important for government or industry to address in order for shale gas to be prudently developed.

For those accidents you identify as a high priority, a pop-up will appear. Please give us an indication of how likely you believe such an accident is to occur per thousand wells in operation over the course of a year. Then, please indicate the likely severity of burdens on the environment if such an accident does occur. Assume these wells are in operation across the plays you know about and across a variety of operating conditions.

Q29) Check if HIGH priority for:

Truck accidents

☑ .

Q29a) Since you answered "Yes", Please respond to the following:

	Which activities does this concern apply to?									What is the perceived probability of this accident occurring? (probabilities are given in percentages, for example 1in 1000=0.1% and 10 in 1,000 = 1%)	What is the likely size of the burden produced by the accident?
	All Activities	Site development and drilling preparation	Drilling	Fracturing and completion	Well production and operation	Water storage and disposal	Shutting-in, plugging, and abandonment	Workovers	Downstream and other activites		
Truck accidents	☐	☑	☐	☑	☐	☐	☑	☐	☐	11-25%	Medium

Less than 0.1%
0.1-1%
1-2%
3-5%
6-10%
11-25%
26-50%
Greater than 50%

Q30) Casing failure

☐ .

Q31) Cement failure

☐ .

2.4 Sampling

An expert survey demands a perspective on sampling and interpretation that is very different from that of a typical survey of the general public. Participants for the latter can be identified from a variety of lists and chosen at random, allowing for a representative sample of the population. But there are no existing, neutral lists of shale gas experts.

Our approach was to collect names of experts from media stories, blogs, the academic literature on shale gas risks, and specific organizations that have a prominent and substantive role in public debates over the future of shale gas development. Over seven months, we collected more than 1,000 names from four major groups: academics, NGOs (primarily environmental groups), regulators (primarily state and federal as well as river basin commissions), and industry. At some of these institutions, we had multiple names.

Initially, we sent an email to each person in the sample, inviting him or her to take the survey, either by providing his or her own views or an institutional response. The link we provided permitted only one survey to be filled out, but it remained active until the respondent completed the survey. RFF staff then followed up with each potential respondent by phone and email to obtain completed surveys, either from the original contact or a more appropriate person in the institution. In all, we received 215 completed surveys.

The response rate is 215 divided by the number of eligible people contacted. Obtaining the denominator is not straightforward. We dropped people from our original sample when we could not reach them or when they self-identified as lacking the necessary expertise. Many other individuals in the sample were dropped if they worked at institutions that decided internally to submit a single completed survey. In this case, we eliminated all but one person from that institution. Because most institutions that returned the survey submitted only one response, we counted only one person in the sample for institutions that did not respond, even though we may have sent the survey to multiple individuals at such nonresponding institutions. The final sample size, given these changes, was 719, giving us an effective response rate of 30 percent.

The names and institutions of individual respondents are confidential, but we provide a general description of the sample in Table 2. Among NGOs, all the major national environmental groups are represented, as are some local groups and specialized groups concerned about particular issues, such as hydraulic fracturing chemicals, that seek a broad presence in the national debate. Among academics, all universities with a significant presence in the shale gas debate are represented, often by multiple respondents; think tanks are classified here as well. Specific fields represented are discussed in Section 4. Within the government category, at least one respondent represents each of the key federal agencies, and about half the states with shale gas resources are represented, as are some river basin commissions. Representation from industry includes many of the major operating and support companies, some trade associations and consulting firms, and law firms that generally work for the industry.

To determine whether the 70 percent of our original sample who did not return the survey are very different from the 30 percent who did, we classified the entire sample into our four stakeholder groups and examined whether the proportions of respondents in each group in the final sample match the proportion in each group in the original sample. They are remarkably similar. On a group-affiliation basis, the NGO and industry proportions are identical, whereas we have a greater percentage of academics and fewer government respondents in our sample than in the original list. It would have been useful to know more about each person in the nonresponsive group, but that data collection was outside the scope of our project.

Table 2. Classification of Organizational Groups

Self-reported group	NGO	Industry	Academia	Gov't	All experts
Extraction sector	0(0)	18(14)	0(1)	0(1)	18(16)
Government	0(0)	0(1)	0(1)	36(5)	36(7)
Academic / university	0(1)	1(0)	47(9)	0(1)	48(11)
Extraction support	0(0)	4(7)	0(0)	0(0)	4(7)
Manufacturing of inputs	0(1)	0(6)	0(0)	0(0)	0(7)
Midstream	0(0)	4(11)	0(0)	0(0)	4(11)
Downstream	0(0)	2(10)	0(0)	0(0)	2(10)
Consulting	2(4)	15(6)	0(5)	0(0)	17(15)
Trade association	1(1)	4(5)	0(0)	0(0)	5(6)
Environmental group	19(6)	0(0)	0(2)	0(1)	19(9)
Other advocacy groups	3(5)	2(3)	0(3)	0(0)	5(11)
Think tank	2(3)	1(1)	7(2)	1(2)	11(8)
Total	35	75	63	42	215

Notes: The first number is the number of experts who selected only one group, whereas the number inside the parentheses is the frequency with which each group was selected by experts who selected more than one group.

3. Data Cleaning and Statistical Approach

In any survey, inevitable issues cause certain respondents to be rejected or other adjustments to be made for unanswered questions, misclassifications, and so on. In our case, we rejected 11 submitted surveys for a variety of reasons—for example, the survey was blank except for comments, or a respondent said he or she had never worked on oil and gas issues.

The survey was designed to eliminate most nonresponses. Occasionally, a respondent failed to list one or more personal characteristics, such as his or her academic degree. Such missing values did not cause us to drop these respondents from the sample. Although 10 respondents did not select any pathway on the risk matrix and 11 did not select any accident as a priority, we considered those to be substantive responses and kept the relevant respondents in the sample. Similarly, we did not drop anyone who selected all, or nearly all, of the 264 pathways as a priority.

We decided to display most of the results by institutional group because many see the debate over shale development as between industry and environmentalists. Further, we thought most observers would view the judgments of academics and government officials as both interesting in their own right and a moderation of those of industry and NGOs, which have a more direct interest.

Therefore, we had all respondents indicate the type of organizational group to which they belonged and the specific group for which they worked, with multiple answers possible for each. Then, using our own judgment, we placed each expert in an affiliation group. We defined NGOs as advocacy groups not primarily funded by the shale gas industry; academia as universities or think tanks primarily focused on research; government as any governmental organization at the state, river basin, or federal level; and industry as any company involved in the shale gas industry, including extraction, consulting, and law firms, as well as any advocacy groups primarily funded by industry. Table 2 in the previous section compares the respondents' organizational type response and our group designation.

4. Survey Results

The discussion of results is organized into 13 sections covering the key issues addressed in the survey and ending with an analysis of respondents' general comments.

4.1 Descriptive Statistics for Respondent Characteristics

The respondents in each group differ in many important ways (see Table 3). Academic and government respondents are far more likely to have a degree in the physical sciences, whereas industry experts are more likely to have engineering degrees. Academic experts are the most educated in terms of higher degrees, whereas industry experts are the least. Industry experts are the most likely to describe themselves as working in gas-related fields, and they have the most experience in these fields. They also are by far the most experienced in oil and gas issues. Academic, industry, and NGO experts have, on average, six or seven years of shale gas expertise, whereas government experts have, on average, only four. Academic and government experts are less likely than NGO and industry experts to have a primary focus on shale gas in their work.

The expertise scores, which are a composite of how participants estimated their expertise with specific shale gas activities and burdens (see Appendix Table A2 for list of burdens and Table 1 for activities), are revealing about how the experts view their familiarity with the issues. NGO and academic respondents estimated that their burden knowledge is higher than their activity knowledge, whereas industry and government experts are more familiar with activities than burdens.

Table 3 also shows the response to a multiple-choice question about the particular plays with which experts are familiar. From the responses, it is clear that knowledge of the lower-profile southern plays is much more common among industry experts, whereas a very large proportion of NGO experts know about the higher-profile Marcellus play in Pennsylvania. Government experts—especially those from federal branches—have less specific knowledge than other experts: 11 of 15 federal employees chose the answer “general knowledge” over “all plays” or any specific play, whereas 14 of 27 state government experts chose this answer.

About one in five experts gave an institutional response (which was almost always their personal opinion as well). Industry experts were most likely to give an institutional response, whereas academic experts never gave one. A handful of mostly academic and industry experts had seen our risk matrix at a seminar before the survey was distributed.

Table 3. Descriptive Statistics of Respondents, by Group

	NGOs	Industry	Academia	Government	All
Respondents	35	75	63	42	215
Degree field[a]					
Physical science	*22%*	*21%*	*44%*	*55%*	*35%*
Social science	*50%*	*39%*	*31%*	*13%*	*33%*
Engineering	*9%*	*27%*	*12%*	*18%*	*18%*
Other degree	*19%*	*12%*	*14%*	*13%*	*14%*
Degree type[b]					
High school	*0%*	*1%*	*0%*	*0%*	*1%*
Bachelors	*22%*	*33%*	*3%*	*26%*	*21%*
Masters	*38%*	*40%*	*17%*	*50%*	*35%*
JD	*28%*	*12%*	*8%*	*3%*	*12%*
PhD	*13%*	*13%*	*71%*	*21%*	*32%*
Mean year of degree	1989	1983	1990	1985	1987
Field you work in now[c]					
Gas fields	*34%*	*83%*	*38%*	*23%*	*50%*
Science fields	*83%*	*44%*	*48%*	*28%*	*48%*
Social science fields	*51%*	*55%*	*35%*	*77%*	*53%*
Other	*23%*	*9%*	*30%*	*23%*	*20%*
Experience in your current field					
Mean years	19.4	26.1	23.9	24.0	23.9
Describe your current or recent work in oil and gas issues					
Only area	*6%*	*43%*	*5%*	*26%*	*22%*
Primary area	*43%*	*31%*	*37%*	*26%*	*33%*
Important area	*40%*	*23%*	*44%*	*37%*	*35%*
Occasionally, rarely, or other[d]	*11%*	*4%*	*14%*	*9%*	*9%*
Mean years experience	9.2	23.2	15.0	13.0	16.5
Describe your current or recent work in shale gas issues					
Only area	*0%*	*9%*	*2%*	*2%*	*4%*
Primary area	*40%*	*36%*	*24%*	*21%*	*30%*
Important area	*54%*	*41%*	*49%*	*51%*	*48%*
Occasionally, rarely, or other[d]	*6%*	*13%*	*25%*	*23%*	*18%*
Mean years experience	6.2	7.4	6.2	4.0	6.0
Expertise scores[e]					
Mean activity expertise score	–0.77	0.55	–1.70	–0.33	–0.50
Mean burden expertise score	0.54	0.33	–0.76	–0.74	–0.16
Knowledge of select plays[f]					
All plays	*11%*	*11%*	*5%*	*0%*	*7%*
General knowledge	*34%*	*49%*	*46%*	*58%*	*48%*
Marcellus	*63%*	*53%*	*54%*	*47%*	*54%*
Utica	*54%*	*37%*	*43%*	*26%*	*40%*
Haynesville	*20%*	*36%*	*21%*	*9%*	*24%*

Barnett	*29%*	*41%*	*32%*	*21%*	*33%*
Eagle Ford	*17%*	*36%*	*19%*	*12%*	*23%*
Is this your personal opinion or institutional opinion?[g]					
Personal	*71%*	*66%*	*98%*	*76%*	*78%*
Institutional	*3%*	*4%*	*0%*	*0%*	*2%*
Both are the same	*26%*	*30%*	*2%*	*24%*	*20%*
Have you seen the risk matrix before?[h]					
Yes	*9%*	*21%*	*16%*	*5%*	*14%*
No	*91%*	*79%*	*84%*	*95%*	*86%*

a Only 195 respondents provided an answer. “Hard science” is a categorization that includes biology, chemistry, environmental science, geology, hydrology, medicine, and seismology. “Social science” includes business, economics, government and political science, and law.

b Only 196 respondents provided an answer.

c Multiple answers were possible. “Gas fields” is a categorization that includes shale gas, other natural gas, and petroleum. “Science fields” includes public health, environmental science, biology, and issue advocacy. “Social science fields” includes economics, government regulation, and law.

d “Occasionally an area,” “rarely an area,” and “other” were three separate categories on the survey, but we combine them here for ease of reporting.

e For each of eight activity categories and seven burden categories, respondents were asked to categorize their expertise as “low,” “medium,” or “high.” To create composite scores, we scored –1 for each low response, 1 for each high response, and tallied totals.

f Multiple answers were possible. Marcellus, Barnett, Utica, Haynesville, and Eagle Ford were the top five specific play responses, respectively.

g Only 212 respondents provided an answer.

h Only 211 respondents provided an answer.

4.2 Identifying Routine Priority Risk Pathways

The survey design permits the identification of priorities from the 264-cell risk matrix in a variety of ways. We started by counting the number of times respondents in a group identified a cell as a priority and broke this count into those cells designated as a priority under typical conditions and those under tail-end conditions. This allowed for a comparison among the groups. We also summarized results of questions asking whether, for a sample of priorities identified, respondents feel that information is sufficient to proceed with action, and whether responsibility lies with government or industry. (In Section A.2 of the appendix, we search for consensus by examining priorities at a higher level of aggregation, using activity, impact, and burden categories as the unit of analysis.)

4.2.1 Number of Priorities

A key component of survey results is a group-by-group comparison of the number of priority pathways identified. The average number of priority risk pathways identified by respondents in the full sample is 55, and the median is 39, indicating that the distribution of this variable has a long tail. About 5 percent of respondents identified more than 214 of the 264 possible risk pathways as a priority, and about 5 percent identified 1 or none. Only one pathway received no votes as a priority.

Breaking these data down by group, industry and government experts average 39 and 40 priorities, respectively, and academic experts average 54. The NGO respondents identified more pathways than the other groups, averaging 105 priorities, with a median of 100. Responses for this group are less skewed—they are simply high across the board—compared with those of the other groups.

Figure 1 (on the following page) shows the distribution of the number of responses for all four groups. Industry and government expert distributions look very similar (and are statistically indistinguishable), clustered tightly around the 1–25 range, and the academic expert distribution is shifted a bit to the right. The NGO group, however, is quite (and statistically significantly) different, with only one respondent identifying fewer than 26 priorities.

We suspect that three reasons explain why NGO experts identified so many more priorities. First, they probably do see many more pathways as having a higher risk than other groups. Second, they also may have a lower level of acceptable risk than experts in the other groups. Third, they may have a perception that the benefits of shale gas extraction are low.

4.2.2 The Top 20 Priorities

We looked for consensus across each group's top 10, 20, and 40 vote-getting pathways. In addition, recognizing that such cutoffs are inherently arbitrary, we created an index based on the standard deviation of a pathway's "rank" (from most often selected to least often selected) across groups to differentiate top consensus pathways from others. The index ranks the most and least selected pathways similarly if all groups agreed on their overall ranking.

In light of the number of priority pathways identified by the groups, we found it most useful to focus primarily on each group's 20 most frequently selected priorities.[5] (See Appendix Figures B1 and B2 for results on the top 10 and top 40.) Because NGO experts chose more priorities, a top 20 pathway means something different within this group relative to the other groups. For instance, the eighth–most selected pathway among NGO respondents was selected by 71 percent of NGO experts, but the eighth–most selected pathways for academic, government, and industry experts were picked by 49 percent, 48 percent, and 43 percent of each group's respondents, respectively.

With the 41 priorities that are in at least one group's top 20 priorities identified, we then looked for the "sweet spot"—the priority risk pathways that are common to all four groups (see Figure 2)—and found that 12 of the pathways are in common for all groups, another 11 are held in common by two or three groups, and 18 are unique to one group.

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[5] Note that, because of ties, the "top 20" included 23 priorities for NGO respondents, 22 for industry respondents, 25 for academic respondents, and 23 for government respondents. If the ties were not included, there would have been 18 priorities for NGO respondents, 19 for academic respondents, 19 for industry respondents, and 19 for government respondents. If these less-inclusive top 20s were used, the agreement among the four groups would have been greater. Instead of having 12, 5, 6, and 18 pathways shared by four, three, two, and one group, respectively, there would have been 11, 2, 8, and 10 pathways shared by the same number of groups.

Figure 1. Distribution of Priority Counts, by Group

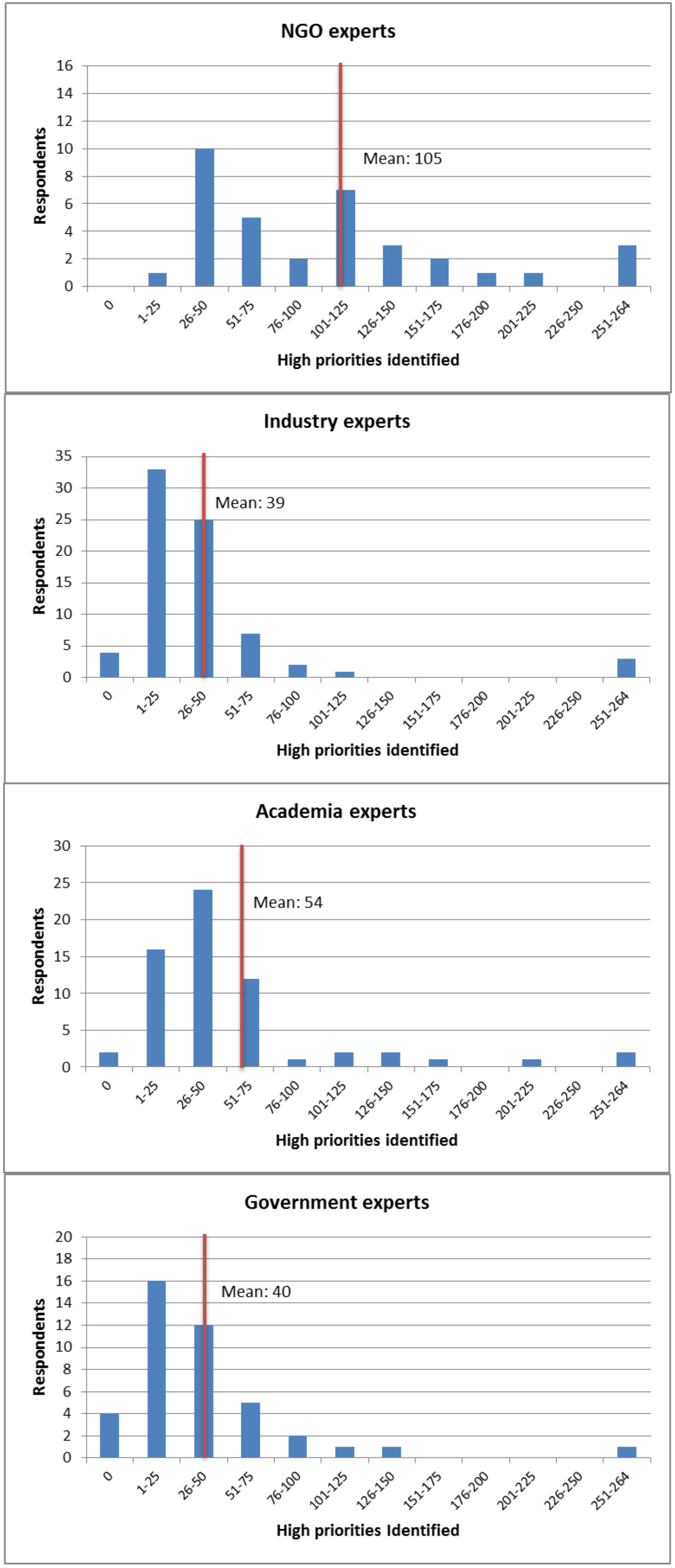
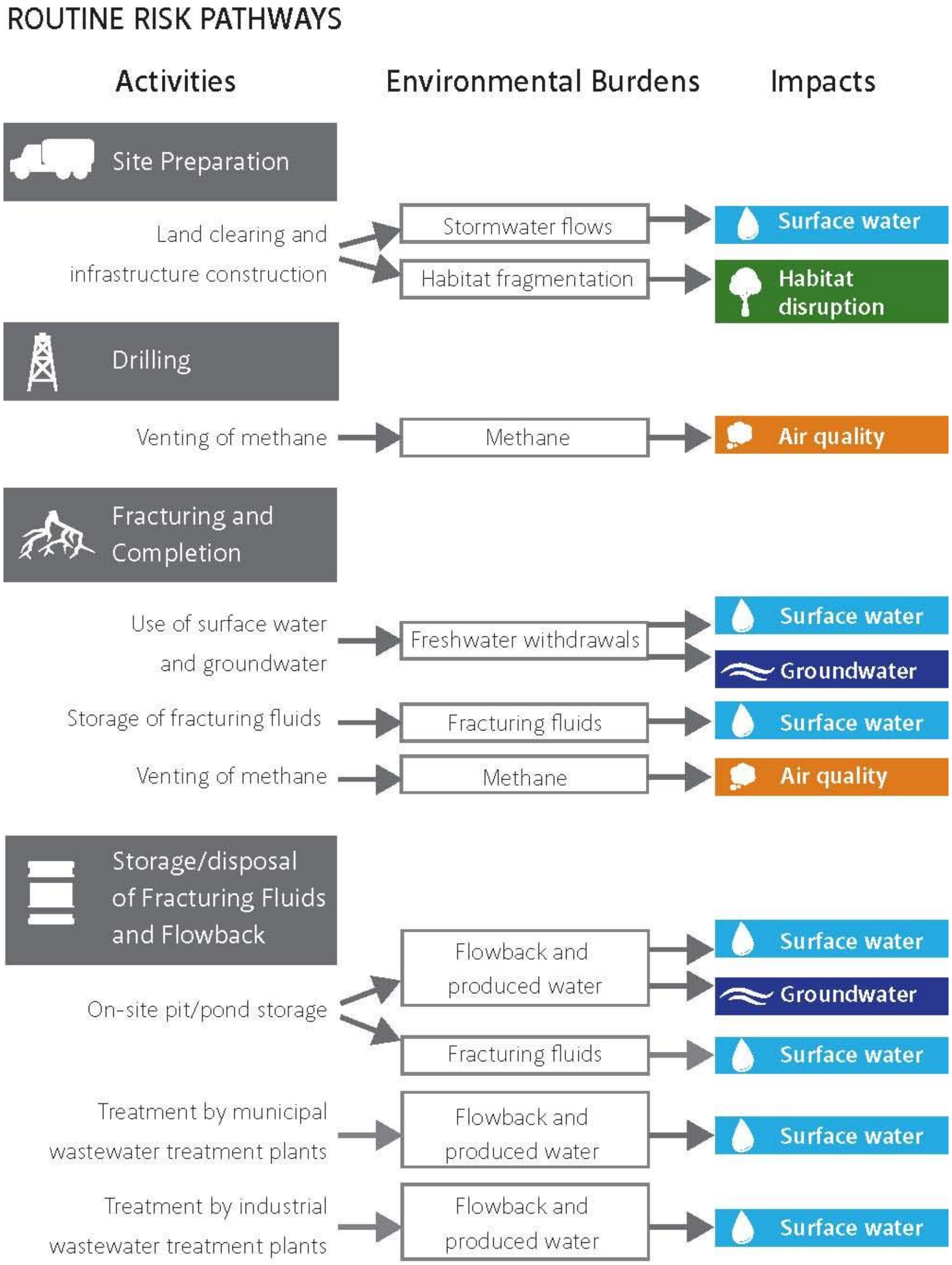


Figure 2. 12 Consensus Routine Risk Pathways



We summarize these combinations with a Venn diagram (Figure 3),[6] in which each oval represents a group and the areas created by overlapping ovals represent all the combinations of consensus, with the green center of the diagram representing the sweet spot.

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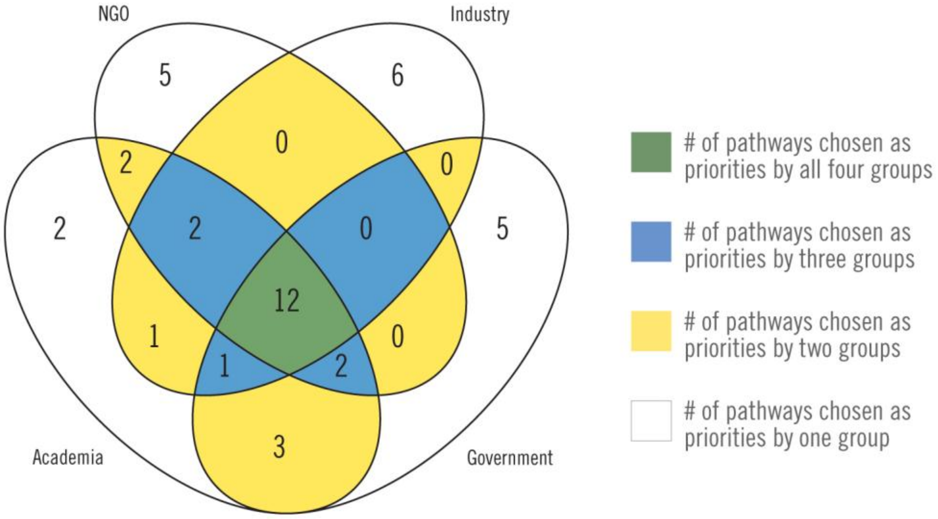
[6] Because the standard Venn diagram with circles can represent counts for only four of the six bilateral agreement combinations, we used the more unusual oblong diagram.

Figure 3. Degree of Agreement among the Expert Groups' 20 Priority Risk Pathways



4.2.3 The 12 Consensus Risk Pathways Agreed upon by All Expert Groups

Of the 12 consensus risk pathways that *all* of the expert groups most frequently chose as priorities (indicated in green in Figure 2):

- 7 involve potential risks to surface water quality,
- 2 involve potential risks to air quality,
- 2 involve potential risks to groundwater quality, and
- 1 is related to habitat disruption.

Despite significant public and regulatory concerns about groundwater risks, risks to surface water were a dominant concern among the experts. Similarly, both of the air quality risks involve methane (which has implications for climate change), rather than conventional local air pollutants (such as nitrogen dioxide). The threat of habitat fragmentation from shale gas development infrastructure is also a consensus risk pathway, despite (or possibly because of) its relatively low profile in the public debate.[7]

Although some of the *impacts* of the 12 consensus risk pathways described above have not received wide media attention, several *activities* associated with these impacts have, including:

- on-site pit and pond storage of flowback liquids,
- freshwater withdrawals for hydraulic fracturing,
- venting of methane, and

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[7] For a report focusing on this issue, see Nels Johnson et al., *Pennsylvania Energy Impacts Assessment, Report 1: Marcellus Shale Natural Gas and Wind* (The Nature Conservancy and Audubon Pennsylvania, 2010), http://www.nature.org/media/pa/tnc_energy_analysis.pdf.

- treatment and release of flowback liquids.

Finally, none of the 27 possible risk pathways that result in potential impacts on soil quality were identified by the experts as priorities. Similarly, all four expert groups identified only 1 of the 31 pathways pertaining to habitat disruption.

Indeed, the most selected pathway was on-site pit or pond storage of flowback water and its potential leakage into surface water. Seventy-four percent of the NGO respondents said this pathway is a priority, making it the fourth–most often selected pathway for that group. Notably, this option was the most frequently chosen pathway in the other three groups, although the percentage of respondents voting for this pathway was lower for these other groups than for the NGO experts.

Where identical risk pathways appeared on the matrix that impacted either groundwater or surface water, the experts almost always selected the surface water pathway as a high priority with more regularity.

Table 4 (see following page) shows all 41 pathways in the Venn diagram in an abbreviated version of the matrix that includes only those activities with a relevant pathway. The figure indicates in parentheses which groups ranked that particular pathway in the top 20 (Table B6 in the appendix shows the rank and percentage selected by group for each of these 41 pathways.)

4.2.4 Federal versus State Experts

We examined whether federal (15 respondents) and state-, local-, and watershed-level respondents (27 respondents) were similar in their identification of top 20 priorities, given their different vantage points and regulatory responsibilities. As a result of ties, 27 pathways for federal experts and 26 pathways for state and local government experts are in the top 20, of which 15 are shared. (Table B7 in the appendix displays the shared and conflicting priorities of the two groups.) What appears to be a remarkable amount of disagreement may be due to the small sample size of the two groups: 15 federal respondents and 27 state and local respondents.

For example, *federal* government expert respondents appear more concerned with air quality risks (notably, flaring of methane), which were less frequently identified by *state* government experts as a whole. However, federal experts rarely identified risks stemming from the disposal of drilling fluids, drill solids, and cuttings as a priority, unlike state experts.

Federal experts listed 1 community disruption pathway in their top 20, whereas state experts—surprisingly—listed none.

Table 4. Top 20 Group Routine Pathways in an Abbreviated Matrix

Activities	**Intermediate impacts**					**Totals***
Site development & drilling preparation	**Groundwater**	**Surface water**	**Air quality**	**Habitat disruption**	**Community disruption**	2-0-0-2/18
Clearing of land/construction of roads, well pads, pipelines, other infrastructure		Stormwater flows		Habitat fragmentation	Industrial landscape(A)	2-0-0-1/9
On-road vehicle activity					Road congestion(I)	0-0-0-1/5
Drilling activities	**Groundwater**	**Surface water**	**Air**	**Habitat**	**Community**	1-2-3-7/45
Drilling equipment operation at surface	Drilling fluids and cuttings(G)	Drilling fluids & cuttings(A,G)			Noise pollution(I)	0-0-1-2/7
Drilling of vertical & lateral wellbore	Intrusion of saline-formation water(G)					0-0-0-1/5
Casing and cementing	Methane(I,A,G) Intrusion of saline-formation water(I)					0-1-0-1/6
On-road & off-road vehicle activity					Road congestion(I)	0-0-0-1/5
Use of surface water & groundwater	Freshwater withdrawals(A)	Freshwater withdrawals(N)				0-0-0-2/5
Venting of methane			Methane			1-0-0-0/2
Storage of drilling fluids at surface		Drilling fluids & cuttings(A,G)				0-0-1-0/6
Disposal of drilling fluids, drill solids, cuttings	Drilling fluids and cuttings(N,A)	Drilling fluids & cuttings(N,I,A)				0-1-1-0/5
Fracturing & completion	**Groundwater**	**Surface water**	**Air**	**Habitat**	**Community**	4-1-1-2/62
Use of surface water & groundwater	Freshwater withdrawals	Freshwater withdrawals				2-0-0-0/5
Flowback of reservoir fluids	Flowback & produced water constituents(N,A)	Flowback & produced water constituents(N,I,A)				0-1-1-0/11
Venting of methane			Methane			1-0-0-0/2
Storage of fracturing fluids at drill site	Fracturing fluids(G)	Fracturing fluids				1-0-0-1/6
On-road & off-road vehicle activity					Road congestion(I)	0-0-0-1/7
Well production & operation	**Groundwater**	**Surface water**	**Air**	**Habitat**	**Community**	0-1-0-3/21
Well production	Flowback & produced water constituents(N)	Flowback & produced water constituents(N,A,G)				0-1-0-1/7
Condensate tank, dehydration unit operation			Volatile organic compounds(N)			0-0-0-1/7
Compressor operation			Conventional air pollutants & CO_2(N)			0-0-0-1/3
Fluid storage & disposal	**Groundwater**	**Surface water**	**Air**	**Habitat**	**Community**	5-1-2-4/80
On-site pit or pond storage	Flowback & produced water constituents Fracturing fluids(G)	Flowback & produced water constituents Fracturing fluids	Volatile organic compounds(N)			3-0-0-2/11
Transport off-site					Road congestion(I)	0-0-0-1/13
Treatment, release by industrial wastewater treatment plants		Flowback & produced water constituents				1-0-0-0/6
Treatment, release by municipal wastewater treatment plants		Flowback & produced water constituents Fracturing fluids(A,G)				1-0-1-0/6
Deep underground injection	Flowback & produced water constituents(G)				Seismic vibrations(I,A)	0-0-1-1/6
Application of wastewater for road deicing, dust suppression		Flowback & produced water constituents(N,A,G)				0-1-0-0/11
Totals*	2-1-2-8 / 52	7-4-3-1 / 53	2-0-0-3 / 53	1-0-0-0 / 31	0-0-1-6 /48	12-5-6-18/ 264

*Totals are: 4 agree-3agree-2agree-1agree/total pathways

Notes: Green = four in agreement, blue = three in agreement, yellow = two in agreement, white = one in agreement. (N) signifies NGO experts, (I) industry experts, (A) academic experts, and (G) government experts. Activities that have no pathways in any group's top 20 are omitted. No "soil quality" pathways or "other activity" pathways were in any group's top 20.

4.2.5 Extraction versus Other Industry Experts

We also split the industry group in two: 32 experts from extraction companies and 43 affiliated with consulting firms, law firms, and industry advocacy groups. Because of ties, 26 priorities are in the top 20 for the extraction sector and 21 pathways are in the top 20 for other industry experts. Of those, 17 are in both groups' top 20. (Table B8 in the appendix displays the shared and conflicting priorities of the two groups.)

Three of the top five most selected pathways for the extraction industry experts involve community disruption. The most cited pathway, for example, is road congestion during site development, which is the 5th–most often selected concern for nonextraction industry and the 16th–most cited pathway for all experts. Extraction experts also selected seismic vibrations during deep underground injection (another community disruption pathway) more frequently than others, making it the 8th–most often selected pathway, compared with 29th for other industry experts and 30th across all experts. Not all routine pathways selected by extraction experts are community based, however. The escape of methane through casing and cementing into groundwater is tied for the 3rd–most selected pathway by extraction experts, whereas it was picked 12th–most often by other industry experts and 8th–most often by all of our experts.

The effect on surface water of the application of wastewater for road deicing is extraction experts' 68th–most often selected pathway, but is the 17th–most often selected by other industry experts and by all of the experts we surveyed. As a result, extraction experts prevented this pathway from joining the 12 consensus pathways. Extraction experts may not have selected it as a high priority because this practice has been prohibited in some areas already.

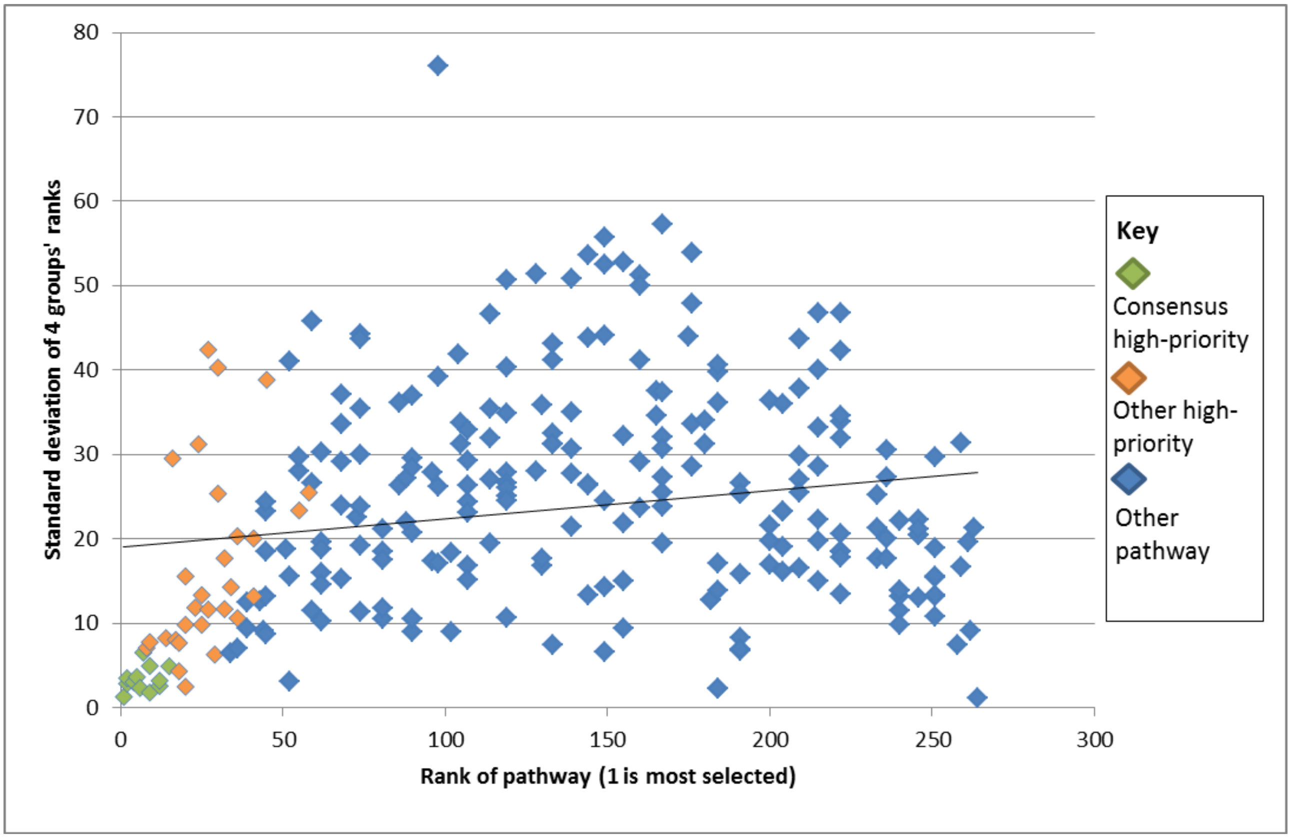
4.2.6 A Specific Measure of Agreement and Disagreement

Categorizing the top 20 pathways is somewhat arbitrary and does not take into account how far out of the top 20 other pathways are. Accordingly, we offer a second way to identify pathway consensus. We took the standard deviation of the four group ranks for all 264 pathways. The median standard deviation of ranks for all pathways is 21.9, and the first-quartile standard deviation is 13.3. Figure 4 shows the relationship between the standard deviation and the rank for all pathways, along with a regression line (green dots are the 12 consensus pathways, and orange dots are the other 29 pathways in the Venn diagram). Clearly, pathways with the lowest variation in ranks are among the most selected pathways. This speaks to a general agreement among groups regarding which pathways are most often selected.

We then examined the 41 pathways that appear in the Venn diagram (the results are included in Table B6 in the appendix). The Venn diagram designations match well with the correlations score, with the consensus pathways being those with 12 of the smallest 15 standard deviations.

Two pathways that were in the top 20 most selected for only one group actually had very low standard deviations. The effect of freshwater withdrawals for fracturing on groundwater is in the top 20 only for academic experts (for whom it is the 18th–most selected) but is a near miss for the other three groups. The same is true for the effect of flowback on groundwater during well production (19th–most selected by NGO experts). Meanwhile, the effect of flowback on surface water (instead of groundwater) during well production is in the top 20 for all but the industry experts (by whom it was selected 26th–most often). Still, these pathways probably do not belong with the other 12. Unlike the 12 consensus pathways, no group has any of these 3 in its top 10 most selected. Nevertheless, the Venn diagram clearly overestimates the amount of disagreement in these cases.

Figure 4. Standard Deviation of Group Ranks of Routine Pathways



4.2.7 Disagreement on High Priorities

Expert groups are divided in the priorities assigned to other risk pathways outside of the 12 consensus pathways.

The industry, NGO, and government groups each selected several pathways that were not selected by any other group (indicated in white in Figure 2). Industry respondents identified six priority risk pathways related to community disruptions (e.g., road congestion from truck traffic associated with shale production). The five unique pathways selected by NGO respondents mostly target conventional air pollutants. The five unique pathways selected by government respondents focus entirely on groundwater risks. Academic respondents identified only two unique risk pathways: one relating to the potential for newly industrialized land to disrupt nearby communities and the other relating to the impact on groundwater from using freshwater withdrawals for drilling.

Some risk pathways produced consensus among two or three groups (indicated in yellow and blue in Figure 2), but not across all four groups.

- The potential impact on surface water from using wastewater for road deicing or dust suppression is a high priority for all expert groups except industry.
- Seismic vibrations caused by deep underground injection of flowback and produced water is a high priority for industry and academic respondents but not for government and NGO respondents.

- The impact on groundwater from hydraulic fracturing flowback was most frequently identified by NGO and academic experts but less so by other experts.

Five of the most disagreed upon pathways are related to community disruptions (including seismic vibrations). Industry respondents (and, to a lesser extent, academic respondents) consistently noted that they were a high priority, more so than did NGO respondents (and, to a lesser extent, government experts).

Pathways selected by only one group might be a near miss for others or could simply be outliers with little attention from the other three groups. In fact, most of the industry respondents' unique picks are truly outliers, but the pathways selected only by the academic respondents are not. In the other two groups, only the NGO experts' focus on volatile organic compounds from condensate operation and only the government respondents' concern about drilling fluids and cuttings polluting groundwater can be considered outliers.

Other than the 12 consensus pathways, industry and NGO experts have only 2 pathways in common, and these also were identified by academic experts: surface water pollution related to flowback and drilling. Academic and government experts have six additional pathways in their top priority list, two of which are shared by the NGO experts and one of which is shared by industry experts.

The standard deviation method allows us to also identify which pathways that appear at least once among the top 20 most commonly selected pathways generated the most disagreement. Of the 41 pathways examined, 8 have standard deviations above the median of all 264 pathways (21.9). These pathways are listed in Table 5.

The only pathway in Table 5 that makes the top 20 most selected of more than one group is seismic vibrations from deep underground injection. Meanwhile, the same activity's effect on groundwater through flowback is the pathway with the *third* most disagreement. Whereas seismic vibrations are in industry and academic experts' top 20, government experts—and, to a lesser extent, NGO experts (who selected it 24th–most often)—are concerned about deep underground injection's effect on groundwater. It seems then that the experts agree that deep underground injection is responsible for burdens that are a high priority, but do not agree what those burdens are.

Five of the most disagreed upon pathways are related to community disruptions (including seismic vibrations). Industry respondents (and, to a lesser extent, academic respondents) consistently noted that they were a high priority, more so than did NGO respondents (and to a lesser extent government experts).

Table 5. Most Controversial Top 20 Routine Pathways

Routine pathway			Ranks					Rank std. dev.
Activity	Burden	Impact	NGO	Industry	Academia	Govt	All experts	
Drilling equipment operation at surface	Drilling fluids and cuttings	Groundwater	82 (45.7%)	63 (20.0%)	70 (25.4%)	20 (31.0%)	55 (27.9%)	23.4
Drilling equipment operation at surface	Noise pollution	Community disruption	82 (45.7%)	15 (37.3%)	30 (36.5%)	54 (21.4%)	30 (35.3%)	25.4
Condensate take, dehydration unit operation	VOCs	Air quality	19 (65.7%)	73 (17.3%)	87 (22.2%)	54 (21.4%)	58 (27.4%)	25.5
On-road vehicle activity during site development	Road congestion	Community disruption	82 (45.7%)	2 (50.7%)	26 (38.1%)	24 (28.6%)	16 (41.9%)	29.5
On-road and off-road vehicle activity during drilling	Road congestion	Community disruption	48 (54.3%)	5 (44.0%)	36 (34.9%)	92 (16.7%)	24 (37.7%)	31.2
Deep underground injection	Flowback and produced water constituents	Groundwater	24 (62.9%)	113 (13.3%)	56 (28.6%)	13 (35.7%)	45 (30.2%)	38.9
Deep underground injection	Seismic vibrations	Community disruption	116 (40.0%)	19 (34.7%)	20 (39.7%)	32 (26.2%)	30 (35.3%)	40.3
Transport off-site (fluids)	Road congestion	Community disruption	116 (40.0%)	3 (45.3%)	36 (34.9%)	76 (19.0%)	27 (36.3%)	42.4

Note: VOCs: volatile organic compounds.

4.2.8 Agreement on What Is Not a Priority

We offered a very large array of possible priorities (264), so the frequency with which groups agree on the top 20 most selected pathways is remarkable. The reverse is also somewhat true: the groups agree on many of the pathways that are *not* priorities. One could define a consensus pathway that is not a priority as one that is not represented in the Venn diagram of Figure 2. As shown in Table 6, 16 activities did not have any pathways in the top 20 for any group; using this definition, 223 pathways are of lesser or no importance.

Relying on the top 20 to identify consensus low priorities is arbitrary, however. In Appendix B.2, an alternate methodology that uses the quartile as the cutoff is presented. By this measure, if a pathway was selected in the bottom three-quarters of pathways for all four groups, we designated it as one that is not a consensus priority. In the appendix, Table B5 displays the frequency with which pathways were selected by cross-sections of activity categories, impacts, and burdens. Habitat and soil pathways and other activities (shutting-in, plugging, workovers, and downstream activities) are dominated by consensus low priorities. Habitat fragmentation resulting from the clearing of land was a consensus high priority, however, so although many others are not a high priority, one habitat routine risk should not be ignored.

Table 6. Routine Activities without a Top 20 High-Priority Pathway

Activity	Number of pathways
Site development and drilling preparation	
Off-road vehicle activity	4
Drilling activities	
Flaring of methane	4
Fracking activities	
Perforation of well casing/cementing	1
Hydraulic fracture initiation	4
Introduction of proppant	8
Flushing of wellbore	10
Flaring of methane	4
Fracturing equipment operation	4
Well production/operation	
Flaring of Methane	4
Fluid storage and disposal	
On-site tank storage	11
On-site treatment and reuse	5
Removal of sludge and other solids to landfills	11
Other activities	
Shutting-in	12
Plugging and abandonment	14
Workovers	10
Downstream activities (e.g., pipeline operation)	2

4.2.9 Hypotheses and Conclusions about Priority Designations

Nearly a year of background research using media reports and discussions with experts led us to formulate a few hypotheses about which routine pathways would be most selected by our surveyed experts. We expected the most frequently selected pathways to be methane seepage from casing and cementing, the venting of methane into the air during either drilling or fracturing, freshwater withdrawals, on-site storage of flowback and produced water, the treatment and release of flowback and produced water constituents, seismic vibrations due to deep underground injection, and the application of wastewater for road deicing. One set of pathways about which we were unsure deals with groundwater impacts during the actual fracturing process, including hydraulic fracture initiation, introduction of proppant, flushing of wellbore, and flowback of reservoir fluids. Much has been made in the media about the potential for these activities to pollute groundwater, but some experts have consistently said that these scenarios are highly unlikely, if not impossible.

Many of our hypotheses turned out to be correct. Both on-site pit and pond storage of flowback pathways and freshwater withdrawals for fracturing pathways are among the top 20 priorities most often selected by experts in all four groups. Two venting of methane pathways and two treatment and release of flowback pathways are also top choices for all groups. These activities have wide coverage in the media, and the experts surveyed confirmed that they are priorities for further action.

Three of our hypothesized pathways are not consensus top 20 picks, however. The application of wastewater for road deicing or dust suppression's effect on surface water is in three groups' top 20 most selected pathways, but experts from the extraction industry rarely picked it. Seismic vibrations from deep underground injection is one of the most controversial pathways, according to the standard deviation of ranks. Consensus clearly does not exist for prioritizing these two pathways, despite their selection by some groups. Finally, methane seepage from casing and cementing is the 8th–most prioritized pathway but does not make the NGO experts' top 20. As we show below, respondents who have a high level of expertise in drilling activities (including NGO respondents with high drilling expertise) picked this pathway very often, so it is a good candidate to be included as a consensus pathway.

As far as pathways involved with the fracturing process and its effect on groundwater, only the flowback of reservoir fluids breaks any groups' top 20 most selected pathways (NGO and academic experts). Curiously, flowback of reservoir fluids' impact on surface water is the ninth–most chosen pathway and just misses being a consensus pathway. All in all though, almost every priority routine pathway that garnered broad attention from experts has to do with risks present in most drilling operations or with the disposal of waste produced by fracturing, not the actual hydraulic fracturing action itself.

A few pathways that we had not expected turned out to be high priorities for all groups. Most notable are (a) stormwater flows and (b) habitat fragmentation from the clearing of land for roads, well pads, pipelines, and other infrastructure. Because these pathways are not specific to the fracturing process, we hypothesize that they do not receive the same coverage from the media and regulators as other top priorities, but the experts surveyed clearly consider them serious issues that need to be addressed.

The effects of flowback on surface water during well production and drilling fluids and cuttings on surface water during disposal are in three groups' top 20 but had not been hypothesized as likely candidates for high consensus. Below, we show that respondents with high expertise in well production and with high expertise in drilling activities selected each of these pathways far less often than other experts. But because of their popularity, these pathways may be good candidates for further attention and research, if not action.

4.3 Typical versus Tail-End High-Priority Risk Pathways

Recall that respondents had the choice of identifying a priority as applying to a typical or tail-end situation. Up to this point, we have aggregated over these designations, but we now look at the distribution of typical and tail-end priorities separately. Over all 56,760 choices that could have been made (264 pathways by 215 respondents), 15.5 percent were designated as typical priorities and 5.2 percent were designated as only tail-end priorities. Almost 80 percent of the available impact pathway*respondent choices were not designated as a priority in either case. Dividing tail-end by typical, only about 25 percent of the identified high priorities applied to tail-end operating conditions only—the rest applied to both typical and tail-end conditions. This percentage is a bit lower for the NGO group of experts and a bit higher for industry experts, with the other groups in the middle.

We looked for high-priority tail-end choices that made big jumps (up and down) in rankings compared with their rankings for the typical case. Two stand out.

- Storage of fracturing fluids at a drill site. This option is the 40th–most chosen typical pathway but is 2nd–most chosen when only tail-end priorities are considered.
- Drilling of vertical and lateral wellbore–intrusion of saline-formation water into fresh groundwater. This option is the 61st–most chosen typical pathway but is the 5th–most chosen tail-end priority.

In contrast, the following pathways fall significantly in the tail-end selection frequency compared to their typical selection frequency, indicating that if respondents felt they were high priorities, they were not unique only to tail-end cases.

- Various fugitive methane pathways.
- Application of wastewater for road deicing, dust suppression from flowback, and produced water constituents (other than fracturing fluids). This option is the 7th–most often selected pathway among typical priorities, but 92nd among tail-end priorities.
- Clearing of land for roads, well pads, pipelines, evaporation ponds, and other infrastructure affecting the industrial landscape. This option is the 17th most selected pathway among typical priorities, but 121st among tail-end priorities.

The percentage of high-priority designations that were only tail-end for each of the 41 Venn diagram pathways is listed in Table B6 of the appendix. Table B10 shows the top and bottom five pathways from this group.

4.4 Justifications for Priority Selection

We asked all respondents to tell us what drove them to designate one typical and one tail-end impact pathway as a priority. Table 7 shows the responses broken down by group. For both typical and tail-end pathways, operator practices are the most commonly cited factor, with consistent support across all groups. Regulator gaps and proximity to a community are the next two most commonly cited factors.

Differences arose between the two types of pathways. Experts cited regulatory gaps and lax enforcement more for typical pathways (significant at the 99 percent and 90 percent levels, respectively), whereas they cited geology more for tail-end pathways (significant at the 90 percent level).

Within both types of pathways, we conducted statistical tests to see if each group's response was different from those of the other three (reported in Table 7). Proximity to ecosystems, geology, regulatory gaps, and lax enforcement are much more important typical-case factors for NGO experts and much less important for industry experts than for the other groups. NGO experts also were most likely to select operator technologies, whereas government experts were least likely to pick this option.

We found less significant disagreement among the groups for tail-end pathways, with a few exceptions. Regulatory gaps and lax enforcement are still of largest concern for the NGO respondents and least for industry experts. Government experts cited proximity to a community much less frequently than did the experts in other groups, consistent with the outcome that government experts also placed the least emphasis of all four surveyed groups on community impacts.

Table 7. Percentage of Experts Citing Particular Driving Factors for Priority Designation

Factor	Typical pathway					Tail-end pathway				
	NGO	Industry	Academia	Gov't	All	NGO	Industry	Academia	Gov't	All
Proximity to ecosystems	54***	21***	33	40	34	46*	29	32	31	33
Proximity to a community	43	48	37	36	41	60***	40	40	24**	40
Geology	31**	8***	21	21	18	31	19	25	26	24
Hydrology	43	27	30	31	31	40	23**	40	33	33
Well characteristics	17	9	13	10	12	23	12	13	14	14
Operator technologies	43***	20	21	5***	21	31	27	16	17	22
Operator practices	63	53	48	45	52	63*	48	46	48	50
Regulatory gaps	80***	28***	54	40	47	63***	25*	37	21*	34
Lax enforcement/reporting	66***	16***	38	29	33	57***	12***	30	26	27
Other	20*	13	6	10	12	3	9*	3	5	6

*,**,*** Percentage selecting this factor for either typical or tail-end pathways is statistically significantly different from the other three groups at the 90%, 95%, and 99% levels, respectively.

4.5 Agreement and Disagreement among Groups

Up to this point, we have not paid much attention to *which* groups are in agreement with one another and on which pathways, beyond the few top priorities that are in disagreement. We hypothesized that industry and NGO experts would agree with each other least of the six possible combinations of two groups. Beyond this, we were agnostic.

Table 8 illustrates the frequency of agreement about priority risk pathways for groups of two and three, by activity and impact categories. In this table, agreement means that the specific pathway is in the same quartile of priority for both (or three) groups. Green cells indicate areas of high agreement, and red cells indicate areas of relatively low agreement, using the overall degree of agreement as a benchmark.

Overall, our hypothesis was not borne out. Looking over activity categories and bilateral agreement, NGO experts disagree about as often with government experts as they do with industry experts. Disagreements are greatest about site development impacts. The data are more dispersed—that is, we found more agreement and disagreement—for impact categories. NGO and industry experts are just as likely to agree above the benchmark level of agreement than to disagree below the benchmark. Community impacts is the category with the most disagreements, and surface water is the category with the most agreements. Finally, looking at the right-hand side of the table, industry, academic, and government respondents seem to agree with each other more than any of these groups does with the NGO group.

Table 8. Percentage of Pathways That Are Ranked in the Same Quartile across Groups

Quartile agreement	NGO & industry	NGO & academia	NGO & gov't	Industry & academia	Industry & gov't	Academia & gov't	Total for bilateral agreement		NGO/ industry/ academia	NGO/ industry/ gov't	Industry/ academia/ gov't	Total for trilateral agreement		All four agree
All pathways	57.6	62.5	57.2	62.5	55.3	58.7	59.0		44.7	38.6	41.3	41.5		31.1
Activity categories														
Site development	38.9	55.6	44.4	55.6	38.9	66.7	50.0		27.8	22.2	38.9	29.6		22.2
Drilling activites	66.7	64.4	60.0	64.4	64.4	51.1	61.9		51.1	48.9	42.2	47.4		37.8
Fracking & completion	59.7	69.4	53.2	69.4	56.5	59.7	61.3		51.6	37.1	43.5	44.1		33.9
Well production	52.4	61.9	42.9	66.7	57.1	47.6	54.8		42.9	28.6	38.1	36.5		19.0
Fluid storage & disposal	55.0	57.5	62.5	58.8	52.5	61.3	57.9		38.8	38.8	38.8	38.8		28.8
Other activities	60.5	63.2	63.2	57.9	55.3	63.2	60.5		47.4	42.1	44.7	44.7		34.2
Impact categories														
Groundwater	61.5	63.5	57.7	53.8	55.8	59.6	58.7		44.2	40.4	38.5	41.0		30.8
Suface water	71.7	69.8	64.2	75.5	67.9	66.0	69.2		62.3	52.8	56.6	57.2		47.2
Soil quality	59.3	66.7	55.6	59.3	44.4	70.4	59.3		44.4	33.3	40.7	39.5		29.6
Air quality	39.6	54.7	47.2	60.4	56.6	52.8	51.9		30.2	24.5	35.8	30.2		17.0
Habitat disruption	74.2	64.5	71.0	71.0	64.5	61.3	67.7		58.1	58.1	51.6	55.9		48.4
Community disruption	43.8	56.3	50.0	54.2	37.5	45.8	47.9		31.3	25.0	25.0	27.1		16.7

4.6 Support for Immediate Action

At the end of the risk matrix portion of the survey, respondents were asked to indicate whether they think information is sufficient to act now on their chosen priority pathways or whether more research is needed. Table 9 shows the average percentage of pathways for which each category of expert believes that enough research has been done. The average expert feels that information is sufficient to act now on 71 percent of the routine pathways he or she designated as a priority. Academic experts, unsurprisingly, were most likely to want more research, picking a percentage of pathways that is statistically significantly different from those of industry experts (significant at the 99 percent level) and government experts (95 percent level). Industry experts, whose selections are statistically different from the NGO experts at the 95 percent level as well, are most confident that enough research exists for action. This could be a result of selection bias, as experts were asked about only the priorities they chose.

Table 9. Is Research Sufficient To Proceed with Action? (Average Percentage of Pathways)

	NGO	Industry	Academics	Government	All experts
Enough research	64.2	78.3	62.3	75.5	70.7
More research	35.8	21.7	37.7	24.5	29.3

We also wanted to know if these conclusions varied by activity category. Respondents are most sure of moving forward in the site development area (83 percent across the sample) and least sure when it comes to managing produced water (65 percent).

We examined responses for the 12 consensus pathways in Table 10 (Table B6 in the appendix displays these values for all 41 priority pathways). For half of the pathways, experts are more likely to believe that enough information exists for further action now than they do for all pathways combined. Both pathways concerning treatment by wastewater plants are in need of more research, according to the experts.

Table 10. Percentage Saying That Information Is Sufficient To Support Regulatory or Voluntary Action[8]

Activity	Burden	Impact	NGO	Industry	Academia	Gov't	All
Clearing of land for roads, well pads, pipelines, evaporation ponds, and other infrastructure	Stormwater flows	Surface water	100.0	90.5	85.7	100.0	92.4
Storage of fracturing fluids at drill site	Fracturing fluids	Surface water	88.9	94.7	77.8	91.7	87.9
On-site pit or pond storage	Flowback and produced water constituents	Surface water	81.8	87.1	83.3	68.8	81.8
On-site pit or pond storage	Fracturing fluids	Surface water	63.6	85.7	75.0	71.4	76.3
On-site pit or pond storage	Flowback and produced water constituents	Groundwater	66.7	83.3	63.2	77.8	73.1
Use of surface water and groundwater during fracking	Freshwater withdrawals	Surface water	61.1	72.0	72.7	91.7	72.7
Venting of methane during fracking	Methane	Air quality	75.0	74.1	66.7	57.1	68.8
Venting of methane during drilling	Methane	Air quality	75.0	70.0	73.3	40.0	68.8
Clearing of land for roads, well pads, pipelines, evaporation ponds, and other infrastructure	Habitat fragmentation	Habitat disruption	90.0	61.9	61.1	66.7	67.2
Use of surface water and groundwater during fracking	Freshwater withdrawals	Groundwater	69.2	62.5	52.2	82.4	64.9
Treatment, release by municipal wastewater treatment plants	Flowback and produced water constituents	Surface water	38.5	69.6	75.0	61.5	64.4
Treatment, release by industrial wastewater treatment plants	Flowback and produced water constituents	Surface water	37.5	50.0	64.7	60.0	54.5
All 264 pathways			62.9	78.0	61.5	73.3	69.0

Notes: Green indicates an above average rate of "enough information" responses for the given pathway. Red indicates a below average rate

4.7 Government Regulation versus Voluntary Action

The survey offered two questions on who should be responsible for addressing priority pathways. As described in Section 2, the first is a general question asked before the risk matrix was presented. It offered six possible answers, ranging from government to industry taking sole responsibility, with shared responsibility in various proportions in between. The second question addressed the same

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[8] The average percentage of pathways in Table 9 is different from "all" 264 pathways in Table 10 because the former is the average percentage of experts who answered "enough," whereas the latter is the percentage who answered "enough," treating each time an expert responded as separate.

issue after the risk matrix portion of the survey, giving respondents a sample of their own selected priority pathways to which to respond and limiting their answers to whether responsibility should lie primarily with government or industry.

When asked to choose government *or* industry as the primary party with authority to address the risks that the experts selected as priorities, NGO, academic, and government experts selected government more often than industry, whereas industry experts selected government and industry equally. When sharing is an option, all groups agree that government *and* industry should share the authority for risk mitigation, to some degree. However, nearly one-half of industry experts say that industry should take a leading role in a sharing arrangement, whereas no more than one-third of any other group takes this position.

There seems to be a consensus that the debate should focus on developing shared arrangements for seeking sustainable shale gas development, except in areas related to priority risks that require additional research to be fully understood—for example, (a) the impacts on surface water and groundwater from the treatment of flowback and produced water by municipal and/or industrial wastewater plants and (b) the impact on air quality due to the venting of methane during fracturing. In these cases, we found a consensus that government should take the lead in addressing those risks.

4.7.1 Sharing Not an Option

When the choice is limited to just the two options applied to a sample of chosen priorities (Table 11), on average, experts recommended that government should be the party responsible for initiating action for just under 70 percent of their priority pathways. Industry respondents are least in agreement that all routine pathways should have primary government responsibility (49 percent), and the NGO respondents are most in agreement (94 percent). NGO respondents' responses are statistically different from those of industry respondents at the 99 percent level, with academic respondents at the 95 percent level, and with government respondents at the 90 percent level; the responses of industry experts are also different from those of academic experts at the 95 percent level.

Table 11. Who Should Take Primary Responsibility for Action? (Average Percentage of Pathways)

	NGO	Industry	Academics	Government	All experts
Government	93.8	49.4	74.9	74.8	69.4
Industry	6.2	50.6	25.1	25.2	30.6

Instead of looking at the average expert, we can dig deeper into these responses by looking at each response individually and considering them at the category level. Table 12 looks at this issue by dividing the responses by impact group and then by activity group. A few interesting results arise. All groups are less likely to assign primary responsibility to the government for community disruption pathways. Conversely, support is relatively strong for government intervention to protect habitat and mitigate air pollution impacts. At the activity level, support from the entire sample is greatest for government action in the flowback/produced water stage and least for the site development stage.

Table 12. Percentage of Responses in Support of Government as Having Primary Responsibility for Action

Intermediate impact level	NGO	Industry	Academia	Gov't	All experts
Groundwater	97.6	56.8	77.9	85.5	77.7
Surface water	94.1	65.9	78.8	81.0	78.4
Soil quality	89.3	61.3	83.3	77.3	78.3
Air quality	99.2	71.4	77.7	77.2	81.1
Habitat disruption	93.2	65.6	79.4	76.6	79.4
Community disruption	86.2	32.6	58.6	46.5	52.1
Activity category level					
Site development & drilling prep	89.4	46.0	68.5	73.9	82.3
Drilling activities	93.1	46.1	71.2	76.9	73.7
Fracturing & completion	93.2	48.0	71.9	79.1	67.6
Well production & operation	93.6	48.7	72.3	79.6	68.4
Waste storage & disposal	94.6	53.5	73.5	77.0	65.1
Other activities	94.3	53.8	73.1	77.3	63.1

We can get even more specific by focusing on the 12 consensus pathways (Table 13 shows these pathways by group, whereas Table B6 in the appendix displays total sample values for all 41 priority pathways). For most of these pathways, experts more often believe that the government should have primary responsibility than they do for all pathways. In addition, the experts believe that industry should take more responsibility during the clearing of land when it comes to stormwater flows but that government needs to be involved in the same action when it comes to habitat fragmentation, possibly because of the more traditional role government has played in wildlife protection.

Combining results from Tables 9 and 12 provides an interesting insight. The two consensus pathways most often thought to have a need for more information are the two pathways *most* likely to be designated as government responsibilities. Similarly, the two pathways most often thought to have enough information for immediate action are the two pathways experts are most likely to designate as responsibilities for industry. So government is trusted more when less information is available.

Table 13. Percentage Saying "Government Should Be Responsible for Addressing This Pathway"

Activity	Burden	Impact	NGO	Industry	Academia	Gov't	All
Treatment, release by municipal wastewater treatment plants	Flowback and produced water constituents	Surface water	100.0	87.0	95.8	92.3	93.2
Treatment, release by industrial wastewater treatment plants	Flowback and produced water constituents	Surface water	100.0	90.5	76.5	90.0	87.3
On-site pit or pond storage	Flowback and produced water constituents	Groundwater	100.0	52.9	89.5	88.2	81.8
Use of surface water and groundwater during fracking	Freshwater withdrawals	Surface water	94.4	70.8	71.4	100.0	81.1
Clearing of land for roads, well pads, pipelines, evaporation ponds, and other infrastructure	Habitat fragmentation	Habitat disruption	100.0	63.2	83.3	88.9	80.4
Use of surface water and groundwater during fracking	Freshwater withdrawals	Groundwater	85.7	65.2	85.0	86.7	79.2
On-site pit or pond storage	Flowback and produced water constituents	Surface water	90.9	58.6	90.0	86.7	78.8
Venting of methane during fracking	Methane	Air quality	100.0	81.5	69.2	66.7	78.3
On-site pit or pond storage	Fracturing fluids	Surface water	90.9	68.4	84.2	66.7	78.2
Venting of methane during drilling	Methane	Air quality	100.0	70.0	80.0	40.0	75.0
Storage of fracturing fluids at drill site	Fracturing fluids	Surface water	100.0	61.1	83.3	58.3	73.7
Clearing of land for roads, well pads, pipelines, evaporation ponds, and other infrastructure	Stormwater flows	Surface water	100.0	40.0	70.0	80.0	66.7
All 264 pathways			94.5	57.0	75.0	77.0	74.0

Notes: Green indicates an above average rate of "enough information" responses for the given pathway. Red indicates a below average rate.

4.7.2 Sharing an Option

Turning now to our initial question about who takes responsibility for addressing risks, we see that support for government primacy across all four groups clearly drops when a sharing option is present (Table 14). A surprisingly similar number of government and industry experts believe that government and industry should share responsibility equally for addressing shale gas risks, with just fewer than one-third of these two groups picking this option. At the same time, 74 percent of NGO respondents and 60 percent of academics want government to be entirely responsible or to take more of the responsibility than industry, with only 11 percent and 23 percent, respectively, wanting industry to lead. In contrast, 51 percent of industry respondents want the industry to be fully responsible for initiating action or to take more responsibility than government. Perhaps most notably, only 39 percent of government respondents favor a lead role for themselves.

Table 14. In General, Who Should Be Responsible for Addressing Remaining Risks? (Percentage of Respondents)

	NGO	Industry	Academia	Gov't	All experts
Only government should be responsible	20.0	0.0	12.9	4.9	8.0
Primarily government, but industry has some role	54.3	18.9	46.8	34.1	35.8
Shared responsibility	14.3	29.7	17.7	29.3	23.6
Primarily industry, but government has some role	11.4	44.6	21.0	31.7	29.7
Only industry should be responsible	0.0	6.8	1.6	0.0	2.8

Overall, these results suggest that the debate should focus on developing shared arrangements for seeking sustainable shale gas development, as opposed to adversarial arrangements, and that more should be explored regarding sharing models where industry takes the lead and government plays a secondary role, as well as vice-versa. In low-information environments, however, we found more consensus that government should take the lead, and in activities where industry and government have traditional roles, experts think these roles should be maintained.

4.8 Differences across Respondents with Expertise in Different Shale Gas Plays

Are priority pathway choices at all affected by respondents' knowledge about plays? Or said another way, are conditions in various plays so different as to affect respondents' choices? Our survey results suggest that the answer is no. We can test this proposition only in a limited way, though, because we allowed participants to select multiple responses for their play knowledge.

Among 61 respondents who said they have only general knowledge and 112 respondents who said they have specific knowledge of one or more plays, 16 of the top 20 most selected priority risk pathways are held in common, with 4 appearing in each group's list uniquely (see Table B9 in the appendix). All but 2 of these pathways are in the top 30 of the other group. The only pathway of much disagreement is the burden of fracturing fluids on groundwater during on-site pit or pond storage, which government experts alone listed as a priority. Those with general knowledge cited it 13th–most often, but those with specific knowledge cited it 50th–most often. We do not know whether being in government, having only general knowledge of plays, or possessing another characteristic (such as the fact that this routine pathway is already banned in certain states) causes this disagreement, but this pathway remains one of the most contentious.

4.9 Shale Gas Boomtowns

In the last section on routine operations, we asked respondents whether boomtown externalities are, on balance, positive or negative and whether addressing any negative impacts is a priority (Table 15). Overall, two-thirds of the sample responded that the boomtown effects are positive, on net, with industry experts being more in agreement about this and the NGO experts strongly disagreeing. Each group's responses are statistically significantly different from those of each other group at the 99 percent level, except for academic and government experts, whose answers are not statistically different. This suggests that consensus on the qualitative effect shale gas has on communities will be much more difficult to achieve, despite the relative agreement on the priorities for more action. Of those saying that the effects are, on balance, negative, most responded that it is a priority to address this issue.

Table 15. Percentage Saying That Boomtowns Are More Negative and, if More Negative, the Percentage Saying That These Effects Are a Priority

	NGO	Industry	Academia	Gov't	All
More negative	76.5	8.0	40.3	27.5	32.2
If more negative: high priority?	84.6	66.7	76.0	54.5	75.0

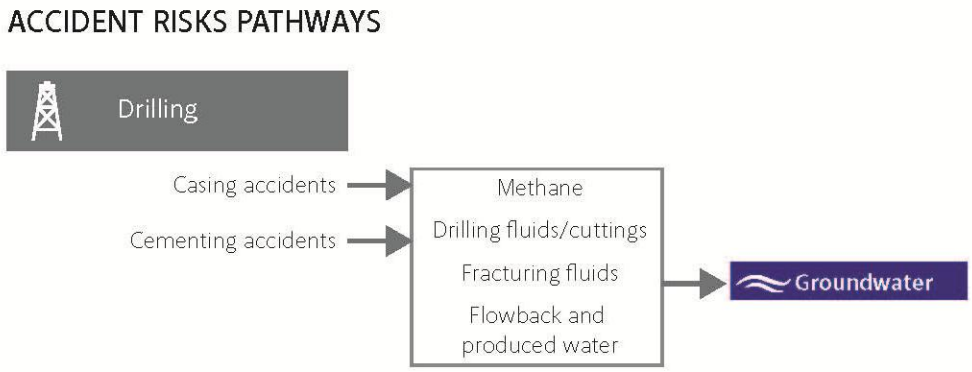
4.10 Accident Priorities

In addition to potential risks associated with routine shale gas development, experts also reviewed a list of 14 potential accidents (such as those involving trucks servicing the development site or a cement or casing failure). They were asked to identify high-priority accidents—those that they believe require further attention by government or industry—and to note the probability of the accident occurring and the likely severity of its impact.

4.10.1 Type and Number of Accidents Selected

As shown in Table 16 all groups share the top two accident priorities: cement and casing failure (Figure 5). Impoundment failure is in the top three for all groups except industry, which placed truck accidents third.

Figure 5.



As with routine risks, NGO respondents chose more accident categories (41 percent) than the other groups did (27 percent for industry, 34 percent for academic, and 31 percent for government respondents). On average, NGO experts picked more accidents than the average industry expert (significant at the 99 percent level) and government expert (significant at the 90 percent level), and the average academic expert picked more than the average industry expert (significant at the 90 percent level) as well. Because of their greater responses across accident categories, NGO experts show greater unanimity: the most selected priority was identified by 80 percent of NGO experts, whereas the most selected priority for the other groups garnered 57–66 percent of votes in their respective groups. This closely mirrors the results for risks from routine operations.

Table 16. Percentage of Experts Who Selected Accidents as a Priority for Additional Action

Accidents	NGO	Industry	Academia	Gov't	All Experts
Cement failure	80.0	58.7	57.1	66.7	63.3
Casing failure	68.6	46.7	61.9	57.1	56.7
Impoundment failure	71.4	33.3	61.9	45.2	50.2
Surface blowout	54.3	34.7	49.2	40.5	43.3
Storage tank spills	42.9	30.7	46.0	28.6	36.7
Truck accidents	37.1	40.0	34.9	28.6	35.8
Pipeline ruptures	42.9	30.7	38.1	33.3	35.3
Surface valve failure	40.0	21.3	27.0	26.2	27.0
Underground well comm.	37.1	14.7	28.6	23.8	24.2
Other spills	22.9	20.0	20.6	23.8	21.4
Underground blowout	31.4	14.7	20.6	23.8	20.9
Hose bursts	22.9	17.3	14.3	16.7	17.2
Other fires or explosions	8.6	13.3	7.9	14.3	11.2
Other not listed here	8.6	5.3	11.1	2.4	7.0
All 14 accidents	40.6	27.2	34.2	30.8	32.2
Average # of accidents selected as high priority	5.69	3.81	4.79	4.31	4.50

Notes: Darkest red is the most often selected for each group, middle red is the second–most often selected, and light red is the third–most selected.

4.10.2 Accident Probabilities[9]

Our sample identified the two lowest-probability categories (< 0.1 percent and 0.1–1 percent) as appropriate for their priority accidents 52 percent of the time (Table 17, last column). The percentage choosing higher-probability categories falls off rapidly from there.

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[9] At this point, the analysis drops responses from “other” accidents (which were “fill-in” options) to make responses more comparable.

Table 17. Severity/Probability for High-Priority Accidents: All Experts

Probability	Severity					Total
	Very low	Low	Medium	High	Very high	
50–100%	0 0.0%	1 0.1%	7 0.8%	3 0.3%	6 0.7%	17 1.9%
25–50%	1 0.1%	0 0.0%	3 0.3%	20 2.3%	11 1.2%	35 4.0%
10–25%	0 0.0%	1 0.1%	14 1.6%	12 1.4%	6 0.7%	33 3.7%
5–10%	3 0.3%	8 0.9%	33 3.7%	13 1.5%	15 1.7%	72 8.1%
2–5%	0 0.0%	16 1.8%	48 5.4%	44 5.0%	9 1.0%	117 13.2%
1–2%	4 0.5%	28 3.2%	51 5.8%	47 5.3%	19 2.1%	149 16.9%
0.1–1%	17 1.9%	42 4.8%	77 8.7%	70 7.9%	27 3.1%	233 26.4%
0–0.1%	27 3.1%	34 3.8%	64 7.2%	57 6.4%	46 5.2%	228 25.8%
Total	52 5.9%	130 14.7%	297 33.6%	266 30.1%	139 15.7%	884 100.0%

Notes: Green indicates 4%—5.9% of the sample, blue is 6%—7.9% of the sample, and purple is 8% or more of the sample.

Breaking these results into groups (Tables 17–20), we see that NGO experts chose primarily the second- to fourth-lowest categories, with the median in the fourth-lowest category of 2–5 percent probability. In a departure from the overall sample, only 25 percent of their choices fall in the two lowest-probability categories, and 11 percent of the choices are in the second-highest probability category of 25–50 percent.

In contrast, for industry and academic experts, 61 percent of choices fall into the two lowest-probability categories. For government respondents, 54 percent of choices are in these two categories. Statistical analyses of these responses confirms that NGO experts chose higher average probabilities[10] across all accidents than did each of the other groups (significant at the 99 percent level compared with industry and academic experts, and at the 95 percent level compared with government experts).

These choices are probably skewed upward because respondents indicated probabilities only for their "priority" accidents. Logically, we expected no one to choose the lowest probability for these accidents, but presumably some respondents assigned a much lower probability to accidents that they did not put into the priority category.

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[10] We describe probability on a 1 to 8 scale, where 0–0.1 percent is 1, 0.1–1 percent is 2, etc.

Table 18. Severity/Probability for High-Priority Accidents: NGO Experts

	Severity					
Probability	Very low	Low	Medium	High	Very high	Total
50–100%	0 0.0%	0 0.0%	1 0.5%	0 0.0%	5 2.7%	6 3.2%
25–50%	0 0.0%	0 0.0%	2 1.1%	12 6.5%	6 3.2%	20 10.8%
10–25%	0 0.0%	1 0.5%	6 3.2%	3 1.6%	1 0.5%	11 5.9%
5–10%	0 0.0%	1 0.5%	5 2.7%	5 2.7%	10 5.4%	21 11.3%
2–5%	0 0.0%	2 1.1%	17 9.1%	20 10.8%	3 1.6%	42 22.6%
1–2%	0 0.0%	2 1.1%	14 7.5%	18 9.7%	5 2.7%	39 21.0%
0.1–1%	0 0.0%	1 0.5%	10 5.4%	11 5.9%	9 4.8%	31 16.7%
0–0.1%	0 0.0%	0 0.0%	7 3.8%	3 1.6%	6 3.2%	16 8.6%
Total	0 0.0%	7 3.8%	62 33.3%	72 38.7%	45 24.2%	186 100.0%
Key	4-5.9% of sample		6-7.9% of sample		≥8% of sample	

Table 19. Severity/Probability for High-Priority Accidents: Industry Experts

Probability	Severity					Total
	Very low	Low	Medium	High	Very high	
50–100%	0 0.0%	1 0.4%	1 0.4%	1 0.4%	0 0.0%	3 1.1%
25–50%	1 0.4%	0 0.0%	1 0.4%	4 1.5%	4 1.5%	10 3.8%
10–25%	0 0.0%	0 0.0%	2 0.8%	4 1.5%	1 0.4%	7 2.7%
5–10%	1 0.4%	5 1.9%	7 2.7%	4 1.5%	3 1.1%	20 7.6%
2–5%	0 0.0%	6 2.3%	12 4.6%	8 3.1%	2 0.8%	28 10.7%
1–2%	1 0.4%	9 3.4%	13 5.0%	8 3.1%	4 1.5%	35 13.4%
0.1–1%	9 3.4%	17 6.5%	19 7.3%	25 9.5%	11 4.2%	81 30.9%
0–0.1%	10 3.8%	9 3.4%	24 9.2%	23 8.8%	12 4.6%	78 29.8%
Total	22 8.4%	47 17.9%	79 30.2%	77 29.4%	37 14.1%	262 100.0%
Key	4-5.9% of sample		6-7.9% of sample		≥8% of sample	

Table 20. Severity/Probability for High-Priority Accidents: Academic Experts

	Severity					
Probability	Very low	Low	Medium	High	Very high	Total
50–100%	0 0.0%	0 0.0%	3 1.1%	1 0.4%	1 0.4%	5 1.9%
25–50%	0 0.0%	0 0.0%	0 0.0%	1 0.4%	1 0.4%	2 0.7%
10–25%	0 0.0%	0 0.0%	1 0.4%	3 1.1%	1 0.4%	5 1.9%
5–10%	1 0.4%	2 0.7%	15 5.6%	4 1.5%	0 0.0%	22 8.2%
2–5%	0 0.0%	6 2.2%	8 3.0%	12 4.5%	2 0.7%	28 10.4%
1–2%	1 0.4%	3 1.1%	13 4.9%	17 6.3%	7 2.6%	41 15.3%
0.1–1%	1 0.4%	12 4.5%	33 12.3%	18 6.7%	3 1.1%	67 25.0%
0–0.1%	4 1.5%	19 7.1%	27 10.1%	27 10.1%	21 7.8%	98 36.6%
Total	7 2.6%	42 15.7%	100 37.3%	83 31.0%	36 13.4%	268 100.0%
Key	4-5.9% of sample		6-7.9% of sample		≥8% of sample	

Table 21. Severity/Probability for High-Priority Accidents: Government Experts

	Severity					
Probability	Very low	Low	Medium	High	Very high	Total
50–100%	0 0.0%	0 0.0%	2 1.2%	1 0.6%	0 0.0%	3 1.8%
25–50%	0 0.0%	0 0.0%	0 0.0%	3 1.8%	0 0.0%	3 1.8%
10–25%	0 0.0%	0 0.0%	5 3.0%	2 1.2%	3 1.8%	10 6.0%
5–10%	1 0.6%	0 0.0%	6 3.6%	0 0.0%	2 1.2%	9 5.4%
2–5%	0 0.0%	2 1.2%	11 6.5%	4 2.4%	2 1.2%	19 11.3%
1–2%	2 1.2%	14 8.3%	11 6.5%	4 2.4%	3 1.8%	34 20.2%
0.1–1%	7 4.2%	12 7.1%	15 8.9%	16 9.5%	4 2.4%	54 32.1%
0–0.1%	13 7.7%	6 3.6%	6 3.6%	4 2.4%	7 4.2%	36 21.4%
Total	23 13.7%	34 20.2%	56 33.3%	34 20.2%	21 12.5%	168 100.0%
Key	4-5.9% of sample		6-7.9% of sample		≥8% of sample	

4.10.3 Accident Severity

As it is with probability, the exercise of assigning average severity, conditional on an accident, is highly subjective and qualitative. In the rightmost columns in Tables 17–21, we list the percentage of high-priority accidents respondents ranked in the upper end of the severity distribution. Over the entire sample, 16 percent of choices indicated this "very high" burden level. By group, the corresponding figure is 24 percent for NGO experts and about 13 percent for the others. Nevertheless, when severity scores are interpreted on a 1 to 5 scale, academics chose a higher average severity level than did industry (significant at the 95 percent level), whereas the average severity picked by NGO experts is significantly higher than that of the industry, academic, and government experts at the 99 percent level.

4.10.4 Probability–Severity Combinations

Table 17 describes the distribution of probability–severity combinations for accidents identified as high priorities in the full sample. Against this sample average color distribution, compare the distribution for NGO experts in Table 18. Compared to the full sample, NGO experts chose both higher probabilities for their selected high-priority accidents and higher severities, shifting the color distribution to the lower right. Unlike any other group, NGO experts have a nontrivial number of responses in the highest levels of probability and almost no responses in the low-burden responses. The corresponding description for industry (Table 19) is quite different. Relative to the average, the color distribution for industry experts' identified accident priorities is definitively nearer the top, indicating lower probabilities. The severity distribution for industry experts appears to be more variable, however, and if anything somewhat further right (indicating higher severities than the average). The color pattern for academics (Table 20) appears to be much more like that of industry experts than NGO experts, with the government respondents (Table 21) between those of industry and academics on the one hand and NGOs on the other.

The color distributions in Tables 16–20 are evocative, but they don't tell us whether the groups are making statistically different choices. To examine this, we calculated a severity–probability score that normalizes both categories to one and then multiplies the appropriate values for each probability–severity pair that a respondent chose. Averaging across all respondents in a group gives the group score. Taking the standard deviation of scores across all individuals in a group permits a statistical test of whether the average scores are different for a given accident relative to the average of other groups.

NGO experts' score for the average of all 11 accidents is significantly higher than those of industry, academic, and government experts at the 99 percent level, but the scores for the other three groups are not statistically different from each other. Table 22 displays the severity–probability scores for cementing failure and casing failure (in all groups' top three), impoundment failure (in all but industry experts' top three) and truck accidents (industry experts' third choice).

Table 22. Mean Severity–Probability Score

	NGO	Industry	Academia	Gov't	All
Cement failure	0.480***	0.236*	0.229	0.298	0.296***
Casing failure	0.436**	0.242*	0.235	0.220	0.274***
Impoundment failure	0.349	0.229	0.223	0.265	0.260**
Truck accidents	0.396	0.264**	0.256*	0.238	0.280***
Average of other 7 accidents§	0.319	0.178	0.186	0.223	0.218
Avg of all 11 accidents§	0.356	0.201	0.222	0.247	0.242

§Does not Include three "other" categories.

*,**,*** Mean score is statistically significantly different from the average of the other 7 accidents for the relevant group at the 90%, 95%, and 99% levels, respectively.

These consensus accidents are not only listed more often as high priorities, but the experts who chose them consistently gave them a severity–probability score that is higher than that assigned to other high-priority accidents.

4.11 Influence of Subaffiliation and Expertise on Choices

So far we have made no distinctions among experts other than their group affiliations. In general, we found that subaffiliation does matter, but expertise and other personal characteristics are rarely important.

With respect to subaffiliation, *federal* government expert respondents appear more concerned with air quality risks (notably flaring of methane), which were less frequently identified by *state* government experts as a whole. However, federal experts rarely identified risks stemming from the disposal of drilling fluids, drill solids, and cuttings as a priority, unlike state experts.

The industry experts are divided into two groups: those representing extraction and producing companies and those affiliated with other parts of the value chain, including consulting firms, law firms, and industry advocacy groups. Whereas industry experts overall chose community impacts more often (relative to other pathways) than other groups, *extraction* industry experts chose community impact risk pathways *even more often* than the industry group as a whole. However, the potential impact on surface water from applying wastewater for road deicing was ranked very low by extraction experts, despite being within the top 20 priority risk pathways for all other groups (including nonextraction industry experts).

One variable that comes up again and again in hypotheses about attitudes toward risks is importance of the expert's degree of expertise. Industry representatives, for instance, argue that they have the most and best-trained experts, who understand that risks associated with shale gas development are quite low despite public perception to the contrary.

To see whether this rhetoric holds, we examined the routine priorities of self-defined "top experts"—those who indicated that they have high expertise in one or more of the activity categories for shale gas development. Table 23 shows the fraction of top experts by group and activity. Note that the entire sample is equally split between top experts and regular experts, but industry has the most experts by far.

Table 23. Number and Percentage of Top Experts, by Group and Activity

	NGO		Industry		Academia		Government		All	
Site development & drilling preparation	7	18% 20%	15	38% 20%	7	18% 11%	11	28% 26%	40	100% 19%
Drilling activities	4	10% 11%	22	54% 29%	7	17% 11%	8	20% 19%	41	100% 19%
Fracturing & completion	5	10% 14%	27	55% 36%	8	16% 13%	9	18% 21%	49	100% 23%
Well production & operation	4	10% 11%	22	56% 29%	5	13% 8%	8	21% 19%	39	100% 18%
Fracturing fluids, flowback, & produced water storage & disposal	4	8% 11%	24	49% 32%	12	24% 19%	9	18% 21%	49	100% 23%
Other activities	6	11% 17%	30	54% 40%	10	18% 16%	10	18% 23%	56	100% 26%
High expertise for at least one activity category	12	12% 34%	48	48% 64%	32	32% 51%	18	18% 42%	101	100% 47%

Notes: The first number is the number of top experts. The top percentage is the percentage of top experts from that group (e.g., x% of top experts are NGO experts), and the bottom percentage is the percentage of the group who are top experts (e.g., x% of NGO experts are top experts).

Self-identified top experts gave priority to 10 of the 12 consensus pathways (the potential impact on surface water from storing fracturing fluids at a drill site before and after using the fluid were *not* identified as priorities very often by either drilling or fracturing top experts). The escape of methane into groundwater as a result of casing and cementing failure was often identified as a priority by drilling top experts, including *all* of the NGO top experts (see Figure 6 top expert pathway). However, the NGO group in general did not select this pathway in its top 20 priorities; this pathway *is* among the top 20 priorities for industry, academic, and government experts. Overall, we add this pathway to the list of consensus pathways.

Figure 6.

We looked at the percentage of top experts from each activity who designated a pathway in that activity as a high priority and determined whether that level of support conflicted with the pathway's current status in the Venn diagram (Table 24).

Three of the priority pathways with increased support from the top experts are community disruptions, which we have noted are a particular concern mostly of industry. Another five are air quality pathways, which NGO experts were more likely to choose than other groups overall. The biggest increase in support came for seismic vibrations from deep underground injection of wastewater, which was selected more frequently by top experts than most consensus pathways were by the entire population of experts. While a very high number of top experts selected these pathways, support was concentrated in certain groups of top experts, so they were not truly consensus picks.

Of the 12 consensus pathways, 10 were selected by more than 42 percent of top experts. We interpret this result as confirmation of the pathways' importance.

The two that failed to garner much support from top experts are the effects of fracturing fluids on surface water during storage of fracturing fluids at a site and during on-site pit or pond storage. Top experts also downplayed the impacts from drilling fluids and cuttings.

Top experts' opinions can also shed some light on the impact of methane on groundwater during casing and cementing. This effect was chosen most without being a consensus pathway because NGO experts did not place it in their top 20. Fifty-one percent of drilling top experts selected this pathway, including all four from NGOs. This makes a strong case that it should be included as a consensus pathway.

Table 24. Top Experts' High Priorities

	Activity	Burden	Impact	All experts high priority	Top experts high priority	Diff	Signifi-cance	Movement
Drilling activities								
	Flaring of methane during drilling	Methane	Air Quality	25 (24.7%)	6 (34.1%)	9.5%	none	↑ into Venn
	Drilling equipment operation at surface	Conventional air pollutants & CO_2	Air Quality	20 (26.5%)	6 (34.1%)	7.6%	none	↑ into Venn
	Drilling equipment operation at surface	Industrial landscape	Community	15 (30.2%)	6 (34.1%)	3.9%	none	↑ into Venn
	Drilling equipment operation at surface	Drilling fluids & cuttings	Surface water	11 (34.9%)	29 (17.1%)	—17.8%	99%	↓ out of Venn
	Use of surface water & groundwater	Freshwater withdrawals	Groundwater	5 (39.1%)	18 (24.4%)	—14.7%	95%	↓ out of Venn
	Disposal of drilling fluids, solids, & cuttings	Drilling fluids & cuttings	Surface water	3 (43.7%)	10 (29.3%)	—14.5%	95%	↓ out of Venn
	Storage of drilling fluids at surface	Drilling fluids & cuttings	Surface water	6 (38.6%)	18 (24.4%)	—14.2%	95%	↓ out of Venn
	Use of surface water & groundwater	Freshwater withdrawals	Surface water	8 (37.2%)	14 (26.8%)	—10.4%	none	↓ out of Venn
	Disposal of drilling fluids, solids, & cuttings	Drilling fluids & cuttings	Groundwater	4 (39.5%)	10 (29.3%)	—10.3%	none	↓ out of Venn
Fracturing & completion								
	Flowback of reservoir fluids	Methane	Air Quality	9 (32.6%)	4 (40.8%)	8.3%	none	↑ into Venn
	Flowback of reservoir fluids	VOCs	Air Quality	11 (26.5%)	7 (34.7%)	8.2%	none	↑ into Venn
	Flaring of methane during fracking	Conventional air pollutants & CO_2	Air Quality	10 (28.8%)	7 (34.7%)	5.9%	none	↑ into Venn
	Storage of fracturing fluids at drill site	Fracturing fluids	Surface water	5 (42.3%)	9 (32.7%)	—9.7%	none	↓ out of top 12
Well production & operation								
	Well production	Flowback & produced water constit.	Surface water	1 (39.5%)	9 (23.1%)	—16.5%	95%	↓ out of Venn
	Well production	Flowback & produced water constit.	Groundwater	2 (35.8%)	9 (23.1%)	—12.7%	90%	↓ out of Venn
Fracturing fluids, flowback, & produced water disposal and storage								
	Deep underground injection	Seismic vibrations	Community	9 (35.3%)	3 (51.0%)	15.7%	99%	↑ into top 12
	Transport off-site	Road congestion	Community	10 (36.3%)	3 (51.0%)	14.7%	95%	↑ into top 12
	On-site treatment & reuse	Flowback & produced water constit.	Surface water	14 (30.2%)	8 (36.7%)	6.5%	none	↑ into Venn
	On-site pit or pond storage	Fracturing fluids	Surface water	4 (48.8%)	9 (32.7%)	—16.2%	99%	↓ out of top 12
	Treatment by municipal treatment plants	Fracturing fluids	Surface water	7 (39.1%)	13 (28.6%)	—10.5%	90%	↓ out of Venn

Notes: All respondents refers to the entire sample including experts. Diff is the difference between the top experts and the entire sample. Significance denotes the level of statistical significance between the percentage of experts and of other experts who listed each pathway as a high priority. The ranks outside of the parentheses are the ranks within each activity category. Casing and cementing during drilling does not appear in this chart because the percent of non-top experts who selected it was already very high.

Three of the priority pathways with increased support from the top experts are community disruptions, which we have noted are a particular concern mostly of industry. Another five are air quality pathways, which NGO experts were more likely to choose than other groups overall. The biggest increase in support came for seismic vibrations from deep underground injection of wastewater and transport of fluids off-site, which were selected more frequently by top experts than most consensus pathways were by the entire population of experts. While a very high number of top experts selected these pathways, support was concentrated in certain groups of top experts, so they were not truly consensus picks.

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Top experts' opinions can also shed some light on the impact of methane on groundwater during casing and cementing. This effect was chosen most without being a consensus pathway because NGO experts did not place it in their top 20. Fifty-one percent of drilling top experts selected this pathway, including all four from NGOs. This makes a strong case that it should be included as a consensus pathway.

4.12 What Characteristics, Other Than Group Affiliation and Expertise, Explain Choices?

In this section, we look even further beyond the group and expertise designation to examine whether other, more fundamental personal characteristics might explain choices in the survey.

Separating out group effects from others is complicated because the choice of group to join is the outcome of a complex employment process that may or may not be explained by one's field, degree, level of expertise, years since degree, and so on. For instance, true experts might have a predilection to become academics (or academia may breed true experts). On the other hand, true experts may be drawn to the higher starting salaries of some industry jobs. To the extent that group affiliation is a surrogate for, or collinear with, these other variables, it will not be possible to identify separate effects.

With careful statistical analysis, however, we can make progress. The idea is either to look at the effect of personal characteristics on choices *within* a group, or to use terms that interact group affiliation with personal characteristics in a multiple regression framework.

We selected five dependent variables that we have already shown are influenced by group: the number of routine priorities, the number of accident priorities, the net effect of boomtowns on communities, who should be primarily responsible for mitigating risks,[11] and the average severity–probability score for each expert.

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[11] To test this, we created a variable that equals –1 for sole or primary industry responsibility, 0 for shared responsibility, and 1 for sole or primary government responsibility.

4.12.1 Activity Expertise

We ran interaction regression models for each of the five dependent variables using a dummy variable for being a top expert for at least one activity. We then ran separate regressions using dummies for being a top expert for each separate activity.[12]

After accounting for group affiliation, the top experts made choices that are not statistically different from those of the regular experts, except in two cases.

- NGO and government top experts picked significantly more high-priority accidents than did regular experts in their respective groups.
- Industry top experts with expertise in fracturing fluids, flowback, and produced water storage and disposal tended to pick more accidents than did regular industry experts.

4.12.2 Oil and Gas Experience

We also tested whether the answers of respondents who indicated that their sole or primary experience is in the oil and gas field were different from those of other experts in their group. For no group did oil and gas experience affect the total number of routine or accident priorities, but academic experts with this experience are more likely than academic experts without it to have a positive view about boomtowns (significant at the 95 percent level) and a lower average severity–probability score for accidents (significant at the 99 percent level).

Most notable is our analysis of experts' views on who should take primary responsibility for addressing risks. Industry, academic, and government experts' experience in the oil and gas industry is associated with an increased likelihood of choosing industry as the responsible party (a result that is statistically significant for industry and government experts at the 95 percent level and for academic experts at the 90 percent level). But NGO experts with oil and gas experience were more likely to choose government (significant at the 99 percent level).

4.12.3 Other Measures of Experience

We attempted to explain responses using three other measures: years of experience in current field, sole or primary experience in shale gas issues, and top expertise in at least one burden (rather than activity) category. None of these variables affected responses except burden top expertise among academic experts, who chose more accident priorities than did academic experts without burden top expertise (significant at the 99 percent level).

4.12.4 Education

We also tested whether experts' type of degree affected responses. We grouped degrees into three categories: social science (business, economics, government, or law); hard science (biology, chemistry, environmental science, geology, hydrology, or seismology); and engineering. Having a social science degree had no significant effects, whereas some weak relationships were associated with a hard science degree. Academic experts with this type of education are more likely than academic experts without a hard science degree to see boomtowns as positive, and industry and government experts with a hard science degree reported smaller severity–probability scores. These relationships are significant only at the 90 percent level. Having an engineering degree was associated with an increased

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[12] As a result of small sample sizes for individual-activity top experts from each group, we were mostly interested in the effect of being a top expert for a specific activity among industry respondents.

likelihood of seeing boomtowns as positive for government and industry experts but a lower chance of seeing them as positive for academic experts (all at the 95 percent significance level).

4.12.5 A Closer Look at Industry and Academic Experts

To break the intertwining of group affiliation with other personal characteristics, we can look for effects of these characteristics within a group. Enough industry and academic experts responded to the survey that we were able to run separate group regressions with more than one type of explanatory variable. For industry experts, we regressed the oil and gas experience and shale gas experience dummies, years of experience in field of work, dummies for degree type, and a dummy for being a top expert in each activity on the five dependent variables. (For academics, we used the dummy for being a top expert in at least one activity rather than the six individual dummies.)

We found that group affiliation dominates the ability to explain choices, with a few exceptions. Three effects are significant at the 95 percent level within the industry group.

- Industry engineers are more likely than nonengineer industry experts to see boomtowns as positive.
- Top experts in well production and operation tended to choose fewer accident priorities than did regular experts.
- Experts with experience in the oil and gas field are more likely to believe that industry should be primarily responsible for addressing risks.

Within the academic group, two other effects are significant.

- Experts with experience in the oil and gas field had lower severity–probability scores (significant at the 99 percent level) and are more likely to view boomtowns as positive (at the 90 percent level).
- Experience in shale gas issues is positively related to the number of accident pathways chosen (significant at the 90 percent level).

Notably, among academic experts, experience in oil and gas is not related to opinions regarding the responsibility for addressing risks under these separate regressions.

4.13 High-Priority Fluid Burdens

Environmental burdens (e.g., air pollutants, intrusion of saline water into aquifers, noise pollution, and road congestion) are the outcomes of shale gas activities. Experts were given an opportunity to identify which burdens are priorities for further government or industry action. This part of the survey focused on the 104 specific fluid burdens created as part of the shale gas development process.

The most frequently identified fluid burden seen as a priority by all four groups are the naturally occurring radioactive materials found in flowback, produced water, drilling fluids, and cuttings. Of the 10 fluid burdens most frequently identified by each group, 6 are common among all of the experts (Table 25).

Table 25. Six Fluid Burdens Identified by All Expert Groups as a "High Priority" for Further Action

High priority fluid burden	Where the burden is found	% high priority
Naturally occurring radioactive materials	Flowback and produced water	31.2
Aromatic hydrocarbons		26.5
Hydrogen sulfide		24.7
Diesel oil	Drilling fluids and cuttings	22.8
Naturally occurring radioactive materials		21.9
Oils (including diesel)	Fracturing fluids	22.8

Expanding the set to the top 20 adds 3 additional fluid burdens to the list: total dissolved solids (which were chosen by 21.9 percent of the experts), arsenic (16.7 percent), and oil and grease (15.8 percent).

We also found notable areas of disagreement. Total suspended solids (TSS) received a high ranking from NGO experts and a low ranking from experts in the other groups. Government experts gave acids a lower ranking than did those in the other groups, but they gave chlorides a higher ranking than did the other groups. Finally, academic experts gave a high ranking to biocides and surfactants relative to NGO experts.

4.14 Comments

We gave respondents an opportunity to write in comments on four topics:

- missing pathways, mis-specified pathways, or other problems with the risk matrix;
- issues specific to a given play;
- risks from inputs to the shale gas development process; and
- general comments about the survey.

We placed comments on the survey's risk characterization into three categories: survey objections, clarifying questions, and pathway objections (Table 26). Survey objections concerned issues with the survey format as a whole. Many of the clarifying comments were too specific for summation, but the most common type concerned the fact that priorities vary across plays (6 of 32). The most common pathway objection (5 of 13 comments) was that some experts want more habitat and community pathways for pipelines (although pipelines were included as part of the site development category).

Table 26. Comments on the Routine Risk Matrix

Type of comment (49 total)	NGO	Industry	Academia	Gov't	Total	% of comments	% of all experts
Survey objection	2	2	0	0	4	8.2	1.9
Clarify choices	7	11	10	4	32	65.3	14.9
Pathways objection	6	4	2	1	13	26.5	6.0

Experts who said that their priorities vary by play were given the opportunity to comment, and the categorized results are in Table 27. Of these 38 experts, 12 have knowledge limited to a specific area and more than half are government experts. Academic experts were most likely to describe specific natural and human features—like the geology of the play, environmental impacts, and proximity to water or communities—as the reason priorities may change.

Table 27. Comments on Plays

Type of comment (38 total)	NGO	Industry	Academia	Gov't	Total	% of comments	% of all experts
Only know about Marcellus	3	1	0	3	7	18.4	3.3
Only know about other play	1	0	0	4	5	13.2	2.3
Natural features	2	1	6	1	10	26.3	4.7
Human features	2	3	2	1	8	21.1	3.7
Both natural and human	1	2	3	2	8	21.1	3.7

Table 28 displays the categorization of comments about risks from industries that support the shale gas development process, such as chemical manufacturing (some comments are in more than one category). Few experts commented about these industries, but of those who did, the most popular concern was about sand mining for the fracturing process.

Table 28. Comments on Other Industries

Type of comment (11 total)	NGO	Industry	Academia	Gov't	Total	% of comments	% of all experts
Sand mining	2	1	2	0	5	45.5	2.3
Chemical plants	2	0	0	0	2	18.2	0.9
Cracker plants	1	0	2	0	3	27.3	1.4
Independent contractors	0	2	0	0	2	18.2	0.9
Industrial waste	0	0	2	0	2	18.2	0.9

Table 29 categorizes the 86 comments experts made when given one last opportunity to comment. Industry experts were particularly keen to register their concerns with the survey design. They most often expressed frustration that the survey forced a choice between industry and government responsibility and did not distinguish state from federal government. Many government experts suggested how to improve regulations, and four industry experts complained about burdensome regulations. Twelve experts mentioned the need for either more outreach (mostly to counter "hysteria") or more transparency from the industry. The rest of the comments were categorized as "clarification" or "new details" and mostly concerned air quality or community disruption.

Table 29. Final Comments

Type of comment (86 total)	NGO	Industry	Academia	Gov't	Total	% of comments	% of all experts
Survey objections:							
No ability to discern responsibility	1	4	2	0	7	8.1	3.3
Didn't address benefits	0	3	1	0	4	4.7	1.9
Other survey objection	4	2	2	1	9	10.5	4.2
Regulations:							
Better regulation	2	4	3	7	16	18.6	7.4
More industry transparency/outreach	1	6	4	1	12	14.0	5.6
Regulations burdensome	0	4	1	0	5	5.8	2.3
Clarify choices or added detail:							
Groundwater & surface water	2	1	1	4	8	9.3	3.7
Air quality	3	1	6	1	11	12.8	5.1
Habitat disruption	0	0	1	0	1	1.2	0.5
Community disruption	3	5	2	3	13	15.1	6.0

5. Key Findings

The potential environmental risks related to shale gas development are not well understood. We surveyed US experts from government agencies, industry, academia, and environmental organizations for their insights into these risks, with the hope of finding common ground. Specifically, the experts were asked to identify the priority environmental risks related to shale gas development—those for which the experts believe government regulation and/or voluntary industry practices are currently inadequate to protect the public or the environment.

The results demonstrate a high degree of consensus among experts about the specific risks to mitigate (see Figure 3). Although this survey does not rank any of these priority risks by level of importance, the results do indicate that progress toward productive dialogues may be most likely achieved around:

- 12 consensus risk pathways related to routine operations,
- 2 additional risk pathways related to potential accidents, and
- a final routine risk pathway identified by a group of top experts within the expert sample.

However, only two of these risk pathways are unique to the shale gas development process; the remainder relate to practices common to gas and oil development.

Out of the possible 264 routine risk pathways, we examined the top 20 pathways chosen most frequently by each expert group—those that are priorities for further government or voluntary industry action. **Out of all of these pathways, 12 were chosen *by all four groups*:**

- Seven involve potential risks to surface water quality, two involve potential risks to air quality, two involve potential risks to groundwater quality, and one is related to habitat disruption.
- At least one-third of the experts in each group identified these 12 specific pathways as priorities from the 264 possible choices. Even so, on average, NGO experts identified about twice as many routine impact pathways as high priorities for further action compared to the experts in the other three groups.

Furthermore, self-identified top experts in drilling selected an additional risk pathway as a priority: the possible routine escape of methane into groundwater as a result of casing and cementing problems.

When asked about priorities for 14 accident risk pathways, all experts identified the same two accidents in their top three most frequently chosen priorities: cement failure and casing failure. All of these risk pathways can be seen in Figure 7 below.

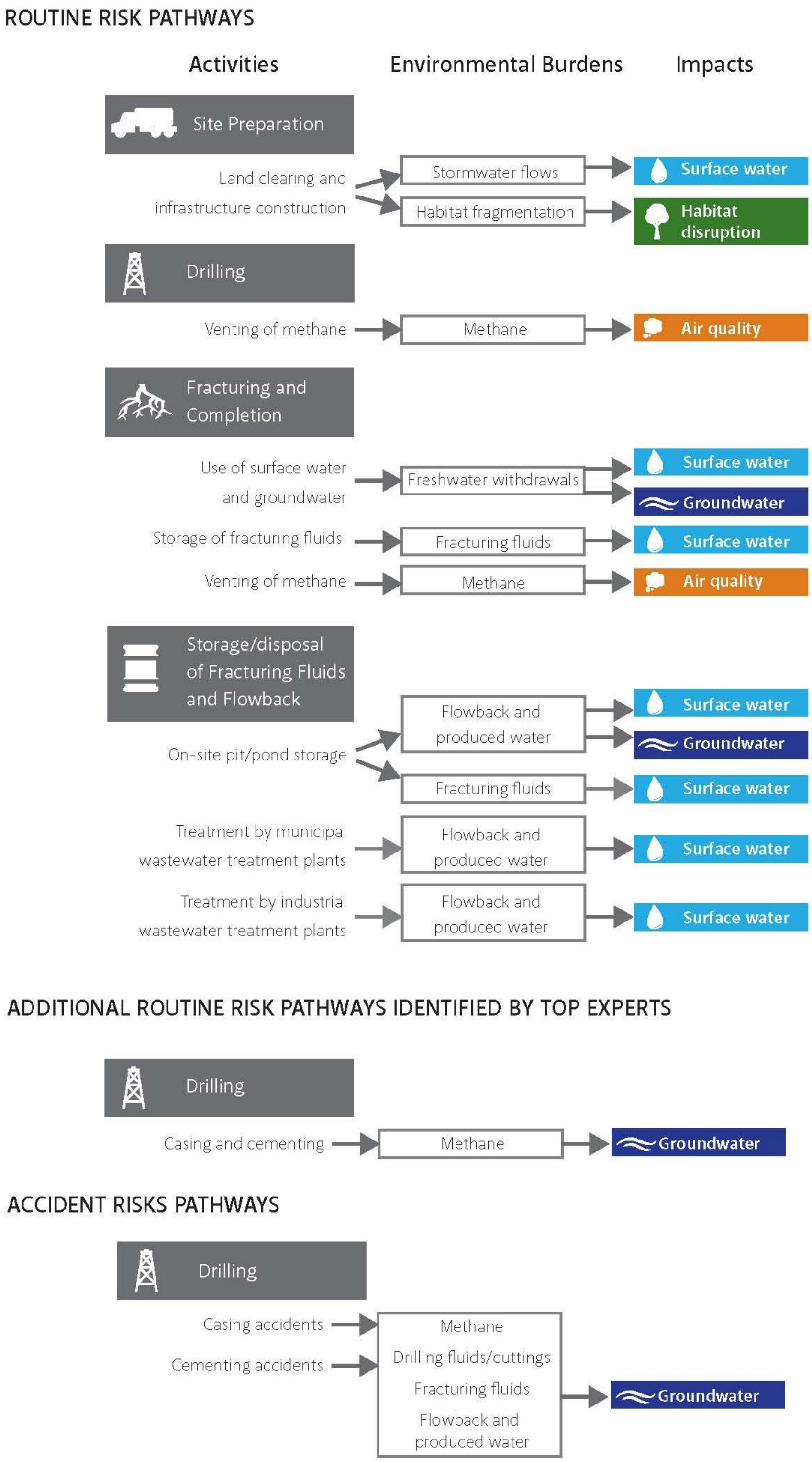
Expert groups are divided in the priority assigned to risk pathways outside of the 12 consensus pathways. A significant number of pathways are included in the top 20 of only one group (see Figure 3).

- Industry respondents uniquely identified six priority risk pathways related to community disruptions, such as road congestion from truck traffic associated with shale production.
- The five unique pathways selected by NGO respondents mostly target conventional air pollutants.
- The five unique pathways selected by government respondents focus entirely on groundwater risks.
- Academic respondents identified only two unique risk pathways: one relating to the potential for these industrial-scale activities to disrupt nearby communities and the other relating to the impact on groundwater from using freshwater withdrawals for drilling.

Experts were also given the opportunity to identify which *environmental burdens* should be priorities for government or industry action. The fluid burden most frequently identified as a priority by experts in all four groups is the naturally occurring radioactive materials found in flowback and produced water as well as in drilling fluids and cuttings.

Differences in self-reported expertise levels, experience, and educational background generally had no effect on survey responses, when controlling for affiliation. For subaffiliation, however, we found some differences in the top 20 most selected pathways. For example, whereas industry experts overall chose community impact risk pathways more often (relative to other pathways) than did other groups, *extraction* industry experts chose community impact risk pathways even more often than did the industry group as a whole.

Figure 7.


ROUTINE RISK PATHWAYS
Activities
Environmental Burdens
Impacts
Site Preparation
Land clearing and infrastructure construction
Stormwater flows
Surface water
Habitat fragmentation
Habitat disruption
Drilling
Venting of methane
Methane
Air quality
Fracturing and Completion
Use of surface water and groundwater
Freshwater withdrawals
Surface water
Groundwater
Storage of fracturing fluids
Fracturing fluids
Surface water
Venting of methane
Methane
Air quality
Storage/disposal of Fracturing Fluids and Flowback
On-site pit/pond storage
Flowback and produced water
Surface water
Groundwater
Fracturing fluids
Surface water
Treatment by municipal wastewater treatment plants
Flowback and produced water
Surface water
Treatment by industrial wastewater treatment plants
Flowback and produced water
Surface water
ADDITIONAL ROUTINE RISK PATHWAYS IDENTIFIED BY TOP EXPERTS
Drilling
Casing and cementing
Methane
Groundwater
ACCIDENT RISKS PATHWAYS
Drilling
Casing accidents
Cementing accidents
Methane
Drilling fluids/cuttings
Fracturing fluids
Flowback and produced water
Groundwater

All groups agreed that if sharing of authority is an option, government and industry should share the authority for risk mitigation, to some degree. When asked to choose government or industry (with no sharing option) as the primary party with authority to address the risks that the experts selected as priorities, NGO, academic, and government experts selected government more often than industry, whereas industry experts selected government and industry equally.

5.1 Some Additional Findings

5.1.1 Typical versus Tail-End Risks

On average, almost 80 percent of the available choices were not designated as priorities. Of the 20 percent selected as priorities, respondents had the choice of identifying their priority risk pathway as applying to a typical or tail-end situation (one with unusually challenging geology or hydrology, particularly sensitive natural environments, etc.). Only about 25 percent of those pathways apply to tail-end operating conditions only—the rest apply to both. We looked for high-priority tail-end choices that make big jumps up in selection frequency compared with their frequency for the typical case. Two stand out: the storage of fracturing fluids at a drill site and the intrusion of saline-formation water into fresh groundwater as a result of drilling a wellbore.

In contrast, three pathways fall significantly in the tail-end selection frequency compared to their typical selection frequency, indicating that if respondents feel they are high priorities, they are not unique only to tail-end cases. These include various fugitive methane pathways; the application of wastewater for road deicing, dust suppression from flowback, and produced water constituents (other than fracturing fluids); and the clearing of land for roads, well pads, pipelines, evaporation ponds, and other infrastructure affecting the industrial landscape.

5.1.2 Unimportant Pathways

The groups agree on many of the pathways that are not priorities: 16 shale gas development activities (out of 40 total) do not have any risk pathways in the top 20 for any group; using this definition, 223 pathways are of lesser or no importance.

5.1.3 Pathways Needing Research

We argue that risk pathways with serious disagreement across the groups are targets for further research. These pathways are listed in Table 5 above. Experts also noted that more research is needed on the impacts on surface water from the treatment of flowback and produced water by municipal and/or industrial wastewater plants before action is taken. Additional RFF research is currently examining this pathway. Among the consensus pathways, those more likely to be chosen as needing more research were also more likely to be chosen as pathways needing government action rather than industry action.

5.1.4 Which Groups More Closely Agree with One Another?

NGO experts conflict with industry experts in their risk pathway selections no more frequently than with government experts. Disagreements between NGO respondents and industry/government respondents are greatest about site development impacts. Industry, academic, and government respondents agree with each other more than any of these groups does with the NGO group.

5.2 Pathways to Dialogue

Our hope of finding common ground was largely realized because of the agreements we found among key stakeholder groups on both the pathways to mitigate and the party that should be responsible for making this happen. Future research at RFF will include developing information on these specific pathways and holding dialogues to make lower risks in these areas a reality.

Appendix A. The Survey

Table A1. The Routine Risk Matrix

Activities	Intermediate impacts					
Site development and drilling preparation	**Groundwater**	**Surface water**	**Soil quality**	**Air quality**	**Habitat disruption**	**Community disruption**
Clearing of land/construction of roads, well pads, pipelines, other infrastructure		Stormwater flows Invasive species	Stormwater flows	CAP and CO2	Habitat fragmentation Invasive species	Industrial landscape Light pollution Noise pollution
On-road vehicle activity		Stormwater flows		CAP and CO_2	Other	Noise pollution Road congestion
Off-road vehicle activity		Stormwater flows		CAP and CO_2	Other	Noise pollution
Drilling activities	**Groundwater**	**Surface water**	**Soil quality**	**Air quality**	**Habitat disruption**	**Community disruption**
Drilling equipment operation at surface	Drilling fluids/cuttings	Drilling fluids/cuttings	Drilling fluids/cuttings	CAP and CO2		Industrial landscape Light pollution Noise pollution
Drilling of vertical and lateral wellbore	Methane Drilling fluids/cuttings Saline water intrusion	Drilling fluids/cuttings		Methane		
Casing and cementing	Methane Drilling fluids/cuttings Saline water intrusion	Drilling fluids/cuttings	Drilling fluids/cuttings	Methane		
On-road and off-road vehicle activity		Stormwater flows		CAP and CO_2	Other	Noise pollution Road congestion
Use of surface water and groundwater	Freshwater withdrawals	Freshwater withdrawals Invasive species			Freshwater withdrawals Invasive species	
Venting of methane				Methane Hydrogen Sulfide		
Flaring of methane				CAP and CO_2 Methane Hydrogen Sulfide		Industrial landscape
Storage of drilling fluids at surface	Drilling fluids/cuttings	Drilling fluids/cuttings	Drilling fluids/cuttings	VOCs	Drilling fluids/cuttings	Industrial landscape
Disposal of drilling fluids, drill solids, cuttings	Drilling fluids/cuttings	Drilling fluids/cuttings	Drilling fluids/cuttings	VOCs	Drilling fluids/cuttings	

Notes: CAP is conventional air pollutants, VOC is volatile organic compounds

Table A1 (Cont). The Routine Risk Matrix

Fracturing and completion	**Groundwater**	**Surface water**	**Soil quality**	**Air quality**	**Habitat disruption**	**Community**
Use of surface water/groundwater	Freshwater withdrawals	Freshwater withdrawals Invasive species			Freshwater withdrawals Invasive species	
Perforation of well casing/cementing						Seismic vibrations
Hydraulic fracture initiation	Fracturing fluids	Fracturing fluids			Fracturing fluids	Seismic vibrations
Introduction of proppant	Fracturing fluids Proppants	Fracturing fluids Proppants		Silica	Fracturing fluids Proppants	Seismic vibrations
Flushing of wellbore	Fracturing fluids Proppants Methane	Fracturing fluids Proppants	Fracturing fluids	VOCs Methane	Fracturing fluids Proppants	
Flowback of reservoir fluids	Flowback/produced water Methane Hydrogen Sulfide	Flowback/produced water Hydrogen sulfide	Flowback/produced water Hydrogen sulfide	VOCs Methane Hydrogen sulfide	Flowback/produced water	
Venting of methane				Methane Hydrogen sulfide		
Flaring of methane				CAP and CO_2 Methane Hydrogen Sulfide		Industrial landscape
Storage of fracturing fluids at drill site	Fracturing fluids	Fracturing fluids	Fracturing fluids	VOCs	Fracturing fluids	Industrial landscape
On-road and off-road vehicle activity		Stormwater flows Invasive species		CAP and CO_2	Invasive species Other	Noise pollution Road congestion
Fracturing equipment operation				CAP and CO2		Industrial landscape Light pollution Noise pollution
Well production/operation	**Groundwater**	**Surface water**	**Soil quality**	**Air quality**	**Habitat disruption**	**Community**
Well production	Flowback/produced water	Flowback/produced water	Flowback/produced water	VOCs Methane Hydrogen Sulfide	Flowback/produced water	
Condensate tank, dehydration unit operation	Condenser and dehydration additives	Condenser and dehydration additives	Condenser and dehydration additives	CAP and CO_2 VOCs Methane		Industrial landscape
Compressor operation				CAP and CO_2		Industrial landscape Noise pollution
Flaring of methane				CAP and CO_2 Methane Hydrogen Sulfide		Industrial landscape

Table A1 (Cont). The Matrix

Fracturing fluids, flowback and produced water storage and disposal	**Groundwater**	**Surface water**	**Soil quality**	**Air quality**	**Habitat disruption**	**Community disruption**
On-site pit or pond storage	Fracturing fluids Flowback/produced water	Fracturing fluids Flowback/produced water	Fracturing fluids Flowback/produced water	VOCs	Fracturing fluids Flowback/produced water	Fracturing fluids Flowback/produced water
On-site tank storage	Fracturing fluids Flowback/produced water	Fracturing fluids Flowback/produced water	Fracturing fluids Flowback/produced water	VOCs	Fracturing fluids Flowback/produced water	Fracturing fluids Flowback/produced water
Transport off-site	Fracturing fluids Flowback/produced water	Fracturing fluids Flowback/produced water Invasive species		CAP and CO2	Fracturing fluids Flowback/produced water Invasive species	Fracturing fluids Road congestion Noise pollution Flowback/produced water
On-site treatment and reuse	Fracturing fluids Flowback/produced water	Fracturing fluids Flowback/produced water		VOCs		
Treatment, release by industrial wastewater treatment plants	Fracturing fluids Flowback/produced water	Fracturing fluids Flowback/produced water				Fracturing fluids Flowback/produced water
Treatment, release by municipal wastewater treatment plants	Fracturing fluids Flowback/produced water	Fracturing fluids Flowback/produced water				Fracturing fluids Flowback/produced water
Removal of sludge and other solids to landfills	Fracturing fluids Flowback/produced water	Fracturing fluids Flowback/produced water	Fracturing fluids Flowback/produced water	VOCs		Fracturing fluids Road congestion Flowback/produced water Noise pollution
Deep underground injection	Fracturing fluids Flowback/produced water	Fracturing fluids Flowback/produced water		VOCs		Seismic vibrations
Application of wastewater for road deicing, dust suppression	Fracturing fluids Flowback/produced water	Fracturing fluids Flowback/produced water	Fracturing fluids Flowback/produced water	VOCs	Fracturing fluids Flowback/produced water	Fracturing fluids Flowback/produced water
Other activities	**Groundwater**	**Surface water**	**Soil quality**	**Air quality**	**Habitat disruption**	**Community disruption**
Shutting-in	Drilling fluids/cuttings Fracturing fluids Flowback/produced water Saline water intrusion	Drilling fluids/cuttings Fracturing fluids Flowback/produced water	Drilling fluids/cuttings Fracturing fluids Flowback/produced water	CAP and CO2 Methane		
Plugging and abandonment	Drilling fluids/cuttings Fracturing fluids Flowback/produced water Saline water intrusion	Drilling fluids/cuttings Fracturing fluids Flowback/produced water	Drilling fluids/cuttings Fracturing fluids Flowback/produced water	CAP and CO2 Methane	Habitat fragmentation	Industrial landscape
Workovers	Drilling fluids/cuttings Flowback/produced water Saline water intrusion	Drilling fluids/cuttings Flowback/produced water	Drilling fluids/cuttings Flowback/produced water	CAP and CO_2 Methane Hydrogen sulfide		
Downstream activities (e.g., pipeline operation)				Methane		Odor

Table A2. List of Burdens

- **I. Air pollutants**
    - a. Conventional air pollutants and carbon dioxide (CO_2)
        - 1. Volatile organic compounds (VOCs)
    - b. Methane
    - c. Hydrogen sulfide
    - d. Silica
    - e. Other
- **II. Drilling fluids and cuttings**
- **1. Base fluids**
    - a. Water
    - b. Diesel oil
    - c. Mineral oils
    - d. Synthetic compounds (esters, paraffins, olefins)
    - e. Others
- **2. Weighting agents**
    - a. Bentonite
    - b. Barite
    - c. Hematite
    - d. Calcium carbonate
    - e. Ilmenite
    - f. Others
- **3. Thickeners**
    - a. Xanthan gum
    - b. Guar gum
    - c. Glycol
    - d. Carboxymethylcellulose
    - e. Polyanionic cellulose
    - f. Others
- **4. Thinners and deflocculants**
    - a. Acrylates
    - b. Polyphosphates
    - c. Lignosulfates
    - d. Lignites
    - e. Others
- **5. Cuttings**
    - a. Naturally occurring radioactive material
    - b. Turbidity
    - c. Others
- **III. Intrusion of saline-formation water into fresh groundwater**
- **IV. Fracturing fluids**
- **6. Base fluids**
    - a. Water
    - b. Oils (including diesel)
    - c. Methanol
    - d. Polymers
    - e. Others
- 7. Acids (hydrochloric, muriatic)
- 8. Potassium chloride
- **9. Proppants**
    - a. Silica sand
    - b. Resin-coated sand
    - c. Man-made ceramics
    - d. Radioactive minerals
    - e. Others
- **10. Foaming agents**
    - a. Nitrogen
    - b. CO_2
    - c. Alcohols
    - d. Glycol ethers
    - e. Others
- **11. Gelling agents**
    - a. Guar gum and derivatives
    - b. Cellulose derivatives
    - c. Others
- **12. Breakers and cross-linkers**
    - a. Enzymes
    - b. Oxidizers (ammonium persulfate)
    - c. Borate salts
    - d. Others
- **13. Other additives**
    - a. Biocides, bactericides, microbicides (glutaraldehyde)
    - b. Corrosion and scale inhibitors (ethylene glycol, methanol, ammonium chloride)

   c. Friction reducers (polyacrylamide, mineral oil, petroleum distillates)
   d. Iron control agents (citric acid)
   e. Surfactants (isopropanol, methanol)
   f. Fluid-loss agents (sands, flours, starches, clays)

V. Flowback and produced water constituents (other than fracturing fluids)

14. **Total dissolved solids**
   a. Chlorides (sodium, potassium)
   b. Bromides (as precursor of DBPs in drinking water)
   c. Carbonates
   d. Sulfates
   e. Nitrates
   f. Others
15. **Total suspended solids**
   a. Iron solids (iron oxide, iron sulfide)
   b. Sand, silt and clay
   c. Others
16. **Metals**
   a. Calcium
   b. Magnesium
   c. Barium
   d. Strontium
   e. Lead
   f. Mercury
   g. Manganese
   h. Molybdenum
   i. Zinc
   j. Arsenic
   k. Aluminum
   l. Lithium
   m. Others
17. **Naturally occurring radioactive materials**
   a. Radium-226
   b. Radium-228
   c. Uranium
   d. Thorium
   e. Others
18. **Acid gases**
   a. CO_2
   b. Hydrogen sulfide
19. Oil and grease
20. Aromatic hydrocarbons (BTEX)
21. Bacteria

VI. Condenser and Dehydration additives

22. Triethylene glycol
23. Other

VII. Habitat and community disruptions

24. Habitat fragmentation
25. Industrial landscape
26. Light pollution
27. Noise pollution
28. Odor
29. Road congestion/accidents
30. Seismic vibrations
31. Freshwater withdrawals
32. Stormwater flows
33. Other

Appendix B. Routine High-Priority Pathway Data

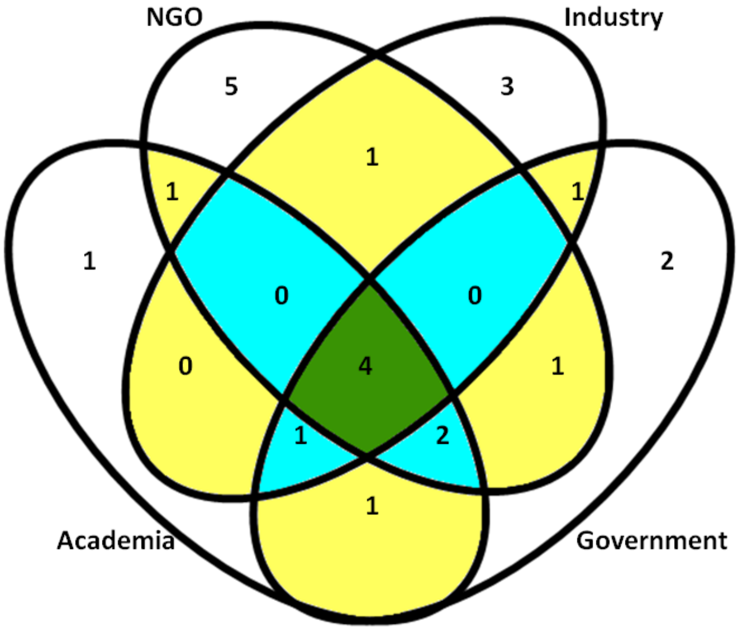
A range of analyses underpins and expands the survey results presented in Section 4. We describe our efforts in more detail here.

B1. Top 10 and 40 Routine Risk Pathways

In Section 4.2.2, we characterize the relative consensus and conflict among groups using the top 20 most selected risk pathways from each group—admittedly an arbitrary cutoff. Here, we provide a broader picture in several ways. First, we consider consensus among the top 10 (Figure B1) and the top 40 (Figure B2) most selected high-priority risk pathways identified by each group.[13] Figure B1 shows that 4 of the 12 pathways common to the top 20 across all four groups are still common to all groups' top 10 most selected. These include two surface water and two groundwater impacts:

- On-site pit or pond storage–flowback and produced water constituents–surface water
- Treatment, release by municipal wastewater treatment plants–flowback and produced water constituents–surface water
- On-site pit or pond storage–flowback and produced water constituents–groundwater
- Use of surface water and groundwater in fracturing–freshwater withdrawals–groundwater

Figure B1. Routine Risk Venn Diagram: Top 10 from Each Group



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[13] Due to ties, the "top 10" most selected risk pathways actually included 14 pathways for NGO experts and 12 pathways for government experts. The "top 40" included 49 pathways for NGO experts, 41 pathways for industry and academic experts, and 43 pathways for government experts.

Figure B2. Routine Risk Venn Diagram: Top 40 from Each Group

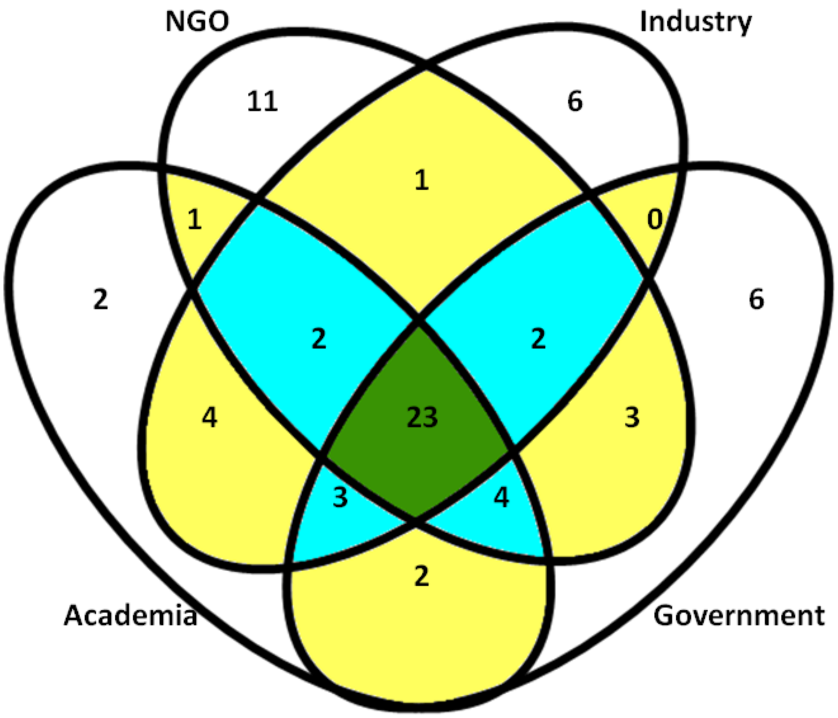

Figure B2 illustrates that a high degree of consensus also holds across all four groups, even as we expand to the top 40 most selected risk pathways by group—23 consensus pathways of 40 is nearly the same fraction as 12 consensus pathways of 20. Another interesting result is that the number of industry experts' priorities that are not shared by the other groups is unchanged at six, and thus shrinking proportionally.

B2. High-Priority Pathways by Aggregate Categories

In Sections 4.2 and 4.3, we consider high-priority pathways individually, chosen from the set of 264 pathways in the cells of Table B1. However, we can also examine priorities at a higher level of aggregation, using major activity categories, impact categories, the 36 activity–impact combinations, and burden types.

B2.1 Pathways by Activity Category

Table B1 shows high priorities across the six activity categories. These percentages are normalized for the number of choices available in a particular category. The entire sample (the rightmost column) selected more pathways that begin with drilling than any other category. At the group level, this preference is also in evidence.

Table B1. Normalized Percentage of Total Pathways Selected, by Activity Category

	NGO % of high	Industry % of high	Academia % of high	Gov't % of high	All % of high
Site development	16.2	20.4	18.5	18.6	18.3
Drilling activities	20.2	21.4	21.0	21.3	20.9
Fracking & completion	15.1	15.8	14.9	15.1	15.2
Well production	20.3	17.2	17.4	18.6	18.4
Fluid storage & disposal	16.2	16.1	18.3	17.1	16.9
Other activities	12.0	9.1	9.9	9.3	10.3

Because reductions in risks would, for the most part, alter how shale gas development activities are performed, it is worthwhile to look at high priorities by activity category. The following list provides the five most selected risk pathways across all experts for each of the six activity categories.

SITE DEVELOPMENT

1) Clearing of land for roads, well pads, pipelines, etc.	Stormwater flows	Surface water
2) Clearing of land for roads, well pads, pipelines, etc.	Habitat fragmentation	Habitat disruption
3) On-road vehicle activity	Road congestion	Community disruption
4)Clearing of land for roads, well pads, pipelines, etc.	Industrial landscape	Community disruption
5) Clearing of land for roads, well pads, pipelines, etc.	Noise pollution	Community disruption

DRILLING

1) Casing and cementing	Methane	Groundwater
2) Venting of methane	Methane	Air quality
3) Disposal of drilling fluids, drill solids, and cuttings	Drilling fluids and cuttings	Surface water
4) Disposal of drilling fluids, drill solids, and cuttings	Drilling fluids and cuttings	Groundwater
5) Use of surface water and groundwater	Freshwater withdrawals	Groundwater

WELL FRACTURING AND COMPLETION

1) Use of surface water and groundwater	Freshwater withdrawals	Surface water
2) Use of surface water and groundwater	Freshwater withdrawals	Groundwater
3) Flowback of reservoir fluids	Flowback and produced water constituents	Surface water
4) Venting of methane	Methane	Air quality
5) Storage of fracturing fluids at drill site	Fracturing fluids	Surface water

WELL PRODUCTION

1) Well production	Flowback and produced water constituents	Surface water
2) Well production	Flowback and produced water constituents	Groundwater
3) Compressor operation	Conventional air pollutants and CO_2	Air quality
4) Flaring of methane	Conventional air pollutants and CO_2	Air quality
5) Compressor operation	Noise pollution	Community disruption

FLUID STORAGE AND DISPOSAL[14]

1) On-site pit or pond storage	Flowback and produced water constituents	Surface water
2) On-site pit or pond storage	Flowback and produced water constituents	Groundwater
3) Treatment, release by municipal wastewater treatment plants	Flowback and produced water constituents	Surface water
4) On-site pit or pond storage	Fracturing fluids	Surface water
5) Treatment, release by industrial wastewater treatment plants	Flowback and produced water constituents	Surface water
6) Application of wastewater for road deicing, dust suppression	Flowback and produced water constituents	Surface water
7) Treatment, release by municipal wastewater treatment plants	Fracturing fluids	Surface water
8) On-site pit or pond storage	Fracturing fluids	Groundwater

OTHER

1) Downstream activities (e.g., pipelines)	Methane	Air quality
2) Plugging and abandonment	Intrusion of saline-formation water	Groundwater
3) Workovers	Flowback and produced water constituents	Surface water
4) Workovers	Flowback and produced water constituents	Groundwater
5) Workovers	Methane	Air quality

A final way to analyze choices by category is to take the average proportion of pathways selected by each group as a high priority (i.e., on average, x percent of NGO experts' selections are site development pathways) and use *t*-tests to examine whether there are differences between groups. We found that a higher proportion of industry experts' high priorities are site development pathways and a lower proportion are fluid storage and disposal pathways compared to the high priorities of academic experts (significant at the 90 percent level). The NGO experts' proportion of well production priorities is higher than that of industry experts (95 percent significance).

B2.2 Pathways by Impact Category

Table B2 reports normalized high-priority choices for impact categories. As shown in the rightmost column, the entire sample chose surface water and groundwater impacts most frequently; they picked habitat and soil quality impacts less often.[15] Across the four groups, we found some differences. NGO experts ranked potential threats to water and air higher than others. Industry experts ranked water and community impacts higher than others, and academic and government experts placed water impacts at the top.

In proportion to the number of priorities they picked, the average industry expert picked more community pathways than did both NGO experts and government experts at the 95 percent significance level.

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[14] We provide eight because there are so many pathways for this activity.

[15] Note that these impact categories can be correlated. For example, surface water quality degradation could reduce the quality of habitat available for aquatic species and others.

Table B2. Normalized Percentage of Total Pathways Selected, by Impact Category

	NGO % of high	Industry % of high	Academia % of high	Gov't % of high	All % of high
Groundwater	19.5	20.2	20.3	22.8	20.4
Surface water	19.2	22.1	22.4	23.8	21.5
Soil quality	15.0	10.9	12.3	14.0	13.0
Air quality	19.3	17.0	16.6	17.8	17.7
Habitat	11.7	9.2	11.1	9.3	10.5
Community	15.4	20.6	17.3	12.4	16.8

B2.3 Pathways by Activity–Impact Combination

We achieved even more detail by analyzing the 36 activity–impact pairs in two ways. First, we simply counted the number of high-priority risk pathways chosen in each activity–impact category pair and expressed this as a percentage of all possible risk pathways in that pair.

The five pairs (out of 36) with the highest percentage of high-priority selections for the entire sample are:

Drilling activities	Groundwater
Fluid storage and disposal	Surface water
Drilling activities	Surface water
Site development	Community
Well production	Surface water

For NGO experts, the top five are the same, except drilling–air pollution replaces site development–community. For industry experts, an additional community impact replaces the drilling–surface water pair. For academic experts, drilling–community replaces well production–surface water. Finally, for government experts, site development–surface water replaces site development–community).

The second approach corrects for the possibility that some individuals may click many of the pathways in a particular activity–impact category pair. For this approach, we examined rankings when each individual is credited with only one choice on an activity–impact category pair, no matter how many individual risk pathways they choose within that pair.

Making this adjustment results in much higher agreement among respondents, ranging from 71 percent among government respondents for the most selected pair to 91 percent among NGOs. We found almost complete agreement on the top five pairs:

Fluid storage and disposal	Surface water
Drilling activities	Groundwater
Fracturing and completion	Surface water
Fracturing and completion	Groundwater
Drilling activities	Surface water

The only exception is that industry replaces drilling–surface water with site development–community.

Because of the very small differences in consensus across these pairs, one should not take the absence of a particular pair as evidence of its unimportance. However, we can also examine the pairs selected least often. We had no pathways listed for site development–groundwater pairing, but with the exception of this and the "other" category, the bottom five are:

Fracturing and completion	Soil quality
Site development	Air quality
Well production	Soil quality
Site development	Soil quality
Well production	Habitat disruption

B2.4 Pathways by Burdens

Organizing by burden category also is useful because many specific burdens appear in multiple pathways and activity–impact pairs. In this subsection, we aggregate across those referencing the same burdens.

Table B3 shows the normalized choice frequency for the sample and specific groups (random selection would result in 14.3 percent in each cell). We found very little variation across these categories for the sample as a whole, although air pollution, fracturing fluids, and condenser emissions were referenced least. Across groups, the NGO respondents are more concerned about air pollution than the entire sample is. Industry respondents are most concerned about saline intrusion. Academic respondents mirror the sample in their choices, and the government respondents made choices most like those of industry respondents.

Table B3. Normalized Percentage of Total Pathways Selected, by Burden Category

	NGO % of high	Industry % of high	Academia % of high	Gov't % of high	All % of high
Air pollution	15.7	13.3	14.4	14.2	14.5
Fracturing fluids	11.8	10.1	13.1	12.9	11.9
Condenser additives	10.9	8.8	7.8	7.4	9.0
Drilling fluids	15.6	14.5	15.7	16.0	15.4
Flowback	15.4	15.7	17.9	15.9	16.3
Habitat and community	13.8	16.7	15.8	13.5	15.1
Saline intrusion	16.8	20.8	15.4	20.1	17.9

As a proportion of all priorities picked, the average industry expert selected statistically significantly fewer fracturing fluid pathways than did NGO experts, academic experts (both at the 99 percent level), and government experts (at the 95 percent level).

B2.5 Category-Level Consensus Priorities for Important and Unimportant Pathways by Group

We can also look at priorities at the category level. We arranged priorities in quartiles for each group based on the percentage identifying a pathway as a priority. Table B4 shows the fraction of pathways that were ranked in the first quartile of the most selected high priority by all four groups.

The first part of the table is for activity–impact combinations, the second is for impact–burden combinations, and the third is for activity–burden combinations. The tables are color-coded to identify where consensus is highest within the quartile. The activity–impact part of this table shows that we found consensus on surface water and groundwater impacts throughout the entire shale gas development process, but these impacts are especially concentrated around drilling activities. The other part of this chart makes clear that the consensus pathways around surface and groundwater pollution are spread evenly across burdens.

Table B5 does the same thing for the bottom three quartiles, illustrating the consensus low-priority pathways (i.e., pathways that no group ranked in its priority quartile). These include habitat disruption and soil quality effects from most of the activities and air quality effects from site development. In addition, condenser and dehydration additives appear unimportant, as do the effects of various fluids on habitats.

Table B4. Fraction of Pathways in Highest Quartile of Priority for All Four Groups

Activity–impact pairs	Groundwater	Surface water	Soil quality	Air quality	Habitat disruption	Community disruption
Site development	0/0	1/4	0/1	0/3	1/4	0/6
Drilling activities	6/10	4/8	0/4	1/11	0/5	0/7
Fracturing and completion	3/11	3/12	0/4	1/14	0/11	0/10
Well production	1/2	1/2	0/2	1/10	0/1	0/4
Fluid storage & disposal	2/18	8/19	0/8	0/7	0/9	0/19
Other activities	0/11	0/8	0/8	0/8	0/1	0/2

Impact–burden pairs	Air pollution	Fracturing fluids	Condenser and dehydration additives	Drilling fluids and cuttings	Flowback and produced water	Habitat and community disruptions	Intrusion of saline water
Groundwater	1/5	2/17	0/1	3/8	3/14	2/2	1/5
Surface water	0/1	5/17	0/1	3/8	6/14	3/12	0/0
Soil quality	0/1	0/10	0/1	0/5	0/9	0/1	0/0
Air quality	3/53	0/0	0/0	0/0	0/0	0/0	0/0
Habitat disruption	0/0	0/10	0/0	0/2	0/6	1/13	0/0
Community disruption	0/0	0/7	0/0	0/0	0/7	0/34	0/0

Activity–burden pairs	Air pollution	Fracturing fluids	Condenser and dehydration additives	Drilling fluids and cuttings	Flowback and produced water	Habitat and community disruptions	Intrusion of saline water
Site development	0/3	0/0	0/0	0/0	0/0	2/15	0/0
Drilling activities	2/13	0/2	0/0	6/14	0/0	2/14	1/2
Fracturing and completion	1/19	2/20	0/0	0/0	2/4	2/19	0/0
Well production	1/10	0/0	0/3	0/0	2/4	0/4	0/0
Fluid storage & disposal	0/7	5/33	0/0	0/0	5/33	0/7	0/0
Other activities	0/8	0/6	0/0	0/9	0/9	0/3	0/3

Notes: Light red indicates 5 percent or less of pathways in highest quartile, medium red indicates 25 percent or less, and dark red indicates 50 percent or less.

Table B5. Fraction of Pathways in Lowest Three Quartiles of Priority for All Four Groups

Activity–impact pairs	Groundwater	Surface water	Soil quality	Air quality	Habitat disruption	Community disruption
Site development	0/0	3/4	1/1	3/3	3/4	1/6
Drilling activities	0/10	2/8	3/4	3/11	4/5	3/7
Fracturing and completion	7/11	8/12	4/4	8/14	10/11	7/10
Well production	1/2	1/2	2/2	3/10	1/1	3/4
Fluid storage & disposal	9/18	6/19	6/8	6/7	9/9	16/19
Other activities	10/11	8/8	8/8	7/8	1/1	2/2

Impact–burden pairs	Air pollution	Fracturing fluids	Condenser and dehydration additives	Drilling fluids and cuttings	Flowback and produced water	Habitat and community disruptions	Intrusion of saline water
Groundwater	3/5	13/17	1/1	3/8	5/14	0/2	2/5
Surface water	1/1	9/17	1/1	3/8	5/14	9/12	0/0
Soil quality	1/1	9/10	1/1	4/5	8/9	1/1	0/0
Air quality	30/53	0/0	0/0	0/0	0/0	0/0	0/0
Habitat disruption	0/0	10/10	0/0	2/2	6/6	10/13	0/0
Community disruption	0/0	7/7	0/0	0/0	7/7	18/34	0/0

Activity–burden pairs	Air pollution	Fracturing fluids	Condenser and dehydration additives	Drilling fluids and cuttings	Flowback and produced water	Habitat and community disruptions	Intrusion of saline water
Site development	3/3	0/0	0/0	0/0	0/0	8/15	0/0
Drilling activities	3/13	2/2	0/0	3/14	0/0	7/14	0/2
Fracturing and completion	13/19	16/20	0/0	0/0	2/4	13/19	0/0
Well production	3/10	0/0	3/3	0/0	2/4	3/4	0/0
Fluid storage & disposal	6/7	24/33	0/0	0/0	18/33	4/7	0/0
Other activities	7/8	6/6	0/0	9/9	9/9	3/3	2/3

Notes: Light blue indicates 50 percent or more of pathways in lowest quartile, medium blue indicates 75 percent or more, and dark blue indicates 90 percent or more.

B3. Top 20 High-Priority Routine Pathways

This section lists each group's top 20 most selected high-priority pathways. Table B6 is a comprehensive list that displays, for each group and the sample as a whole, the percentage of experts who selected a pathway as a high priority, along with the rank within each group. In addition, the standard deviation of the four group's ranks, the percentage of responses indicating that enough information is known to take action, the percentage of responses indicating that government should be responsible for more action, and the percentage of total high-priority designations indicating that the priority is only for tail-end cases are also given. In tables B7 and B8 the top 20 for federal versus state and local government experts and for extraction versus nonextraction industry experts, respectively, are displayed. Table B9 displays the top 20 most selected pathways for those with and without specific play knowledge. Table B10 displays the 5 pathways that were most and least likely to be selected as a tail-end priority of the 41 pathways in at least one group's top 20.

Table B6. Information about Top 20 High-Priority Routine Pathways

	Routine impact pathways			High-priority ranks (percentage selected)					Std. dev. of ranks	% Enough known	% Gov't respon-sible	% Priority tail-end
	Activity	**Burden**	**Impact**	**NGO**	**Industry**	**Academia**	**Govt**	**All**				
All Four												
1	On-site pit or pond storage	Flowback and produced water constituents	Surface water	4 (74.3)	1 (54.7)	1 (68.3)	1 (57.1)	1 (62.3)	1.30	81.8	78.8	34.3
2	Treatment, release by municipal wastewater treatment plants	Flowback and produced water constituents	Surface water	1 (80.0)	5 (44.0)	2 (57.1)	10 (38.1)	2 (52.6)	3.50	64.4	93.2	18.6
3	On-site pit or pond storage	Flowback and produced water constituents	Groundwater	8 (71.4)	9 (41.3)	4 (54.0)	2 (54.8)	2 (52.6)	2.86	73.1	81.8	35.4
4	Clearing of land for roads, well pads, pipelines, evaporation ponds, and other infrastructure	Stormwater flows	Surface water	4 (74.3)	11 (40.0)	4 (54.0)	4 (50.0)	4 (51.6)	3.03	92.4	66.7	20.7
5	Use of surface water and groundwater during fracking	Freshwater withdrawals	Surface water	1 (80.0)	11 (40.0)	4 (54.0)	5 (42.9)	5 (51.2)	3.63	72.7	81.1	30.9
6	Use of surface water and groundwater during fracking	Freshwater withdrawals	Groundwater	8 (71.4)	9 (41.3)	8 (49.2)	3 (52.4)	6 (50.7)	2.35	64.9	79.2	22.9
7	On-site pit or pond storage	Fracturing fluids	Surface water	19 (65.7)	14 (38.7)	3 (55.6)	5 (42.9)	7 (48.8)	6.53	76.3	78.2	31.4
8	Venting of methane during fracking	Methane	Air quality	15 (68.6)	5 (44.0)	18 (41.3)	10 (38.1)	9 (46.0)	1.80	54.5	87.3	30.3
9	Treatment, release by industrial wastewater treatment plants	Flowback and produced water constituents	Surface water	8 (71.4)	11 (40.0)	13 (44.4)	10 (38.1)	9 (46.0)	4.95	68.8	78.3	18.2
10	Venting of methane during drilling	Methane	Air quality	15 (68.6)	15 (37.3)	8 (49.2)	16 (33.3)	12 (45.1)	3.20	68.8	75.0	17.5
11	Clearing of land for roads, well pads, pipelines, evaporation ponds, and other infrastructure	Habitat fragmentation	Habitat disruption	8 (71.4)	15 (37.3)	11 (46.0)	13 (35.7)	12 (45.1)	2.59	67.2	80.4	21.6
12	Storage of fracturing fluids at drill site	Fracturing fluids	Surface water	15 (68.6)	20 (33.3)	20 (39.7)	8 (40.5)	15 (42.3)	4.92	87.9	73.7	44.0
All Except NGO												
1	Casing and cementing	Methane	Groundwater	24 (62.9)	8 (42.7)	7 (50.8)	8 (40.5)	8 (47.9)	7.08	67.3	74.5	35.0
All Except Government												
1	Flowback of reservoir fluids	Flowback and produced water constituents	Surface water	8 (71.4)	3 (45.3)	13 (44.4)	24 (28.6)	9 (46.0)	7.78	63.5	68.3	32.3
2	Disposal of drilling fluids, drill solids, and cuttings	Drilling fluids and cuttings	Surface water	4 (74.3)	20 (33.3)	8 (49.2)	24 (28.6)	14 (43.7)	8.25	79.5	82.9	36.2

Table B6 (Cont). Information about Top 20 High-Priority Routine Pathways

	Routine impact pathways			High-priority ranks (percentage selected)					Std. dev. of ranks	% Enough known	% Gov't respon-sible	% Priority tail-end
	Activity	**Burden**	**Impact**	**NGO**	**Industry**	**Academia**	**Govt**	**All**				
All Except Industry												
1	Application of wastewater for road deicing, dust suppression	Flowback and produced water constituents	Surface water	4 (74.3)	26 (29.3)	20 (39.7)	16 (33.3)	17 (40.5)	8.05	67.4	83.0	12.6
2	Well production	Flowback and produced water constituents	Surface water	15 (68.6)	26 (29.3)	20 (39.7)	16 (33.3)	18 (39.5)	4.32	60.0	83.3	30.6
NGO and Academia												
1	Disposal of drilling fluids, drill solids, and cuttings	Drilling fluids and cuttings	Groundwater	8 (71.4)	28 (28.0)	16 (42.9)	24 (28.6)	18 (39.5)	7.68	66.7	84.1	31.8
2	Flowback of reservoir fluids	Flowback and produced water constituents	Groundwater	3 (77.1)	32 (26.7)	16 (42.9)	44 (23.8)	20 (39.1)	15.56	57.7	68.8	36.9
Academia and Government												
1	Treatment, release by municipal wastewater treatment plants	Fracturing fluids	Surface water	24 (62.9)	37 (25.3)	11 (46.0)	16 (33.3)	20 (39.1)	9.82	75.0	97.7	19.0
2	Storage of drilling fluids at surface	Drilling fluids and cuttings	Surface water	24 (62.9)	42 (24.0)	13 (44.4)	13 (35.7)	23 (38.6)	11.85	82.1	84.6	34.9
3	Drilling equipment operation at surface	Drilling fluids and cuttings	Surface water	38 (57.1)	47 (22.7)	20 (39.7)	20 (31.0)	32 (34.9)	11.69	80.6	62.5	33.3
Industry and Academia												
1	Deep underground injection	Seismic vibrations	Community disruption	116 (40.0)	19 (34.7)	20 (39.7)	32 (26.2)	30 (35.3)	40.31	38.0	64.0	43.4
Academia only												
1	Use of surface water and groundwater during drilling	Freshwater withdrawals	Groundwater	24 (62.9)	23 (32.0)	18 (41.3)	24 (28.6)	20 (39.1)	2.49	54.8	83.3	23.8
2	Clearing of land for roads, well pads, pipelines, evaporation ponds, and other infrastructure	Industrial landscape	Community disruption	59 (51.4)	32 (26.7)	20 (39.7)	32 (26.2)	34 (34.4)	14.29	87.5	86.8	12.2

Table B6 (Cont). Information about Top 20 High-Priority Routine Pathways

	Routine impact pathways			**High-priority ranks (percentage selected))**					Std. dev. of ranks	% Enough known	% Gov't respon-sible	% Priority tail-end
	Activity	**Burden**	**Impact**	**NGO**	**Industry**	**Academia**	**Govt**	**All**				
Industry Only												
1	On-road vehicle activity during site development	Road congestion	Community disruption	82 (45.7)	2 (50.7)	26 (38.1)	24 (28.6)	16 (41.9)	29.54	82.4	39.2	24.4
2	On-road and off-road vehicle activity during drilling	Road congestion	Community disruption	48 (54.3)	5 (44.0)	36 (34.9)	92 (16.7)	24 (37.7)	31.22	85.0	41.0	32.1
3	Transport off-site	Road congestion	Community disruption	116 (40.0)	3 (45.3)	36 (34.9)	76 (19.0)	27 (36.3)	42.42	97.7	38.6	17.9
4	Drilling equipment operation at surface	Noise pollution	Community disruption	82 (45.7)	15 (37.3)	30 (36.5)	54 (21.4)	30 (35.3)	25.37	94.6	40.5	35.5
5	Casing and cementing	Intrusion of saline water	Groundwater	24 (62.9)	20 (33.3)	65 (27.0)	32 (26.2)	32 (34.9)	17.71	69.7	62.5	41.3
6	On-road and off-road vehicle activity during fracking	Road congestion	Community disruption	71 (48.6)	15 (37.3)	49 (30.2)	54 (21.4)	36 (34.0)	20.33	87.5	41.7	24.7
NGO only												
1	Use of surface water and groundwater during drilling	Freshwater withdrawals	Surface water	8 (71.4)	32 (26.7)	26 (38.1)	32 (26.2)	25 (37.2)	9.84	73.0	85.7	30.0
2	Well production	Flowback and produced water constituents	Groundwater	19 (65.7)	28 (28.0)	36 (34.9)	32 (26.2)	29 (35.8)	6.30	50.0	82.9	35.1
3	On-site pit or pond storage	VOCs	Air quality	19 (65.7)	73 (17.3)	36 (34.9)	32 (26.2)	41 (32.1)	20.06	46.2	89.2	14.5
4	Compressor operation	Conventional air pollutants and CO_2	Air quality	19 (65.7)	47 (22.7)	44 (31.7)	54 (21.4)	41 (32.1)	13.21	80.8	92.3	10.1
5	Condensate tank, dehydration unit operation	VOCs	Air quality	19 (65.7)	73 (17.3)	87 (22.2)	54 (21.4)	58 (27.4)	25.51	72.2	87.5	13.6
Government only												
1	On-site pit or pond storage	Fracturing fluids	Groundwater	38 (57.1)	37 (25.3)	30 (36.5)	5 (42.9)	25 (37.2)	13.35	77.8	78.8	31.3
2	Drilling of vertical and lateral wellbore	Intrusion of saline water	Groundwater	24 (62.9)	23 (32.0)	49 (30.2)	20 (31.0)	27 (36.3)	11.64	62.1	57.1	43.6
3	Storage of fracturing fluids at drill site	Fracturing fluids	Groundwater	24 (62.9)	42 (24.0)	44 (31.7)	20 (31.0)	36 (34.0)	10.62	80.0	60.0	38.4
4	Deep underground injection	Flowback and produced water constituents	Groundwater	24 (62.9)	113 (13.3)	56 (28.6)	13 (35.7)	45 (30.2)	38.86	64.3	96.2	30.8
5	Drilling equipment operation at surface	Drilling fluids and cuttings	Groundwater	82 (45.7)	63 (20.0)	70 (25.4)	20 (31.0)	55 (27.9)	23.38	70.4	63.6	16.7

Table B7. Top 20 High-Priority Routine Pathways for Federal Government Experts and for State and Local Government Experts

	Routine impact pathway			High-priority ranks (percentage selected)		
	Activity	**Burden**	**Impact**	**Federal**	**State/local**	**All experts**
Both federal and state/local government						
1	On-site pit or pond storage	Flowback & produced water	Surface water	1 (80.0)	4 (44.4)	1 (62.3)
2	On-site pit or pond storage	Flowback & produced water	Groundwater	2 (60.0)	1 (51.9)	2 (52.6)
3	Clearing of land for roads, well pads, pipelines, evaporation ponds, & other infrastructure	Stormwater flows	Surface water	5 (53.3)	3 (48.1)	4 (51.6)
4	Use of surface water & groundwater during fracking	Freshwater withdrawals	Surface water	10 (46.7)	5 (40.7)	5 (51.2)
5	Use of surface water & groundwater during fracking	Freshwater withdrawals	Groundwater	5 (53.3)	1 (51.9)	6 (50.7)
6	On-site pit or pond storage	Fracturing fluids	Surface water	10 (46.7)	5 (40.7)	7 (48.8)
7	Casing and cementing	Methane	Groundwater	2 (60.0)	12 (29.6)	8 (47.9)
8	Venting of methane during fracking	Methane	Air quality	5 (53.3)	12 (29.6)	9 (46.0)
9	Treatment, release by industrial wastewater treatment plants	Flowback & produced water	Surface water	5 (53.3)	12 (29.6)	9 (46.0)
10	Venting of methane during drilling	Methane	Air quality	18 (40.0)	12 (29.6)	12 (45.1)
11	Storage of fracturing fluids at drill site	Fracturing fluids	Surface water	10 (46.7)	8 (37.0)	15 (42.3)
12	Treatment, release by municipal wastewater treatment plants	Fracturing fluids	Surface water	18 (40.0)	12 (29.6)	20 (39.1)
13	Storage of drilling fluids at surface	Drilling fluids and cuttings	Surface water	18 (40.0)	10 (33.3)	23 (38.6)
14	On-site pit or pond storage	Fracturing fluids	Groundwater	10 (46.7)	5 (40.7)	25 (37.2)
15	Deep underground injection	Flowback & produced water	Groundwater	10 (46.7)	12 (29.6)	45 (30.2)
Federal government only						
1	Treatment, release by municipal wastewater treatment plants	Flowback & produced water	Surface water	2 (60.0)	27 (25.9)	2 (52.6)
2	Flowback of reservoir fluids	Flowback & produced water	Surface water	18 (40.0)	43 (22.2)	9 (46.0)
3	Clearing of land for roads, well pads, pipelines, evaporation ponds, & other infrastructure	Habitat fragmentation	Habitat	5 (53.3)	27 (25.9)	12 (45.1)
4	On-road vehicle activity during site development	Road congestion	Community	10 (46.7)	58 (18.5)	16 (41.9)
5	Application of wastewater for road deicing, dust suppression	Flowback & produced water	Surface water	10 (46.7)	27 (25.9)	17 (40.5)
6	Storage of fracturing fluids at drill site	Fracturing fluids	Groundwater	18 (40.0)	27 (25.9)	36 (34.0)
7	On-site pit or pond storage	VOCs	Air quality	18 (40.0)	58 (18.5)	41 (32.1)
8	Flowback of reservoir fluids	Methane	Air quality	18 (40.0)	111 (11.1)	52 (0.0)
9	Drilling equipment operation at surface	Conventional air pollutants & CO_2	Air quality	10 (46.7)	111 (11.1)	62 (0.0)
10	Drilling of vertical and lateral wellbore	Methane	Groundwater	18 (40.0)	77 (14.8)	68 (26.0)
11	Flaring of methane during well production	Methane	Air quality	18 (40.0)	111 (11.1)	74 (25.1)
12	Flaring of methane during fracking	Methane	Air quality	18 (40.0)	188 (3.7)	74 (25.1)
State and local government only						
1	Disposal of drilling fluids, drill solids, & cuttings	Drilling fluids & cuttings	Surface water	52 (26.7)	12 (29.6)	14 (43.7)
2	Well production	Flowback & produced water	Surface water	52 (26.7)	8 (37.0)	18 (39.5)
3	Disposal of drilling fluids, drill solids, & cuttings	Drilling fluids & cuttings	Groundwater	91 (20.0)	10 (33.3)	18 (39.5)
4	Drilling of vertical and lateral wellbore	Intrusion of saline-formation water	Groundwater	28 (33.3)	12 (29.6)	27 (36.3)
5	Well production	Flowback & produced water	Groundwater	91 (20.0)	12 (29.6)	29 (35.8)
6	Drilling equipment operation at surface	Drilling fluids and cuttings	Surface water	28 (33.3)	12 (29.6)	32 (34.9)
7	Treatment, release by industrial wastewater treatment plants	Fracturing fluids	Surface water	52 (26.7)	12 (29.6)	36 (34.0)
8	Drilling equipment operation at surface	Drilling fluids & cuttings	Groundwater	28 (33.3)	12 (29.6)	55 (27.9)
9	Deep underground injection	Fracturing fluids	Groundwater	52 (26.7)	12 (29.6)	59 (27.0)
10	Disposal of drilling fluids, drill solids, & cuttings	Drilling fluids & cuttings	Soil quality	135 (13.3)	12 (29.6)	62 (26.5)
11	Hydraulic fracture propagation	Fracturing fluids	Groundwater	91 (20.0)	12 (29.6)	68 (26.0)

Table B8. Top 20 High-Priority Routine Pathways for Extraction and Other Industry Experts

	Routine impact pathway			High-priority ranks (percentage selected)		
	Activity	**Burden**	**Impact**	**Extraction**	**Other industry**	**All experts**
Both extraction and other industry						
1	On-site pit or pond storage	Flowback and produced water constituents	Surface water	5 (40.6)	1 (65.1)	1 (62.3)
2	On-site pit or pond storage	Flowback and produced water constituents	Groundwater	10 (34.4)	17 (51.2)	2 (52.6)
3	Treatment, release by municipal wastewater treatment plants	Flowback and produced water constituents	Surface water	3 (43.8)	2 (39.5)	2 (52.6)
4	Clearing of land for roads, well pads, pipelines, evaporation ponds, and other infrastructure	Stormwater flows	Surface water	5 (40.6)	17 (39.5)	4 (51.6)
5	Use of surface water and groundwater during fracking	Freshwater withdrawals	Surface water	20 (28.1)	5 (48.8)	5 (51.2)
6	Use of surface water and groundwater during fracking	Freshwater withdrawals	Groundwater	16 (31.3)	5 (48.8)	6 (50.7)
7	On-site pit or pond storage	Fracturing fluids	Surface water	10 (34.4)	12 (41.9)	7 (48.8)
8	Casing and cementing	Methane	Groundwater	3 (43.8)	12 (41.9)	8 (47.9)
9	Flowback of reservoir fluids	Flowback and produced water constituents	Surface water	8 (37.5)	2 (51.2)	9 (46.0)
10	Venting of methane during fracking	Methane	Air quality	10 (34.4)	2 (51.2)	9 (46.0)
11	Treatment, release by industrial wastewater treatment plants	Flowback and produced water constituents	Surface water	10 (34.4)	10 (44.2)	9 (46.0)
12	Venting of methane during drilling	Methane	Air quality	20 (28.1)	10 (44.2)	12 (45.1)
13	Clearing of land for roads, well pads, pipelines, evaporation ponds, and other infrastructure	Habitat fragmentation	Habitat	16 (31.3)	12 (41.9)	12 (45.1)
14	On-road vehicle activity during site development	Road congestion	Community	1 (53.1)	5 (48.8)	16 (41.9)
15	On-road and off-road vehicle activity during drilling	Road congestion	Community	5 (40.6)	8 (46.5)	24 (37.7)
16	Transport off-site	Road congestion	Community	2 (50.0)	12 (41.9)	27 (36.3)
17	Drilling equipment operation at surface	Noise pollution	Community	16 (31.3)	12 (41.9)	30 (35.3)
Extraction industry only						
1	Use of surface water and groundwater during drilling	Freshwater withdrawals	Groundwater	20 (28.1)	22 (34.9)	20 (39.1)
2	On-site pit or pond storage	Fracturing fluids	Groundwater	16 (31.3)	60 (20.9)	25 (37.2)
3	Drilling of vertical and lateral wellbore	Intrusion of saline water	Groundwater	10 (34.4)	33 (30.2)	27 (36.3)
4	Deep underground injection	Seismic vibrations	Community	8 (37.5)	29 (32.6)	30 (35.3)
5	Casing and cementing	Intrusion of saline water	Groundwater	10 (34.4)	29 (32.6)	32 (34.9)
6	Flowback of reservoir fluids	Methane	Air quality	20 (28.1)	90 (16.3)	52 (28.8)
7	Fracturing equipment operation	Noise pollution	Community	20 (28.1)	60 (20.9)	62 (26.5)
8	On-road vehicle activity during site development	Noise pollution	Community	20 (28.1)	44 (25.6)	74 (25.1)
9	Transport off-site	Noise pollution	Community	20 (28.1)	53 (23.3)	98 (22.3)
Other industry only						
1	Disposal of drilling fluids, drill solids, and cuttings	Drilling fluids and cuttings	Surface water	27 (25.0)	17 (39.5)	14 (43.7)
2	Storage of fracturing fluids at drill site	Fracturing fluids	Surface water	27 (25.0)	17 (39.5)	15 (42.3)
3	Application of wastewater for road deicing, dust suppression	Flowback and produced water constituents	Surface water	68 (15.6)	17 (39.5)	17 (40.5)
4	On-road and off-road vehicle activity during fracking	Road congestion	Community	27 (25.0)	8 (46.5)	36 (34.0)

Table B9. Top 20 High-Priority Routine Pathways for Different Plays Knowledge

	Routine impact pathway			**High-priority ranks (percentage selected)**		
	Activity	Burden	Impact	General knowledge	Specific knowledge	All experts
Both general and specific knowledge						
1	On-site pit or pond storage	Flowback and produced water constituents	Surface water	1 (65.6)	1 (60.7)	1 (62.3)
2	Treatment, release by municipal wastewater treatment plants	Flowback and produced water constituents	Surface water	12 (44.3)	2 (58.9)	2 (52.6)
3	On-site pit or pond storage	Flowback and produced water constituents	Groundwater	2 (54.1)	6 (54.5)	2 (52.6)
4	Clearing of land for roads, well pads, pipelines, evaporation ponds, and other infrastructure	Stormwater flows	Surface water	3 (50.8)	5 (55.4)	4 (51.6)
5	Use of surface water and groundwater during fracking	Freshwater withdrawals	Surface water	3 (50.8)	3 (58.0)	5 (51.2)
6	Use of surface water and groundwater during fracking	Freshwater withdrawals	Groundwater	6 (47.5)	4 (56.3)	6 (50.7)
7	On-site pit or pond storage	Fracturing fluids	Surface water	6 (47.5)	9 (50.9)	7 (48.8)
8	Casing and cementing	Methane	Groundwater	6 (47.5)	7 (52.7)	8 (47.9)
9	Venting of methane during fracking	Methane	Air quality	16 (39.3)	11 (49.1)	9 (46.0)
10	Flowback of reservoir fluids	Flowback and produced water constituents	Surface water	9 (45.9)	15 (46.4)	9 (46.0)
11	Clearing of land for roads, well pads, pipelines, evaporation ponds, and other infrastructure	Habitat fragmentation	Habitat	9 (45.9)	14 (47.3)	12 (45.1)
12	Venting of methane during drilling	Methane	Air quality	5 (49.2)	17 (45.5)	12 (45.1)
13	Disposal of drilling fluids, drill solids, and cuttings	Drilling fluids and cuttings	Surface water	9 (45.9)	18 (44.6)	14 (43.7)
14	Storage of fracturing fluids at drill site	Fracturing fluids	Surface water	17 (37.7)	10 (50.0)	15 (42.3)
15	On-road vehicle activity during site development	Road congestion	Community	17 (37.7)	11 (49.1)	16 (41.9)
16	Use of surface water and groundwater during drilling	Freshwater withdrawals	Groundwater	13 (41.0)	20 (43.8)	20 (39.1)
Only specific knowledge						
1	Treatment, release by industrial wastewater treatment plants	Flowback and produced water constituents	Surface water	22 (34.4)	8 (51.8)	9 (46.0)
2	Application of wastewater for road deicing, dust suppression	Flowback and produced water constituents	Surface water	35 (27.9)	13 (48.2)	17 (40.5)
3	Well production	Flowback and produced water constituents	Surface water	26 (32.8)	15 (46.4)	18 (39.5)
4	Treatment, release by municipal wastewater treatment plants	Fracturing fluids	Surface water	26 (32.8)	18 (44.6)	20 (39.1)
Only general knowledge						
1	Storage of drilling fluids at surface	Drilling fluids and cuttings	Surface water	17 (37.7)	29 (40.2)	23 (38.6)
2	Drilling equipment operation at surface	Drilling fluids and cuttings	Surface water	13 (41.0)	22 (42.0)	25 (37.2)
3	Use of surface water and groundwater during drilling	Freshwater withdrawals	Surface water	17 (37.7)	27 (41.1)	25 (37.2)
4	On-site pit or pond storage	Fracturing fluids	Groundwater	13 (41.0)	50 (32.1)	32 (34.9)

Table B10. Tail-End or Typical Priority Pathways (from 41 Venn Pathways)

Activity	Burden	Impact	All expert rank	% tail-end of total selections
Five highest percentages				
Storage of fracturing fluids at drill site	Fracturing fluids	Surface water	15	44.0
Drilling of vertical and lateral wellbore	Intrusion of saline-formation water into fresh groundwater	Groundwater	27	43.6
Deep underground injection	Seismic vibrations	Community disruption	30	43.4
Casing and cementing	Intrusion of saline-formation water into fresh groundwater	Groundwater	32	41.3
Storage of fracturing fluids at drill site	Fracturing fluids	Groundwater	36	38.4
Five lowest percentages				
Compressor operation	Conventional air pollutants and CO_2	Air quality	41	10.1
Clearing of land for roads, well pads, pipelines, evaporation ponds, and other infrastructure	Industrial landscape	Community disruption	34	12.2
Application of wastewater for road deicing, dust suppression	Flowback and produced water constituents	Surface water	17	12.6
Condensate tank, dehydration unit operation	VOCs	Air Quality	58	13.6
On-site pit or pond storage	VOCs	Air Quality	41	14.5