What Experts Say About the Environmental Risks of Shale Gas Development

Alan J. Krupnick and Hal G. Gordon

Public discourse suggests a lack of consensus in the United States regarding the environmental impacts of shale gas development. Newly available shale gas has reduced the cost of electricity and heating and replaced coal, but public fears about the environment threaten to curtail those gains. We designed the first survey-based analysis of the views of government, industry, academic, and nongovernmental experts to identify their priorities for regulation and voluntary action among 264 routine and 14 accidental environmental risk "pathways." We find that nongovernmental experts select many more problems but that there is considerable agreement on the most important ones, which can guide research, policies, and practices so that shale gas benefits continue and environmental impacts are limited.

Key Words: risk pathways, shale gas development

Public discourse suggests a lack of consensus in the United States regarding the environmental impacts of shale gas development. On 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, public fears about the environmental effects of shale gas development threaten to dim or eliminate these prospects. In an effort to find a way out of this uneasy state of affairs, we identify areas of consensus among experts about the environmental risks from shale gas development in the sense of their highest priorities for further government regulatory and/or voluntary industry actions. We collect responses from 215 experts in academia, government regulatory agencies, the industry, and environmental nongovernmental organizations (NGOs) using a highly technical, structured internet survey. The survey

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presented 264 “impact pathways” that linked specific shale gas development activities—from site development to well abandonment—to burdens such as air pollution, noise, and ground water contamination and fourteen “accident categories,” generating their qualitative assessments of the probability of such accidents occurring and how severe they might be. They were also asked whether industry or government should have the primary responsibility for acting on each priority.

Methods

We summarize the sample and survey used in the study here and provide additional detailed information online (see *www.rff.org/Documents/RFF-Rpt-PathwaystoDialogue_FullReport.pdf*). To elicit experts’ highest priorities for impacts, we first had to determine the full set of potential pathways, which we divided into risks associated with routine, everyday operations and risks arising from accidents.

We characterized the routine impact pathways by creating a risk matrix (the complete matrix is provided in the survey, which is available in supporting materials online at *www.rff.org/shalematrix*). The risk matrix illustrates how activities associated with widespread development of shale gas wells can create burdens that can affect intermediate points that people care about, such as ground water and soil quality, and various other effects such as traffic that disrupt local communities. It is important to note that the matrix shows all risks that could plausibly occur under normal and unusual operating conditions rather than tallying impacts that have occurred. The list of risks arising from accidents is more concise (see Figure S1, questions 29–42 in the supplemental materials).

For each risk, survey respondents were given a binary choice: Is this risk a high priority for you? Hence, when we identify a pathway as a top priority for a group, we simply mean that it was a top vote-getter among respondents in that group. Each participant selected high-priority routine activities by clicking on an interactive version of the matrix. Then, two subsequent questions collected additional information about a randomly selected subset of the respondent’s high-priority pathways: (i) Is there enough information about the pathway to support regulatory and/or voluntary action or is further research needed? (ii) Does primary responsibility for addressing the risk rest more with the government through regulation or with the industry through voluntary action?

When selecting risks associated with accidents, respondents were asked about the likely frequency of occurrence of that problem per thousand wells and, if the problem occurred, how severe it was likely to be. They chose from a list of potential probabilities stated as percentages and severities defined by qualitative statements. Together, each respondent’s probability and severity choices were treated as notional descriptions of expected values.

We identified potential experts using media stories, blogs, the academic literature on shale gas risks, and information about organizations that have played a prominent and substantive role in the debate, generating more than one thousand names of experts from four core groups: academics, NGOs (primarily environmental groups), regulators (primarily state and federal regulators plus river-basin commissions), and the industry. We dropped people from our original sample when we could not reach them or when they self-identified as lacking the necessary expertise. Other individuals were dropped when they worked at institutions that chose internally to submit a single completed survey. Because most institutions that returned the survey submitted a single response, we counted nonresponding institutions as one person even though we may have sent the survey to multiple individuals there. The final sample size, given these changes, was 719. We sent a link to the survey via email to those individuals and received completed responses from 215 of them, representing a response rate of 30 percent.

To help determine whether the nonresponding 70 percent of the sample was significantly different from the 30 percent that did respond, we assigned all 719 persons to one of the four stakeholder groups and determined whether the proportion of respondents from each group matched the proportion that group represented in the original sample. They were remarkably similar. On a group-affiliation basis, the proportions for the NGO and industry groups were identical while the proportion of academic respondents was greater and the proportion of government respondents was smaller than in the original list. It would have been useful to know more about the individuals in the nonresponding group, but collection of that data was beyond the scope of the study.

Respondents were assured of anonymity so we can only summarize the organizations they represented. Additional details on the qualifications of the respondents are available in the supplementary material.

- NGO experts (35): All major national environmental groups, some local groups, and several specialized groups that focus on particular issues, such as chemicals used in hydraulic fracturing.
- Academics (63): All U.S. universities and think tanks that have a significant presence in the shale gas debate, often involving more than one respondent per institution.
- Government (42): At least one respondent from each key federal agency and from about half of the states that have shale gas resources plus representatives from several river-basin commissions.
- Industry (75): Many of the major operating and support companies, some trade associations and consulting firms, and law firms that generally work for the industry.

Results for Routine Pathways

The survey imposed no limit on the number of routine pathways that could be selected as high priority. The average NGO expert selected about twice as many (105.2) as the average expert overall (54.7), and industry and government experts picked about 40 on average. The especially large number of priority risks identified by NGO experts seems to suggest that their views have little in common with the views of experts in the other groups, but our analysis of the risks chosen to prioritize shows otherwise.

Strategies for Identifying the Most Important Priorities

Since we did not allow respondents to rank their priorities, we identified each group's highest priorities by tallying the votes. After identifying each group's top ten, twenty, and forty pathways, we found it most useful to focus primarily on the top twenty priorities (see the supplementary material for the other classifications and ties). Given the much larger number selected by the NGO group, the top twenty pathways mean something different in the NGO group. For instance, the NGO group's eighth most-selected pathway was selected as a priority by 71 percent of the group's members while the eighth most-selected pathways for the academics, regulators, and industry experts were picked by only 49 percent, 48 percent, and 43 percent of each group's respondents, respectively.

After identifying each group's top twenty priorities, we looked for the "sweet spot"—the high-priority impact pathways common to all four groups. Surprisingly, twelve pathways were selected by all groups, another eleven were selected by two or three groups, and eighteen were selected by a single group. We summarize these results in the Venn diagram in Figure 1**.** Each oval represents a group, and the areas created by overlapping ovals represent the common choices—that is, areas of consensus. The darkest center section identifies the sweet spot (additional diagrams and distributions for the top ten and top forty are provided in the supplementary material). Figure 2 provides the exact activity, environmental burden, and impact of each of the twelve consensus pathways.

The survey asked respondents about their expertise in each activity category (see Table S6). As a robustness check, we identified the consensus pathways when only the highly qualified "top" experts' votes were taken into account. In this analysis, only one additional pathway was added to our twelve consensus pathways (see Figure 2).

We recognize that setting a cut-off for consensus or disagreement at twenty is arbitrary and fails to suggest where the greatest disagreement lies. Therefore, we calculated the standard deviation of each pathway's rank by number of votes across the groups and compared the 12 consensus pathways to the other 29 high-priority pathways (according to at least one group's top twenty)

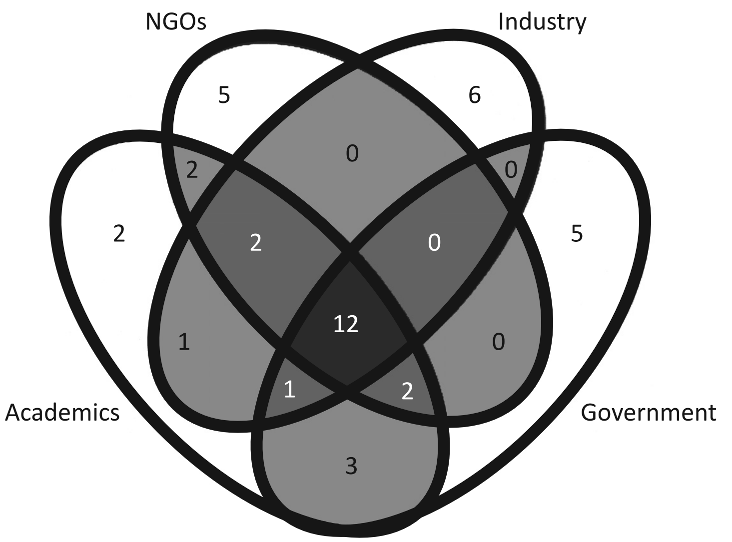

Figure 1. Venn Diagram of Top-twenty High-priority Routine Pathways

and the 223 non-priority pathways. Figure 3 shows the relationships of the standard deviations and rankings for all pathways along with a regression line. All of the consensus pathways have a deviation of less than ten, reinforcing the general agreement among groups regarding the most important risk pathways to address. The standard deviation for 8 of the 41 high-priority pathways exceeded the median of 21.9 for all 264 pathways.

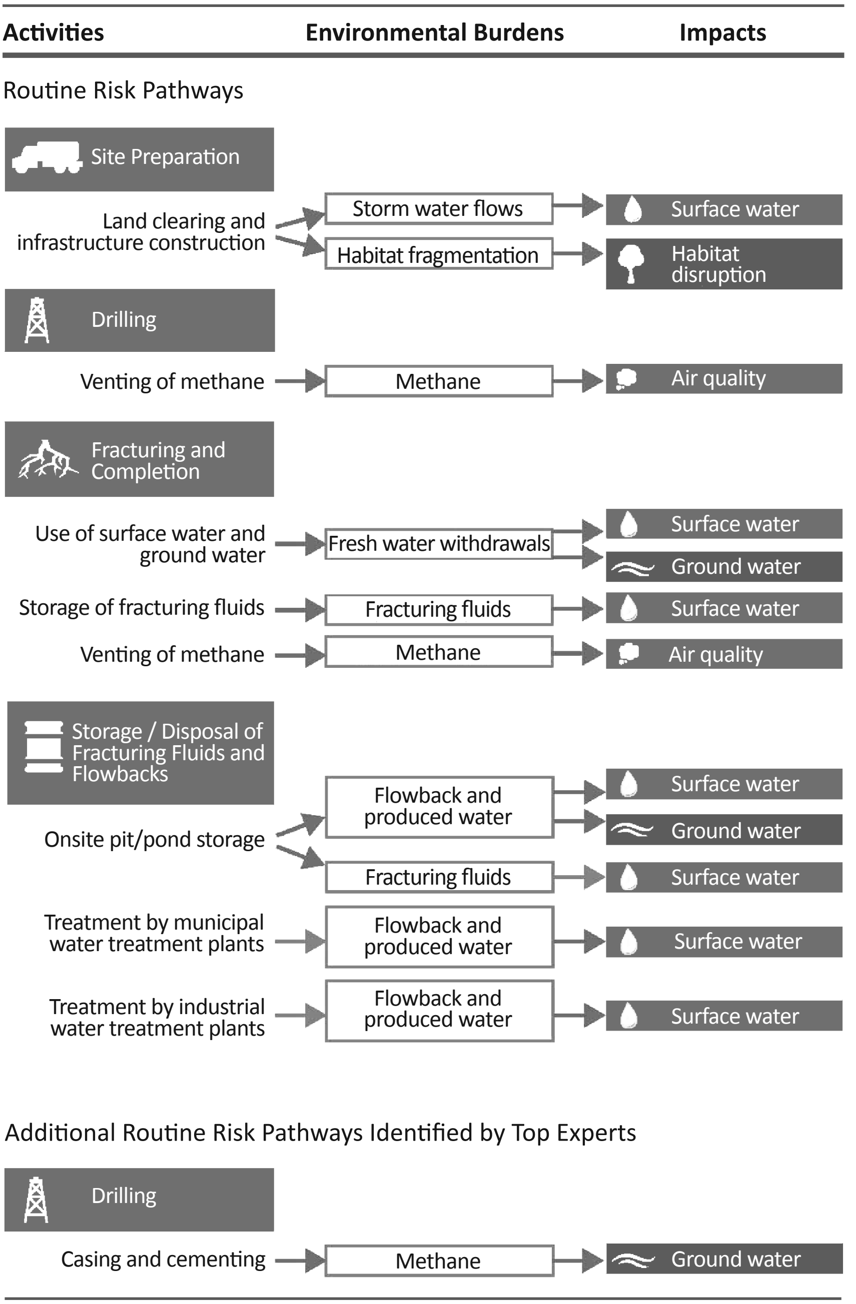

Figure 2. Consensus High-priority Pathways

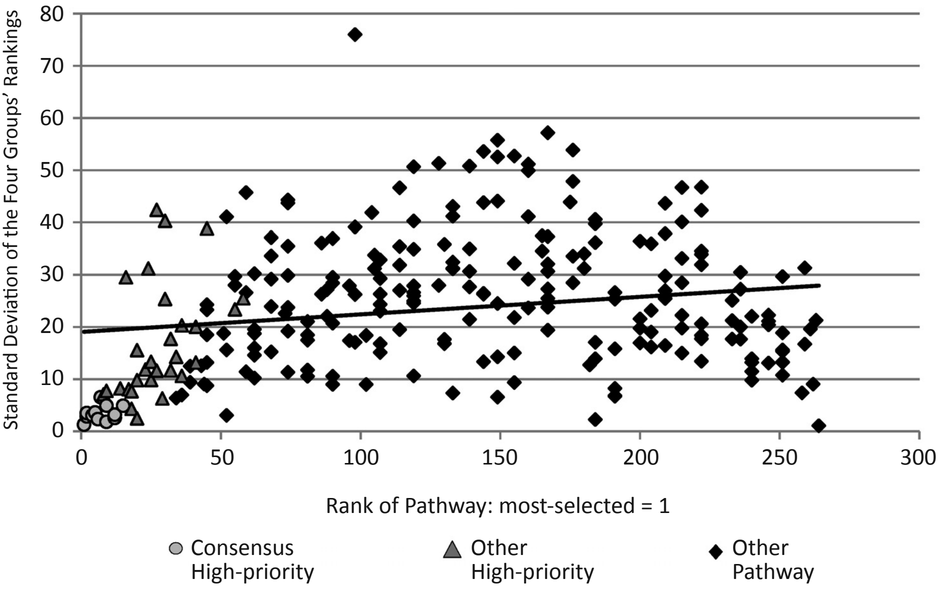

Figure 3. Standard Deviations of Group Rankings of Routine Pathways

Infrequently selected pathways indicate a strong consensus about their relatively small importance; in our sample, 223 pathways were not included in any group's top twenty. Specifically, none of the soil-related pathways, only one of the habitat disruption pathways (clearing land for site development), and none of the "other" activities (shutting-in, plugging, and workovers) came up in a top-twenty list.

Drilling Activities

Before drilling can begin, a five-acre site must be cleared. We included risk pathways for that activity and for related increases in vehicle traffic. We find that two of the twelve consensus activities occur during this process: storm water flows on surface water and habitat disruption from fragmentation caused by land clearing and infrastructure construction. These impacts are rarely described in media reports, but the experts' consensus suggests that they should be given more attention. The impact of site-clearing on habitats is unique—it is the only habitat pathway that was included in a top-twenty list.

We find a lack of consensus in prioritizing the risk of road congestion. It was the second most-selected pathway among industry experts but did not quite make the top twenty for government and academic experts and was not even in the top fifty for NGO experts. In addition, the standard deviation of rankings of this pathway was the fifth largest of all pathways (Table S7). This is the first of several examples of one of the most glaring disagreements among the experts: community disruptions in general and road congestion in particular were often chosen by industry experts but were not high priorities for the other groups, especially NGOs. Whether this reflects exposure of industry experts to direct complaints about such impacts or a genuine difference in priorities is not clear, but the disagreement is robust across activities in the matrix.

After sites are cleared, wells are drilled vertically for at least one mile and then horizontally through the shale seam. We included potential risks that are common to all drilling operations and relate to drilling, casing and cementing of the wells, vehicle and engine activity, methane emissions, and drilling fluids. Of the drilling activities, only one was commonly chosen as a high priority: the impact of vented methane on air quality. Migration of methane into ground water during casing and cementing was the eighth most-selected pathway among all experts but just missed the NGO group's top twenty. It was also regularly selected by the top drilling experts and was selected by all of the top NGO drilling experts so we have classified this type of methane migration as a consensus priority (in addition to the original twelve).

Once again, the industry group prioritized pathways associated with community disruptions (noise pollution and road congestion) while the other groups did not. Both were included in the top seven most disputed pathways according to our ranking of standard deviations.

Fracturing and Well Completion Activities

To extract the gas, the rock reservoir is fractured using small explosives and a high-pressure fluid slurry consisting of water, sand, and a number of chemicals. The potential risks included in the survey related to direct fracturing activities, the flowback and storage of the slurry, methane leaking into ground water supplies, and industrial activities at the surface. We find a consensus on the importance of the risks posed by four of the activities: withdrawals of fresh water on supplies of ground water, withdrawals on supplies of surface water, storage of fracturing fluids on the quality of surface water, and venting of methane on air quality. The consensus regarding risks associated with extracting fresh water point to water supplies as a significant issue for all involved.

Flowback risks to ground water[1] were the third most-selected pathway for the NGO group but were not included in the top twenty for government and industry experts. Top experts on fracturing and completion chose fresh-water withdrawals and methane venting at about the same rate as other experts but chose the effect of storage of fracturing fluids on surface water less often.

Well Production and Operation Activities

After the well is drilled, production commences and can continue for several decades. We identified a small number of potential risks associated with this activity that relate to gas production, operation of the condensate tank and compressors, and flaring of methane. We find that these activities are not included in the consensus pathways. Nor were they in any group's top ten priorities. Only the effect of flowback and produced water constituents on surface water during production made the top twenty and only in the non-NGO groups. However, subsequent analyses will show that there is much stronger agreement on this pathway's importance during the fluid storage and disposal stage.

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[1] During fracturing activities, some of the fracturing fluid returns to the surface (flowback) and the rest remains in the formation, which usually also contains large amounts of "produced water" that is a remnant of the water body that supported the life that was converted into oil and gas. This water, along with any chemicals in it, reaches the surface throughout the fracking, completion, and production process.

The impact of volatile organic compounds on air quality during condensate tank and dehydration unit operation was a particularly contentious risk. It was the nineteenth most-chosen priority in the NGO group but was not in the top fifty priorities for the other groups. Two other air-quality pathways made the NGO top twenty but were not high priorities for the other groups, indicating that NGOs are particularly concerned about air quality.

Fluid Storage and Disposal Activities

Much of the fluid used in hydraulic fracturing returns to the surface. We identified three methods of storage and disposal of these fluids as risk pathways: treatment and release, removal of sludge to landfills, and underground injection. Five of the twelve risks for which there is consensus occur during fluid storage and disposal, including the three risks most selected by all experts: the effect of flowback and produced water on ground and surface waters during onsite pit/pond storage and on surface water during treatment and release by municipal treatment plants. These pathways were in every group's top ten. The other two consensus risks are the effect of constituents of flowback and produced water on surface water after industrial treatment and of fracturing fluids on surface water during onsite pit/pond storage. Self-identified top experts in fluid storage chose the fracturing-fluid pathway less than other experts but were still concerned about storage of fracturing fluid and the other consensus pathways to a similar degree. The flowback risk pathways were the most picked by all respondents regardless of group. Thus, there was a consensus that those risks were important to address.

The three most disputed pathways according to our standard deviation measure also are in this activity group. One of the contested risks is road congestion, which was a high priority for the industry but not for the other groups. The other two relate to deep underground injection. Disruption of communities caused by seismic vibrations was a top-twenty pathway for industry and academic experts but was not even in the top one hundred for the NGO group, once again demonstrating that NGO groups tend to be focused strictly on environmental issues. The potential for flowback water to affect ground water during deep water injections was a top-twenty priority for government experts but was not in the top one hundred priorities of industry experts. Not surprisingly, the government group is more concerned about ground water risks than the other groups; five of the government's top twenty pathways concern ground water, and none of those five pathways is in the other groups' top twenty.

Ground water risks from this activity group generally are far less likely to have garnered a consensus than other types of risks. Eight of the eighteen pathways that appeared in only one group's top twenty had an effect on ground water. Meanwhile, seven of the twelve consensus pathways concerned surface water. In contrast, a real consensus exists that surface water risks need to be given more attention.

Shutting-in, Plugging, Abandonment, and Workover Activities

After a well ceases production, it is sealed, which is called shutting-in and plugging. Workovers involve reworking the well to increase its gas production. None of the pathways from these activities made a top-twenty list.

Support for Immediate Action and Government versus Voluntary Action

At the end of the risk matrix portion of the survey, respondents were asked whether they believed there was enough information currently available for actions to be taken on their priority risks or whether more research was needed. In addition, they were asked whether government or industry should take primary responsibility for such actions. The results are reported in Table 1. Across groups, the average expert felt that there was enough information to act now on 70 percent of the routine pathways designated as high priorities. As expected, academics were most likely to want more research; they chose a statistically significantly greater share of pathways as lacking adequate information relative to the industry and government groups.

The average expert across groups more often assigned responsibility for high priorities to the government. In the case of the twelve consensus priorities, at least two-thirds favored government responsibility. Voluntary action was favored for only two of the twelve (Table S12).

Interesting insights can be gleaned from combining the results from the information and responsibility questions. The two consensus pathways thought to most need more information were the ones *most* likely to be designated as government's responsibility—treatment of produced water by municipal and industrial treatment plants. Similarly, the two pathways thought to least need information for immediate action were the ones experts were most likely to designate as the industry's responsibility—storm water flows from clearing of land and the effect of storing fracturing fluids near drill sites on surface water. Thus, government is trusted more when less information is thought to be available (Tables S12 and S13).

In a separate question that was not linked to a specific pathway, the survey asked who generally should have primary responsibility for addressing risks from hydraulic fracturing—government only, primarily government with industry involvement, shared responsibility, primarily industry with government involvement, or solely the industry. While there were some differences between the groups (Table S15), almost 90 percent of the respondents indicated that the responsibility should be shared in some way.

Table 1. Results of the Information and Responsibility Questions by Group

	Average Percent of Pathways Selected				
	NGO	**Industry**	**Academics**	**Government**	**All Experts**
Is there enough research to proceed with action?					
Enough	64.2	78.3	62.3	75.5	70.7
More needed	35.8	21.7	37.7	24.5	29.3
Who should take primary responsibility for action?					
Government	86.8	65.5	75.3	76.4	73.9
Industry	13.2	34.5	24.7	23.6	26.1

Results for Accident Pathways

In addition to rating routine risks associated with shale gas development, respondents were asked to prioritize fourteen risk paths for types of accidents at well sites (e.g., truck accidents, failures of casings or cement) for further action by government and/or industry. For activities selected as a high priority, respondents were asked to note their assessments of the probability of the accident occurring and how severe such incidents would likely be.

As shown in Table 2, cement and casing failures were two of the top three priorities for all groups. Impoundment failure was in the top three for the government, NGO, and academic groups. The industry placed truck accidents third, once again prioritizing community impacts.

Once again, NGO respondents chose the largest number of pathways. The average NGO respondent selected more accident priorities than the average industry respondent (significant at the 99 percent level) and average government respondent (significant at the 90 percent level) while the average academic respondent chose more priorities than the average industry respondent (significant at the 90 percent level). Because of the relatively large number of high priority activities chosen, there was greater unanimity among NGO respondents; 80 percent of those respondents selected cement failure as a priority. Among non-NGO responders, cement failure was selected by 57–66 percent of respondents. This result closely mirrors the results for routine operations.

Figure 4 reports the results of respondents' predictions of how frequently accidents will occur and the severity of such accidents. The choices are shaded by how frequently each range was selected within the group. Our expectation was that respondents would generally rate high-priority types of accidents as severe but would also assign low probabilities of occurrence since few accidents have occurred to date. Thus, the shaded cells should be concentrated in the lower right portion of the matrix. And for all experts (Table S16), that is the pattern, but not strongly so. Figure 4 depicts each group's pattern. The most

Table 2. Percent of Experts Who Selected the Top Accident Risks as High Priorities and the Rank Given to that Risk by the Group

	NGO	Industry	Academics	Government	All Experts
Cement failure	80.0 (1)	58.7 (1)	57.1 (3)	66.7 (1)	63.3 (1)
Casing failure	68.6 (3)	46.7 (2)	61.9 (1)	57.1 (2)	56.7 (2)
Impoundment failure	71.4 (2)	33.3 (5)	61.9 (1)	45.2 (3)	50.2 (3)
Truck accidents	37.1 (8)	40.0 (3)	34.9 (7)	28.6 (6)	35.8 (6)
All fourteen accidents	40.6	27.2	34.2	30.8	32.2
Average no. of high priorities	5.69	3.81	4.79	4.31	4.50

Note: The numbers in parentheses indicate the rank of each accident risk by the group. Only the accidents that were top-three selections by a group are shown. See Table S15 for results for all accident risks.

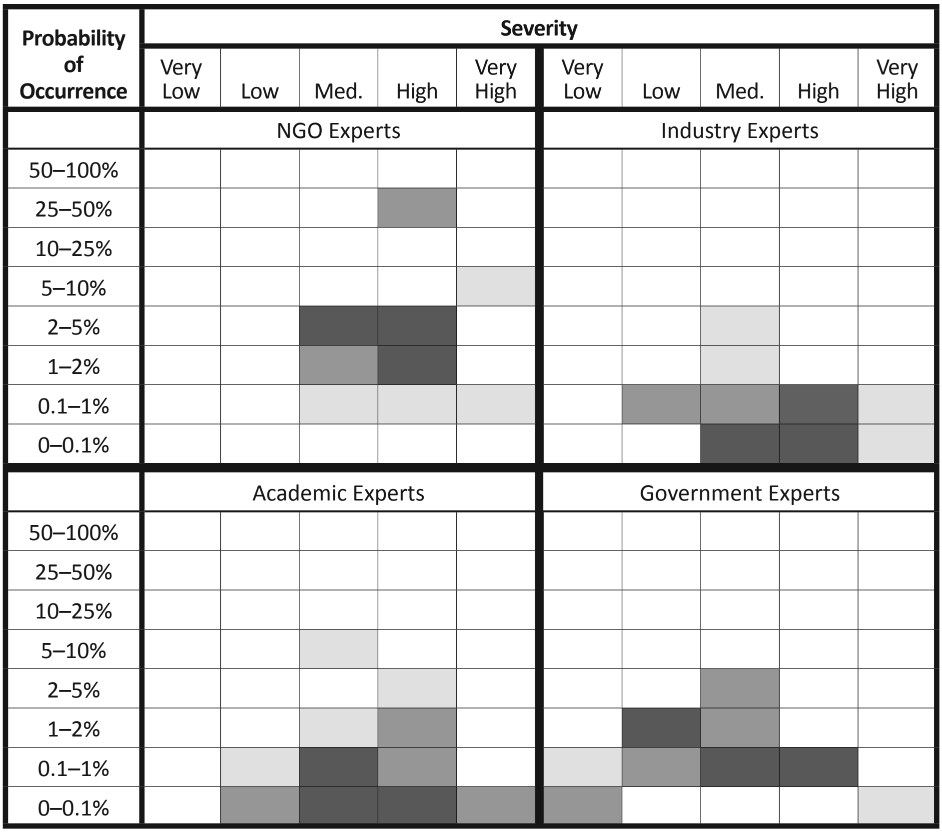

Figure 4. Severity-Probability Scores for High-priority Accident Pathways by Group

Light gray: 4.0–5.9 percent of sample. Medium gray: 6.0–7.9 percent of sample. Dark gray: 8.0 percent or more of sample.

obvious finding is that NGO respondents generally assign higher probabilities to accidents than industry respondents. However, the distribution of priority accidents over the levels of severity is not obviously different across groups (see Tables S17–S20 for detailed results).

To determine whether the groups made statistically different assessments of the risks, we calculated a severity-probability score that normalizes both categories to one and then multiplies the appropriate values for each probability-severity pair chosen. We average across all respondents in a group to assign a group score. We then can use the standard deviations of scores across all individuals in a group to statistically test whether a group's average score for a given accident differs from the average scores of the other groups. The NGO group's average score for the eleven accidents identified as high priorities is significantly higher than the average scores of the industry, academic, and government groups at a 99 percent level; the scores for the other groups are not statistically different from each other.

We also wanted to know if the most-selected accident pathways received relatively high rankings of the probability of occurring and of predicted severity. We find that severity-probability scores assigned to the high-priority pathways were consistently higher for consensus pathways than for nonconsensus pathways (Table S21).

Factors Affecting Choice of Priorities

Group affiliation could be a surrogate for other, more fundamental characteristics. Accordingly, the survey collected information about a variety of personal characteristics: education (degree and field of study), current field of employment, years in current job, years of experience with oil and gas and with shale gas, and knowledge of specific activities and impacts associated with shale gas development and of various U.S. shale gas fields. We looked for correlations between these characteristics and various metrics, such as number of routine priorities selected, number of accident priorities selected, assignment of responsibility to the industry or government, and average severity-probability score assigned to accidents. No uniform effects were found for these variables but there were some relationships within groups.

We also ran a separate regression for each of these dependent variables interacted with the organizational variables. In most cases, there were no relationships. However, top industry experts in fracturing fluids, flowback, and produced water storage and disposal tended to pick a greater number of accidents as high priorities than regular experts in all four groups. In addition, the degree of experience of industry, academic, and government respondents with the oil and gas industry was associated with an increased likelihood of assigning mitigation responsibility to the industry (a result that is statistically significant for the industry and government groups at the 95 percent level and for the academic group at the 90 percent level). Conversely, NGO respondents with experience with the oil and gas industry were more likely to assign responsibility for action to the government (significant at the 99 percent level).

We had a large enough sample of industry and academic respondents to regress those experts separately for the entire set of dependent variables to examine the effect of personal characteristics within each group. In general, the personal characteristics did not do a good job of explaining variations in the dependent variables.

Thus, we conclude that group affiliation, with a few exceptions, dominates the ability to explain choices. In the industry group, (i) top experts in well production and operation tend to choose fewer accident pathways as priorities than regular experts in all four groups (significant at the 95 percent level) and (ii) experience in the oil and gas field is related to believing that the industry should be primarily responsible for addressing risks (95 percent).

Within the academic group, two other effects are significant: (i) experience in the oil and gas field is related to lower severity-probability scores (99 percent), and (ii) experience with shale gas is positively related to the number of accident pathways chosen (90 percent). Notably, among academics, experience in oil and gas is not related to assigning responsibility for addressing risks to the government vs. the industry under these regressions.

Research and Policy Implications

Considering the cacophony of differing opinions dominating the media and even scientific conferences, our finding that there is a general consensus among the key stakeholder groups on thirteen routine impact pathways and two accident pathways is quite surprising. The most immediately important result in terms of policy is that only two of the agreed-on concerns are unique to shale gas development (both involve risks posed by fracking fluids leaking into the environment). This result suggests that invective aimed at shale gas development is misdirected. At the same time, the large volumes of water needed for fracking exacerbate the potential for negative consequences for surface water and communities (from truck traffic). The consensus on these risks indicates that all involved could benefit from immediate further evaluation of the risks, best practices, feasible and effective regulations, and costs of mitigation associated with each pathway. Indeed, on the risk side, the dominance of concerns about surface water has led to at least one study of that risk in Pennsylvania (Olmstead et al. 2013), which found that spills from drilling sites had statistically insignificant effects on rivers and streams, although the now much-reduced practice of sending liquid waste to industrial and municipal treatment plants had affected stream quality below the plants' outfalls.

Agreement on the importance of understanding methane leaks is perhaps less surprising but points to an urgent continuing need for research since efforts so far have done little to quell debate (Allen et al. 2013). The high-priority pathway from faulty casings and cementing to ground water pollution also remains poorly understood, although a recent report from the EPA (2015) found just a few documented instances of effects on drinking water sources. Much of the data that could be used to estimate this risk has been suppressed by legal agreements between landowners and operators. Traditionally, nearby water wells have not been tested before drilling commences to establish the baseline water quality, but that tradition is changing.

The surprising appearance of habitat concerns associated with construction of well pads and roads and with pipeline activities suggests that greater attention should be paid to how pads are sited within a lease holding and across holdings in an area and that models should be built to accommodate all interested and regulated parties.[2]

A final implication is drawn from assignment of responsibility for action to the government or to the industry. On one hand, the industry has led many efforts to establish best practices that can reduce the environmental risks associated with shale gas development (Marcellus Shale Coalition 2014, American Petroleum Institute 2013). This focus on best practice is in line with growth of movements for corporate responsibility. On the other hand, a majority of the respondents in this study assigned responsibility for action for eleven of the twelve consensus pathways to the government. This emphasis on the role of government is apparent from states' efforts to update their regulations pertaining to shale gas development to make them more stringent (Richardson et al. 2013).

Given the seeming lack of public trust in oil and gas operators, the highly visible impacts of shale gas development on communities, and ongoing drilling, establishing a consensus that shale gas development is sustainable will be challenging. The results of our survey of experts can guide many of those efforts.

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[2] See a description of such a model, EnSitu, which is The Nature Conservancy's Appalachian shale siting tool (*www.nature.org/ourinitiatives/regions/northamerica/unitedstates/pennsylvania/the-nature-conservancys-shale-siting-tool-summary.pdf*).

Supporting Information

Additional materials on methods and results noted in the text are available online at *www.rff.org/Documents/RFF-Rpt-PathwaystoDialogue_FullReport.pdf*.

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