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Defining and defending risk: conceptual risk formulas in environmental controversies

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Abstract Environmental risks are contested topics, and definitions of risk often vary across contexts, disciplines, and institutions. Identifying and describing differences between risk definitions is particularly important because they directly impact risk assessment and management practices. This paper describes how stakeholders rhetorically define and technically operationalize the risks of industrial chemicals, focusing on contemporary debates over flame retardant chemicals that in recent years have been the subject of numerous risk assessments, regulatory activities, and activist campaigns. This paper uses a multi-method approach to develop six conceptual risk formulas which delineate the components that go into evaluating risk and the relationships between those components: the classic risk formula, the emerging toxicology risk formula, the exposure-proxy risk formula, the exposure-centric risk formula, the hazard-centric risk formula, and the either-or risk formula. Using chemical alternatives assessment as an example, this analysis demonstrates how conceptual risk definitions influence the operationalization of risk assessment and management activities.

Keywords Risk definition · Risk-based regulation · Human and environmental health · Flame retardant chemicals

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Introduction

In environmental policy arenas, the concept of risk is often subject to competing social and technical definitions which vary across contexts, disciplines, and institutions. Risk definition is important because before decision makers can calculate whether something poses a risk to human health or the environment, they need to identify how that risk should be calculated. Scholars have highlighted differences in risk approaches between academic disciplines, described the different conceptions and misconceptions of risk, and distinguished between realist, subjectivist, psychometric, and sociocultural approaches (Althaus 2005; Zinn 2008; Aven 2010). But little attention has been paid to the details of risk definitions used by competing groups of stakeholders engaged in policy debates.

In this paper, I describe six "conceptual risk formulas" which delineate the components that go into evaluating human health risks from environmental chemical exposures and the relationships between those components: the classic risk formula, the emerging toxicology risk formula, the exposure-proxy risk formula, the exposure-centric risk formula, the hazard-centric risk formula, and the either-or risk formula. Previous work has discussed the risk classifications used by academics or risk assessment professionals. In contrast, my approach focuses on the terms used and the definitions favored by those actively participating in debates over chemical risk and safety. These stakeholders' risk definitions matter because of their centrality to environmental policy making. After briefly summarizing the social science literature on risk definition and conceptualization, I describe my qualitative research methods and then discuss each conceptual risk definition in detail. In conclusion, I discuss why risk definition matters and identify important policy implications.

Risk definition and conceptualization

The social definitions of environmental and technological risk determine whether certain courses of action are viewed as legitimate and preferable, and thus these definitions structure risk-based decisions (Renn 2008). Risk definitions and their attendant power struggles are central to how contemporary society experiences, debates, and responds to risk (Beck 2010). As early work on risk perception demonstrated, "the concept 'risk' means different things to different people" (Slovic 1987:283). These differences in how risk is conceptualized determine people's experiences of and responses to risks (Renn et al. 1987). When the stakes are high—when profits or public health are threatened, for example—the legitimate bounds of risk assessment become sites of intense competition between stakeholders. Though risk society theorists have suggested that risk definition is generally the purview of experts (Beck 2010; Beck et al. 1994), sociologists have shown that risk assessors and environmental regulators do not set the risk agenda on their own (Goldblatt 1996; Kinchy 2012). Other actors in contested policy fields, especially social movement organizations and activists, play key roles in framing risks and making them meaningful.

Though risk assessment is a well-developed field of scientific study and practice, the field lacks general consensus on the conceptualization of foundational risk concepts and principles (Aven 2012). One approach to the heterogeneity of the field is to present multiple perspectives and then offer a concluding, parsimonious definition of risk (Aven 2010). Another is to examine how risk definition varies across disciplines or institutions (Althaus 2005). Thematic approaches in the social science distinguish between realist, subjectivist, psychometric, technocratic, and sociocultural approaches, among others (Krimsky and Golding 1992; Zinn 2008). Building on work by environmental sociologist William Freudenburg (e.g., Freudenburg 1988), scholars have highlighted how risk calculations and risk management decisions are socially influenced and often reflect stakeholders' values and economic and political interests (Tierney 1999; MacGillivray et al. 2011).

My perspective in this paper is different in two ways. First, I am less interested in how academic commentators or risk assessors talk about risk than I am in how practitioners and stakeholders themselves describe and operationalize risk in the midst of unfolding events, hoping to influence those events. This aligns with work on how risk and safety are discussed related to other chemical controversies, including Vogel's study of the safety of Bisphenol-A (Vogel 2013) and Joyce's work on institutional assessments of methylmercury in fish (Joyce 2011). Second, I am interested in stakeholders' conceptual risk formulas, rather than risk as an overarching concept. As I show in this paper, different risk formulas allow or require different types and amounts of scientific data and describe different relationships between bodies of evidence.

By studying multiple definitions of the risks of one class of chemicals, I am able to see risk as a concept that travels, changes, and operates within and across institutions (Kinchy 2012). The institutionalization and codification of risk formulas act as rules that govern the assessment of chemical safety, setting the boundaries for subsequent risk assessments and risk management activities and revealing distributions of power (Frickel and Moore 2006). The adjudication of these rules thus has significant implications for chemical policy, chemical production, and environmental health. For example, Frickel et al. (2009) found that the institutionalization of risk assessment procedures shaped regulatory responses to natural disasters like hurricanes.

Flame retardant chemicals

I develop six conceptual risk formulas using the case study of controversies over flame retardants, widely used chemicals with suspected environmental and human health impacts. Flame retardants are a particularly interesting example of controversies over environmental risks because they are ubiquitous and unavoidable, the adequacy of regulation is fiercely contested, and health guidelines on safe exposure levels rarely exist. The amount of research on flame retardants has greatly increased in the past decade, pushing these areas to the forefront of environmental health science and the center of ongoing regulatory controversies (Brown and Cordner 2011; U.S. EPA 2014a).

Chemical flame retardants have been used in the USA since the 1960s to meet fire safety and flammability regulations for a variety of products, ranging from upholstered furniture to building insulation (MacGillivray et al. 2011). Flame retardants are ubiquitous and rapidly accumulate in the environment, wildlife, and people, who are exposed to these chemicals from household dust, physical contact, ingestion, smoke, contaminated air, and, less universally, manufacturing sources (Betts 2009). The widespread use of chemical flame retardants has coincided with state and national policies, educational campaigns, and behavioral changes (especially declining smoking rates) that have decreased fire mortality, injuries, and incidence in the USA (Evarts 2011; Karter 2012). However, flame retardants used in some consumer applications may increase risks from fires in other ways, even if they slow ignition, because materials containing flame retardants release smoke that can be more toxic (Shaw et al. 2010; Stec 2012). Additionally, flame retardants may not provide significant protection against open flames in consumer products like upholstered furniture (CPSC 2012), amplifying concerns about the health impacts of long-term exposure to these chemicals.

Several types of flame retardants were regulated in the 1970s following dramatic episodes of contamination in

children's pajamas (Blum and Ames 1977; CPSC 1977) or in livestock (Reich 1983; Egginton 2009). Research in the late 1990s on the widely used polybrominated diphenyl ether (PBDE) flame retardants initially raised concerns about high levels in breast milk and house dust (Meironyte et al. 1999; Rudel et al. 2003). Since then, scientists have found that PBDEs are endocrine disruptors and are toxic in laboratory animal studies (Messer 2010). In humans, PBDE exposure is associated with certain cancers, reproductive effects, thyroid disorders, neuro-developmental disorders in children, and diabetes (Kim et al. 2014). Though PBDEs are no longer manufactured in the USA, many other flame retardants remain in production and are widely used in consumer and industrial applications. A large number of flame retardants are now facing increasing regulatory pressure because of growing scientific concerns about their impacts on human health and the environment (California OEHHA 2014; U.S. EPA 2014a).

Research methods

This work is part of a larger mixed method project on the social implications of flame retardant chemicals and risk and hazard assessment of chemicals (Brown and Cordner 2011; Cordner and Brown 2015; Cordner 2015). I conducted in-depth interviews and participant and non-participant observation at multiple sites, supplemented by a detailed literature review, archival research, and a content analysis of published documents and testimony. The research was approved by Institutional Review Boards at Brown University (Protocol 1006000211) and Whitman College (Protocol 13/14-02).

I interviewed 115 individuals, including scientists in academia (17), the government (23), and consulting or nonprofit institutes (5); state regulators (7); federal regulators (20); legislators (4); flame retardant and supply chain industry representatives (23); firefighters and fire safety experts (6); and activists from environmental and health organizations (10). An additional 12 interviews (8 activists and 4 fire safety actors) were conducted by research assistants. Interviews were conducted in person whenever possible, with 22 interviews conducted over the phone.

Additionally, I conducted ethnographic observations between June 2010 and May 2012 at five sites: a flame retardant industry research and development lab, two offices of the Environmental Protection Agency (EPA), an environmental health non-profit organization, and an academic environmental chemistry lab. Multi-sited ethnography is a form of participant observation that is particularly well-suited for topics such as risk definition and chemicals policy that are interdisciplinary and not confined to a single geographic location (Marcus 1995; Hannerz 2003). Additionally, I attended and participated in industry, scientific, and activist conferences on risk, environmental health, and flame retardants between 2010 and 2013.

All interviews were transcribed with identifying information removed to protect confidentiality. I analyzed the data through multiple readings of the transcripts and field notes. All coding was done in NVivo 10.0, a software program for managing and analyzing qualitative data. I developed a hierarchical list of codes based on interview questions and developed and added additional codes following repeated readings of the transcripts. I identify stakeholders according to their employment at the time of my interview with them (e.g., environmental activist or EPA scientist), though I recognize that the boundaries between these categories are often imperfect and fluid.

Conceptual risk formulas

In interviews and publicly available documents, stakeholders described how human health risks from environmental chemicals should be evaluated using six conceptual risk formulas, summarized in Table 1.

Classic risk formula

The "classic risk formula" states that risk is a function of hazard and exposure. Hazard is understood to be the danger or severity of something, exposure refers to its likelihood or probability, and the function incorporates uncertainty about these two factors. This is similar to Zinn's "technical-objectivist definition of risk" (Zinn 2008), or Aven's definition of risk as "uncertainty about and severity of the consequences of an activity" (Aven 2010).

The classic risk formula identifies a multiplicative or linear relationship between exposure and hazard. That is, it assumes a toxicological dose-response relationship: the response (or hazard) should increase as dose (or exposure) increases, and therefore risk increases with dose. This reflects the foundational tenet of toxicology that "the dose makes the poison" (Richards 2008).

This formula is frequently utilized in formal risk assessment practices to describe dose-response relationships and to identify reference doses or safety factors. Official EPA risk assessments are explicitly grounded in this definition of risk. For example, the website providing an overview of the New Chemicals Program states in bold, italic letters, "***Hazard x Exposure=Risk***" (U.S. EPA 2010). As another example, the EPA's Integrated Risk Information System defines risk as "the probability of adverse effects resulting from exposure to an environmental agent or mixture of agents," and uses this model to calculate a reference dose for a given health endpoint (U.S. EPA 2013).

Multiple EPA scientists echoed this definition in interviews. As an exposure scientist explained, "we go to the zoo and we feel safe, even though there is a high hazard, because

Table 1 Conceptual risk formulas

	Formula	Key features	Sites and stakeholders
Classic	Risk=*f* (hazard × exposure)	Function is linear and multiplicative; dose-response relationship	Discipline of toxicology
			Regulatory bodies
			Discourse from industry and EPA
Emerging toxicology	Risk=*f* (hazard exposure)	Function includes individual susceptibility and exposure includes timing of exposure	Low institutionalization but growing scientific and regulatory awareness and acceptance
		Rejection of linear dose-response in favor of more nuanced understanding of dose-response relationships	EPA's Office of Children's Health Protection
		Particular relevance with certain classes of chemical (e.g., hormone disruptors) or moments of exposure (e.g., fetal development)	
Exposure-proxy	Risk=*f* (hazard exposure persistence/ biaccumulation)	All components draw on the most protective measures available	Prioritization or screening of chemicals of concern
		Assumes that exposure is expected if a chemical is persistent and bioaccumulative	EPA's Chemical Work Plan process
Exposure-centric	Risk=*f* (hazard × exposure potential* × human exposure levels)	Function includes a measured dose-response relationship (i.e., exposures below a certain threshold are of no risk)	Prominent in chemical industry discourse and evaluation
		Exposure potential is multifaceted, including mechanism and pathway of human exposure	
Hazard-centric	Risk=*f* (hazard* × exposure)	Hazard is multifaceted and includes characteristics of exposure potential	Low institutionalization but growing awareness
		Exposure is assumed to be under-measured	Alternative assessment programs in government and non-governmental organizations
		Reduce risk by reducing hazard within functional use categories	
Either-or	Risk=*f* (hazard) or risk=*f* (exposure)	Either hazard or exposure provide grounds for action	Environmental advocacy
		Alignment with precautionary principle	Low institutionalization
		Toxic trespass perspective	State biomonitoring programs

there is no exposure. There are 200 hungry carnivores, which are a potential hazard, but there is very low exposure. Risk equals hazard times exposure, and any number times zero is zero." This chemist also emphasized dose-response: "The simplification is, the dose makes the poison… Too much of anything, water, oxygen, nitrogen, right, is harmful." Similarly, representatives of the flame retardant industry also often invoked the classic risk formula. As one industry scientist described, "the common definition of risk… [is], what is the probability that there will be a problem, that something will happen, and what is the seriousness of the effect." He explained that a chemical that was low hazard and low exposure would pose no risk: "if you have a chemical which has relatively low toxicity and then the probability that anybody will be exposed to it is very low, there is no risk." While EPA and industry stakeholders do not draw exclusively on the classic risk formulas, these examples show how stakeholders can define risk as a linear and multiplicative relationship between hazard and exposure.

Emerging toxicology risk formula

An emerging body of research in toxicology demonstrates that, for some toxicants, the assumption that the dose makes the poison inaccurately estimates risks because the relationship between hazard and exposure varies based on the amount of exposure, the timing of exposure, and individual susceptibility. These revisions are impacting discourses and practices in various institutions through what I call the "emerging toxicology risk formula." This risk formula modifies the classic risk formula to include individual susceptibility and exposure timing and to reject the assumption of linearity in identifying a dose-response relationship.

For some dose-response curves, the relationship between exposure and effect does not monotonically increase—and may change shape or even decrease—from low to high doses (Calabrese and Baldwin 2003; Do et al. 2012). For example, certain vitamins are beneficial at low doses but harmful at higher doses. In the environmental health field, researchers have learned that hormone disrupting chemicals can induce significant effects at very low levels of exposure (Krimsky 2000; Vandenberg et al. 2012). Additionally, timing of exposure impacts health effects (Vogel 2013). In particular, in utero and early childhood exposures to some chemicals may induce strong later-life effects (Bergman et al. 2012). Health effects can also span generations (Schmidt 2013). A well-known example is diethylstilbestrol (DES), a drug used in the mid-1900s by millions of women under the mistaken belief that it would improve pregnancy outcomes. Exposure to DES led to greatly increased risks of cancer and reproductive effects in children who had been exposed to the drug in utero (Bell 2009). Special concern also surrounds exposures during childhood. As the EPA's Office of Children's Health Protection has codified, children are not just small adults, due to their behaviors, physiological differences, metabolic systems, and windows of susceptibility (U.S. EPA 2015). Furthermore, as one environmental health advocate explained in an interview, "children are at the top of the food chain" when they are in the womb or when they are breastfeeding.

Finally, developments in genetic toxicology, epigenetics, and the environmental health sciences point to variation in individual response and susceptibility to exposure (Shostak 2013). Linda Birnbaum, Director of the National Institute of Environmental Health Sciences, rhetorically supported the emerging toxicology risk formula, explaining, "We now know it's not only the 'dose that makes the poison,' it's [also] timing, it's inherent susceptibility" (Hoban 2012). The emerging toxicology formula complicates the dose-response relationship with these additional factors.

Exposure-proxy risk formula

In several programs, the EPA moves beyond the classic risk formula and makes protective determinations of risk by adopting the "exposure-proxy risk formula," which includes chemical persistence and bioaccumulation alongside hazard and exposure. The exposure-proxy formula assumes that even if exposure has not yet been measured, it is likely to occur if a chemical is persistent and bioaccumulative (that is, if does not readily break down and can be absorbed and accumulated in the body). In essence, this formula calculates chemical risk as a multiplicative function of hazard, exposure, and potential to persist and bioaccumulate.

This exposure-proxy risk formula is used in the EPA's New Chemicals Program to evaluate whether newly developed chemicals pose an "unreasonable risk" to human health and the environment (U.S. EPA 2014b). Each new chemical is reviewed by EPA experts for hazard, exposure, and persistence and bioaccumulation potential. This third component represents an immediate departure from the classic risk formula, and is one way that the EPA accounts for uncertainty when evaluating newly developed chemicals with little or no exposure measurements. If chemicals will persist in the environment and accumulate in tissues, then exposure is likely to occur, and thus the potential consequences for otherwise underestimating risks are more substantial. An EPA researcher explained that EPA thinks of the combination of persistence (P) and bioaccumulation (B) as a "proxy for exposure, because we assume if it is P and B, we will be exposed." This approach mirrors work in Europe under Registration, Evaluation, Authorisation, and Restriction of Chemicals (REACH) to prioritize "Very Persistent, Very Bioaccumulative" chemicals.

This formula was used by the EPA in 2012 to identify and prioritize Workplan Chemicals for additional review under the Toxic Substances Control Act (U.S. EPA 2012). The EPA first

identified a list of 345 candidate chemicals based on existing concerns or use patterns (e.g., children's products) and then screened these chemicals more thoroughly. Based on a review of the scientific literature, consultation with experts, and structure-activity relationship evaluation, the EPA assigned each chemical a hazard score, an exposure score, and a persistence/bioaccumulation score of 1, 2, or 3. These three numbers were added together, normalized, and grouped as low, moderate, or high priority (U.S. EPA 2012). The exposure-proxy formula uses this type of persistence and bioaccumulation assessment to inform the risk assessment process.

Exposure-centric risk formula

The "exposure-centric risk formula" expands the classic risk formula with a multifaceted understanding of exposure. This formula splits exposure into four pieces, each of which can be assigned values—including, potentially, a value of zero—in the process of calculating risk. First, exposure potential depends on the physical-chemical properties of the chemical. A product development manager told me that reactive flame retardants, which are bound to products, have no exposure potential outside of occupational exposures: "If you develop flame retardants that are reactive… they will never, never expose anybody." The flame retardant industry is also developing large molecular-weight compounds that are believed to be too large to be absorbed and thus are predicted by industry-funded assessments to be low exposure and low risk (Williams 2012).

Second, exposure potential is based on a chemical's use scenarios. An industry advocacy representative explained that flame retardants uses in home insulation can be assumed to have a low exposure potential, uses in furniture or electronics have a moderate exposure potential, and uses in cell phones have a high exposure potential. These different exposure potentials lead to different calculations of overall risk in the industry's preferred risk formula.

Exposure assessment in the exposure-centric risk formula also involves identifying and documenting an exposure pathway from source through absorption in the human body (Maxwell 2009). As part of the exposure-centric risk formula, documenting how exposure happens is very important. A public health researcher explained, "there could be nasty stuff in the dust in this room, but that doesn't mean that I have exposure to it." Without an accurately characterized exposure pathway, risk calculations could be inaccurate.

The final component of exposure definition is that levels of the chemical must be actually measured in people or the environment. Without this data, even if there is exposure potential based on physical-chemical properties, use patterns, or exposure pathways, the exposure-centric risk formula suggests that exposure is not a concern. For example, responding to a publication identifying certain flame retardants in baby products (Stapleton et al. 2011), the American Chemistry Council, a large trade association for the US chemical industry, issued a press release stating: "This study attempts to examine the existence of certain flame retardants in a small sampling of children's products; it does not address exposure or risk" (American Chemistry 2011). Although non-reactive flame retardants in baby products would seemingly have a high exposure potential, the association argued that the research did not address exposure because it did not test for levels of the chemicals in people or the environment, and did not address risk because it did not connect these levels to a dose required to cause a toxic effect.

The exposure-centric risk formula also maintains strict adherence to a multiplicative relationship between exposure and risk. If any component or sub-component of exposure is assessed to be zero, the risk equation as a whole can equal zero, regardless of the magnitude of other components in the model. As an industry representative explained, "you could have something that's highly toxic but there's not going to be any exposure, so it's not going to be a concern." Because it identifies multiple components of exposure and assigns each of them a multiplicative status, the exposure-centric risk formula can more easily arrive at a determination that the chemical or product in question poses no risk.

Hazard-centric risk formula

The "hazard-centric risk formula" modifies the classic risk formula with the assumptions that hazard is complex and multifaceted, exposure is hard to measure, and some aspects of exposure can be reconceived as hazard characteristics. Instead of emphasizing exposure potential and measurement, proponents of this formula argue that decreasing hazard will decrease risk overall. The hazard-centric formula acknowledges and emphasizes the uncertainty that surrounds toxicity data, even as it works to fully characterize a chemical's expected hazard. This formula emphasizes a multifaceted understanding of hazard endpoints and assumes that assessments should be protective, relying on the most conservative endpoint available. For example, the EPA's Design for the Environment program assesses over a dozen hazard endpoints for clearly defined toxicity outcomes, and if multiple studies of comparable quality exist for the hazard endpoint, the program will make a hazard determination based on the study that found effects at the lowest dose (U.S. EPA 2011).

Proponents of the hazard-centric risk formula describe their position as a response to the scientific limitations of characterizing toxicity pathways, mechanisms of action, low-dose and non-monotonic effects, and the reliability of animal studies. As a toxicologist explained, "I can tell you if there's a five percent increase in the tumors… But EPA regulates at one in ten-thousand. I'm at five in a hundred. One in ten thousand is not necessarily an unreasonable number, but I'm not getting

there with an animal." Toxicology traditionally extrapolates from high-dose animal studies to low-dose human disease rates, yet animal models are imperfect predictors of illness in humans (Gottmann et al. 2001). Tox21, an ongoing research effort involving collaboration between four US government agencies and research institutes, uses high-throughput screening of in vitro assays to evaluate thousands of chemicals against hundreds of toxicity endpoints in order to identify toxicity pathways and improve understanding of chemical hazard (Rice et al. 2013). This type of effort to better understand and evaluate chemical toxicity is consistent with the hazard-centric risk formula's assertion that although hazard is multifaceted and complex, understanding chemical toxicity is useful and necessary for the screening and evaluation of environmental health risks.

A final significant departure from the classic risk formula is that some chemical characteristics typically associated with exposure, such as persistence or bioaccumulation potential, are redefined as hazard characteristics. Like the exposure-proxy risk formula, the hazard-centric risk formula sees persistence and bioaccumulation as concerning, particularly because, as several EPA scientists told me, "exposure controls can, do, and will fail." Others argued that risk assessment and risk management strategies were useful only if exposures were perfectly known and controlled, an unlikely scenario. But while the exposure-proxy risk formula evaluates persistence and bioaccumulation as a third component of the risk formula, the hazard-centric risk formula sees these characteristics as part of a chemical's overall hazard profile. Thus, the hazard-centric risk formula relies on a multifaceted conceptualization of hazard and utilizes multiple strategies to develop protective assessments under conditions of scientific uncertainty.

Either-or risk formula

A final risk formula rejects multiplicative risk calculation altogether. As an environmental health activist explained, her work on flame retardants was motivated both by exposure and by hazard, but not by the classic risk formula: "One of the reasons that we chose to work on flame retardants was because of the widespread use in consumer products. Flame retardants were in everybody's homes, they were in virtually everybody's body… And the science was really developing, as to the harmful nature of these chemicals. How harmful is this to people? How prevalent, how widespread it is?" Though she mentioned both harm and prevalence, she did not feel the need to integrate the two into a "safe" exposure level; instead she explicitly rejected the "risk-based approach… It's flawed in many ways."

This final re-definition of the risk formula, the "either-or risk formula," asserts that a chemical can pose an unreasonable risk based on hazard or exposure data, not necessarily on the combination of the two. That is, a risk can be actionable based on documented hazard but no proven exposure, or can be actionable based on documented exposure, especially to certain vulnerable populations, but no proven hazard.

In the words of one environmental health organizer, risk assessment "basically says…, 'this is how high the stack of bodies can be.'" Another noted that risk assessment does not adequately protect vulnerable populations since it is often based on "a healthy, white, 30-year-old, 150 pound male" and ignores vulnerable populations, cumulative exposures, and synergistic effects. This is a common argument in environmental health social movements (Brown 2007). Activists told me that determinations of risk require unreasonably high standards of proof and impossibly large volumes of data, leading to easy manipulation of assessments, and creating a bias toward the finding of "no risk." They would likely agree with former EPA Administrator William Ruckelshaus, who wrote, "risk assessment data can be like the captured spy: if you torture it long enough, it will tell you anything you want to know" (Ruckelshaus 1984). Advocates also asserted that they wanted to avoid the "dueling science" of comparing stacks of scientific evidence regarding flame retardant safety, identified by scholars as a common industry strategy for delaying regulation (Oreskes and Conway 2010).

Following the either-or risk formula, hazard is seen as sufficient on its own to prioritize and regulate chemicals and is a piece of information that individuals can use to make their own decisions about products. As one activist explained it, "we [her organization] prefer a hazards-based approach, which is, let's look at the chemicals. If it's hazardous, don't use it." Thus, the argument is that hazardous chemicals should not be used, regardless of exposure. This piece of the either-or risk formula aligns with the hazard-centric risk formula's emphasis on decreasing risk by decreasing the inherent toxicity of chemicals chosen for use.

The biggest distinguishing characteristic of the either-or risk formula is the assertion that exposure could be sufficiently risky on its own. That is, in some cases documented exposure should provide sufficient justification for regulation or other action, without the need for hazard data or a known dose-response relationship. As an activist said, this approach calls attention to faulty assumptions in the past that chemicals "were in the products and stay there." Instead, it should be assumed that chemicals used in consumer product will migrate out of those products and thus that human exposure is likely to occur. One environmental health organizer explained, "even if we were to stop right now, some of these chemicals are very persistent, like the flame retardants, and they're not going away any time soon." Instead, some highly persistent chemicals will be around—and in human bodies—for generations to come.

Following the either-or risk formula, one activist explained that "the trespass is the harm," particularly for exposures to

fetuses or children. One advocate described the impact of a study that found flame retardants in cord blood: infants have "never breathed the air, they've never eaten our food, never drank the water, yet they're born with these chemicals in them… It points out a flaw in the system." Another activist expressed the either-or risk formula, saying "you don't even have to show a health effect. If you're showing that these chemicals are getting into my body, that trespass is unauthorized." Advocates used this to counter arguments from industry stakeholders that low levels of exposure pose no risk. In the words of an environmental health activist, "companies can dish all they want about how these levels are not significant and they're not very high, and this and that. But it's just an indefensible position. These chemicals shouldn't be in our bodies, period." This then becomes an ethical argument about consent, right-to-know, and environmental outrage, in addition to an argument about toxicity and health effects. Within the either-or risk formula, either hazard or exposure data can be sufficient for decision-making; the two need not be combined and evaluated together to adequately assess risk.

Implications of risk definition for environmental policy

Risk formulas lay the foundation for risk assessment and management activities. Before stakeholders or institutions can disagree over whether chemicals pose a risk to human health or the environment, they have to identify how that risk should be calculated and what goes into a risk formula. Focusing on risk formulas requires scholars to pay attention not just to the risk management decisions and activities supported by competing stakeholders but also to how each term and process is defined and implemented.

As a particularly relevant example, these consequences can be seen in how risk formulas impact the type of Chemical Alternatives Assessment (CAA) preferred by different stakeholders. CAAs compare potential human health and environmental impacts of multiple chemicals that perform the same function as a chemical of concern, often a chemical scheduled for regulation (U.S. EPA 2014c). These assessments can be used by decision makers to identify potential functional substitutes for a chemical of concern, select replacement chemicals with preferable health and environmental profiles, and incorporate information about hazards for further analysis.

The EPA's Design for the Environment program conducts CAAs that reflect the hazard-centric risk formula (Lavoie et al. 2010). The program evaluates a wide range of hazard endpoints, along with persistence and bioaccumulation, and makes protective hazard determinations when multiple findings exist for a given health endpoint. In interviews, program representatives acknowledged the multiplicative relationship between hazard and exposure, while arguing that reducing hazard is a more effective tool for reducing risk than reducing exposure. This type of CAA, anchored in the hazard-centric risk formula, is designed to facilitate long-term industry decision-making by giving companies greater confidence in chemical substitution choices, since no matter their exposure patterns, chemicals with low expected hazard will be less likely to face future regulatory action.

In contrast, the American Chemistry Council advocates for a CAA model that follows the exposure-centric risk formula, looking well beyond hazard profiles to evaluate chemicals, and including exposure potential, documented exposure pathways, use profiles, and human exposure in its comparative evaluation. The Council's statement on CAA practice argues that chemical hazard should be assessed alongside of "product use and exposure" as part of a "comprehensive risk-based safety assessment of alternatives" (Jack 2012). This CAA model specifically rejects the hazard-centric risk formula, stating that "any comparative assessment methodology that relies solely on hazard can be grossly misleading," and rejects the either-or risk formula, arguing that "the presence of a chemical in biomonitoring studies does not necessarily indicate there is a likelihood of harm" (Jack 2012). Instead, the American Chemistry Council states their preference for a multifaceted evaluation of exposure that includes exposure pathways, use patterns, exposure levels, and exposure potential: that is, it follows the exposure-centric risk formula.

These two examples demonstrate that risk formulas matter greatly when it comes to developing and interpreting environmental policy, with the EPA's CAA model clearly aligning with the hazard-centric risk formula and the chemical industry's CAA model supporting the exposure-centric risk formula. Which CAA model, and thus which risk formula, is institutionalized has significant consequences for public and environmental health. Like the classic risk formula and formal risk assessment generally (Winner 1986), the exposure-centric risk formula favors industry stakeholders. Because the formula is strictly multiplicative, the absence of data suggests the absence of risk, favoring the chemical industry's interests in maintaining and expanding markets for chemical products. In the words of an EPA representative, this allows industries to justify the continued use of "nasty chemicals" that are toxic but have low estimated exposure. In contrast, the hazard-centric risk formula is more supportive of public health protection because of its multifaceted understanding of toxicity endpoints, its recognition that exposure is difficult to measure, and its reliance on protective assessments in the absence of scientific certainty.

Risk definition matters in areas of environmental regulation beyond CAA, and additional research is needed to examine how these formulas inform the implementation and operationalization of risk management practices across agencies and geographic scales. For example, do conceptual risk formulas impact stakeholder preferences or merely reflect those preferences? To what extent do risk formulas reflect

different epistemological orientations toward risk, and to what extent do they reflect stakeholder economic and political interests? Additionally, risk formulas map imperfectly onto institutional categories. As I have shown, the chemical industry generally favors the exposure-centric risk formula, while environmental activists generally support the either-or risk formulas. These associations may hold for some groups of stakeholders and not for others. Additionally, overlaps are likely across different risk formulas. For example, the hazard-centric and exposure-proxy risk formulas share the assumption that persistent and bioaccumulative chemicals are likely to cause significant human exposures if widely used.

Future research should examine whether these six conceptual risk formulas or others are present and dominant in different contexts and around different types of controversies. This framework was developed using controversies around the risks of chronic, low-dose exposure to toxic chemicals. A different set of risk formulas may dominate the discourse and practice in other areas of risk assessment and management, such as ecological risk assessment, risk assessment outside of the USA, risk assessment for acute toxicity, or risk assessment of radiation exposure.

Controversies over chemical risks are multi-sited, involve a broad spectrum of actors, and are ongoing. Thus, examination of these controversies can reveal how policy-relevant, contested scientific knowledge is impacted by political, economic, and institutional concerns. Stakeholders compete to define risks as being higher or lower, but they also debate the conceptual definition of risk because these definitions identify how chemicals and other environmental risks will be evaluated and regulated. Different risk definitions thus favor the goals of different actors and institutions. In all cases, on-site investigation through ethnographic and interview approaches allows for a more thorough understanding of how different actors and institutions develop and conduct risk assessment.

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