Toxic Chemical Governance Failure in the United States: Key Lessons and Paths Forward

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Over 40 years of regulations in the United States have failed to protect human and environmental health. We contend that these failures result from the flawed governance over the continued production, use, and disposal of toxic chemicals. To address this failure, we need to identify the broader social, political, and technological processes producing, knowing, and regulating toxic chemicals, collectively referred to as toxic chemical governance. To do so, we create a conceptual framework covering five key domains of governance: knowledge production, policy design, monitoring and enforcement, evaluation, and adjudication. Within each domain, social actors of varying power negotiate what constitutes acceptable risk, creating longer-term path dependencies in how they are addressed (or not). Using existing literature and five case studies, we discuss four paths for improving governance: evolving paradigms of harm, addressing bias in the knowledge base, making governance more equitable, and overcoming path dependency.

Keywords: toxic chemicals, governance, innovation, path dependency, coproduction

Despite decades of legislation (Wagner 2007) and public-interest litigation (Lind 2015), contemporary society remains saturated with environmental pollution risks of its own production (Beck 2008). Globally, these failures of environmental protection cause millions of premature deaths per annum and cost society billions of dollars in economic damages (Landrigan et al. 2017). These pervasive and increasing environmental threats often remain unknown until publicized by private citizens, scientists, nongovernmental organizations, or the media. Warnings issued with increasing frequency by the scientific community (e.g., Ripple et al. 2017) are all too often met with policy gridlock and a lack of substantive government action. Despite the existence of cleaner technologies whose economic and social benefits exceed transition costs, environmental pollution has become the leading global cause of preventable death (Landrigan et al. 2017).

Significant gains have been made in reducing global primary emissions of some highly regulated chemicals (SC 2017), although debate continues on the overall impacts of shifting global geographies of the production of toxic risks (Rasli et al. 2018). The United States serves as an excellent case study on the multifaceted nature of governing toxic chemical risks. It has lagged behind the European Union in adopting the precautionary principle, especially with regards to importing consumer and industrial products (Becker 2010), and in dealing with emerging contaminants (Bao et al. 2015). And, as elsewhere, partial solutions have led to unintended outcomes, such as increases in ozone exposure concomitant with declines in particulate pollution due to the widespread adoption of catalytic converter technology (HEI 2019).

As an interdisciplinary group of scholars crossing the domains of environmental science, public administration, and political science, we attribute failures within the United States to a more general failure of environmental governance (Mol 2016). A focus on governance highlights how different domains of social decision-making define and manage risks and responsibilities associated with the production and distribution of toxic substances. Governance also centers on the long-running concerns of professional versus layperson knowledge (Brown 1992, Brulle and Pellow 2006), contestations over "facts" in the "post-truth" era, and the degree to which administrative power can shift regimes of environmental governance established through years of legislation (Revesz 2019).

Existing work documents how failures of environmental governance results in environmental injustice through the

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inequitable distribution of exposure to toxic chemicals based on racial and socioeconomic identities (Landrigan et al. 2017). This unevenness has resulted from racist and opportunistic practices of uneven permitting and enforcement (Morello-Frotsch and Shenassa 2006) and contributes to the framing of governance failures as someone else's problem (Pastor and Morello-Frotsch 2018). Simultaneously, toxic chemical risks are ubiquitous and systemic in nature, affecting humans across the globe regardless of their socioeconomic class (Schwarzenbach et al. 2010). Existing support for high environmental quality across the political spectrum (Feinberg and Willer 2013), combined with rising rates of developmental and chronic diseases (Landrigan et al. 2017), indicates that there is an urgent need to frame both risks and policy proposals in a way that mobilizes those of diverse political orientations.

The current political climate in the United States indicates significant resentment against the political establishment, typified by a resurgent anti-administrative state agenda reminiscent of the 1980s (Hejny 2018) with significant negative consequences for public and environmental health (Cutler and Dominici 2018). On the upside, the current administrative swing has exposed the long-standing pattern of elite interests disproportionately writing, lobbying, and adjudicating environmental laws in their narrowly defined self-interest and has increased mobilization of nongovernmental organizations, community based organizations, and science-based advocacy organizations (Mol 2016). This political landscape highlights a need for scientists to engage directly with increased public scrutiny (Latour 2004) by calling for democratic governance to employ best available knowledge for protecting the quality of our environment and public health.

With this goal in mind, we provide a conceptual overview of the governance structure of toxic risk management in the United States. We use our conceptual framework to analyze several high-profile case studies and discuss a proposed set of principles, ongoing initiatives, and challenges of improving toxic chemical governance in the United States.

Toxic substances policy in the United States

Literature in the United States has documented numerous instances of failure across diverse classes of pollutants, natural systems, and regulatory contexts (e.g., Davies and Mazurek 1998, Paavola 2006, Fletcher 2009). Common causes of attributed failure include a failure to regulate classes of toxic chemicals (Mesnage et al. 2015), standards inadequate to achieve protection (Vogel and Roberts 2011, Boone et al. 2014), and nonenforcement of existing regulations (Farber 1999). We define failure as unacceptable levels of human and environmental exposure to toxic chemicals during their production, use, transport, and fate in the environment.

Although existing regulations and policies written by legislatures and enacted by executive and administrative branches of government (e.g., federal, state, tribal, and local agencies) ostensibly act in the public interest, other social actors actively shape their design and language (e.g., lobbying from industry and citizen groups; Davies and Mazurek 1998, Cash et al. 2006) to constrain their effectiveness. In addition, manufacturers, installers, and users of potentially toxic substances routinely evade effective regulation through legal and illegal means (Lynch and Stretesky 2014). In response to these recognized drivers of failure, remediation efforts generally prioritize stricter regulation based on the perceived risks of the substance in question. Tactics include limiting harmful exposure and environmental releases via command and control regulation, mitigating ongoing exposures with funds generated from regulation, and, in some cases, providing incentives for eliminating sources of risk by shifting to alternative technologies (Wilson and Schwarzman 2009). However, the technological capabilities of manufacturing often evolve faster than their regulatory apparatuses, and industries themselves have built up a technological, intellectual, and regulatory ecosystem that has effectively excluded many greener technologies (Woodhouse 2006).

In the United States, the current policy framework around toxic substances remains highly fragmented among jurisdictions of federal agencies such as the Environmental Protection Agency (EPA), the US Department of Agriculture, the Food and Drug Administration (FDA), and the Department of Health and Human Services. Some states have additional regulations, such as California's proposition 65, requiring the state to publish and annually update a list of known chemical carcinogens or reproductive toxicants (Nelson 2013). Mirroring jurisdictional fragmentation resulting from sector-specific regulations, variation exists for different media (e.g., soil, air, water; Caliman and Gavrilescu 2009, Rudel and Perovich 2009).

In addition to poor policy design and fragmentation, the current policy framework leaves many chemicals un- or under-regulated. The primary federal toxic chemical regulation, the Toxic Substance Control Act (TSCA; implemented in 1976), has grandfathered in nearly 62,000 previously unregulated chemicals without evaluation of risk (Vogel and Roberts 2001), a number not including the manufacturing by-products of those chemicals or their environmental derivatives. A hard-fought 2016 amendment to TSCA established a schedule for evaluating the estimated 85,000 existing chemicals in the marketplace, shifted toxicological analyses toward a risk-based framework, limited the ability of companies to claim commercial confidentiality, and has eliminated the consideration of cost in risk assessment (Frank R. Lautenberg Chemical Safety Act 2016). With a risk-based framework, the burden of proof for evaluating potential harms to humans and the environment is placed on the regulatory agency, who will only regulate a chemical if it is shown to pose a risk to human and environmental health in a highly specified exposure pathway. TSCA remains in litigation over fundamental procedural issues, including the process of prioritizing different substances for evaluation, definitions of *unreasonable* risk, and whether the EPA should consider the feasibility of replacement substances in prioritization (Bergeson and Graham 2017, CW 2019).

Despite the 2016 TSCA requirements for EPA to evaluate all new chemicals before market release, EPA remains underfunded and understaffed for timely evaluation. Exacerbating the situation, TSCA does not require companies to provide toxicological data, and the annual evaluations of 20 high-risk and 20 low-risk chemicals cannot keep pace with new chemical production (Botos et al. 2018).

In addition to TSCA, substances that pose threats to human and environmental health are regulated by a number of other regulatory instruments including the Clean Air Act, the Clean Water Act, the Safe Drinking Water Act, the Resource Conservation and Recovery Act, and various workplace regulations under the Occupational Safety and Health Administration—all of which rely on similar processes of analyzing risk to determine the extent to which they should be regulated (Steward 1995). In addition, chemicals intended for human consumption as food stuffs, pharmaceuticals, tobacco products or derivatives, and personal care products undergo their own regulatory procedures through the Food and Drug Administration. Further fragmenting the regulatory environment, the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA), regulates the sale of agricultural chemicals not registered with the EPA. Although this process requires stringent manufacturer testing, labeling, and periodic recertification (every 15 years) of pesticides, designation of critical economic importance can outweigh human and environmental risks, especially if those substances have become widespread, or engineered into crop production systems. Perhaps because of this it is rare for a pesticide to be denied re-registration unless there is overwhelming evidence of human and ecological harm. Both FIFRA and TSCA suffer in effectiveness because of their definitions of risk, and the ease of industry influence on their decision-making processes.

In contrast, the European Union's Registration, Evaluation, Authorization and Restriction of Chemicals (REACH) legislation, uses precautionary principles, putting the burden of proof of safety on the industries that produce them (Silbergeld et al. 2015). Under the precautionary principle, new substances and their derivatives are assumed to pose risk until proven otherwise, and the responsibility for proving the absence of risk is placed on both the producer and the regulator. REACH also requires producers to provide the European Chemicals Agency with toxicological information, and uses a spectrum of safety standards matched with appropriate use restrictions and mandatory labeling.

All of the above policies, struggle with inadequate resources for chemical assessment and are vulnerable to lobbying and uneven adjudication. A primary challenge with REACH, for example, is that EU member states are responsible for implementing the chemical evaluation process, leading to inconsistencies in implementation. Despite the improvements made to TSCA, it still falls short of REACH's founding precautionary principles. This comparison indicates the importance of strong guiding principles in effective toxic chemicals governance. Although the incorporation of precautionary principles will be an important step toward better regulation of toxic chemicals in the United States, it alone is inadequate. Effective protection from toxic chemical risks will require changes in governance practices and an evolution of the technologies and practices that generate risk to align with public and environmental health goals.

A framework for understanding toxic chemical governance

Governance includes the social practice of designating rules, standards, and norms according to which actors and institutions negotiate and make decisions (Rogers and Hall 2003), including what knowledge is considered valid and useful (Wynne 2003). A focus on governance identifies how the present conditions of our society, environment, and technological infrastructures are interdependent with the forms of expertise and political authority deemed necessary to manage harms to humans and the environment (Scott 1998, Jasanoff 2004, Latour 2004). In particular, governance highlights the process of classifying potentially hazardous substances as risks, the consideration of different forms of knowledge or expertise in that process, and the path dependency—or inertia—resulting from prior decisions. We describe these concepts below and use them later to evaluate five high profile cases of toxics regulation success or failure in the United States.

The construction of risk around toxic chemicals can be defined as a social process of emphasizing some dangers over others (Douglas and Wildavsky 1983). Formal risk analysis involves calculating the probability of a specified level of chemical exposure multiplied by the probable consequences of that exposure (Bocking 2004). However, in practice, such an analysis relies on a set of assumptions about social behavior alongside physiological and toxicological data and often disregards risks experienced by affected communities (Bocking 2004, Beck 2008). In this sense, standard risk analysis treats risks to public health and the environment as end-of-pipe problems and unplanned releases as public relations problems. Such thinking ignores that the generation of risk results from choices about how chemicals can be produced. These choices produce systems that have global consequences, normalize the production of toxic byproducts, and have significant sunken costs in facilities and the development of economic sectors dependent on those kinds of inputs (Beck 2008).

Although different social actors perceive and calculate risks in different ways, risk management is generally seen as an activity worthy of professional expertise. Expertise in this sense refers to the social practices of designating individuals, institutions, technologies, and methods as sources of authoritative knowledge (Scott 1998, Wynne 2003, Bocking 2004, Jasanoff 2004). Expertise often has disciplinary boundaries, which prevent synthesis across and within disciplines (Cartwright 1999). As social actors vie for legitimacy within networked political, financial, environmental, social, and technical systems (Grabowski et al. 2017) institutions take on more stable forms, routing social decision-making

processes into established mechanisms and fora exhibiting different forms of path dependency.

Path dependency refers to the way in which future possibilities are seen as constrained by present conditions and largely results from decisions about financial, institutional, intellectual, and bureaucratic investments in social ways of doing, infrastructures, and technology (Jasanoff 2004, Woodhouse 2006, Beck 2008). Path dependencies may lead to the generation of systemic bias in what type of knowledge is produced and considered relevant, which is often contested by popular movements (Hess 2015). Disrupting path dependency generally requires major events, a form of punctuated equilibrium (Pierson 2000). Systemic path dependencies result when agents within institutions prevent change despite widely recognized problems (Sydow et al. 2009). For example, toxic chemical risks have often been framed as byproducts or externalities or as attributes of chemicals to be managed when, in fact, they are embedded within "normal" operations (Perrow 1984, Beck 2008).

Drawing on these concepts of risk, expertise, and path dependency, we present a conceptual framework of the current toxic chemical governance system in the United States. We break down the overall governance system into five interdependent domains in which toxic chemical regulations are interpreted, implemented, and evaluated: knowledge production, policy design, monitoring and enforcement, evaluation, and adjudication (figure 1). Each domain operates simultaneously in time and space, although problems can flow from one to another (e.g., failures of enforcement often result in adjudication).

Knowledge production. Although different forms of expertise and knowledge are embedded in all domains, the *knowledge base* refers to the overall organization of information pertaining to toxic chemicals. This includes "facts," information, and the accepted methods for producing them, which invokes the ways institutions, values, norms, and discourses within a social system decide what type of knowledge is legitimate or useful (Jasanoff 2004, Stehr 2015). Many stakeholders are involved in toxic chemical knowledge creation, including affected communities, the scientific community, the media, and industry representatives. Each stakeholder group constructs their knowledge differently, leading to different claims about toxic chemicals. These varied claims and perspectives on what constitutes legitimate knowledge, and how it is and should be produced, lead stakeholders to identify and categorize threats to health and the environment in radically different and often incompatible ways (Wynne 2016).

Policy design. Policy design includes processes for describing present conditions, framing goals, creating incentives or regulations to achieve those goals, and assigning rights and responsibilities to different social actors within an overarching policy architecture. This domain heavily influences monitoring, enforcement, and evaluation activities, and sets the stage for adjudication. It is here that the interests and values negotiated within the knowledge base become codified into legislation via regulations, incentives, and budget allocations. Top-down policy architecture is more easily implemented but less flexible for local stakeholders, whereas bottom-up approaches are adaptive and flexible, but can be difficult to create given disagreement among stakeholders or lead to unequal environmental regulations across the country (Bocking 2004). Canonical descriptions of the policy process divide participants into decision-makers, generally referring to elected officials, and stakeholders, including affected communities, industries, and special interest groups. It has been observed that local affected communities engaged in the policy process often demand a precautionary approach to protect their local human and environmental safety (e.g., Bullard and Johnson 2009), whereas industry interests push for limiting regulation and including policy language that allows them to continue current business operations (e.g., Boone et al. 2014).

Monitoring and enforcement. Monitoring and enforcement refers to the mechanisms of observing regulated activities and the ability to coerce compliance with standards and operating procedures as written. Enforcement can take place via three primary approaches. First, the formal regulatory arena: local, state, and federal executive and regulatory agencies issue fines for limit exceedances and issue release permits, among other codified approaches to compliance. This requires sufficient resources for detecting and correcting violations. Second, self-regulated monitoring and enforcement: In the absence of close regulatory oversight, private-contract auditing agencies oversee industry groups to ensure compliance, often via certification programs. Third, complaints by affected communities who identify misconduct, draw media attention, and place political pressure on industry groups to comply with regulations. This often happens when there are limitations in agency resources. Proper enforcement requires adequate policy design, including initial political will, coherence in writing legislation, and consistent, long-term political and financial support for monitoring and enforcement efforts (Wagner 2007).

Programmatic and policy evaluation. Programmatic and policy evaluation refers to evaluation of policies designed to manage chemical exposure, production, and transportation, and the creation of alternative technologies and practices. This domain is tightly linked to policy design, whereby program and policy evaluations should inform future policy designs. Major actors involved in this domain include federal, state, and local regulatory government agencies, affected communities, industries, the scientific community (including nongovernmental agencies and nonprofits), and the media. Judicial agencies can also perform policy evaluations in response to publicity of toxic chemical risk to human or environmental health, and initiatives within industry to change their practices or use of certain chemicals may also be involved. This is the domain in which stakeholder claims

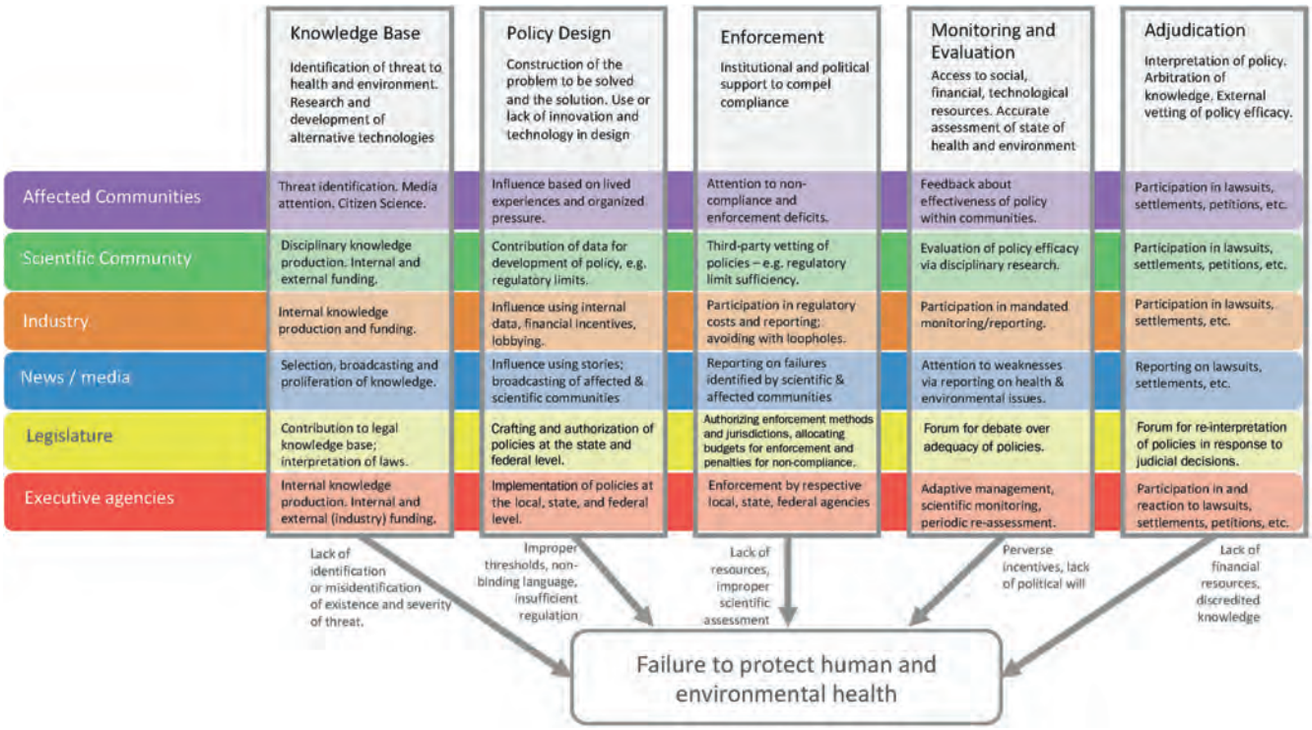

Figure 1. Conceptual framework of US toxics governance domains, and the actors who contribute to each domain. At the base of each box, a summary of common ways these domains contribute toward governance failures are listed. Affected communities bear the costs and risks of contaminants, or benefit from current practices. The scientific community can include academic, government, and industry scientists, who identify and define risk, but also develop the technologies that create risks. **Industry** ***refers to private companies creating and owning the technologies producing or using chemicals. News or media outlets procure and disseminate information to the public about risks.***

about the impacts of policies are evaluated, then either used to evolve policy or disregarded.

Adjudication. Adjudication is the legal process by which disputes are settled, policies are interpreted (e.g., claims of harm and liability), and enforcement activities are contested (e.g., ongoing TSCA litigation pertaining to procedural rules for chemical risk evaluation). A key part of adjudication pertains to the formal determination of compliance, liability, harm, and responsibility to parties involved in litigation.

More broadly, adjudication is the process by which knowledge claims, policy efficiency, and the distribution of benefits or burdens of a particular substance are vetted by the judicial branch of government. Affected or scientific communities, nongovernmental interest groups, government agencies, and industries often initiate adjudication (Hoffman 1999) as a means of changing activities within the other governance domains. These changes may include policy design modifications, enforcement of compliance, increased monitoring and enforcement, and promoting or contesting evaluation. Common forms of adjudication include petitions to state and federal agencies, settlements with regulatory and private sector entities, or lawsuits. Although the courts can settle issues of human and environmental failures, this approach is, by definition, reactionary and can only interpret legislation to nullify or clarify obligations, or set appropriate enforcement actions, through slow, costly, and often adversarial means (Silbergeld et al. 2015). Adjudication can preemptively affect policy as legislatures shy away from creating unenforceable policies.

Application of governance system conceptual framework

We expand our conceptual framework of five governance domains (i.e., knowledge production, policy design, monitoring and enforcement, evaluation, and adjudication) to determine how patterns of flawed governance lead to unsafe exposure of select chemicals. We create a qualitative evaluative framework for governance issues related to risk definition, knowledge production, and path dependency across the five domains (figure 2). Based on aspects of the governance literature discussed above, we consider whether risk, expertise, and path dependency are succeeding, failing, or partially succeeding, corresponding with a numerical ranking (see figure 3). Risk is qualitatively evaluated as succeeding if there is plurality and consensus of how the risk is framed and it is considered failing if risk

	KNOWLEDGE PRODUCTION	POLICY DESIGN	MONITORING AND ENFORCEMENT	POLICY EVALUATION	ADJUDICATION
RISK	Nonexistent	No addressing of risks	Nonexistent	No evaluation of policy effectiveness	No independent judiciary
	Constrained scope, widespread disagreement	Disagreement about adequacy (e.g. known loopholes), risks shifted to marginalized communities	Uneven across communities, weak, delayed, or underfunded	Partisan or fragmented, and/or not based off best available information	Court system biased towards specific interests and knowledge when interpreting law and events
	Robust, plural, and in agreement about adequacy	Works to eliminate risk in all communities, transparent distribution of costs and benefits	Transparently utilizes independent monitoring, corrective and punitive actions are swift	Plural and robust framings of causality, and changes in the social distribution of risks, costs, and benefits	Transparent procedures insure accountability for violations of spirit of regulations, designate liability appropriately
EXPERTISE	No knowledge considered authoritative	Ignores most relevant experiences and expertise	Nonexistent	No agreement on feasibility of policy evaluation	Adjudication relies only on legal expertise
	Legitimacy limited to industry or scientific professionals; produced opaquely	Disagreement over utilization of only certain forms of knowledge/expertise	Disagreement about adequacy of M&E processes	Disagreement over adequacy of process for evaluating policy	Adjudication processes allow only certain types of expert knowledge to be considered
	Widespread and plural agreement on transparency, sources are varied, equally scrutinized, and appropriately utilized	Policy process equally weighs diverse forms of expertise; adequate funding for knowledge built in	Widespread agreement that M&E processes are adequate and robust, including localized and decentralized accounts of toxic failures	Includes a range of expertise, utilizes industry-specific protocols, and identifies systemic connections to inform policy changes	Recognizes multiple forms of expertise. Experiential harms are valued; knowledge from adjudication process informs other domains
PATH DEPENDENCY	Inadequate and stagnant	Based exclusively on policy history	Nonexistent or prohibitively underfunded	Nonexistent or not applicable to evolving design	Adjudication increases disagreement and confusion about processes under consideration
	Passively shifts according to technological change without directionality	Minor and iterative changes due to inadequate capacity or oppositional politics	Does not keep pace with changes in knowledge, technology, or context	Underfunded, opaque, and/or privileges the status quo	Disagreement over fairness, relief is partial and does not address governance challenges
	Information and technologies and evaluates its social and technological accomplishments and trajectory	Policy architecture maintains a transparent incentive structure, and yet is sustainable and adaptive to changing circumstances and new knowledge	Independence from regulated entities via sustained, independent funding. Procedures adaptive to technological, social, and environmental change	Adapts to include best practice methods are transparent and accountable; resources are sufficient for adaptive evaluation	Adequate updating and contextualizing precedence and liability

Figure 2. Evaluative framework for examining governance issues of risk, expertise, and path dependency in each governance domain. Green highlighting indicates success (agreement), grey indicates partial success (partial agreement), and red indicates failure (disagreement).

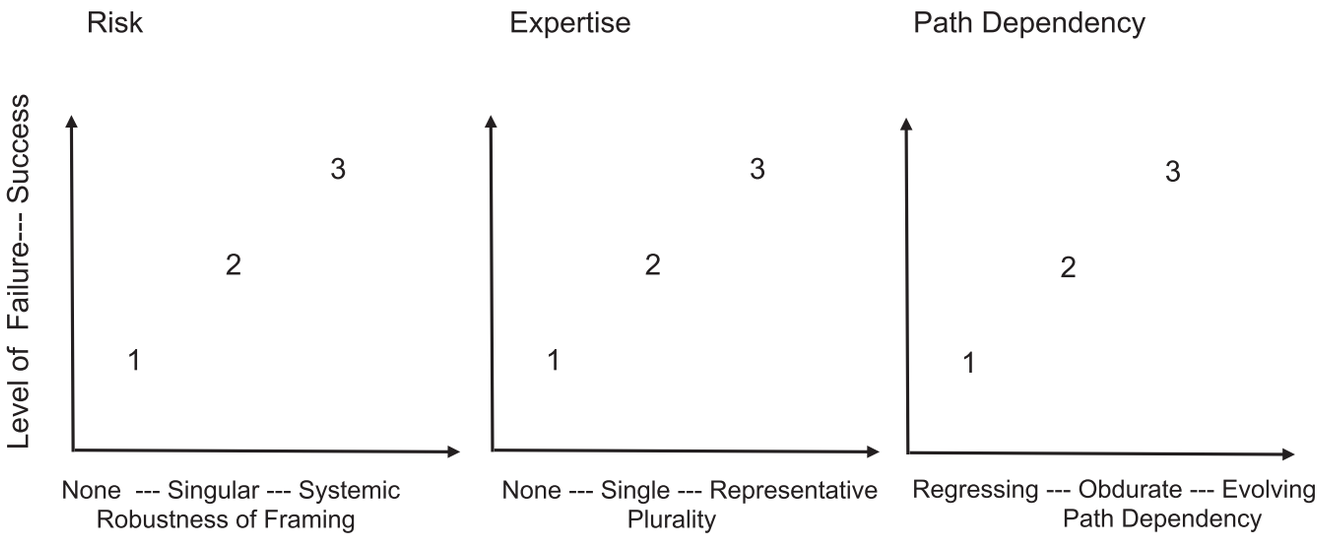

Figure 3. Each indicator was evaluated by level of failure and success (y-axis) and criteria based on attributes of each indicator (x-axis).

is understood only from one perspective or is highly contested. Expertise is qualitatively evaluated as succeeding if there are multiple forms of knowledge and participants in addressing the risk, including those most affected by the decision; it is considered failing when only one form of expertise or knowledge is used and the perspectives of affected parties are disregarded. Path dependency is considered succeeding if the system is evolving to address emerging risks and challenges and is considered failing if it is regressing or failing to evolve despite an acknowledged need to do so.

We then apply this evaluative framework (figure 2) to five high-profile case studies. We chose a set of toxic substances case studies based on their representativeness within infrastructure systems (lead and SOx), manufacturing (heavy metals in light industry), agriculture (glyphosate), and consumer products (bisphenol-a, BPA). For each case, we assembled literature reviewing the evidence base for each case, collected popular media accounts describing the policy responses, and examined relevant legislation and enabling policies of their regulation (supplement 1). Each coauthor described the conditions of a case by each domain, and then used the subjective scoring system to rank the robustness of risk framing, representativeness of expertise, and the degree of path dependency per the evaluative framework in figure 3. For each case, we averaged the group's scoring for risk, expertise, and path dependency within each governance domain to compare the perceived level of success or failure between cases, and then discussed the group's findings to achieve consensus on a final ranking. Applying this evaluative framework draws out where failures in toxics governance are rooted in each case and where there are similarities and differences across cases.

Key findings

Most cases ranked between failing (score = 1) and partially succeeding (score = 2) out of a total possible score of success (score = 3; figure 2). Overall, we found that although most cases had robust risk knowledge that included diverse perspectives for framing risk, ongoing issues with path dependency, and in some cases policy regression, were common throughout the cases evaluated.

Lead in school drinking water (score: 1.4/3). Schools serving children across socioeconomic strata nationwide have unsafe lead levels in drinking water fountains (Wines et al. 2016), because the Safe Drinking Water Act regulates water lead levels at water treatment facilities, but not at the tap. Updated "lead-free" plumbing rules maintain allowable lead content, and legacy plumbing and water infrastructure management can cause significant lead leaching. Well-publicized cases include schools in Washington, DC in 2000 and 2004, Seattle, WA in 2004, Flint, MI in 2014, Newark, NJ, New York, NY and Portland, OR in 2015 and 2016. The persistence of this issue is caused by failures within the enforcement, monitoring and evaluation, and adjudication domains, along with path dependences within all domains (figure 4a).

Heavy metals in light industry (score: 1.8/3). Bullseye Glass in Portland, Oregon creates art and architectural glass products. Because of regulatory exemptions for small-scale industry, they lacked scrubbers and were releasing heavy metals, including known carcinogens such as cadmium and arsenic (Donovan et al. 2016). Portland residents filed eight complaints across multiple decades to the state Department of Environmental Quality, but no action was taken until the media was notified that the US Forest Service found levels of

A(. Case Study: Lead in school drinking water

	KNOWLEDGE BASE	POLICY DESIGN	MONITORING AND ENFORCEMENT	POLICY EVALUATION	ADJUDICATION
RISK	The health risks of soluble and particulate lead, the social and racial contexts of lead exposure, and the role of water treatment operations.	Risks primarily defined as exposure to soluble lead concentrations, disregarding concerns around allowable lead concentrations in plumbing under the Safe Drinking Water Act, as well as infrastructure operation and particulate issues.	Procedures do not adequately assess risk; SDWA monitoring and enforcement only pertains to water supply, not monitoring at tap. Voluntary monitoring does not take into account particulate risks.	Nonexistent at federal level. Local initiatives in relative infancy, though appear to increase engagement of affected communities and have eliminated some systemic drivers of exposure.	No clear assignment of responsibility despite extensive litigation. Remediation often relegated to water filters, with unclear responsibilities for maintenance schedules.
EXPERTISE	Lead may be at harmful levels in drinking water, but community experiences have been disregarded and knowledge collection remains opaque.	Physical science integration remains limited (e.g. particulate issues, dishonest lead-free certification), integrating social dimensions remains largely an unfunded environmental justice mandate at EPA.	Arguments around what constitutes relevant monitoring protocols; extensive work on unequal spatial and social distribution of lead in school drinking water risks not translated into adequate monitoring regimes.	Academic scientists and others outside of formal policy making have conducted evaluations of the overall policy framework, but such evaluations remain external to policy processes.	Courts have called for new information, but significant lack of consensus reflects political economy of interests.
PATH DEPENDENCY	Knowledge production remains focused on increasing precision of estimates of exposure instead of producing relevant knowledge about the systematic and lived risks of affected communities.	The issue of lead risk in school drinking water has been known for some time with no political motivation or resources allocated to create robust federal policy.	Despite widespread knowledge of inadequacy of current monitoring and enforcement regime, limited incentives exist to change behavior by responsible agencies.	Unresolved issues with monitoring prevent effective evaluation in vicious cycle, policy responses remain complaint driven.	Adjudication burden falls to citizens. Policy loopholes and regulatory hierarchy make it difficult to assign liability. Voluntary programs emerging from litigation may show promise for evolving national scale policy framework.

B Case Study: Heavy metals in light industry

	KNOWLEDGE BASE	POLICY DESIGN	MONITORING AND ENFORCEMENT	POLICY EVALUATION	ADJUDICATION
RISK	Health risks of airborne heavy metals are well documented and understood by scientists, government agencies, and the public, including their social distribution.	While policy is designed to mitigate risk from large-scale operations, it misses the risks of small operations, thus shifting the burden to those in range of small-scale industries operating under the loophole.	Heavy metals release exceeded EPA limits, yet because of inadequate regulations, glass companies were in compliance with inadequate permits. State resources were not allocated to monitor the risks of small operations.	National policies have not been re-evaluated, but Oregon regulations for glass furnaces have changed in response to the moss study, and Cleanr Air Oregon, which closes federal regulatory gaps, was adopted.	Proper adjudication was not conducted prior to discovery of environmental failure. Citizens are unsatisfied with the outcome and have taken to litigation, with locally successgul outcomes.
EXPERTISE	Oregon Department of Environmental Quality, USFS, and local citizens had knowledge of heavy metal emissions contamination and had reported it, but no action was taken and complaints were left unresolved.	EPA regulatory loophole exempted small scale glass manufacturing and allowed for privileging of industry knowledge while citizen concerns were ignored.	Formal monitoring by agencies was not conducted. Community members reported concerns of contaminant release, but actions were not taken until agency scientists unintentionally discovered high levels of heavy metals.	Cleaner Air Oregon was developed as a result of collaboration between regulators, citizens, industry, and scientists. However, the exemptions that led to this case study still exist at the national level under the Clean Air Act.	Adjudication was not conducted prior to discovery of environmental failure, thus ignored broader expertise of local residents.
PATH DEPENDENCY	Community complaints and social risks of contaminant exposure continue to be a low priority in the acknowledgement of risk. Manufacturing sector technologies remain dated with limited research for innovation change.	EPA regulatory loopholes are based exclusively on policy history: exemptions exist for small scale industry despite their potential risk to the community, and focus is more on manufacturer-level economic concerns than risks to society.	Toxic release of heavy metals by small scale industry would have continued if not for unintentional detection. Community concerns did not gain power until agencies' scientific findings supported their concerns.	No policy evaluation was conducted until scientific data and community pressure demonstrated a potential human health risk. Now, policies have been improved in Oregon, but not nationally.	EPA has been recently ordered to update its risk reviews for 9 criteria pollutants, but these actions remain overdue and are yet unproven to mitigate for risk.

Figure 4. Application of indicators to five case studies across multiple chemical classes, including (a) lead in school drinking water, (b) heavy metal emissions from light industry, (c) sulfur and nitric oxide emissions, (d) bisphenol-a, and (e) glyphosate use in agriculture. For references, see supplement 1.

C ('Case Study: Sulphur and Nitric Oxides

	KNOWLEDGE BASE	POLICY DESIGN	MONITORING AND ENFORCEMENT	POLICY EVALUATION	ADJUDICATION
RISK	There is a substantial body of knowledge of the impacts of SOx and NOx on human health and natural environment (although exact effects are uncertain)	The Acid Rain Program established a cap-and-trade program to reduce major emissions of SOx and NOx from power plants and create tighter standards on vehicle emissions. However, many rules remain administrative and subject to rollback by executive decision-making, and limited agreement exists on how policy should address risks.	Most power generating facilities have Continuous Emissions Monitors reporting smokestack pollution into an emissions trading market with penalties for noncompliance. Vehicle emissions however remain unmonitored, reliant on inaccurate testing protocols,' and emissions standards have been systematically avoided by major automobile manufacturers.	SOx and NOx emissions have significantly declined at the national level, but the slow reversal of harms of acid rain on ecosystems remain contingent upon complex factors. Catalytic converter technology has shifted risks from vehicle emissions from SOx and NOx to ground level ozone, which has increased due to rising automobile densities.	Successful lawsuits against American Electric Power Co., VW Group North America, and General Motors for failing to meet emissions standards illustrate that the risks of SOx and NOx are agreed upon in litigation.
EXPERTISE	A diverse set of disciplinary knowledge created a fairly comprehensive understanding of the sources and impacts of SOx on human and environmental health. However, industry sectors are the primary knowledge producers. Strategies for reducing emissions from urban and regional planning are not well integrated.	Policy framing remains based around technological and market-based solutions, while systemic solutions framed by academics are less likely to be included in policy discourse.	Community level impacts of pollution, and the social unevenness of them, poorly considered in monitoring. Because monitoring occurs at the pipe, knowledge produced about ambient levels within urban and other affected communities is ignored, except in extreme cases.	End of pipe expertise remains dominant in policy evaluation; little consideration is given to the systemic and risk-shifting aspects of both stationary and mobile sources.	Attempts to broaden the mandate of the EPA to promote systemic energy and transportation transitions have been stalled by the Supreme Court. The EPA under new administration has reversed its position and has reverted to seeking input on appropriate regulation only from the regulated industries.
PATH DEPENDENCY	There have been significant investments in developing technologies of 'scrubbing' SOx and NOx from fossil fuel combustion sources, but overall reliance on fossil fuel-based power generation, heating, and transportation remains largely unchanged	Disagreement persists as to the need for comprehensive overhaul and guidance as to the complex social and technological drivers of emissions. However, federal and state energy policies, and energy markets, appear to be shifting thegrid generation mix away from emissions heavy sources of coal and oil and towards renewables and natural gas	Enforcement regimes depend on administrative policy architecture. Current monitoring regime insufficient to parse liability for fluctuations in regional air quality due to mobile sources.	While recent initiatives have expanded regulatory oversight of SOx and NOx emissions, present administrative changes threaten to reverse the systemic overhaul of the power production sector via the Clean Power Plan. Difficulties with reliably enforcing vehicle emissions standards. Limited push to evolve transportation policy away from fossil fuel dependency.	Doctrines of liability in USA, combined with unlimited corporate influence in elections, have compromised independence of judiciary and enshrined private property rights at cost of public health.

D ' " Case Study: Bisphenol-a (BPA)

	KNOWLEDGE BASE	POLICY DESIGN	MONITORING AND ENFORCEMENT	POLICY EVALUATION	ADJUDICATION
RISK	Risk was not adequately evaluated prior to market release. It is now well accepted by the public and scientific community that BPA is unsafe to use in food and beverage containers, especially for babies and young children, however the perceived risk is mismatched between industry, and scientists and the public.	Under TSCA, compounds are not required to be tested and evaluated for their chronic long-term effects, biophysical risks, or societal risks before going to market, as burden of proof is placed on industry labs or industry-contracted scientists. Post production burden of proof for harm is placed on victims.	There is no formal process for monitoring the risks of compounds under TSCA, and any monitoring that does exist is inadequate for substances that have cumulative risk factors and are not acute toxic substances.	Formal policy evaluation not required, and existing evaluations are reactionary. Changes due to evaluation are incremental and do not typically lead to changes in policy design or reassessment of risk. Decreasing use is due to market pressure, which has primarily focused on labeling, not chemistry of replacement substances which may be just as toxic.	Petition filed to the FDA resulted in the amendment of food additive regulations to no longer "provide for the use of BPA" in baby bottles and sippy cups, and infant formula packaging. This change only narrowly addresses the full array of risks associated with BPA and does not assign liability to manufacturers.
EXPERTISE	Knowledge is primarily produced using industry standard dose-response methods instead of research on of endocrine disruption caused by environmentally relevant concentrations.	TSCA and related policies overseeing chemicals like BPA do not adequately consult multiple forms of expertise. Data (or lack thereof) produced by industry-sponsored labs is the primary determinant of market release and/or restrictions on use.	Monitoring of long-term effects of chemicals on the market, such as BPA, is not required of manufacturers or enforcement agencies. Instead, scientists and communities independently serve as "monitors."	TSCA was updated in 2016 due to significant public and scientific pressure. Pre-market review of chemicals added, but disagreement remains over adequacy; evaluation of overall impact on protecting human and environmental health limited.	The passing of the above amendments shows that adjudication can be successful if it requires minor actions that take minimal enforcement, but does not address risks produced by all forms of knowledge.
PATH DEPENDENCY	Manufacturing practices have started to acknowledge the risks of BPA, however, the systematic way in which knowledge is produced for governance has remained constant; BPA merely replaced by new chemicals that are not adequately tested.	Current FDA policies now no longer list BPA as an approved additive in certain products, but this is less a recognition of its health hazard and more a reaction to its discontinued use by industry due to consumer pressure.	Monitoring is not required by TSCA.	Policy evaluation does not occur unless significant evidence of toxic risk and significant pressure exists, in which case incremental changes occur that tend to perpetuate status quo, as seen by de-listing BPA as an additive instead of banning it or requiring re-evaluation.	Adjudication has been mildly successful, but has come at the expense of those who petitioned the FDA. Disagreement remains on the effectiveness of adjudication in resolving the chemical's underlying risk; outcomes have not substantially improved governance of chemicals like BPA.

Figure 4. Continued.

E (. Case Study: Glyphosate in agriculture

	KNOWLEDGE BASE	POLICY DESIGN	MONITORING AND ENFORCEMENT	POLICY EVALUATION	ADJUDICATION
RISK	Health risk contested; health standards based on a dose-response approach, despite evidence of endocrine disruption at environmentally relevant concentrations. Some studies report carcinogenic and endocrine-disrupting properties, while EPA testing has not.	The Food Quality Protection Act allows industry to be the primary assessors of consumer risk, and Worker Protection Standards only pertain to applicators. Both policies shift burden of risk to consumers, agricultural communities, and ecosystems. Federal re-certification requires periodic re-assessment every 10 years.	No formal mechanisms for assessing persistent and cumulative risk of glyphosate use. The Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) requires commercial users to hold an applicators license, and pesticides to have proper labeling and directions, but applicators are not required to report usage.	Extensive evaluation has been conducted by the scientific community demonstrating the need for a precautionary approach, however, industry-funded studies and lobbying hampers the actions necessary to mitigate risk; despite existing regulations, evidence indicates risks of pesticides have continued to increase.	Definitions of risk highly contested, historically relying on proof of acute toxicity and industry generated studies (e.g. within CA Prop. 65 listing, pending FIFRA re-certification). Current court cases have opened up risk characterization and issues has received increased attention by media, scientific community, and affected communities.
EXPERTISE	Traditional dose-response approaches privileged over others such as studies of endocrine disruption and epidemiological approaches, leading to increased application level allowances, despite growing evidence of health and environmental danger.	Lack of precautionary measures and are driven by industry lobbying. Does not consider peer-reviewed literature or affected communities' concerns, except during re-certification. Consistently disregards knowledge on alternative means of crop protection.	No formal requirements for monitoring, independent scientific research is typically the only source of data, often in response to community concerns and/or pressure, but the results re not linked to enforcement protocols and have limited ability to change standards.	Policy evaluation continues to examine pesticide policies based on needs and concerns of producing industries, not the social and environmental knowledge base.	Historically did not consider broader expertise, and burden of proof linking specific health and environmental impacts falls on affected communities and public interest scientists in face of extensive industry sponsored research.
PATH DEPENDENCY	Food system has become increasingly dependent on increasing inputs of glyphosate and other pesticides of known toxicity, despite long term warnings about the need for holistic agricultural management. Agencies appear to favor industry-produced knowledge and risk assessment.	Continues to disproportionately benefit industrial operations reliant on increasing levels of chemical additives, only regulated to prevent acute harm. Recertification processes provide limited adaptive governance potential.	Formal monitoring and enforcement activities are not required by pesticide policies and results of independent monitoring activities have limited ability to change pesticide standards.	Profound disagreements persist over necessity and scope of evaluation.	Compensatory wins' possible for affected communities and individuals, have come at great cost, and show limited potential to shift overall industry model of producing toxic chemicals for agricultural production.

Figure 4. Continued.

cadmium almost 50 times above Oregon's benchmark of 0.6 nanograms per cubic meter during a moss air monitoring project (Donavan et al. 2016). A class action lawsuit against Bullseye Glass was subsequently filed, and a cease and desist order was issued for any uncontrolled furnaces. Regulatory gaps are now addressed by the Cleaner Air Oregon initiative, but still exist at the federal level. Based on our evaluative framework, we determined that risk evaluation for this case was moderately successful, and that the release of unsafe levels of heavy metals can mainly be attributed to failures of expertise and path dependency (figure 4b).

Sulfur and nitric oxides (score: 2/3). Sulfur oxides (largely SO2) result from burning sulfur or sulfur-containing materials, mostly coal, but present in all fossil fuels. Nitric oxides (NOx), which form during hydrocarbon combustion under an excess of oxygen, are both harmful to human health (affecting respiratory, cardiovascular, and neurological systems) and the built and natural environment as the leading causes of acid rain and deposition (Likens 1974, McCubbin and Delucchi 1999). Risk of unsafe exposure still exists because of industry influence on policy design and monitoring and enforcement and because of failures of expertise and path dependency within the policy evaluation and adjudication domains (figure 4c).

Bisphenol-a in consumer products (score: 1.3/3). This endocrine disruptor (compound that interferes with proper hormone signaling) is present in many plastics to mitigate brittleness. BPA became notorious when scientists identified that it can leach into food and drinks and onto skin, and consumption or absorption of this compound, especially early in development, may increase cancer risk because of its endocrine-disrupting properties (e.g., Seachrist et al. 2016). Despite these findings, the use of BPA is still allowed in most products, although market pressure has resulted in its phaseout, and the FDA has removed it from the list of allowable additives in baby and children's food and drink products. Although some risk has been mitigated thanks to moderately successful knowledge production and adjudication, failures are still pervasive around proper monitoring and enforcement because of privileging of expertise and systemic path dependency, and the use of replacement chemicals with uncertain toxicity (figure 4d).

Glyphosate in agriculture (score: 1.4/3). Glyphosate is the active ingredient in Roundup, one of the most commonly

applied pesticides in the United States, where laws require reasonable certainty of no harm as a prerequisite for pesticide certification. Industries typically determine such risk by assessing health effects at increasingly higher doses (dose–response); however, scientists have found that low, environmentally relevant concentrations of glyphosate can mimic and interfere with hormone signaling (endocrine disruption) and may also be associated with non-Hodgkin's lymphoma (Mesnage et al. 2015). Despite this growing body of scientific literature on the risks of glyphosate, the threshold for maximum glyphosate residues on food and animal feed—known as the tolerance level—continues to increase, and glyphosate was recertified for use in 2015 (Benbrook 2016). The persisting risk of glyphosate exposure can be attributed to pervasive failures across all governance domains, particularly with respect to policy design, monitoring and enforcement, and evaluation. Industry influence over the governance processes has continued to affect ongoing adjudication processes; although harmed individuals have achieved some postharm compensation litigation is ongoing (figure 4e).

Paths forward

Our analysis of a diverse set of failures to protect public and ecological health from toxic risks indicates a strong need to improve the overall governance of toxic chemical production and use throughout the United States. Four major patterns emerge from our analysis of governance failures. First, governance allowing the production and release of toxic chemicals with inadequate assurance of safety leads to inevitable harm to human and environmental systems. Second, certain forms of knowledge, particularly those that favor industry over public and environmental health, are privileged when assessing the extent and risk of this harm. Third, knowledge inequality is exacerbated by unequal formal mechanisms for resolving disputes over the assessment, mitigation, and redressing of harms. And lastly, path dependency of technological, administrative, and knowledge-producing systems makes effective change difficult and perpetuates harm, despite regulatory action.

For each of these interrelated issues, we identify paths forward based on a reinterpretation of the purpose of toxic chemicals governance, provide examples of developing real world initiatives addressing them, and discuss challenges to their continued development and success.

Issue 1: Incomplete paradigms of mitigation and risk management—the inevitability of harm from toxic chemical production. It is clear from our case studies of lead, glyphosate, SOx, heavy metals, and BPA that many toxic chemical risks are persistent both in their sources and their biological consequences. These risks often only become known after enough harm has accrued to communities to elicit a social response (Mesnage et al. 2015, Silbergeld et al. 2015). Patterns of enforcement and adjudication indicate that present regulatory processes generally only mitigate or act retroactively, not preventatively. At the current rate of evaluation under TSCA, new chemicals are being manufactured faster than existing chemicals are being evaluated, especially those produced outside of the United States (Bernhard et al. 2017). Even for regulated chemicals that have reporting requirements, existing data sets fail to communicate the frequency of chemical exposures or releases that are occurring, leading to enforcement failures as evidenced by the pervasive presence of toxic chemicals in global ecosystems and human populations (Schwarzenbach et al. 2010, Bernhardt et al. 2017). Good governance should therefore incorporate a paradigm shift around toxic chemicals management from one of mitigating risk to one of eliminating risk and supporting clean production to improve the long-recognized need for coordinated global and regional governance (Vogel 1997).

Principle 1: The right to be free from toxic chemical risks. Enshrining the right to be free from harm from toxic chemicals in policy will provide a clear articulation of our overall goals as a society with regards to what rights are sacrosanct and which can be negotiated (Hayward 2002). Ambitious policy goals of eliminating the production of toxic chemicals and supporting the right of humans and ecosystems to be free from harm caused by toxic chemicals will enable transformation of the complex systems producing toxic chemical risks (Jasanoff 2004, Woodhouse 2006). Given the economic benefits that industrialized countries have already realized by engaging in compliance-based environmental regulation (Wallace 1995), further benefits could be realized by addressing the interdependent threats of anthropogenic climate change and global pollution, all while revitalizing US manufacturing and providing millions of jobs in the process (Bain et al. 2016).

To overcome the significant political, economic, and technological inertia of addressing these interdependent threats, we can look to the precedent of using purity as a rhetorical tool for political mobilization and for overcoming industry special interests (Barkan 1985). Existing research recognizes a high degree of support for protecting environmental purity and human health across the political spectrum, despite ideological differences over the role of government in regulating businesses, requiring sustained public mobilization to enact significant legislative reform (Feinberg and Willer 2013). Although such mobilization can set a legislative agenda for technological and economic evolution, a need remains for generating knowledge to enable systemic transformation (McCormick and Kautto 2013).

Issue 2: Biased and incomplete knowledge. Across our cases, we observed a consistent privileging of certain forms of knowledge in defining and managing risks, which generally favors biophysical laboratory science over field observation, including epidemiological, anthropological, and social science accounts of experienced risk and harm. Even after harm becomes known, industry and responsible parties will consistently challenge accounts of harm while hiding behind the same scientific uncertainty that would cast doubt

on their initial risk assessments. This tactic is present at the forefront of litigation over glyphosate and lead in school drinking water. Our case studies mirror larger systemic problems in risk assessment, including affiliation bias in the risk assessment arena (Slovic 2016), targeted attacks on independent researchers (Reeves 2015), and the large volume of industry-sponsored toxicological risk assessments (Hartung 2009).

Knowledge production around toxic substances in the United States remains fragmented by the physiochemical and toxicological properties of regulated materials. As chemical classes affect different exposure pathways, placement of chemicals within the overall economic system (e.g., during their production, release in the environment, or use in consumer products) is an important consideration in proper regulation. However, there is little systematic coordination in the production of knowledge of contaminant classes based on their chemical structure and mode of action, or how these classes are used and released. Current toxic chemical governance uses a narrow approach to knowledge production instead of, for example, evaluating substances on the basis of classes with shared chemical structure, such as organochlorines or brominated flame retardants, or even on the basis of shared mode of actions, such as level or type of carcinogenicity. A class-based approach may lead to more effective and efficient regulation and protection from chemical risks (e.g., Sanderson et al. 2004), and has been partially adopted by the current TSCA.

The failure to include broad expertise in the governance process has cascading effects: Policy design does not adequately prevent failures, and often does not provide architecture for effective monitoring and enforcement. As path dependency is rigid, effective policy evaluation is often nearly impossible. This means that adjudication is necessary to attempt to address grievances, whereas effective change is made difficult by poor policy design, lack of monitoring and enforcement, and the institutional challenges to quality policy evaluation, including major limitations on building a knowledge base for alternative chemical production.

Principle 2: Support diverse knowledge systems. Evolving the knowledge base entails supporting the generation and synthesis of diverse forms of knowledge for a more robust understanding of the complex nature of toxic chemical risks and the resulting sociotechnical transformations needed. At present, advances have been made in funding independent evaluations of chemical toxicity and in improving both laboratory and field-based methods for assessing toxic chemical risks. However, some promising technologies, such as the use of cell cultures and metabolic micro arrays instead of animal testing, could dramatically cut the costs of risk assessment but require sustained investment in order to penetrate a field dominated by animal testing (Hartung 2009). These advances in laboratory science should also be interdependent with field-based, public health, and experiential knowledge of toxicity. Increases in knowledge generation and synthesis about the impacts of toxic chemicals also need to inform and integrate research on alternative modes of clean production for substances of similar function, all which could be funded by implementing fees on the production of certain chemical classes (Thornton 2000). Building such a diverse knowledge system is not without its challenges, many of which can be overcome by providing an inclusive, representative, outcome focused, and independently evaluated research process for different classes of toxic chemicals (Reed et al. 2014). However, as our case studies indicate, integrating diverse knowledge requires substantive changes throughout the rest of the governance system.

Issue 3: Uneven and unequal governance. In cases in which laboratory science presents significant evidence of risk of widely used chemicals, such as BPA, glyphosate, and lead in plumbing, unequal policy and enforcement mechanisms privilege the material interests of powerful actors over the health and well-being of communities and ecosystems. A lack of resources for adequate regulatory enforcement and policy and program implementation is symptomatic of the skewed priorities of the existing governance system. Some of our case studies exhibited partial success in one or more domains. For example, adjudication in glyphosate under the logic of compensation, allows for continued operations, serving as a bandage to mitigate core weaknesses in policy design and enforcement. This model of governance disproportionately affects vulnerable populations, including children, elderly, low-income individuals, and future generations in favor of industry (Elliott et al. 2004, Landrigan et al. 2017).

Part of the reason for this uneven and unequal governance is the influence industry has on shaping the present policy sphere. These types of failures result from targeting public opinion (Robbins 2007) and from lobbying and influencing legislators (Fredriksson et al. 2003, Hall and Deardorff 2006) to the point that legislation drafted by industry associations can become law (Potter 2011). This legislative capture is often reinforced by regulatory capture, occurring when an executive agency meant to protect the public interest instead protects the industry it regulates (Shapiro 2012). Arguments for this close relationship between regulators and industries hinge on the idea that the two entities are supposed to collaborate to provide economic growth while protecting public values and interests (Lind 2015). By extension, the relatively limited influence on the policy process exerted by environmental and public health interest lobbyists, has caused them to invest in legal expertise, has resulting in a system of "regulation by litigation" (EPA 2017) by the "public interest law complex" (Lind 2015). Overall, these tensions highlight that although some adjudication can lead to substantive enforcement actions, without significant policy change and associated governance evolution, seeking financial redress from toxic industries may perversely promote increased or dirtier production as companies must finance compensatory penalties from their operating budgets.

Principle 3: Inclusive, transparent, and accountable institutions. Overall, effective governance comes from increasing the representativeness and transparency of democratic processes, and allowing for the direct involvement of affected communities in policy design and implementation. Such a principle supports two primary initiatives: building a collaborative governance body and identifying cross-scale institutional links needed to address the complexity of contemporary global industrialization.

The creation of a collaborative governance body may help alleviate some of the patterns we have highlighted. Successfully building a collaborative governance body involves bolstering participatory science approaches (e.g., citizen science programs) to narrow the science–policy gap. Specifically, a collaborative governance body would (1) consider and evaluate traditional ecological knowledge, scientific knowledge, and the experiential knowledge of affected communities (e.g., Bäckstrand 2003); (2) include diverse stakeholders in knowledge exchange (Reed et al. 2014); and (3) engage procedural elements, such as independent moderation, to ensure a balance of power within the group (Purdy 2012). Collaborative governance is also mutualistic with collaborative knowledge production, and it decreases monitoring costs and increases industry accountability while empowering communities (Johnson et al. 2014).

Examples of such bodies presently exist, although not without their own challenges. As with toxic chemicals, our oceans are governed by a diversity of laws, regulations, and agencies. To address this fractured governance, the National Ocean Policy Act (NOPA) was passed in 2010, establishing the National Ocean Council, a collaborative body that includes representatives of the federal departments and agencies with major jurisdiction over the oceans to share resources and collaborate to implement policy. The NOPA marks the first national effort to implement a holistic, multiagency approach to managing our coasts and oceans, although contrasting priorities between executive administrations have limited its effectiveness (Malakoff 2018). The implementation and challenges of the NOPA indicate that governance of complex social, environmental, and technological systems requires operating horizontally across sectors (industries, media, academic scientists) and vertically across levels (communities, agencies, legislatures, national governments; Cash et al. 2006).

Issue 4: Path dependency and inertia. The path dependency exhibited in each case results from the costs sunken into certain means of production (i.e., technologies producing toxic risks), the persistence of many toxic materials, privileging of knowledge (Brown 1992), and the general absence of self-corrective behavior by industries, barring significant social influence. Current market logics enabled by state regulation have proven inadequate for internalizing the costs of production and have violated the economic principles of functioning markets (Haldane et al. 2017). More troublingly, industry priorities have continued to shape research and development toward minimizing costs and maximizing profits as opposed to alternative means of production (Woodhouse 2006).

In addition, many emergent risks are systemic, in that they emerge from complex interactions between society, the environment and technologies, such as SOx and NOx resulting from automotive pollution. Although small technological fixes such as improved catalytic converter technology and conversion to electric vehicles are possible, the aggregate influence of car-dependent suburban development has outstripped gains from cleaner combustion technology. At the same time, innovation in some sectors has been shown to reduce risks from long-entrenched interests, evidenced by the grid purchasing power parity of wind farms over coal, facilitated by direct investments in research and development, and significant policy support for fledgling industries (Jenkins et al. 2010). A proper innovation-oriented approach can facilitate long-term system evolution, as opposed to the reactionary method of bureaucratizing risk that have led to systemic path dependencies that undermine sufficient toxic chemical governance.

Principle 4: Invest in innovation and real-world deployment. Policies need to identify and incentivize ways of producing substances that meet the goals and needs of contemporary society without exposing people to toxic chemicals. Existing command and control, and other end-of-pipe regulations, although insufficient to protect human and environmental health, have stimulated extensive innovations in industry, creating jobs while improving human and environmental health (Wallace 1995, Pearce and Stillwell 2008). These models can be significantly improved using initiatives such as cradle-to-cradle manufacturing (Braungart et al. 2007), the bioeconomy (McCormick and Kautto 2013), and the increasingly loud call for a Green New Deal (Jones 2009). Embracing such transitions will support our rights to a pure and high-quality environment. Economically, it will reduce and eventually eliminate compliance costs, increase labor productivity, provide greater long-run certainty over operational costs, reduce the economic burden of healthcare costs on society, and increase the economic advantage of US industries (Braungart et al. 2007, Jones 2009). Although some polluting industries may oppose such initiatives, the above arguments invalidate their rhetorical claims about the need to reduce regulations to protect jobs and economic advantage. In the face of such path dependency, it has become incumbent on the scientific community to evolve industries to eliminate harms from toxic chemicals, especially given their role in accelerating the existential threat of rapid anthropogenic climate change.

Conclusions

After over 40 years of modern environmental regulations, toxic chemical risks remain pervasive and largely unacknowledged in the United States, despite their significant negative impacts on public health, the economy,

and life-sustaining ecosystems. Crisis response and risk mitigation have pervaded environmental regulations around toxic chemicals. Effective toxic chemical governance will require sustained effort to produce better knowledge in the service of large-scale industrial and social transformations and the creation of inclusive governance bodies. A transition to a regenerative economy that eliminates the concept of waste and permissible harm is urgently needed. To do so, researchers, industries, communities, policymakers, and the media must continue to craft collaborative visions and produce knowledge that enable public and private investments in clean and ecologically sound technologies and land management practices. Evaluation of existing systems highlights research priorities for those seeking to transform governance to improve human and environmental health. By lifting the veil around the science and technology of producing and managing toxic chemical exposure risks, we can improve democratic governance and insure a healthier, economically robust, and equitable future for all.

Supplemental material

Supplemental data are available at *BIOSCI* online.

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