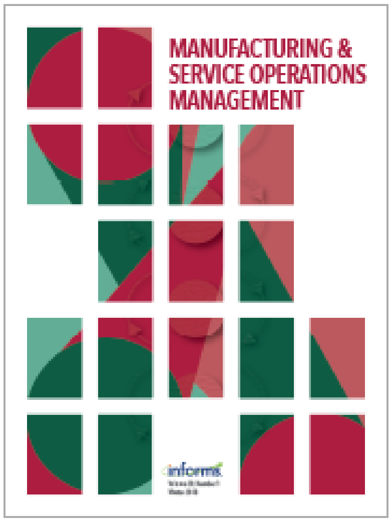

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Are Hazardous Substance Rankings Effective? An Empirical Investigation of Information Dissemination About the Relative Hazards of Chemicals and Emissions Reductions

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Abstract. ***Problem definition***: Whether information dissemination about chemical hazards drives managers at facilities to undertake corresponding environmental actions, remains an open question that has not been adequately examined in the literature. ***Academic/practical relevance***: We fill this gap in the literature by empirically investigating reductions in chemical emissions by facilities in relation to changes in the assessed hazard levels of chemicals evidenced in periodically-updated public information. We also examine the moderating effects of operational leanness—an attribute that prior studies have shown to be associated with better environmental performance—in our setting wherein the assessed hazard levels of chemicals change over time. ***Methodology***: We draw data from four U.S. sources—the Substance Priority List from the Agency for Toxic Substances and Disease Registry, the Toxics Release Inventory from the EPA, the National Establishment Time-Series, and Compustat. We employ a panel model with facility-chemical- and time-fixed effects. ***Results***: We find that public information dissemination on chemical hazards is effective, as indicated by the significant association between increases in the assessed hazard levels of chemicals and greater subsequent emissions reductions. Specifically, we find that facilities reduce emissions by an additional 4.28% on average, and their use of source reduction increases by 3.07% on average when the relative assessed hazard level of a chemical increases compared to when it decreases. We find that, overall, leaner facilities outperform less lean facilities with respect to emissions reductions. However, when the assessed hazard level increases, less lean facilities increase their emissions reductions more than leaner facilities. ***Managerial implications***: Our findings provide insights for managers prioritizing environmental actions, including the extent of emissions reductions achievable by practicing lean. Our results can also be leveraged by governmental/nongovernmental organizations to anticipate responses to informational updates on chemical hazards, depending on characteristics of the affected facilities.

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1. Introduction

Enacting environmental legislation, such as limits on emissions, requires detailed cost and benefit assessments, involves many players, typically proceeds in a long-drawn fashion and thus has an uncertain outcome (Beavis and Dobbs 1986, Hartl 1992, Batabyal 1995, Drake and Just 2016). In contrast, despite not directly regulating the behavior of facilities or firms, information-based regulatory approaches—such as the *public dissemination of information* on the potential hazards of chemicals or the requirement that *facilities or firms disclose emissions* of certain chemicals (e.g., as is required under the United States Environmental Protection Agency's (U.S. EPA's) Toxics Release Inventory (TRI) Program)—may drive facilities or firms to internalize the risks revealed by the hazard information by engaging in emissions reductions efforts.

An example of the public dissemination of information on chemicals is the Substance Priority List (SPL), published by the Agency for Toxic Substances and Disease Registry (ATSDR). Established under the Comprehensive Environmental Response, Compensation, and Liability Act of 1980, commonly known as the "Superfund" Act, ATSDR is the main source of information in the United States about the health effects of exposures to hazardous chemicals. ATSDR is responsible for maintaining toxicological databases and sharing information with other governmental agencies and public health professionals (ATSDR 2009, 2012). ATSDR gathers information on the hazards of candidate chemical substances identified at National Priorities List (NPL) sites. ATSDR also scores these chemicals based on their toxicity, frequency of occurrence at NPL sites, and probability of human exposure, and biennially publishes a ranked list (i.e., the SPL) comprising the chemicals with the top 275 scores. The agency prioritizes these chemicals for continuing toxicological research efforts and the compilation and dissemination of their toxicological profiles to the public (ATSDR 1994a, b; 2014).

The toxicology information prepared by ATSDR is referenced in various regulatory programs, including the TRI program, and in industry news outlets and publications (e.g., Keiser 2003, Pearl 2008, Paul et al. 2015). In addition, ATSDR assists other agencies in determining future regulations pertaining to chemical substances (ATSDR 2009). For example, in 2002, the agency recommended to the National Toxicology Program (NTP) that pentachlorophenol—ranked 43 in the 2001 SPL—be included in the Report on Carcinogens (RoC) (NTP 2002, 2012). Subsequently, the substance was included in the RoC in 2014 (NTP 2014), and firms have since been required to warn employees about their exposure to the chemical (Occupational Safety and Health Administration 2012).

In addition to the regulatory stature of the SPL, there is broader public interest in the information provided by ATSDR. The list of subscribers (shared with us in an anonymized format by ATSDR) for the agency's "Toxic Substances" topic numbered 56,587 email addresses as of February 2017. This subscription includes email notifications when the SPL is updated. Our analysis of this list shows that the subscribers span a variety of institutions and organizations such as law firms, research laboratories, schools, universities, healthcare systems, nongovernmental and community organizations, and even The White House. Furthermore, we find significant overlap between organizations that report to the TRI and that access ATSDR's SPL webpage: using 2004–2016 Adobe SiteCatalyst web metrics data (also shared with us by ATSDR) on visits to the SPL webpage, we found that 25.7% of the TRI records (178,332 out of 692,726 facility-chemical records) during 2004–2012 can be linked through the "Public Contact Email" field in the TRI data to facility or parent-firm domain names tracked in the SPL webpage visits. These observations provide summary evidence for the emphasis placed by the general public and managers at facilities on ATSDR's public information regarding the assessed hazards of chemical substances.

As an outcome of progress in toxicology research, the relative assessed hazard levels of chemicals—reflected in their ranks in the SPL—change over time. For example, environmental studies have resulted in growing concerns about the use of trichlorobenzenes (TCBs), which are commonly used as dye carriers in polyester dyeing processes (World Health Organization 2004). The SPL rank of one of its variants, 1, 2, 3-TCB, advanced from 334 in 1992 to 137 in 2015. Concurrently, Nike encouraged its suppliers to specifically phase out TCBs from their manufacturing processes (Nike Inc. 2016, Zero Discharge of Hazardous Chemicals 2016). Another example is glycol ethers, a group of ether-based solvents and cleaning agents that are widely used in industrial cleaning. As the rank of glycol ethers in the SPL advanced from 575 in 1992 to 319 in 2015, the use of these solvents attracted considerable media attention, and industrial cleaning firms have been actively seeking a substitute (Quaker Chemical Corp 2015; Substitution Support Portal 2015a, b, c). The anecdotal evidence may suggest that firms acknowledge the assessments of chemical hazards and undertake environmental actions in response. On the other hand, anecdotal evidence in other contexts has shown that instead of responding to information about an increase in the assessed hazard of a chemical by limiting the use or emissions of the chemical in question, firms may wait or even direct resources toward preventing legislative actions. For example, after discoveries about the potential harm that chlorofluorocarbons (CFCs) can cause to the stratospheric ozone layer, many firms including DuPont initially lobbied against regulatory actions citing scientific uncertainties and substantial costs (Barrett 1992, Maxwell and Briscoe 1997).

Despite the availability of periodically updated public information about the potential hazards of specific chemicals, limited empirical research has been devoted to examining (1) the link between such information and the environmental efforts of facilities that use the chemicals of concern and (2) the implications of the operational characteristics of the facilities on the extent and nature of the environmental efforts. We add to the understanding of these relationships by investigating reductions in chemical emissions (including the use of source reduction and end-of-pipe, or EOP treatment) in relation to changes in the relative assessed hazard levels of the chemicals, as evidenced in the periodically updated SPL published by ATSDR. To capture reductions of chemical emissions, we use data from the TRI. The TRI program mandates facility-level reporting of emissions of over 650 chemicals. TRI data has been extensively used in the literature to examine the environmental actions of facilities or firms (e.g., Hart and Ahuja 1996; Klassen and Whybark 1999; King and Lenox 2001, 2002; Toffel and Marshall 2004; Doshi et al. 2013).

Studies in the environmental management literature suggest that emissions reductions efforts, driven by the management of business risk, should reflect the hazards of chemicals released by a firm's facilities (Reinhardt 1999, Kleindorfer and Saad 2005). When a chemical is found to potentially cause greater harm compared to other chemicals, firms can expect higher future costs for environmental compliance and consumer and occupational liabilities related to that chemical (Kraft et al. 2013). Thus, when the relative assessed hazard level of a particular chemical substance increases (reflected as upward movement in the SPL), facility managers would be more likely to prioritize reductions of emissions of that chemical—either through source reductions or EOP treatment. Furthermore, the three pillars of institutional theory—namely, the *regulative* dimension—in particular, informal processes that involve disapproval or censure, the *normative* dimension, which relaxes the strict definition of fiduciary behavior to be grounded within a relevant social context, and the *cognitive* dimension, which explains why managers may adopt actions that would not cause them to stand out—also explain why facilities may be driven to internalize the information about the potential hazards of chemicals in the form of emissions reduction efforts (Scott 2013).

Perhaps the most significant operations management practice pertinent to environmental actions beyond regulatory compliance is lean operations. Broadly defined, lean operations principles aim to eliminate waste and reduce variability (Hopp and Spearman 2004, Shah and Ward 2007). The phrase "lean is green" has emerged as a result of the rationale that because of the focus on waste, leaner facilities or firms can be expected to achieve better financial as well as environmental performance (King and Lenox 2001, Kleindorfer et al. 2005, Corbett and Klassen 2006). However, studies have also posited that operational leanness may not necessarily imply better environmental performance because of the possible avoidance of effective EOP methods and more frequent equipment changeovers (Rothenberg et al. 2001, Zhu and Sarkis 2004). Lean facilities or firms having closely integrated operations with limited slack may be less flexible to respond to risks than those that allow operational buffers (Yusuf and Adeleye 2002, Kleindorfer and Saad 2005, Narasimhan et al. 2006). Therefore, we examine how operational leanness *moderates* the relationship between changes in the relative assessed hazard levels of chemicals and facilities' reductions of emissions of the chemicals, as well as their use of source reduction and EOP treatment.

To test our hypotheses, we draw secondary data from four U.S. sources—the SPL from ATSDR, the TRI from the EPA, the National Establishment Time-Series, and Compustat. We employ a panel model with facility-chemical- and time-fixed effects and control for various facility and industry factors. We find that public information dissemination on the relative hazards of chemicals is effective, as indicated by the significant association between increases in the relative assessed hazard levels of chemicals and greater subsequent emissions reductions as well as the increased use of source reduction. Specifically, we find that facilities reduce emissions by an additional 4.28% on average and their use of source reduction increases by 3.07% on average when the relative assessed hazard level of a chemical increases compared to when it decreases. We also find that operational leanness has an overall positive effect, i.e., leaner facilities outperform less lean facilities with regard to emissions reductions (or, "lean is green"). However, we find partial support for a *negative* moderation effect of operational leanness—when the relative assessed hazard level increases, less lean facilities increase their emissions reductions more than leaner facilities (or, "the benefits of leanness may be limited in contexts that involve risk").

To the best of our knowledge, our study is among the first in the environmental management and sustainable operations literatures to analyze the effects of publicly disseminated information pertaining to the relative assessed hazard levels of chemicals, on the operational decisions (emissions reductions and the use of source reduction and EOP treatment) of facilities using those chemicals. By explicitly accounting for operational characteristics of facilities in our analysis, we develop key insights for practitioners (i.e., governmental/nongovernmental organizations as well as managers) related to designing and responding to information-based environmental programs.

2. Literature and Hypotheses

In the following sections, we position our work in the context of the related literature and introduce our hypotheses pertaining to the relationships between changes in the relative assessed hazard levels of chemicals and the extent and nature of emissions reductions for the chemicals, including the moderating effects of operational leanness.

2.1. Changes in Assessed Hazards of Chemicals and Emissions Reductions

The effects of mandatory disclosure by firms on their use or releases of chemicals have been examined in different contexts (e.g., Doshi et al. 2013, Kalkanci and Plambeck 2017). The literature, however, contains fewer studies pertaining to the effects of information dissemination of chemical hazards by governmental agencies or nongovernmental organizations. One of these few studies is by Gormley and Matsa (2011), who hypothesized that chemicals newly added to the RoC expose firms that routinely use these chemicals to significantly greater occupational liability in the form of legal fees, damage payments, and insurance premiums. Using an event-study approach, they found that firms exposed to the newly added chemicals were more likely to undertake financial actions for growth such as capital investment and acquisitions compared to unexposed firms, so as to limit the future financial burden arising from greater liability risks. While Gormley and Matsa (2011) focused their attention on financial actions of firms, the literature has not yet studied how information dissemination about chemical hazards shapes operational decisions.

As discussed previously, there is evidence of broader public interest in the information on the hazards of chemicals provided by ATSDR, with subscribers to the information spanning a variety of key institutions and organizations. Furthermore, there is significant overlap between organizations that report to the TRI and that access ATSDR's SPL webpage. Clearly, emphasis is placed by the general public and managers at facilities on this public information regarding the assessed hazards of chemical substances. Consistent with Gormley and Matsa (2011), therefore, we contend that facilities associate a higher relative assessed hazard level for a chemical with greater likelihood of new or more stringent regulations, stricter enforcement, higher expected costs of ensuring occupational safety, or greater liability for harm caused by the chemical to employees and the public. Accordingly, we expect facilities to address these greater risks by undertaking operational actions to reduce emissions of the chemical of concern.

The prior literature on environmental management provides support for our position that risk management considerations motivate facilities to take environmental actions beyond regulatory compliance. Reinhardt (1999) suggested that business risk management is the fundamental driver of actions beyond compliance because, despite their likely negative economic ramifications in the short term, such actions may reduce the probability or magnitude of losses from liability, damage to reputation, and operational disruptions caused by future litigation or changes in regulations. Berry and Rondinelli (1998) also proposed that the increasing cost of merely complying with legal requirements (that gradually become more stringent and complex) drives firms to take proactive environmental actions. Similarly, Reid and Toffel (2009) proposed that beyond-compliance actions are preemptive responses by firms to mitigate future risks such as additional regulations and more stringent enforcements. Kleindorfer et al. (2005) list compliance with probable future regulations, limiting liability, and enhancing employee health and safety as drivers for managers to undertake environmental actions that go beyond current regulatory compliance. Furthermore, when enhancing their risk management systems, firms quantitatively link factors such as customer liability and employee safety to proactive, risk-reducing actions such as pollution prevention (Kleindorfer and Saad 2005).

Drawing from the discussions in Scott (2013, pp. 55–86) and the references therein, the three pillars of institutions—namely, *regulative*, *normative*, and *cognitive*—also explain why facilities or firms may be driven to internalize the information about the potential hazards of chemicals by engaging in emissions reduction efforts. Aligned with the regulative dimension of institutions, the public availability of up-to-date information on chemical hazards helps independent entities such as nongovernmental organizations, community groups, and the press assess the negative environmental and societal impacts of a firm's or a facility's operations on the basis of its pollutant releases (e.g., as reported to the TRI). Thus, the public availability of information on chemical hazards may enable these entities to formulate sanctions—through informal external processes that involve disapproval or censure—to influence managerial behavior. The normative pillar, which relaxes the strict definition of fiduciary behavior, emphasizes legitimate means to valued ends (such as making a profit while adopting environmentally responsible business practices). This pillar helps explain that while reductions in chemical emissions beyond current regulatory compliance may not be financially justifiable in the short run, managerial responses to updated information about chemical hazards are grounded within a relevant social context that is either intrinsically recognized by managers or established through industry associations, professional publications, or educational venues (Campbell 2007). The cognitive pillar explains why, on a collective scale, facility managers may respond similarly to changing information about the relative hazards of chemicals. Specifically, managers may respond to such information by adopting actions that would not cause them to stand out (as would be the case if a facility did not engage in emissions reductions efforts for a chemical with an elevated assessed hazard level).

From an empirical standpoint, in their investigation of the nature of corporate social responsibility principles, processes, and stakeholder issues discussed in the webpages of U.S. and European firms, Maignan and Ralston (2002) found that firms' motivations for engaging in socially responsible behavior included (a) stakeholders such as community groups, customers, and regulators pressuring the firms to engage in such behavior; (b) managers intrinsically valuing such behavior; (c) managerial assessments or beliefs of such behavior enhancing financial performance. Thus, both the theoretical and empirical underpinnings of institutional theory help explain the motivation behind environmentally responsible managerial actions. Based on the preceding discussion, we hypothesize the following:

Hypothesis 1A (H1A). *An increase in the relative assessed hazard level of a chemical is positively associated with reductions in emissions of the chemical.*

2.2. Use of Source Reduction and End-of-Pipe (EOP) Treatment

Source reduction (also referred to as "pollution prevention"), which includes changing product designs and modifying production processes to *avoid* pollution, has long been recommended as a way to achieve better environmental performance, gain competitive advantages, promote innovation, and improve financial performance (Klassen and Whybark 1999, King and Lenox 2002). EOP treatment (also referred to as "pollution control") includes the use of equipment or methods to recycle, burn, or neutralize (i.e., *treat*) pollutants. While EOP treatment is typically not regarded to be as strategically valuable as source reduction, it requires no modifications to existing product designs, has a limited disruptive effect on production processes and the workforce, may be financially less burdensome in the short run, is an inexpensive way of assessing process health, and serves as a protective "buffer" from future changes in regulations (Klassen and Whybark 1999, Klassen 2000a, Rothenberg et al. 2001, Dutt and King 2014). For our context, we posit that to respond to increases in the relative assessed hazard levels of chemicals and to achieve meaningful reductions in emissions of the chemicals, facility managers may need to increase the use of source reduction as well as increase the use of EOP treatment.

Indeed, several studies have suggested the need for facilities to dedicate efforts to both source reduction and EOP treatment to achieve reductions in emissions that go beyond current regulatory compliance (Aragón-Correa 1998, Rothenberg et al. 2001, Kroes et al. 2012). In their study of automobile assembly plants, Rothenberg et al. (2001) discussed limits to reducing emissions of volatile organic compounds (VOCs) by improving process efficiency and limiting the solvent content of materials; in addition, EOP abatement methods need to be resorted to in preparing for anticipated future regulatory requirements. Aragón-Correa (1998) found that the environmentally most advanced firms employ not only preventive, at-source methods but also corrective, EOP methods. Kroes et al. (2012) found empirical support for their position that with a specific pollutant receiving emphasis, affected firms or facilities would direct their energies to that pollutant as opposed to a more general pursuit of overall emissions reductions. In such a setting, EOP methods may be attractive for reducing pollutant emissions beyond the reductions offered by at-source methods. Furthermore, Dutt and King (2014) found evidence that the relationship between source reduction and EOP treatment is not substitutive but complementary. Specifically, EOP treatment helps obtain diagnostic information about emissions, subsequently allowing facility personnel to undertake efforts that result in sustained emissions reductions. Therefore, based on the preceding discussion, we hypothesize the following:

Hypothesis 1B (H1B). *An increase in the relative assessed hazard level of a chemical is positively associated with the use of source reduction for the chemical.*

Hypothesis 1C (H1C). *An increase in the relative assessed hazard level of a chemical is positively associated with the use of EOP treatment for the chemical.*

2.3. Moderating Effect of Leanness on Emissions Reductions

Studies in the sustainable operations literature suggest that the outcomes of practicing lean—(1) the identification and minimization of waste, (2) the empowerment of employees and facilitation of their in-depth know-how of production processes, and (3) continuous improvements in all aspects—help facilities achieve better operational and environmental performance simultaneously, yielding the "lean is green" concept (King and Lenox 2001, Kleindorfer et al. 2005, Corbett and Klassen 2006). Furthermore, lean operations initiatives may reduce the cost of discovering opportunities for emissions reductions, thereby enhancing the pursuit of those opportunities (King and Lenox 2001). Overall, since a focused awareness of waste and enhanced know-how of processes could facilitate the prioritization of waste reduction efforts and enhance the effectiveness of the efforts, operational leanness can be expected to *positively moderate* emissions reductions when the relative assessed hazard level of a chemical increases. Consistent with this view, King and Lenox (2001) found evidence of a negative association between facility leanness (measured by the summation of the maximum inventory levels across all chemicals) and overall emissions. Also, Klassen (2000b) observed that waste minimization and just-in-time (JIT) systems at furniture manufacturing plants reduced inventory levels of hazardous substances and curtailed the disposal of expired inventories; thus, emissions of hazardous chemicals decreased as investments in JIT systems increased.

On the other hand, lean principles may end up inhibiting environmental performance. Lean facilities may consciously avoid effective EOP methods as they focus on pollution prevention through process changes (King and Lenox 2001, Rothenberg et al. 2001). Therefore, despite their pollution prevention efforts, facilities with a greater adoption of lean practices may be able to reduce emissions to a lesser extent than less lean facilities (Rothenberg et al. 2001). Indeed, in their study of automotive assembly plants, Rothenberg et al. (2001) found support for a negative association between adoption of lean practices and environmental performance measured by VOC emissions. Also, smaller batch sizes and more frequent changeovers in leaner production may entail more frequent cleaning of production equipment and increased overall disposal of packaging waste, cleaning waste, and unused process material (King and Lenox 2001, Zhu and Sarkis 2004). Furthermore, the benefits of leanness may be tempered by contextual factors (Zipkin 1991, Eroglu and Hofer 2011). Facilities or firms having closely integrated operations with limited slack may be less flexible to respond to risks than those that allow operational buffers (Yusuf and Adeleye 2002, Kleindorfer and Saad 2005, Narasimhan et al. 2006). Thus, when encountering increases in the relative assessed hazard levels of chemicals used in their operations, leaner facilities may not be able to reduce emissions as much as less lean facilities or, that operational leanness may instead *negatively moderate* the relationship between increases in relative assessed hazard levels and reductions in emissions.

Based on the previously made competing arguments, we offer the following competing hypotheses for the moderating effect of operational leanness on emissions reductions:

Hypothesis 2A(B) (H2A(B)). *Operational leanness positively (negatively) moderates reductions in emissions of a chemical when the relative assessed hazard level of the chemical increases. That is, leaner facilities increase their emissions reductions to a greater (lesser) extent than less lean facilities when the relative assessed hazard level of the chemical increases.*

2.4. Moderating Effects of Leanness on Source Reduction and EOP Treatment

According to the principles of lean operations, waste and inefficiencies are resolved at the source. Thus, leaner facilities can be expected to use source reduction to a greater extent than less lean ones. Similarly, since EOP methods only symptomatically treat problematic chemicals at the end of the process, leaner facilities would be less likely to employ EOP treatment. Overall, since reducing emissions at the source rather than treating them at the end-of-pipe has a similar logic to incorporating quality at the source rather than inspecting quality at the end of the process, managers at leaner firms can be expected to engage more in source reduction and less in EOP treatment (King and Lenox 2001, Corbett and Klassen 2006). From an empirical standpoint, Rothenberg et al. (2001) found that managers of leaner facilities regard EOP treatment as the last resort and would rather explore pollution prevention through process changes than adopt EOP treatment methods. Thus, when the relative assessed hazard level of a chemical increases, managers at leaner facilities can be expected to pursue source reduction for the chemical to a greater extent than less lean facilities. Moreover, leaner facilities can be expected to pursue EOP treatment to a smaller extent than less lean facilities.

On the other hand, despite the emphasis on avoiding waste at-source, pollution prevention at leaner facilities may be hindered because of the operational, financial, and workforce risks involved; source-reduction initiatives may be deemed disruptive to lean processes that are optimized for quality, cost, and efficiency (Freeman et al. 1992, Klassen 2000a, Dutt and King 2014). Dutt and King (2014) propose that EOP methods may, in fact, be aligned with principles of lean operations and quality management. EOP operations serve as "quality sensors," revealing information about waste that would otherwise go unnoticed. Thus, EOP operations provide diagnostic information on process health and thereby contribute valuable contextual knowledge to process improvement efforts (King 1995, Rothenberg 2003, Dutt and King 2014). From an empirical standpoint, although King and Lenox (2001) proposed that leaner firms would engage less in EOP treatment, they did not find evidence to support this contention. Relatedly, certain studies on lean operations have evidenced a trade-off between tight synchronization through minimization of slacks and the capability to respond to risks (Yusuf and Adeleye 2002, Kleindorfer and Saad 2005). Analogously, for our context, in responding to increasing relative assessed hazard levels of chemicals, closely integrated production processes at lean facilities may be unamenable to additional source reduction activities, resulting in EOP treatment being favored.

Based on the competing sets of arguments presented, we propose the following competing hypotheses for the moderating effects of operational leanness on the use of source reduction and EOP treatment:

Hypothesis 3A(B) (H3A(B)). *Operational leanness positively (negatively) moderates the use of source reduction for a chemical when the relative assessed hazard level of the chemical increases.*

Hypothesis 4A(B) (H4A(B)). *Operational leanness positively (negatively) moderates the use of EOP treatment for a chemical when the relative assessed hazard level of the chemical increases.*

3. Data, Variables, and Empirical Approach

3.1. Data

As discussed previously, we use the SPL from ATSDR (published to the Federal Register biennially) as the data source for the relative assessed hazard levels of chemicals. To determine facility-level reductions in chemical emissions and the use of source reduction and EOP treatment, we use TRI data from the EPA. For various facility and industry controls, we draw data from two more sources: the National Establishment Time-Series (NETS) data from Walls and Associates, and the Compustat North America annual data from Standard and Poor's. We focus on the period 2001–2009 for two reasons: First, ATSDR did not publish the 2009

SPL because of a transition to a new database. Second, the EPA expanded the list of chemical substances that facilities were required to report to the TRI, and lowered the reporting quantity thresholds of persistent bio-accumulative toxic chemicals in 2000. Since the SPL is published biennially, we define *event year t* based on the schedule of the SPL, i.e., $t \in [2003, 2005, 2007]$ and measure our variables based on these event years. Note that our data spans two years before the earliest event year to two years after the latest event year (i.e., the period 2001–2009) because of our use of measures of chemical ranks in the previous event year, and emissions two years after an event year.

3.1.1. Substance Priority List (SPL). As the lead agency for implementing the health-related provisions of the Comprehensive Environmental Response, Compensation, and Liability Act (or Superfund Act), ATSDR is charged

> to assess the presence and nature of health hazards at specific Superfund sites, to help prevent or reduce further exposure and the illnesses that result from such exposures, and to expand the knowledge base about health effects from exposure to hazardous substances. (ATSDR 2009)

To determine the relative hazard levels (or the "ranks") of chemical substances, ATSDR aggregates the "points" assigned to over 800 candidate chemicals based on three criteria: toxicity, frequency of occurrence at NPL sites, and potential for human exposure (ATSDR 2014). The chemicals are ranked in descending order based on their total points (i.e., the most hazardous chemical is ranked #1). The top 275 chemicals constitute the SPL (published biennially) and receive substantial focus. For these top 275 chemicals, ATSDR is responsible for performing additional toxicological tests, preparing detailed toxicological profiles, and distributing the information to state officials, public health administrators, and other healthcare professionals. This information includes materials on the surveillance and screening of emissions, and diagnoses and treatments of injuries and diseases related to human exposure to the chemicals (ATSDR 2009, 2012, 2014).

We focus our analysis on those chemical substances that appeared in at least one of the SPLs during the period 2001–2007, noting that changes in chemical ranks over time reflect changes in their relative assessed hazard levels. ATSDR provided us with the following additional information: The SPL is derived from data abstracted from historical site documents that are accumulated in ATSDR's database. Once documents and data on substances found at hazardous waste sites enter into the database, they are never removed. As of December 2016, the database contained about a quarter million raw contaminant data records collected over 26 years. Furthermore, there is a time lag between contaminant releases and these contaminants being identified at NPL sites. Therefore, it is highly unlikely that the actions of facilities or firms could influence the SPL rankings of chemicals in the short run.

3.1.2. Toxics Release Inventory (TRI). To capture chemical emissions by facilities and their use of source reduction or EOP treatment, we draw data from EPA's TRI Basic Plus (version 12) data set. In addition to the amounts of chemicals released into the environment (air, water, or land) by facilities, the TRI also captures the amounts of the chemicals that are managed through recycling, energy recovery, and treatment (EPA 2016). We illustrate the data captured in the TRI using the conceptual waste flows in Figure 1. Chemicals in TRI data are indexed by Chemical Abstracts Service Registry Numbers, whereas facilities are indexed by facility identification (FID) numbers assigned by the EPA. After merging the TRI data with the SPL, we obtain a panel data set with 43,417 observations, spanning 120 chemical substances and 9,170 facilities over the period 2001–2009 (i.e., these 120 chemicals appeared in at least one of the SPLs during the period 2001–2007, and releases of these chemicals were reported by one or more facilities to the TRI). The ranks of these chemicals changed in 76.4% of the instances during the event years 2003, 2005, and 2007, with an average rank change of 5.46.

3.1.3. Compustat and NETS. For additional facility and industry information, we supplemented the merged SPL and TRI data with NETS and Compustat data. We first matched the Dun and Bradstreet (DUNS) numbers in the NETS data with the EPA FIDs to pull facility information such as SIC code and number of employees. Since facilities may relocate and report to the TRI under various FIDs while their DUNS numbers remain the same, we used the DUNS number as the primary facility identifier in assembling our data set. For our industry-level measures, we use data from Compustat and from Compustat "Segments" (which reports data by industry for firms that operate across multiple industries).

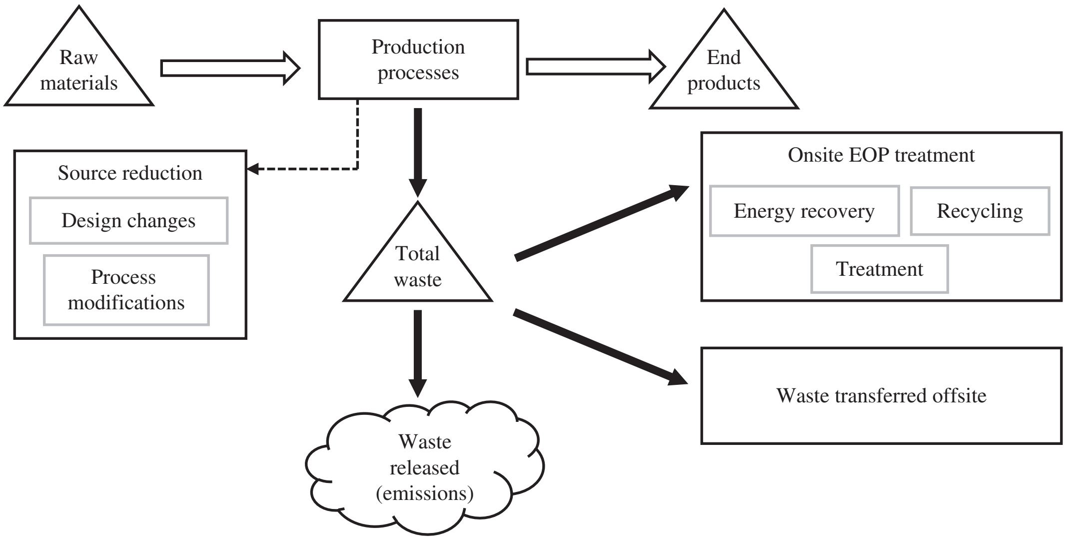
3.2. Variables and Measures

We employ a panel model that controls for various facility and industry factors. In this section, we discuss the dependent variables, main independent variables, and controls included in our model. Table 1 reports descriptive statistics and correlations.

3.2.1. Dependent Variables.

Emissions reductions. The SPL for an event year typically becomes publicly available either toward the end of that year or the beginning of the following year: The 2003 SPL was published in November 2003, the 2005 SPL was published in December 2005, and the

Figure 1. Waste Flows Captured in TRI Data



Notes. Black arrows denote waste flows. The dotted line represents the effect of source reduction on the waste generated from production processes. For each chemical c at facility i during year t, TRI data includes the amount of waste released ($Release_{i,c,t}$), the amounts of waste processed under energy recovery ($EnergyRecovered_{i,c,t}$), recycling ($Recycled_{i,c,t}$), and treatment ($Treated_{i,c,t}$), and the amount of waste transferred offsite ($TransferredOffsite_{i,c,t}$). Thus,

$$Total\ Waste_{i,c,t} = Release_{i,c,t} + EnergyRecovered_{i,c,t} + Recycled_{i,c,t} + Treated_{i,c,t} + TransferredOffsite_{i,c,t},$$

and

$$EOP_{i,c,t} = EnergyRecovered_{i,c,t} + Recycled_{i,c,t} + Treated_{i,c,t}$$

2007 SPL was published in March 2008. Therefore, to avoid contamination, we consider the difference in emissions between the event year and the second year after the event year. Specifically, we measure facility i's emissions reductions of chemical c as the ratio of the total quantity of the chemical released during the second year after the event year, i.e., $Release_{i,c,t+2}$ to the quantity released during the event year, i.e., $Release_{i,c,t}$. To suppress the effect of extreme values but maintain approximate linearity of the ratio around the mode, we take the natural logarithm of the ratio and multiply it by 100 (Kesavan et al. 2010, Dutt and King 2014). Lastly, for ease of interpretation, we apply a negative sign to the ratio to arrive at the emissions reductions ($ER_{i,c,t}$) for chemical c at facility i corresponding to event year t, as follows:

$$ER_{i,c,t} = -100 \times \ln\left(\frac{Release_{i,c,t+2}}{Release_{i,c,t}}\right).$$

Use of source reduction. Source reduction (or pollution prevention) includes changing product designs and modifying production processes to avoid pollution or waste. We capture a facility's use of source reduction for a chemical as the change in the total amount of waste of the chemical generated by the facility's production processes (see Figure 1). Using TRI data, we calculate the total waste ($Total\ Waste_{i,c,t}$) for chemical c at facility i in year t by summing the quantities released, treated onsite, and transferred offsite, and measure the use of source reduction ($SR_{i,c,t}$) as follows:

$$SR_{i,c,t} = -100 \times \ln\left(\frac{Total\ Waste_{i,c,t+2}}{Total\ Waste_{i,c,t}}\right).$$

Use of EOP treatment. EOP treatment (or pollution control) includes the use of equipment or methods to burn, recycle, or neutralize (i.e., *treat*) pollutants. We capture the change in the use of EOP treatment for a chemical at a facility as the ratio of the quantity of waste of the chemical treated end-of-pipe onsite during the second year after the event year to the quantity treated during the event year. In other words, we measure facility i's change in the use of EOP treatment ($\Delta EOP_{i,c,t}$) for chemical c and event year t, as

$$\Delta EOP_{i,c,t} = 100 \times \ln\left(\frac{EOP_{i,c,t+2}}{EOP_{i,c,t}}\right).$$

3.2.2. Independent Variables.

Change in relative assessed hazard level of a chemical. To capture the change in the relative assessed hazard level of a chemical, we use a categorical measure, $RelHazard_{c,t}$, which indicates the direction of change in the rank ($Rank_{c,t}$) of chemical c in event year t. Thus,

$$RelHazard_{c,t} = \begin{cases} Increased\ if\ Rank_{c,t} < Rank_{c,t-2} \\ Decreased\ if\ Rank_{c,t} > Rank_{c,t-2} \\ NoChange\ if\ Rank_{c,t} = Rank_{c,t-2} \end{cases}.$$

Table 1. Descriptive Statistics and Correlations

Variables	Mean	S.D.	1	2	3	4	5	6	7	8	9	10	11	12	13
1 *Emissions Reductions*	15.074	129.766													
2 *Source Reduction*	11.991	125.603	0.440***												
3 *Change in the use of EOP treatment*	−9.219	126.295	−0.225***	−0.760***											
4 *RelHazard = Increased*	0.336	0.472	0.020***	0.016***	−0.020***										
5 *RelHazard = Decreased*	0.323	0.467	−0.025	−0.032***	0.043***	−0.491***									
6 *RelHazard = NoChange*	0.341	0.474	0.005	0.016***	−0.023***	−0.512***	−0.497***								
7 *SPL entry*	0.002	0.045	−0.002	−0.003	−0.002	0.063***	−0.031***	−0.032***							
8 *SPL exit*	0.001	0.033	−0.003	0.001	0.008	−0.024***	0.048***	−0.024***	−0.002						
9 *Leanness*	−0.000	0.354	0.012	0.014***	−0.023***	−0.053***	−0.033***	0.086***	−0.004	0.013***					
10 *Market concentration*	0.168	0.174	0.023***	0.027***	−0.020***	0.013***	−0.017***	0.003	−0.006	−0.016***	−0.001				
11 *Industry growth*	−0.001	0.069	−0.017***	−0.014***	−0.000	0.008*	0.021***	−0.029***	0.007	0.006	0.007	−0.109***			
12 *Operating scale change*	−0.001	0.071	−0.002	0.001	0.012	−0.009*	0.011**	−0.001	−0.002	0.014***	0.011	0.019***	−0.002		
13 *Facility size*	4.787	1.563	0.004	−0.010**	0.011	0.042***	0.016***	−0.058***	0.006	0.007	−0.009**	−0.115***	−0.015***	−0.009**	
14 *Operational complexity*	12.008	20.225	−0.048***	−0.019***	0.018**	−0.002	0.034***	−0.031***	0.037***	0.030***	0.013***	−0.050***	−0.010**	−0.023***	0.074***

***$p < 0.01$; **$p < 0.05$; *$p < 0.1$.

We observed from the SPL data that the *NoChange* group typically included chemicals at the top of the list (average rank of 49) whereas the *Increased* and *Decreased* groups were more similar in the spread of the ranks of chemicals within them (average ranks of 140 and 177, respectively). Therefore, we chose the *Decreased* group as the reference group for our analysis. We performed a Chow test (Chow 1960, Greene 2003) to examine whether there are significant differences in parameter distributions between the *NoChange* group and the *Increased* and *Decreased* groups. The test failed to reject the null hypothesis of insignificant differences, and therefore we include all three groups in our estimations.

Operational leanness. Lean operations closely relate to practices that minimize buffer stocks or inventories. We construct a facility-level measure of leanness similar to the use-of-inventory measure developed by King and Lenox (2001). For this purpose, we utilize data on the maximum inventories of chemicals reported by each facility to the TRI. The maximum inventory of a chemical at a facility is the maximum total quantity of the chemical across storage tanks, process vessels, on-site shipping containers, etc., at the facility at any time during the reporting year. Other aspects of practicing lean beyond inventory use (such as work systems and human resource management practices; Rothenberg et al. 2001), or other inventory measures (such as cash-to-cash cycle or inventory turns; Hendricks et al. 2009, Lieberman and Dhawan 2005), while of potential interest, are precluded from consideration because of the limited availability of facility-level data.

We calculate the average of the maximum inventories of the chemicals at a facility in the year subsequent to the event year, take the natural logarithm of this average, and mean-center the resulting value by industry at the three-digit SIC level to account for differences across industries (Hendricks et al. 2009). Since a lower value of this measure, $MaxInv_{i,t}$, for facility i and event year t indicates more efficient utilization of buffer stocks compared to industry peers, or leaner operations (King and Lenox 2001), for ease of interpretation we set our measure of leanness to be the negative of $MaxInv_{i,t}$; i.e., $Leanness_{i,t} = -MaxInv_{i,t}$.

3.2.3. Control Variables. We employ a variety of controls to account for factors that may explain emissions reduction efforts in response to changes in the relative assessed hazard levels of chemicals.

Market concentration. The studies by Arora and Cason (1995) and Fernández-Kranz and Santaló (2010) found the intensity of industry competition to be associated with environmental actions by firms. To control for this potential effect, we compute the Hirschman-Herfindahl Index (HHI) at the three-digit SIC level using Compustat data, for the year subsequent to the event year. A higher HHI indicates a higher market concentration or lower intensity of competition.

Industry growth. To control for industry growth or decline, we employ a measure that captures the change in total industry sales using data from Compustat. Although Compustat data does not include information for private firms, we use the total sales of all public firms in an industry as a proxy for total industry sales. Specifically, we calculate the ratio of total sales of all public firms in an industry (at the three-digit SIC level) during the second year after the event year to the total sales during the event year, take the natural logarithm of this ratio, and multiply it by 100.

Operating scale change. The operating scale of a facility may affect its production, waste generation, and thus, emissions. Using NETS data, we measure changes in scale as the ratio of facility sales during the second year after the event year to the sales during the event year; we take the natural logarithm of this ratio and multiply it by 100.

Facility size. To control for the effect of facility size on emissions reduction efforts (e.g., Arora and Cason 1995, King and Lenox 2002), we use the natural logarithm of the number of employees at the facility in the year subsequent to the event year. Since the effect of facility size can be nonlinear (Arora and Cason 1995), we also incorporate its squared term.

Operational complexity. The overall scope and complexity of a facility's operations and environmental management efforts may have implications for the emissions reductions efforts for individual chemicals. To account for this potential effect, we incorporate the number of chemicals reported to the TRI by the facility in the event year as a control.

SPL entry or exit. Chemicals that newly appear in the SPL in an event year may receive additional attention compared to chemicals that also appeared in the SPL in the preceding event year and moved up in the rankings. Conversely, a chemical that exits the SPL in an event year may receive less emphasis compared to chemicals that also appeared in the SPL in the preceding event year and moved down in the rankings. Therefore, we include separate indicator variables corresponding to (i) whether the chemical entered the SPL in the event year, and (ii) whether the chemical exited the SPL in an event year.

Lagged dependent variables. We incorporate lagged dependent variables to control for diminishing returns to environmental efforts (Beavis and Dobbs 1986, Hartl 1992, Hart and Ahuja 1996). In other words, we expect that the emissions reductions achievable during a period would be negatively associated with the emissions reductions during the prior period. Since the effect can be expected to be nonlinear, we also incorporate squared terms of the lagged dependent variables.

3.3. Empirical Approach

While we control for a variety of facility- and industry-level factors that may influence the extent of emissions reductions and the use of source reduction or EOP treatment, to address unobserved heterogeneous characteristics among facilities and chemicals, we employ a (panel) model that includes facility-chemical-fixed effects. Hausman tests supported this fixed effects specification over alternative random effects specifications (with random effects included at the facility-chemical level, or included at the facility and at the chemical-within-facility levels) with $p < 0.01$ for all of our empirical models listed in Table 2. We also incorporate time-fixed effects to account for temporal conditions (for example, differences in overall emissions reductions across years). In addition, to address heteroskedasticity, we employ robust standard errors throughout our analyses. To test for the moderating effect of operational leanness, we incorporate interaction terms between change in relative assessed hazard level and operational leanness. Thus, we have the following:

Our empirical model for testing H1A and H2A(B) is

$$\begin{aligned} ER_{i,c,t} &= \beta_{Inc}(RelHazard_{c,t} = Increased) \\ &\quad + \beta_{NC}(RelHazard_{c,t} = NoChange) + \beta_{Lean}Leanness_{i,t} \\ &\quad + \beta_{Inc\times Lean}[(RelHazard_{c,t} = Increased) \times Leanness_{i,t}] \\ &\quad + \beta_{NC\times Lean}[(RelHazard_{c,t} = NoChange) \times Leanness_{i,t}] \\ &\quad + \boldsymbol{\beta}_{Controls}\mathbf{Z}_{i,c,t} + \alpha_{i,c} + \mu_t + \varepsilon_{i,c,t} \end{aligned} \quad (1)$$

Our empirical model for testing H1B and H3A(B) is the following:

$$\begin{aligned} SR_{i,c,t} &= \beta_{Inc}(RelHazard_{c,t} = Increased) \\ &\quad + \beta_{NC}(RelHazard_{c,t} = NoChange) + \beta_{Lean}Leanness_{i,t} \\ &\quad + \beta_{Inc\times Lean}[(RelHazard_{c,t} = Increased) \times Leanness_{i,t}] \\ &\quad + \beta_{NC\times Lean}[(RelHazard_{c,t} = NoChange) \times Leanness_{i,t}] \\ &\quad + \boldsymbol{\beta}_{Controls}\mathbf{Z}_{i,c,t} + \alpha_{i,c} + \mu_t + \varepsilon_{i,c,t} \end{aligned} \quad (2)$$

Our empirical model for testing H1C and H4A(B) is the following:

$$\begin{aligned} \Delta EOP_{i,c,t} &= \beta_{Inc}(RelHazard_{c,t} = Increased) \\ &\quad + \beta_{NC}(RelHazard_{c,t} = NoChange) + \beta_{Lean}Leanness_{i,t} \\ &\quad + \beta_{Inc\times Lean}[(RelHazard_{c,t} = Increased) \times Leanness_{i,t}] \\ &\quad + \beta_{NC\times Lean}[(RelHazard_{c,t} = NoChange) \times Leanness_{i,t}] \\ &\quad + \boldsymbol{\beta}_{Controls}\mathbf{Z}_{i,c,t} + \alpha_{i,c} + \mu_t + \varepsilon_{i,c,t}. \end{aligned} \quad (3)$$

In the models, $\alpha_{i,c}$ represents facility-chemical-fixed effects, μ_t represents time-fixed effects, and $\mathbf{Z}_{i,c,t}$ is the set of control variables.

Table 2. Main Results

Variables	Model 1-1 ER	Model 1-2 SR	Model 1-3 ΔEOP	Model 2-1 ER	Model 2-2 SR	Model 2-3 ΔEOP	Model 3-1 ER	Model 3-2 SR	Model 3-3 ΔEOP	Model 4-1 ER	Model 4-2 SR	Model 4-3 ΔEOP
RelHazard = NoChange				−1.85	0.36	−6.54*	−1.90	0.32	−6.43*	−2.00	0.07	−6.25*
				(2.249)	(2.101)	(3.712)	(2.248)	(2.100)	(3.711)	(2.250)	(2.095)	(3.702)
RelHazard = Increased				4.34**	3.08*	−0.68	4.28**	3.03*	−0.61	4.15**	3.06*	−0.65
				(1.978)	(1.819)	(3.181)	(1.979)	(1.818)	(3.181)	(1.992)	(1.816)	(3.174)
Leanness							9.57**	8.02*	−9.94	12.55**	12.10**	−18.15*
							(4.263)	(4.459)	(7.217)	(5.502)	(5.290)	(9.610)
Leanness × *RelHazard = NoChange*										−3.84	−12.49*	15.95
										(7.158)	(7.290)	(14.806)
Leanness × *RelHazard = Increased*										−5.01	0.29	9.91
										(6.355)	(5.247)	(10.012)
Market concentration	26.04**	50.19***	−4.55	24.91*	49.20***	−4.38	25.06*	49.32***	−3.24	25.25*	49.88***	−3.30
	(13.186)	(12.174)	(16.798)	(13.223)	(12.208)	(16.827)	(13.224)	(12.202)	(16.830)	(13.231)	(12.214)	(16.784)
Industry growth ($\times 10^3$)	1.42	4.35	44.57***	1.49	4.38	44.87***	1.15	4.10	44.78***	1.02	3.82	44.67***
	(10.296)	(9.629)	(14.214)	(10.294)	(9.628)	(14.243)	(10.272)	(9.621)	(14.227)	(10.275)	(9.632)	(14.262)
Operating scale change ($\times 10^3$)	0.14	9.45	−4.01	0.34	9.53	−3.55	0.01	9.26	−3.34	−0.02	9.34	−3.79
	(11.040)	(10.091)	(15.276)	(11.038)	(10.086)	(15.263)	(11.034)	(10.066)	(15.224)	(11.032)	(10.065)	(15.200)
Facility size	−14.40***	−18.87***	11.56	−14.27***	−18.80***	11.58	−14.27***	−18.80***	11.78	−14.30***	−18.87***	11.64
	(5.213)	(5.234)	(8.648)	(5.208)	(5.237)	(8.645)	(5.204)	(5.230)	(8.633)	(5.203)	(5.227)	(8.633)
Facility size^2	1.52***	2.15***	−1.05	1.50**	2.14***	−1.06	1.49**	2.14***	−1.09	1.50**	2.14***	−1.07
	(0.584)	(0.597)	(0.961)	(0.583)	(0.597)	(0.961)	(0.583)	(0.597)	(0.960)	(0.583)	(0.596)	(0.960)
Operational complexity	−1.57***	0.04	−0.36	−1.57***	0.04	−0.36	−1.72***	−0.09	−0.26	−1.73***	−0.08	−0.26
	(0.418)	(0.253)	(0.258)	(0.419)	(0.253)	(0.258)	(0.424)	(0.256)	(0.259)	(0.424)	(0.256)	(0.259)
SPL entry	7.75	8.42	−21.77	8.07	8.38	−20.77	8.00	8.33	−20.51	7.99	8.29	−20.45
	(23.186)	(15.779)	(15.286)	(23.189)	(15.791)	(15.295)	(23.141)	(15.762)	(15.302)	(23.138)	(15.785)	(15.293)
SPL exit	−20.92	35.01	−35.78	−17.81	37.21	−36.08	−17.46	37.51	−36.56	−17.40	37.62	−36.72
	(31.060)	(35.317)	(39.035)	(31.074)	(35.343)	(39.084)	(31.082)	(35.335)	(38.903)	(31.100)	(35.333)	(38.813)
Lagged ER	−0.41***			−0.41***			−0.41***			−0.41***		
	(0.009)			(0.009)			(0.009)			(0.009)		
Lagged ER^2 ($\times 10^3$)	−0.15*			−0.15*			−0.15*			−0.15*		
	(0.083)			(0.083)			(0.083)			(0.083)		
Lagged SR		−0.45***			−0.45***			−0.45***			−0.45***	
		(0.011)			(0.011)			(0.011)			(0.011)	
Lagged SR^2 ($\times 10^3$)		−0.19**			−0.19**			−0.19**			−0.19**	
		(0.080)			(0.080)			(0.080)			(0.080)	
Lagged ΔEOP			−0.46***			−0.46***			−0.46***			−0.46***
			(0.014)			(0.014)			(0.014)			(0.014)
Lagged ΔEOP^2 ($\times 10^3$)			0.28***			0.29***			0.29***			0.28***
			(0.073)			(0.073)			(0.073)			(0.073)
Observations	43,417	43,417	14,615	43,417	43,417	14,615	43,417	43,417	14,615	43,417	43,417	14,615
R-squared	0.2142	0.2283	0.2376	0.2144	0.2284	0.2379	0.2147	0.2285	0.2382	0.2147	0.2287	0.2384

Note. Robust standard errors in parentheses: $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.10$; Facility-chemical and time fixed effect estimates are omitted for brevity.

4. Results

We present our main results in Table 2. Models 1-1 to 1-3, respectively, in Table 2 correspond to Equations (1)–(3) with only the control variables included. Notably, the coefficients of the lagged dependent variables are all significant and consistently suggest diminishing returns to emissions reduction efforts. The effect of operational complexity is significant and negative in Model 1-1, indicating a negative relationship between the scope of environmental management efforts and emissions reductions for individual chemicals. In addition, we find a U-shaped relationship between facility size and emissions reductions (including the use of source reduction); specifically, small and large-size facilities are associated with greater emissions reductions and greater use of source reduction compared to mid-size facilities. Also, we find that facilities in industries with higher market concentrations are associated with greater emissions reductions and greater use of source reduction.

Models 2-1 to 2-3 in Table 2 incorporate the independent categorical measure $RelHazard_{c,t}$, which indicates the direction of change in the relative assessed hazard level of chemical c in event year t. We find that an increase in the relative assessed hazard level is significantly associated with greater emissions reductions and is weakly associated with greater use of source reduction ($\beta_{Inc} = 4.34$ with $p = 0.028$ in Model 2-1; and $\beta_{Inc} = 3.08$ with $p = 0.090$ in Model 2-2). However, we do not find a significant association between an increase in the relative assessed hazard level and change in the use of EOP treatment ($\beta_{Inc} = -0.68$ with $p = 0.830$ in Model 2-3). Thus, H1A and H1B are supported, but not H1C.

Following Kennedy (1981) to estimate the percentage change in emissions from the coefficient estimate of the categorical dummy variable (*RelHazard* = *Increased*) in our loglinear regression model, we find that facilities reduce emissions by an additional 4.28% on average, and their use of source reduction increases by 3.07% on average when the relative assessed hazard level of a chemical increases compared to when it decreases.

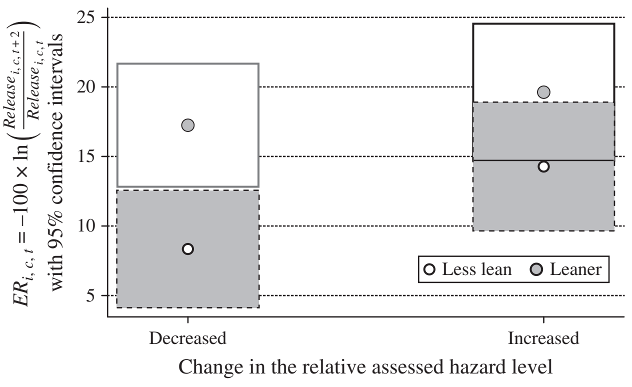
To examine the overall effect of operational leanness, Models 3-1 to 3-3 incorporate the independent measure $Leanness_{i,t}$. We find that leanness is significantly associated with greater emissions reductions and is also weakly associated with greater use of source reduction ($\beta_{Lean} = 9.57$ with $p = 0.025$ in Model 3-1 and $\beta_{Lean} = 8.02$ with $p = 0.072$ in Model 3-2). However, leanness is not significantly associated with change in the use of EOP treatment ($\beta_{Lean} = -9.94$ with $p = 0.168$ in Model 3-3).

Models 4-1 to 4-3 include interaction terms between change in relative assessed hazard level and operational leanness. We test for the moderation effect of operational leanness in two ways. First, we check the significance of the total effect of all interaction terms using the multiple degree of freedom omnibus F-test (Frazier et al. 2004) and the significance of each product term. Overall, we find that the interaction terms are not significant. Second, because of the possibility of nonlinearities in how *Leanness* may influence the relationship between an increase in the relative assessed hazard and emissions reductions, and to facilitate interpretation when the main effects and the interaction terms have different signs, we evaluate the effect of *RelHazard* at one standard deviation above and below the mean of *Leanness* (Baron and Kenny 1986, Dawson 2014).

Based on the results of Model 4-1, the effect of an increase in the relative assessed hazard level on emissions reductions for leaner facilities (i.e., $+1\sigma_{Leanness} = 0.354$) is $\beta_{Inc} + (\sigma_{Leanness} \times \beta_{Inc\times Lean}) = 2.375$ with a Wald-test $p = 0.456$ for the linear hypothesis test (Cameron and Trivedi 2009), whereas the effect for less lean facilities (i.e., $-1\sigma_{Leanness}$) is $\beta_{Inc} - (\sigma_{Leanness} \times \beta_{Inc\times Lean}) = 5.930$ with $p = 0.0350$. This suggests partial support for a *negative* moderation effect of operational leanness on emissions reductions (H2B). Figure 2 plots the predicted measure of emissions reductions for leaner and less lean facilities (including the 95% confidence intervals) when the relative assessed hazard level increases or decreases.

Based on the results of Model 4-2, the effect of an increase in the relative assessed hazard level on the use of source reduction for leaner facilities is $\beta_{Inc} + (\sigma_{Leanness} \times \beta_{Inc\times Lean}) = 3.160$ with a Wald-test $p = 0.231$, whereas the effect for less lean facilities is $\beta_{Inc} - (\sigma_{Leanness} \times \beta_{Inc\times Lean}) = 2.955$ with $p = 0.249$, suggesting lack of evidence of a moderation effect of operational

Figure 2. Predicted Reductions in Emissions for Leaner and Less Lean Facilities When the Relative Assessed Hazard Level Increases/Decreases



Notes. To illustrate the effect of operational leanness, we set the *Leanness* value for a leaner facility to be one standard deviation above the mean value of *Leanness* (i.e., $\mu_{Leanness} + \sigma_{Leanness}$), whereas we set the value for a less lean facility to be one standard deviation below the mean value (i.e., $\mu_{Leanness} - \sigma_{Leanness}$), where $\sigma_{Leanness} = 0.388$. As a result, the distance between the dots in Figure 2 for leaner and less lean facilities is $\beta_{Lean} \times 2\sigma_{Leanness}$ when the relative assessed hazard level decreases and $(\beta_{Lean} + \beta_{Inc\times Lean}) \times 2\sigma_{Leanness}$ when the relative assessed hazard level increases.

leanness on the use of source reduction (i.e., neither H3A nor H3B is supported).

Finally, based on the results of Model 4-3, the effect of an increase in the relative assessed hazard level on change in the use of EOP treatment for leaner facilities is $\beta_{Inc} + (\sigma_{Leanness} \times \beta_{Inc\times Lean}) = 2.260$ with a Wald-test $p = 0.586$, whereas the effect for less lean facilities is $\beta_{Inc} - (\sigma_{Leanness} \times \beta_{Inc\times Lean}) = -3.562$ with $p = 0.429$, suggesting lack of evidence of a moderation effect of operational leanness on the use of EOP treatment (i.e., neither H4A nor H4B is supported).

5. Robustness Checks

We examine the robustness of our main findings to (i) alternative measures of our main independent variable (change in relative assessed hazard level), (ii) expansion of the set of chemicals considered in our sample (from a focus on the top 275 that appear in the SPL to all candidate chemicals ranked by ATSDR), and (iii) consideration of additional explanatory factors. Tables of results for the robustness checks are included in the appendix.

(i) *Alternative measures of our main independent variable* (*change in relative assessed hazard level*).

(a) As mentioned previously, to determine the relative hazard levels of chemicals (or their ranks), ATSDR aggregates and publicly reports the points assigned to chemicals based on three criteria: toxicity, frequency of occurrence at polluted sites, and potential for human exposure (ATSDR 2014). As an alternative to using the direction of change in rank, we calculated the *ratio of the total points received by a chemical in the event year, to the total points received in the prior event year*. Since the total points assessed for chemicals generally increase over time as ATSDR researches additional polluted sites, we mean-centered this ratio across all chemicals, by event year. Thus, a positive mean-centered ratio for a chemical indicates an above-average increase in its assessed hazard level ($PointsRatio_{c,t} > 0$). On the other hand, a negative mean-centered ratio for a chemical indicates a below-average increase in its assessed hazard level ($PointsRatio_{c,t} < 0$). The results of the corresponding models with this alternative binary independent measure (reported in online appendix Table A1) weakly support H1A and H1B, and partially support H2B. Additionally, we find partial support for H3B, i.e., operational leanness *negatively* moderates the use of source reduction for a chemical when the relative assessed hazard level of the chemical—measured as *PointsRatio*—increases.

(b) Recall that we used a categorical measure, $RelHazard_{c,t}$, in our main analysis to capture the *direction of change* in the rank of a chemical in an event year. However, the numerical rank of the chemical could itself play a role in the emphasis placed on the chemical for emissions reductions efforts (analogous to the order effects observed in the adoption of energy efficiency recommendations in the study by Muthulingam et al. 2013). To capture the magnitude of change in the hazard assessment of a chemical relative to its position on the SPL, we calculated the *ratio of a chemical's rank in the event year, to its rank in the prior event year*. Then we took the natural logarithm of this ratio, mean-centered it, and interacted its absolute value ($RankRatio_{c,t}$) with $RelHazard_{c,t}$ to dichotomize it according to the direction of rank change. The results of the corresponding models with these independent measures (reported in online appendix Table A2) similarly support H1A and H2B, as before. However, we do not find support for H1B; i.e., we do not find sufficient evidence for an increase in the relative assessed hazard level of a chemical to be positively associated with the use of source reduction for the chemical.

(ii) *Expansion of the set of chemicals considered in the sample*.

We expanded our sample to include all candidate chemicals that were ranked by ATSDR over the period of our study, beyond the top 275 that constitute the SPL and that receive significant subsequent attention. The expanded sample contains 65,594 observations (10,598 facilities and 214 chemicals). Since candidate chemicals that are ranked low experience substantial rank changes arising from only minor changes in total assessed points, we employed the alternative binary independent measure ($PointsRatio_{c,t} > 0$) as in the robustness check i(a). The results weakly support H1A, support H1B, and partially support H2B. Additionally, H3B is also partially supported, i.e., operational leanness *negatively* moderates the use of source reduction for a chemical when the relative assessed hazard level of the chemical increases. For brevity, we omit the table summarizing the results of this analysis.

(iii) *Additional explanatory factors*.

(a) Chemicals that exhibit greater variance in their position in the SPL (i.e., greater rank variance across event years) may induce environmental actions to a different extent than chemicals whose ranks are more stable. Using a rolling nine-year rank history, we calculated the rank variance-to-mean ratios for the chemicals for each event year. Additionally we mean-centered this variance measure ($RankVartoMeanRatio_{c,t}$) and interacted it with $RelHazard_{c,t}$, to account for the potential difference in the effects of rank uncertainty when the relative assessed hazard level increases versus when it decreases. The results (reported in online appendix Table A3) similarly support H1A, H1B, and H2B, as before. Interestingly, we find evidence for the increased use of EOP treatment when the relative assessed hazard level increases for chemicals with greater rank uncertainty (coefficient of $RankVartoMeanRatio \times (RelHazard = Increased)$ in Model 3 is 1.20 with $p = 0.002$). This finding offers support for the contention in Rothenberg et al. (2001) that

EOP treatment may serve as a protective "buffer" from future changes in regulation, to the extent that greater rank variance for a chemical serves as a proxy for greater regulatory uncertainty for the chemical.

(b) As noted earlier in Section 3.2.2, in our data, the *No Change* group typically included chemicals at the top of the list (average rank of 49) whereas the *Increased* and *Decreased* groups were more similar in the spread of the ranks of chemicals within them (average ranks of 140 and 177, respectively). To control for the potential effect of historically highly-ranked chemicals, we used a 9-year rolling history to calculate the average rank of a chemical and added a binary indicator variable ($TopAvgRank_{c,t}$) to capture if the chemical's average rank is below 50 in an event year. The results (reported in online appendix Table A4) weakly support H1A, support H1B, and partially support H2B. Furthermore, the results show that being historically ranked at the top of the SPL is negatively associated with the use of source reduction, likely because source reduction opportunities for these chemicals have been well tapped, whereas the associations with emissions reductions and change in the use of EOP treatment are insignificant.

(c) Earlier studies have suggested that local environmental preferences may influence the environmental actions of managers. As a measure of environmental preferences local to the state in which a facility is located, we used data from the National Environmental Scorecard published by the League of Conservation Voters. Similar to Doshi et al. (2013), we used the percentage of environmental bills that were favored by members of the U.S. House of Representatives, by state, in the year following the event year. We mean-centered this score (*LCVH*) by year and interacted it with $RelHazard_{c,t}$. The results (reported in online appendix Table A5) support H1A, H1B, and H2B, as before. Consistent with the results in Doshi et al. (2013), this measure of local environmental preferences is not significantly associated with emissions reductions, source reduction, or change in the use of EOP treatment.

(d) Environmental actions may depend on the degree of regulatory attention or scrutiny received by an industry. To contrast the pollution damages of industries with their net contributions to national output, Muller et al. (2011) estimated the marginal damages of major air pollutants and factored the emitted quantities in 2006 to derive the gross environmental damages (GEDs) of industries at the six-digit NAICS level. They then calculated the ratio of the GED of an industry to the value added (VA) by the industry. The VA of an industry is calculated as the market value of outputs less that of inputs, not including labor, land, and capital (using data from the U.S. Bureau of Economic Analysis and the U.S. Census Bureau's Economic Census). We recomputed the year-2006 GED/VA values at the three-digit NAICS level and mean-centered these values. Thus, if the ratio for an industry is positive, the industry is likely under-regulated, and if the ratio is negative, the industry is likely over-regulated. We incorporated this additional measure, *GED_VA_Ratio* in our model and interacted it with *RelHazard*. The results (reported in online appendix Table A6) continue to show similar support for H1A, H1B, and H2B. Furthermore, the results show that facilities in over-regulated industries are weakly associated with greater reductions in emissions, greater use of source reduction, and smaller change in use of EOP treatment when the relative assessed hazard level increases. (The coefficients of $GED\_VA\_Ratio \times (RelHazard = Increased)$ are −0.02 with $p = 0.050$ in Model 1, −0.01 with $p = 0.097$ in Model 2, and 0.02 with $p = 0.079$ in Model 3.)

(iv) *Other robustness checks*.

First, in our main analysis, for each event year t, we measure operational leanness and the controls for market concentration and facility size in year $t + 1$. However, our results remain largely unchanged if for each event year t, we measure them either in year $t + 2$ or as averages across years $t + 1$ and $t + 2$. Second, we exclude waste treated offsite in measuring the use of EOP treatment in our main analysis. However, our results remain fully consistent when we consider waste treated offsite either as part of our EOP treatment measure or through a separate dependent measure. Third, our main results remain unchanged if we use facility sales as a measure of size instead of number of employees. Fourth, while we do not use the $RelHazard = NoChange$ group as a reference group for the reasons mentioned in Section 3.2.2, we still find an increase in the relative assessed hazard level to be significantly associated with greater emissions reductions if the *NoChange* group is used as the reference group instead of the *Decreased* group. The tables summarizing the results of these additional analyses are excluded for brevity.

6. Discussion

With the increasing use of chemicals and growing concerns regarding their potential hazards to human health and the environment, understanding how firms or facilities respond to the dissemination of public information on the relative hazards of chemicals is important for researchers, policy makers, environmental managers, and society as a whole. We discuss the contributions of our research and implications of our findings in the following sections.

To the best of our knowledge, our study is among the first in the environmental management and sustainable operations literatures to empirically examine firms' or facilities' environmental actions in response to the dissemination of public information about the relative hazards of chemicals. We find evidence that this public information dissemination is effective, as indicated by the significant association between increases in the relative assessed hazard levels of chemicals and greater subsequent emissions reductions. Our findings provide evidence that managers of facilities recognize changes in the relative assessed hazard levels of chemicals and internalize the associated risks by undertaking corresponding environmental actions. In addition, we find evidence that in dealing with chemicals with increasing relative hazard, managers devote greater effort to source reduction, which has also been suggested in the prior literature to be a strategically better option than EOP treatment (Hart and Ahuja 1996, Klassen and Whybark 1999, King and Lenox 2002).

With regard to the implications of operational leanness, we find that its overall effect is positive, i.e., overall, leaner facilities outperform less lean facilities with regard to emissions reductions. However, we find that leaner and less lean firms may respond differently to increases in relative hazard. Specifically, we find evidence that when the relative assessed hazard level of a chemical increases, managers in less lean facilities increase (or are able to increase) their emissions reductions more than managers in leaner facilities. We propose three potential explanations for this observation: First, the adoption of lean practices provides internal incentives for eliminating waste and reducing emissions (de Treville and Antonakis 2006). In the absence of such internal incentives, information about the relative hazards of chemicals can help managers in less lean facilities prioritize their environmental actions. Second, smoothed production processes and minimized operational slacks may prevent managers in leaner facilities from achieving further emissions reductions (and, in particular, source reductions) in response to increases in relative assessed hazard. Finally, consistent with the observed overall positive effect of leanness on emissions reductions, leaner facilities may already have lower levels of emissions and therefore may have less room for further emissions reductions in responding to an increase in the relative assessed hazard level of a chemical.

Our findings provide important insights for managers prioritizing environmental actions. First, we establish that the "lean is green" assertion is robust even after accounting for changing assessments of chemical hazards. However, managers contemplating the application of lean practices should be cautioned against overestimating the extent of emission reductions achievable in response to increases in relative assessed hazard levels of chemicals. Second, our results reveal that managing a wider set of chemicals may undermine emissions reduction efforts for individual chemicals experiencing elevated assessed hazard levels. Therefore, in managing risks associated with the potential hazards of chemicals, a trade-off for managers to consider is the benefits of diversification versus limits to emissions reduction efforts from a wider set of chemicals being managed.

For policy makers and planners designing information-based regulations and environmental programs, our findings support the notion that the dissemination of public information can influence facilities' or firms' prioritization of environmental actions. While we focus on a specific example of public information dissemination, our findings are pertinent to other settings where governmental and nongovernmental organizations have made commitments to disseminate information publicly. Examples include the National Toxicology Program (which publishes the Report on Carcinogens), the International Chemical Secretariat (which publishes the Substitute It Now!, or SIN, List), and Greenpeace (which publishes the Dirty Laundry Report). We believe that our results can be leveraged by these organizations to anticipate the effects of informational updates on firms' or facilities' reductions of chemical emissions. In addition, our results show that the effectiveness of an information dissemination program depends on operational characteristics of affected facilities. For example, evidence from our setting suggests that information dissemination on the relative hazards of chemicals is more effective at influencing environmental actions at facilities that are less lean and that are in more concentrated or more regulated industries. Understanding the implications of facility or firm characteristics and anticipating differences in responses will be particularly helpful for policy makers and planners in the design or targeted refinements of such programs.

We recognize that our findings may be subject to the data sources that we use for our independent and dependent measures. First, we leverage the ranks of chemicals published by ATSDR as a measure of their relative assessed hazard levels. Although hazard assessments are closely tied to the methodologies employed, we believe that the exhaustive nature of the quantitative assessments by ATSDR, its federal charter to conduct public health assessments, and its authority to assist the EPA in determining which substances should be regulated and the levels at which substances may pose a threat to human health, render the ATSDR ranks of candidate chemicals as perhaps the most credible source available for the relative hazards of these chemicals. Second, although reductions in emissions reported to the TRI have been widely recognized and employed as a measure of environmental actions by facilities (Hart 1995, King and Lenox 2001, Doshi et al. 2013), they are self-reported as opposed to data from continuous emissions monitoring systems, for example. However, monitoring systems for the 650-plus chemicals reported under the TRI program would be very challenging and appear unlikely. Instead, we expect penalties for TRI noncompliance to continue into the foreseeable future. Finally, while lean practices include additional aspects such as work systems and human resource management practices, we leverage the use of inventory buffers as a measure of leanness. Although facility-level data on other aspects of practicing lean beyond inventory use are challenging to obtain, it would nonetheless be interesting to examine the robustness of our findings to alternative measures of leanness.

Notwithstanding these limitations, our findings are robust to (i) alternative measures of our main independent variable (change in relative assessed hazard level), (ii) expansion of the set of chemicals considered in our sample (from a focus on the top 275 SPL chemicals to all candidate chemicals assessed and ranked by ATSDR), and (iii) consideration of additional explanatory factors. Moreover, our study is an initial step toward understanding the effects of information dissemination in the context of managing chemical emissions. The dissemination of information on chemical hazards may have different implications for the use of chemicals in production processes versus their use within products; therefore, it will be worthwhile to contrast the effects of information dissemination on environmental actions in these two scenarios. In addition, other factors—such as the characteristics of an information dissemination program (e.g., frequency with which information is updated), the attributes of salient institutions (e.g., locations of facilities and community demographics), and managers' incentives and attitudes toward risk—could magnify or dampen the effects of information dissemination. Explorations of such factors are avenues for future research.

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