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# The Impact of Pollution Prevention on Toxic Environmental Releases from U.S. Manufacturing Facilities

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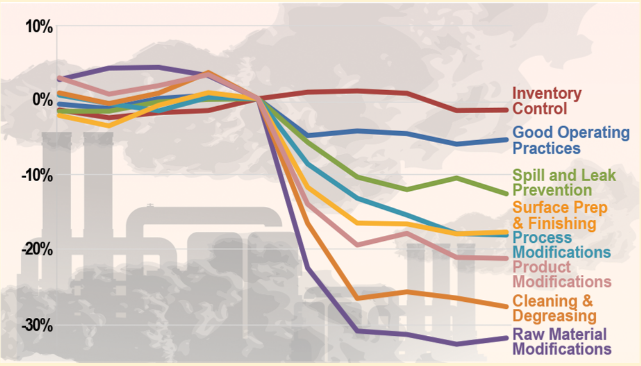
Ⓢ *Supporting Information*



**ABSTRACT:** Between 1991 and 2012, the facilities that reported to the U.S. Environmental Protection Agency's Toxic Release Inventory (TRI) Program conducted 370 000 source reduction projects. We use this data set to conduct the first quasi-experimental retrospective evaluation of how implementing a source reduction (pollution prevention) project affects the quantity of toxic chemicals released to the environment by an average industrial facility. We use a differences-in-differences methodology, which measures how implementing a source reduction project affects a facility's releases of targeted chemicals, relative to releases of (a) other untargeted chemicals from the same facility, or (b) the same chemical from other facilities in the same industry. We find that the average source reduction project causes a 9−16% decrease in releases of targeted chemicals in the year of implementation. Source reduction techniques vary in effectiveness: for example, raw material modification causes a large decrease in releases, while inventory control has no detectable effect. Our analysis suggests that in aggregate, the source reduction projects carried out in the U.S. since 1991 have prevented between 5 and 14 billion pounds of toxic releases.

## 1. INTRODUCTION

Source reduction, as defined by the U.S. Pollution Prevention Act of 1990, is any practice that "reduces the amount of any hazardous substance, pollutant, or contaminant entering any waste stream or otherwise released into the environment (including fugitive emissions) prior to recycling, treatment, or disposal". More informally, it includes a wide variety of pollution prevention techniques for reducing the volume or toxicity of waste by changing the products, raw materials, or processes that generate pollution in the first place.[1] Source reduction is a widespread practice: between 1991 and 2012, the industrial facilities that reported to the U.S. Environmental Protection Agency's (EPA's) Toxics Release Inventory (TRI) program carried out 370 000 source reduction projects. Furthermore, because pollution prevention is an appealing way to reduce the environmental impacts of industrial operations, federal and state governments have engaged in a number of efforts to promote adoption of source reduction practices.[2]

Despite this demonstrated enthusiasm, there is little rigorous evidence quantifying the effectiveness of source reduction. Most research to-date has been based on case studies of particular companies or chemical processes.[3] What is not clear is how much of an impact source reduction has had on broader industry releases of toxic chemicals. For example, although the green chemistry literature suggests that some facilities and industries have had real success in reducing pollution,[4] there have also been documented cases of "greenwashing".[5]

To address this gap in the literature, this paper conducts the first quasi-experimental retrospective evaluation of the effectiveness of source reduction. Our analysis is based on annual reporting data on toxic releases and source reduction projects from the U.S. manufacturing facilities that report to the TRI program. We use these data to measure how the toxic releases reported by each facility change in the year before and after implementing a source reduction project. The research question we investigate is the following: how does source reduction affect toxic releases from the typical industrial facility? In other words, we test the null hypothesis that source reduction has no effect on toxic releases. However, our goal is broader than simply establishing whether source reduction "works". Instead, we seek to develop an estimate of the average percentage reduction in toxic releases achieved by a typical source reduction project. We also estimate and compare the effectiveness of different types of types of source reduction

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approaches. In doing so, our paper is motivated by the critical need for evidence-based guidance that firms and policymakers can use to target resources toward pollution control techniques that are most effective in real-world settings.

Our paper makes three main contributions. First, it provides the most comprehensive study to-date of the impact of pollution prevention on toxic releases in the United States. A few previous studies have measured the aggregate effects of state-level programs that encourage pollution prevention,[6−9] or have analyzed how end-of-pipe pollution controls affect facility-level TRI releases.[10] However, only a small number of studies have investigated how facility-level releases change after implementing source reduction projects.[11−14] Most of these studies rely on relatively small samples of facilities, limiting their generalizability. In contrast, our analysis is based on a data set that includes 334 000 source reduction projects carried out by 21 550 facilities over a 22 year period.

Second, our paper addresses many empirical concerns that may have influenced the results of previous research. Previous studies all share an important statistical limitation: finding a credible way to control for the many ongoing trends—in production, technology, and regulations—that would have influenced toxic releases anyway, had facilities chosen not to implement source reduction projects. To control for changes in these unobservable confounding factors, our paper compares the change in releases of chemicals that are targeted by source reduction projects in a particular year against the change in releases from (a) other untargeted chemicals from the same facility, or (b) the same chemical from other facilities in the same industry. The result of each of these two "differences-in-differences" approaches is an estimate of the average impact that source reduction projects have on toxic releases from typical facilities. This quasi-experimental methodology controls for a wide variety of time-varying omitted variables, while at the same time avoiding imposing a functional form on how toxic releases change in the years following a source reduction project.

Third, our paper develops the first estimates of the cumulative impact of source reduction on toxic releases from U.S. manufacturing facilities between 1991 and 2012. We generate these estimates by summing the predicted effects from our regressions across facilities and years.

## 2. MATERIALS AND METHODS

### 2.1. Data Sources.

Our analysis draws upon public data from EPA's TRI program. Since 1987, the TRI program has required U.S. facilities that manufacture, process, or otherwise use more than a threshold quantity of a listed toxic chemical to submit an annual report. Reporting is currently required for over 600 chemicals. The reports submitted by facilities must cover environmental releases of each chemical, the medium of release (i.e., air, water, or land), and facility characteristics (e.g., industry). Beginning in 1991, facilities were also required to report information about any source reduction projects they initiated, including the project type and the chemicals to which the project applied. Table 1 lists the eight major categories of source reduction projects.

From 1987 to 2012, 56 498 facilities reported one or more of 605 different chemicals or chemical categories to the TRI program in at least one year. We use these data to construct a panel data set that contains one record for every reported facility-chemical combination for each year from 1987 to 2012. (We use the term "facility-chemical" to refer to releases of a

Table 1. Source Reduction Project Categories and Definitions

| | |
|---|---|
| **Good Operating Practices:** | Improved maintenance scheduling, record keeping, or procedures; Changed production schedule to minimize equipment and feedstock changeovers; Introduced in-line product quality monitoring or other process analysis system |
| **Spill and Leak Prevention:** | Improved storage or stacking procedures; Improved procedures for loading, unloading, and transfer operations; Installed overflow alarms or automatic shut-off valves; Installed vapor recovery systems; Implemented inspection or monitoring program of potential spill or leak sources |
| **Process Modifications:** | Optimized reaction conditions or increased synthesis efficiency; Instituted recirculation within a process; Modified equipment, layout, or piping; Used a different catalyst; Minimized discarding of empty bulk containers; Reduced use of organic solvent; Used biotechnology in manufacturing process |
| **Surface Preparation and Finishing:** | Modified spray systems or equipment; Substituted coating materials used; Improved application techniques; Changed from spray to other system |
| **Inventory Control:** | Instituted procedures to ensure that materials do not stay in inventory beyond shelf life; Use outdated material if still effective; Eliminated shelf life requirements for stable materials; Instituted better labeling procedures; Instituted clearinghouse to exchange materials that would otherwise be discarded |
| **Raw Material Modifications:** | Increased purity of raw materials; Substituted raw materials; Substituted a feedstock or reagent with a different chemical |
| **Cleaning and Degreasing:** | Modified stripping/cleaning equipment; Changed to mechanical stripping/cleaning (from solvents); Changed to aqueous cleaners (from solvents); Modified containment procedures for cleaning units; Improved draining procedures; Redesigned parts racks to reduce drag out; Modified or installed rinse systems; Improved rinse equipment design; Improved rinse equipment operation |
| **Product Modifications:** | Changed product specifications; Modified design or composition of product; Modified packaging; Developed a new chemical product to replace a previous chemical product |

particular chemical by a particular facility.) After excluding facilities that never reported a source reduction project, excluding observations for which a facility did not report a particular chemical, and limiting the panel to the longest time period over which reporting requirements for each chemical and industry were consistent, we are left with a final data set that contains 21 550 facilities, 557 chemicals, and 1.3 million facility-chemical-year observations. Of the 370 000 source reduction activities reported at unique facility-chemical-year combinations in the full TRI data set, our final analysis sample includes 334 000 projects.

The outcome variable in our analysis is the quantity of each chemical released each year from each facility. We define this variable as the sum of on-site releases (air emissions, water discharges, and land disposal) and off-site releases (at landfills and waste management sites).

We represent source reduction projects using eight dummy variables that indicate whether a facility applied the given type of source reduction project to a particular chemical that year. Additionally, we create a single overall source reduction variable that indicates whether the facility applied *any* type of source reduction project to the chemical that year.

**2.2. Research Design.** Measuring the causal effect of source reduction projects on toxic releases requires confronting an important statistical obstacle. Many factors—such as changes in production levels or regulations—have affected toxic releases from U.S. facilities over the last 25 years. Thus, a simple comparison of facility-level releases, before and after implementing source reduction projects, would inappropriately capture the effects of these correlated factors. Furthermore, there is no way to determine whether this omitted variable bias would be positive or negative.

To address this challenge, we use a "differences-in-differences" methodology. This methodology is a quasi-experimental statistical technique that is commonly used in retrospective economic research to measure the impact of an intervention on an outcome variable.[15,16] This technique involves measuring how the outcome variable changes in the group that receives the intervention (the treatment group) and in a similar group that does not receive the intervention (the control group). The difference between these two changes is interpreted as the causal effect of the intervention. The purpose of subtracting the change in the control group from the change in the treatment group is to account for all other factors that would have changed anyway in the treatment group, had it not received the intervention.

In this paper, we use the differences-in-differences approach to estimate how source reduction projects (the "treatment") affect TRI facilities' toxic releases (the "outcome variable"). This methodology controls for the changes in releases that would have occurred anyway at TRI facilities, had they not implemented source reduction projects. The key to the approach is finding a control group of facility-chemicals that had similar trends in releases but were not affected by source reduction projects. We use two alternative approaches to develop a control group for chemicals that are targeted for source reduction by a particular facility in a particular year.

First, we use releases of different chemicals from the same facility. Since changes in production strongly influence toxic releases, an ideal control group would capture facility-level changes in output. This suggests that in order to estimate counterfactual releases of chemicals that were targeted by a source reduction project at a particular facility, an appropriate control group might be other chemicals from the same facility that were not targeted by a source reduction project that year. This approach assumes that on average, if the facility had not implemented the source reduction project, the trends in the facility's releases of the two sets of chemicals would have been similar.

Second, we use releases of the same chemical from different facilities within the same industry sector. Variation in toxic releases is influenced by chemical- and industry-specific trends related to regulations, technological advances, and economic conditions. To capture these factors, an appropriate control group for releases from facility-chemicals with source reduction projects might be releases of the same chemical from other facilities in the same industry that did not implement source reduction projects that year. This requires the assumption that on average, if a facility had not implemented a source reduction project, the trends in the facility's releases of the targeted chemical would have been similar to releases of that chemical by other facilities in the same industry.

To provide some visual intuition for the differences-in-differences approach, Figure 1 presents trends in average normalized log releases from facilities in the computer and electronics manufacturing industry (NAICS 334). The black line represents all facility-chemicals with a new source reduction project in 2003 (the treatment group), and the gray line represents facility-chemicals that did not have a source reduction project in 2003 (the control group). We limit the control group to facility-chemicals with a nonzero release in 2003. The figure shows that before 2003, trends in these two groups of facility-chemicals moved almost in parallel. Then, in 2003, releases in the treatment group decreased substantially relative to the control group. In subsequent years, the two series again moved roughly in the same direction. Under the differences-in-differences methodology, the difference in the change in releases between the two groups in 2003 is interpreted as the causal effect of source reduction.

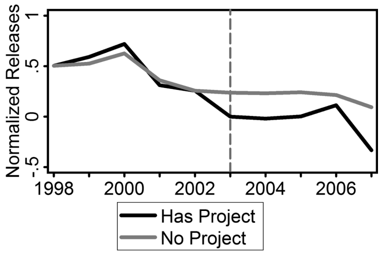

**Figure 1.** Average trends in toxic releases from the computer and electronic product manufacturing industry (NAICS 334), for facility-chemical combinations with and without newly initiated source reduction projects in 2003.

**2.3. Statistical Details.** One practical challenge to using TRI data to implement a differences-in-differences analysis is that most facilities do not report consistently over the entire period from 1987 to 2012. Instead, a facility will often begin reporting a particular chemical, continue for a few years, and then stop reporting that chemical (when its use of the chemical falls below the reporting threshold, or when the facility closes). This is potentially problematic because closed facilities do not provide a good counterfactual for active facilities.

To address this issue, we treat each year between 1987 and 2012 as a separate "experiment", in which the facility-chemicals with source reduction projects that year are part of the "treatment group", and those without projects that report that year are part of the "control" group. Our goal is to compare how releases from facility-chemicals in the treatment group for a particular baseline year (e.g., 1994) change in the years before and after that baseline year, relative to facility-chemicals in the control group for that baseline year. The purpose of limiting the sample in this way is to ensure that the control group for each baseline year only includes facilities that were active in the baseline year.

To implement this approach, we base our analysis on a "stacked" panel data set that includes five years of pre- and post- data for each facility-chemical combination reported in each baseline year. For example, for every facility-chemical combination reported to the TRI program in 1994, our data set includes a set of ten observations spanning the period from 1989 to 1998. Similarly, for every facility-chemical combination reported in 1995, we also include five years of pre- and post- data; etc. The result is a data set that includes up to ten copies of each facility-chemical-release year observation, each of which is indexed by a different baseline year. (In the discussion below, we use the subscript *b* to denote baseline year, and *y* to denote release year.)

We then estimate two versions of the differences-in-differences model, reflecting the two control groups described in the previous section. Model 1 is based on different chemicals at the same facility. Model 2 is based on the same chemical at different facilities in same industry.

The regression framework for Model 1 is as follows:

$$\begin{aligned}\text{logreleases}_{\text{icyb}} = {} & \alpha_{\text{icb}}\cdot\text{facility}_{\text{i}}\cdot\text{chemical}_{\text{c}}\cdot\text{baselineyear}_{\text{b}} \\ & + \tau_{\text{iyb}}\cdot\text{facility}_{\text{i}}\cdot\text{year}_{\text{y}}\cdot\text{baselineyear}_{\text{b}} \\ & + \sum_{\text{t}\in[-5,4]}(\beta_{\text{t}}\cdot\text{postproject}^{\text{t}}{}_{\text{icyb}}) \\ & + \varepsilon_{\text{icyb}}\end{aligned}$$

In this regression, $\text{logreleases}_{icyb}$ represents the natural logarithm of toxic releases from facility *i* of chemical *c* in reporting year *y*, for the observations included in the treatment or control groups in baseline year *b*. The variables $\text{facility}_i$, $\text{chemical}_c$, $\text{year}_y$, and $\text{baselineyear}_b$ are facility-specific, chemical-specific, year-specific, and baseline year-specific dummy variables. The variable $\text{postproject}^t{}_{icyb}$ is a dummy variable that takes value 1 only if facility *i* implemented a source reduction project in baseline year *b* that affected chemical *c*, and if the reporting year *y* is equal to $b + t$.

The equation includes two sets of dummy variables (or "fixed effects"). First, the coefficient $\alpha_{icb}$ captures the average level of toxic releases of chemical *c* from facility *i*, in the set of observations for baseline year *b*. Second, the coefficient $\tau_{iyb}$ captures the average change in releases of all chemicals from facility *i* in release year *y*, in the set of observations for baseline year *b*. Together, these two sets of fixed effects control for permanent characteristics of particular facilities and chemicals, as well as time-varying trends in releases common to all chemicals from the same facility. Although it would be possible to include other variables as controls, the differences-in-differences methodology implicitly accounts for those variables.

The equation also includes a set of coefficients, $\beta_{-5}$, ..., $\beta_0$, ..., $\beta_4$ that represent the average effect of a source reduction project on releases *t* years after the project occurs. Year zero is a "post-project" year, so that there are five years of preproject and five years of postproject coefficients. Because the dependent variable is the natural log of releases, each coefficient $\beta$ has an approximate interpretation as the percentage decrease in releases that occurs *t* years after a source reduction project takes place.

The final component of the equation is the error term $\varepsilon_{icyb}$, which captures other sources of variation in releases.

The regression equation for Model 2 (same chemical from different facilities in same industry) is similar:

$$\begin{aligned}\text{log releases}_{\text{icdyb}} = {} & \alpha_{\text{icb}}\cdot\text{facility}_{\text{i}}\cdot\text{chemical}_{\text{c}}\cdot\text{baselineyear}_{\text{b}} \\ & + \tau_{\text{dcyb}}\cdot\text{industry}_{\text{d}}\cdot\text{chemical}_{\text{c}}\cdot\text{year}_{\text{y}}\cdot\text{baselineyear}_{\text{b}} \\ & + \sum_{\text{t}\in[-5,4]}(\beta_{\text{t}}\cdot\text{postproject}^{\text{t}}{}_{\text{icdyb}}) \\ & + \varepsilon_{\text{icdyb}}\end{aligned}$$

Most variables are defined analogously to Model 1. However, Model 2 includes a subscript for industry *d*, and rather than including facility-by-year fixed effects, now includes industry-by-chemical-by-year fixed effects ($\tau_{dcyb}$).

Because of the possibility that different facility-chemicals have correlated releases, due to shared industry shocks or pollution regulations, we cluster standard errors in both models at the reporting year level.[17]

## 3. RESULTS AND DISCUSSION

This section presents our main results and discusses their implications.

**3.1. The Effect of Source Reduction on Facility-Level Releases.** We begin by presenting our main differences-in-differences results. Because the regressions include a large number of variables, the results are easiest to understand in graphical format. Figure 2 presents the regression results. The figure contains two panels, corresponding to our two different approaches to generating a control group. In each panel, the *x*-axis represents years elapsed since the source reduction project

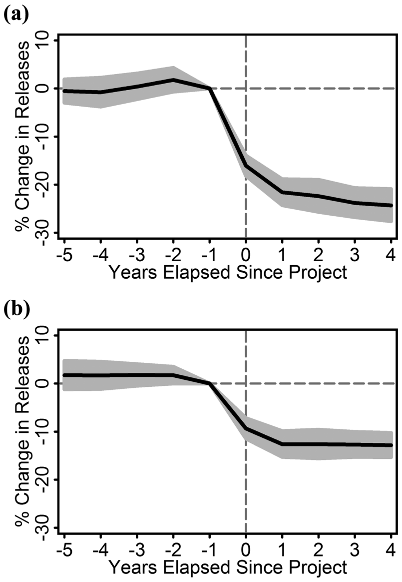

**Figure 2.** Effect of a source reduction project on an average facility's toxic releases of targeted chemicals, with 95% CIs, based on (a) Model 1 and (b) Model 2.

was implemented, and the *y*-axis represents the change in releases relative to the year before the project.

As the figure shows, the coefficients for pretreatment changes in releases are not statistically different from zero. However, beginning in the year the project is implemented, there is a sharp, statistically significant decrease in releases. Based on Model 1, releases decrease 16% in the year a source reduction project is implemented. Based on Model 2, the decrease in releases is 9%. These effects last for at least the next five years.

To investigate whether the effects of source reduction vary by technique, we estimate regression models that include separate coefficients for eight categories of source reduction projects. We refer to these regressions as Model 3 (which uses the same control group as Model 1) and Model 4 (which uses the same control group as Model 2). Figure 3 presents the results from Model 3. The figure shows that there is considerable variation in how different types of projects affect releases. For example, inventory control has no detectable effect on releases, and good operating practices has only a small effect (roughly −5%). In contrast, raw material modifications, cleaning and degreasing, and product modifications all cause large decreases in releases, of −20%, −15%, and −13%, respectively. The pattern of results based on Model 4 (not shown) is similar, although the estimates are lower in magnitude.

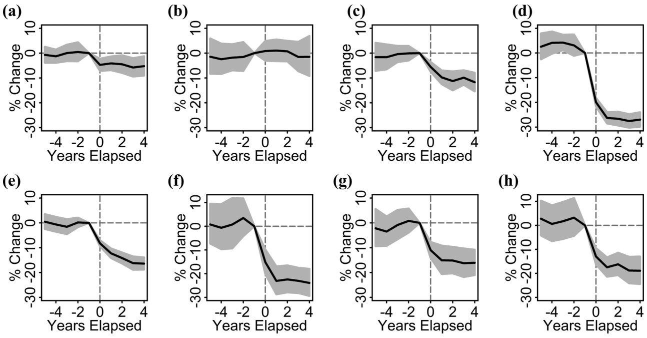

**Figure 3.** Effect of a source reduction project on an average facility's toxic releases of targeted chemicals, with 95% CIs, for projects based on (a) good operating practices, (b) inventory control, (c) spill and leak prevention, (d) raw material modifications, (e) process modifications, (f) cleaning and degreasing, (g) surface preparation and finishing, and (h) product modifications.

We also investigate whether the effectiveness of source reduction differs across industries. Figure 4 presents the average reduction in releases achieved in the year of source reduction (based on Model 1), for eight industries that have many TRI-reported source reduction projects. The figure suggests that there is considerable variation in effectiveness across industries. However, the 95% confidence intervals for most industries are wide, and we hesitate to draw strong conclusions about industry-level differences.

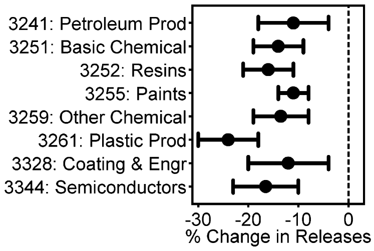

**Figure 4.** Estimated changes in toxic releases caused by source reduction, with 95% CIs, by NAICS industry.

As a robustness check, we have run regressions that allow for differential trends at facilities of different sizes, in different states, and with different numbers of previous source reduction projects. The results from these alternative specifications are similar to our main findings, and are available in the Supporting Information. We have also tested a specification that uses production-related waste as the dependent variable. Production-related waste includes toxic releases, plus quantities of waste that are recycled, combusted for energy, or treated. Because this variable reflects the total quantity of chemical waste that is initially generated (as opposed to ultimately released), it implicitly controls for changes in downstream waste handling, such as installing pollution controls. We find that source reduction has similar effects on production-related waste and toxic releases, suggesting that our results are not confounded by the potential endogeneity of facility efforts to reduce releases through other end-of-pipe waste management techniques.

Finally, in order for the differences-in-differences design to produce credible estimates of the causal effect of source reduction, the control group must provide a good counterfactual for how releases would have changed if facilities had not implemented source reduction projects. Although counterfactual releases are by definition unobservable, we can at least check whether the trends in releases before source reduction occurs are similar at facilities with and without projects. Figure 2 shows that in the years before a project occurs, there is no difference in release trends at facilities in the treatment and control groups. This similarity in years −5 through −1 suggests that the control groups for Models 1 and 2 are appropriately chosen.

### 3.2. Implications for Aggregate U.S. Toxic Releases.

Our regression results suggest that source reduction projects cause sharp, highly significant decreases in facility-level releases of targeted chemicals. Although the effects of individual projects are modest, TRI facilities implemented 370 000 projects between 1991 and 2012. To characterize the potential aggregate impact of this large number of projects, we present estimates of how much toxic pollution may have been prevented through source reduction at TRI facilities over the last twenty-two years in the United States.

These illustrative calculations involve three steps. First, we calculate total aggregate releases reported from 1991 to 2012 across all U.S. facilities and years. Second, for each TRI facility, we estimate releases avoided through source reduction by applying our regression coefficients to actual releases from each facility. For example, based on Model 1, we assume that in the years following a project, releases would have been 19% higher (the inverse of a 16% decrease) if the project had not occurred. To illustrate the considerable uncertainty involved in these calculations, we report separate results for each of the four regression models. Third, after calculating counterfactual releases avoided by source reduction at each facility in each year, we sum avoided releases across years to estimate the total quantity of U.S. releases avoided over the last two decades.

Between 1991 and 2012, actual aggregate historical U.S. TRI releases were 46.9 billion pounds. Our analysis suggests that without source reduction, counterfactual releases would have been between 51.6 and 61.3 billion pounds. These estimates imply that source reduction prevented approximately 4.8 to 14.4 billion pounds of toxic releases between 1991 and 2012, corresponding to a 9−24% reduction. Figure 5 shows how these counterfactual releases have evolved over time relative to actual releases, for chemicals that had consistent TRI reporting requirements over the full period. Although there is considerable uncertainty across models, the figure suggests that a substantial part of the long-term declining trend in U.S. toxic releases may be due to source reduction.

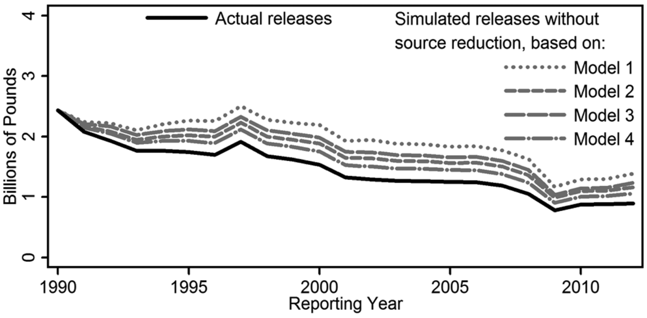

**Figure 5.** Cumulative effect of source reduction on aggregate U.S. toxic releases of consistently reported chemicals, 1991−2012.

**3.3. Discussion.** This paper generates three key results. First, we find that the average source reduction project results in a 9−16% decrease in releases of targeted chemicals. This drop in releases is sharp and lasts for at least five years. In contrast, previous research suggests that the effects of source reduction projects dissipate within five years.[14]

Second, we find that there are substantial differences in the average effectiveness of different source reduction techniques. The approaches that cause the largest toxic reductions—such as raw material modification and product modification—also appear to be more complex and resource intensive. In contrast, the techniques that have smaller effects—such as inventory control and good operating practices—are typically easier to implement. We conclude that with source reduction, "you get what you pay for". This finding suggests that firms and policymakers should consider not only the ease and cost of implementing different source reduction approaches, but also the quantity of toxic reductions achievable through different techniques.

Finally, we estimate that in aggregate, the source reduction projects that have been carried out in the United States since 1991 have resulted in the elimination of between 5 and 14 billion pounds of toxic releases. These estimates span a wide range and have important caveats, but still indicate that source reduction has been—and is likely to continue to be—an effective tool for reducing releases of toxic chemicals.

Our analysis has some potential limitations. One limitation is that the differences-in-differences approach requires that source reduction does not have spillover effects. If source reduction involves substituting one TRI-reportable chemical for another, then Model 1 will overestimate the effects of source reduction. Chemical substitution could explain why the estimated effect of source reduction on releases is greater when Model 1 compares across chemicals within the same facility (−16%) versus when Model 2 compares the same chemical across different facilities in the same industry (−9%).

A second limitation is that facilities that implement particularly successful source reduction activities might fall below the TRI reporting thresholds, and as a result, not need to report to the TRI program. Because these projects would not appear in our data set, our results are likely to be conservative, in the sense of underestimating the impact that source reduction has on toxic releases. Additional research is needed to quantify the effects of these highly successful projects.

## ■ ASSOCIATED CONTENT

### Ⓢ Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.5b02367.

Additional information including Figures SI1−SI6 and Tables SI1−SI3 (PDF)

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### Notes

The authors declare no competing financial interest.

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