Management Science

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To cite this article:
Suresh Muthulingam, Suvrat Dhanorkar, Charles J. Corbett (2022) Does Water Scarcity Affect Environmental Performance? Evidence from Manufacturing Facilities in Texas. Management Science 68(4):2785-2805. https://doi.org/10.1287/mnsc.2021.4013

http://pubsonline.informs.org/journal/mnsc

MANAGEMENT SCIENCE
Vol. 68, No. 4, April 2022, pp. 2785–2805
ISSN 0025-1909 (print), ISSN 1526-5501 (online)

Does Water Scarcity Affect Environmental Performance? Evidence from Manufacturing Facilities in Texas

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Received: October 7, 2019
Revised: May 24, 2020; November 29, 2020
Accepted: December 31, 2020
Published Online in Articles in Advance: November 1, 2021

https://doi.org/10.1287/mnsc.2021.4013

Abstract. It is well known that manufacturing operations can affect the environment, but hardly any research explores whether the natural environment shapes manufacturing operations. Specifically, we investigate whether water scarcity, which results from environmental conditions, influences manufacturing firms to lower their toxic releases to the environment. We created a data set that spans 2000–2016 and includes details on the toxic emissions of 3,092 manufacturing facilities in Texas. Additionally, our data set includes measures of the water scarcity experienced by these facilities. Our econometric analysis shows that manufacturing facilities reduce their toxic releases into the environment when they have experienced drought conditions in the previous year. We examine facilities that release toxics to water as well as facilities with no toxic releases to water. We find that the reduction in total releases (to all media) is driven mainly by those facilities that release toxic chemicals to water. Further investigation at a more granular level indicates that water scarcity compels manufacturing facilities to lower their toxic releases into media other than water (i.e., land or air). The impact of water scarcity on toxic releases to water is more nuanced. A full-sample analysis fails to link water scarcity to lower toxic releases to water, but a further breakdown shows that manufacturing facilities in counties with a higher incidence of drought do lower their toxic releases to water. We also find that facilities that release toxics to water undertake more technical and input modifications to their manufacturing processes when they face water scarcity.

History: Accepted by David Simchi-Levi, operations management.
Supplemental Material: Data and the online appendix are available at https://doi.org/10.1287/mnsc.2021.4013.

Keywords: environmental performance • water scarcity • drought • toxic chemical releases • manufacturing

1. Introduction

Manufacturing activity can have a significant impact on the environment because the production of goods invariably generates waste that may result in toxic emissions (e.g., chemicals, gases, liquids, metals) into the environment. These toxic releases can harm the environment and affect humans (see, e.g., Environmental Protection Agency 2019), so regulators across the world monitor them. For example, the United States established the Toxics Release Inventory (TRI) program in 1986 to monitor the toxic releases of manufacturing facilities (Toxics Release Inventory 2019).

The operations management (OM) literature has also recognized the effect of manufacturing activities on the environment (Klassen and Whybark 1999, King and Lenox 2001b). The predominant focus of this literature has been to understand how various operational factors affect the environment. Scholars have shown that the environmental impact of manufacturing activities can be shaped by a variety of factors, including the organization of production processes (see, e.g., Rajaram and Corbett 2002), incentives and penalties (Porteous et al. 2015), punitive and supportive tactics (Dhanorkar et al. 2018), and inspection activity (Mani and Muthulingam 2019a).

However, very little work has investigated the converse effect: whether specific conditions in the natural environment influence manufacturing activity. For instance, many manufacturing facilities have faced shortages of critical natural resources over the past several years because of the increased variability in climatic conditions (e.g., water or food grains, as in International World Wildlife Fund 2016). Naturally, such resource scarcity is bound to influence the configuration and execution of manufacturing operations, which in turn can affect environmental outcomes. To the best of our knowledge, hardly any research explores whether resource scarcity affects manufacturing activity and thus affects the concomitant environmental outcomes. Our research seeks to bridge this gap.

We focus on water to explore the impact of resource scarcity. We do this for three reasons. First, water is extensively used in many industrial operations and supply chains (Hoekstra 2017). Water is a crucial ingredient in the final products of several industries (e.g., food products, winemaking, pharmaceuticals); in many production processes, water facilitates the execution of operational tasks (e.g., fracking, metal cutting, casting); and, in several manufacturing operations, water is used as a carrier for production discharges, waste, or effluents (Hoekstra 2017). Therefore, any restrictions on water availability can affect a wide range of production processes.

Second, water is typically sourced locally for production activities. This is unlike oil, metals, or chemicals, all of which can be sourced from global markets. This means there will be greater temporal and spatial variability in water scarcity than in the scarcity of such global commodities, so it is more likely that any effect of local water scarcity can be isolated from other global factors.

Third, in several parts of the world, reliable supply of water for industrial activity has been threatened by a combination of depleting water resources and rising human consumption.[1] Increasingly, many manufacturing facilities face the challenge of operating in periods of water scarcity.

For these reasons, water serves as an apt context to explore how resource scarcity influences manufacturing activities and their attendant environmental outcomes. Our study draws from the literature on resource scarcity to explore how water scarcity can affect manufacturing facilities. Several papers have explored how individuals respond to scarcity. The general assessment across a variety of settings is that scarcity captures the attention of individuals and elicits more attention to the limited resource in question (Shah et al. 2012, Mullainathan and Shafir 2013, Shah et al. 2015).

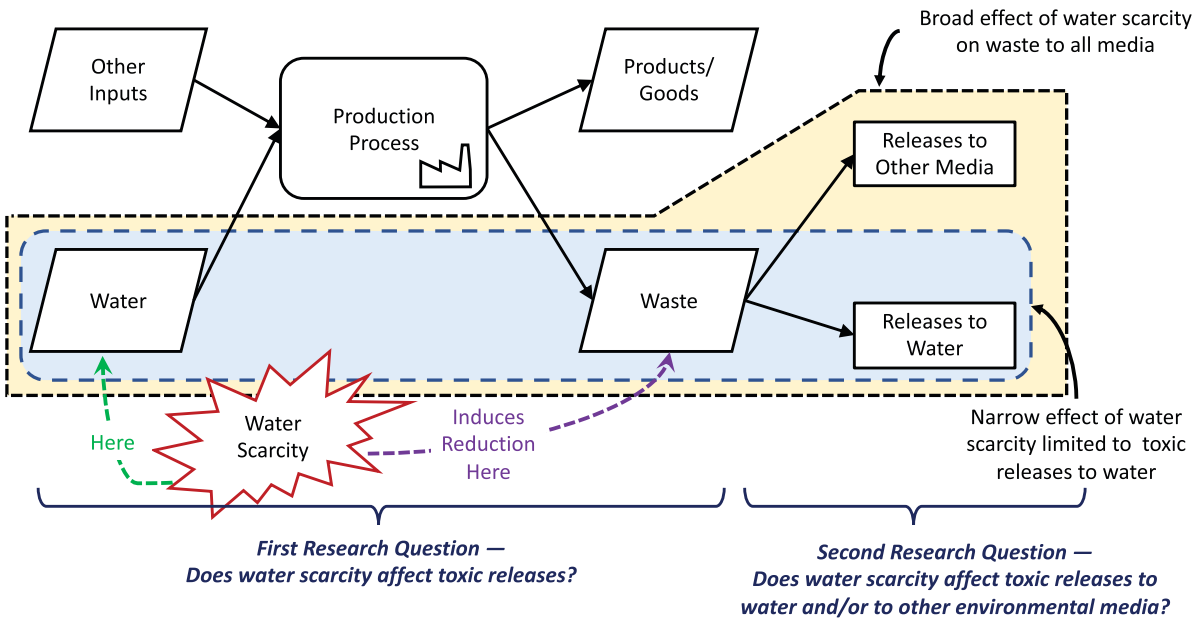
Individuals recognize the trade-offs required to meet the pressing needs that result from scarcity (Shah et al. 2012). In a similar manner, we expect that water scarcity will prompt manufacturing facilities to review their operations more intensively when faced with scarcity of this limited natural resource. Manufacturing facilities could gain a deeper understanding of how production activities use water and, in the process, also develop a better understanding about how operations generate waste. Logically, manufacturing facilities would leverage their understanding of the production activities to conserve water. Indeed, several studies note that firms take steps to reduce water consumption when they face water scarcity (see, e.g., Sojamo and Larson 2012, Hoekstra 2014). But what is less obvious is that water scarcity could also spur manufacturing facilities to leverage their understanding of operations to reduce waste and concomitantly lower the resulting toxic releases into the environment. Therefore, in our first research question, we explore whether manufacturing facilities improve their environmental performance as measured by toxic releases, when they face periods of water scarcity.

When manufacturing processes release waste, depending on the process characteristics, it can get discharged across environmental media such as water, land, and air. For instance, boilers can discharge toxics: to water from wastewater releases, to air from fuel combustion, and to land from ash disposal. Therefore, waste reduction efforts can lead to lower toxic releases across the different environmental media (i.e., water, land, and air). If water scarcity induces a narrow focus on water-related waste, then we would expect that manufacturing facilities will only reduce the waste they release to water. On the other hand, if water scarcity induces broader emphasis on waste reduction in general, then we would expect that manufacturing facilities will also reduce the waste discarded into other media (i.e., land and air). Therefore, to understand whether water scarcity stimulates a broader mechanism, in our second research question we delve deeper and explore whether water scarcity promotes lower toxic releases into water and/or to other media (besides water). In Figure 1, we illustrate the underlying research questions of this study.

To explore our research questions, we concentrate on the manufacturing industry in Texas. Four reasons guided our attention to Texas. First, Texas has widely varying levels of water scarcity, and several regions face persistent drought-like conditions. Second, Texas has significant manufacturing activity, including food, petroleum, coal products, chemicals, and metal products. Third, Texas has limited and less stringent environmental regulations on manufacturing activity relative to other states (e.g., California, Minnesota). See, for example, US News (2019), which ranks Texas as the 40th out of the 50 states in the U.S. in terms of "natural environment rankings." Thus, regulatory factors, which govern the environmental performance of manufacturing firms, are less likely to be confounded with the impact of exogenous environmental shocks (such as water scarcity). Finally, Texas records detailed information on the incidence of drought and the imposition of water rationing across its territories. Whereas drought captures the existing environmental conditions, rationing captures the government-imposed restrictions on water use. Thus, the state has multiple measures that enable us to validate the effect of water scarcity on the environmental performance of manufacturing firms.

To support our analysis, we compiled information from several data sources. For our primary outcome

Figure 1. (Color online) Illustration of Research Questions



variable, we obtained information on facility-level toxic releases from the Environmental Protection Agency's (EPA's) TRI program. We measure water scarcity using information from two separate sources: the United States Drought Monitor (USDM), which records information on droughts, and the Texas Commission on Environmental Quality (TCEQ), which provides information on water rationing. Our data span the years 2000–2016, and they allow us to relate facility-level toxic releases to the water scarcity experienced by a manufacturing facility.

To better understand the water scarcity data, we interviewed water scientists from TCEQ and the United States Geological Survey (USGS) to gain insights on the criteria for drought-like conditions and the implications for water availability. Additionally, to better understand the impact of water scarcity, we interviewed managers across a variety of firms in Texas, ranging from engineering services and construction (e.g., SNC Lavalin) to metal processing firms.

In one interview, the global director for process technologies at SNC Lavalin stated (Gopinath 2019),

> Changes to water availability or changes in rates for water could prompt manufacturing units to fine-tune their cooling water network each season so that water will be used effectively. Moreover, in this process, facilities could end up optimizing the energy usage (such as fuel-firing) and energy recovery to improve fuel efficiency.

This statement indicates the kind of changes that manufacturing facilities may undertake in response to water scarcity. Overall, our interactions with these experts suggest that water scarcity can shape changes to production processes, which could affect the toxic releases of manufacturing firms to water as well as to other media (e.g., land, air).

Our empirical analysis starts by examining the impact of water scarcity on the toxic releases of all manufacturing facilities in Texas. Next, we examine manufacturing facilities with higher reliance on water because water scarcity is more likely to affect them. Then, we examine the remaining facilities with lower reliance on water, which also serves as a manipulation check, because they are less likely to be directly affected by water scarcity. We conclude our analysis by examining potential mechanisms that may explain how water scarcity affects toxic releases.

Our results show that when manufacturing facilities experience water scarcity, they lower their overall toxic releases. If the measure of water scarcity (defined in Section 4.3 as the log of weeks with severe drought) is increased by one standard deviation from the average value, then manufacturing facilities lower their average toxic releases by 2.49% across all chemicals they report. Thus, our results contribute to the literature by drawing attention to the link between the resource scarcity faced by manufacturing facilities and the resultant improvement in environmental performance.

We find that the effect of water scarcity is mainly observed for facilities that released toxic chemicals to water rather than for facilities that released toxic chemicals only to other media (e.g., land, air). This is unsurprising, as facilities with no releases to water are

less likely to be affected by water scarcity. However, although the reductions occur for facilities with releases to water, those reductions are not in their toxic releases to water but in their toxic releases to other media. In general, we do not observe a link between water scarcity and toxic releases to water. A post hoc analysis (Section 6.3) suggests that only facilities located in the most drought-prone counties (the top quintile) show significant reduction in their toxic releases to water. In other words, under conditions when water is most scarce, facilities do reduce the volume of toxics released to water. By contrast, we find that in most cases, water scarcity leads to significant reduction of toxic chemicals released to other media. Thus, we contribute to the literature by providing a deeper understanding of how water scarcity affects the toxic chemicals released across different environmental media (i.e., water, land, and air).

Furthermore, we analyze the activities that facilities undertake to reduce toxic releases and our results suggest that water scarcity induces facilities to initiate some form of modifications in their manufacturing processes. We find that there are differences in how plants with water releases and plants without water releases respond to water scarcity—the former focus more on modifications that involve technological or input related changes, whereas the latter focus mainly on modifications that involve changes to the management of operations. Our results are relevant to regulators and managers because they highlight how the scarcity of a critical resource can help drive improvements in environmental performance.

The rest of the paper is organized as follows: Section 2 reviews the relevant literature. Section 3 presents our hypotheses. Section 4 describes the data and the measures used in our analysis. Section 5 discusses our methodology, and Section 6 presents our results. Section 7 discusses the implications of our findings and the limitations of our analysis.

2. Literature Review

Our work draws on and contributes to the literatures on scarcity, toxic releases, and environmental issues in OM. In this section, we provide a broad overview of the relevant literature in these areas, and we discuss the key differences in our study. However, we defer a more detailed discussion to Section 3.

A large body of work finds that when individuals perceive that resources are low in comparison with their needs, a scarcity mindset emerges, and this affects their decision making (Shah et al. 2012, Mani et al. 2013). We discuss this literature in detail later when we formulate our hypotheses. Several studies have explored the effect of scarcity on individual decision makers, but the research on the effect of scarcity in an organizational context is limited. Therefore, we contribute to the scarcity literature by focusing on understanding how resource scarcity affects organizational outcomes.

The TRI program was started in the United States with the enactment of the Emergency Planning and Community Right-to-Know Act (EPCRA) in 1986. The objective of the TRI program is to track the release of toxic chemicals that may pose a threat to humans and the environment (Environmental Protection Ahency 2019). The program provides a quantified measure for the environmental performance of firms and manufacturing facilities in terms of toxic releases, and this has spurred research on a variety of aspects that can affect environmental performance.

The initial research on toxic releases sought to assess whether it pays for firms to be green (Hart and Ahuja 1996, King and Lenox 2001a). Later, the literature advanced to explore the link between lean operations and environmental performance. This research indicates that firms can benefit more from waste prevention than from end-of-pipe (EOP) solutions for reducing toxic releases (King and Lenox 2002). But Dutt and King (2014) point out that EOP solutions play an important role in generating the impetus to lower toxic releases. Our empirical setup (e.g., panel data, unit of analysis) is similar to Dutt and King (2014). However, we differ from Dutt and King (2014) because they focus on exploring how management decisions (e.g., EOP treatment) affect toxic releases, whereas we focus on understanding the impact of externally occurring water scarcity on toxic releases.

Additionally, research illustrates that a variety of factors can influence the amount of toxic releases that firms discharge into the environment. For instance, studies show that multiple factors can affect the quantity and the type of toxic chemicals that firms release into the environment, including (a) the rankings of hazardous substances (Fu et al. 2019), (b) the ratings provided by external agencies (Chatterji and Toffel 2010), and (c) acquisition or divestiture activity (Berchicci et al. 2017).

In sum, this body of work has expanded our knowledge of the relation between operational factors and environmental outcomes. We add to this body of work by illustrating that environmental factors such as water scarcity can also play a role in shaping operational processes that, in turn, affect environmental outcomes.

Research shows a significant overlap between environmental issues and OM (Corbett and Klassen 2006, Plambeck 2013). The overlap can be seen in three forms. First, studies have shown that environmental issues can affect operations across several settings, such as industrial manufacturing (Fu et al. 2019), supplier management (Porteous et al. 2015), and

waste management (Dhanorkar 2019). Second, studies show that efforts to improve environmental performance can spur improvements in operational performance. For instance, Pil and Rothenberg (2003) show that initiatives to address environmental concerns also serve as an important driver for superior quality performance at automotive firms. Third, studies have shown that operational improvements can spur superior environmental performance such as lower water or energy consumption (Rajaram et al. 1999, Rajaram and Corbett 2002) and reduction in toxic releases (Florida 1996, King and Lenox 2001b). Our work adds a new dimension by illustrating that environmental factors (e.g., water scarcity) by themselves can play a role in eliciting operational modifications that induce improved environmental performance.

In summary, our study contributes by illustrating that water scarcity can prompt firms to improve their environmental performance and by highlighting the conditions that augment the impact of water scarcity. Next, we discuss the related literature in more detail as we formulate our hypotheses.

3. Hypotheses

We leverage the literature on scarcity and the body of work that links scarcity to behavioral changes in individuals and organizations to understand how water scarcity can affect the environmental performance of manufacturing facilities.

3.1. Linking Water Scarcity to Environmental Performance

Resource scarcity can capture the attention of decision makers. This is because the limited availability of a resource prompts decision makers to consider how the scarce resource is used (Shah et al. 2012, Mullainathan and Shafir 2013, Shah et al. 2015). Often, scarcity induces decision makers to focus more on managing the scarce resource. For instance, in the context of individual decision makers, research shows that impoverished individuals focus more on expenses (see, e.g., Shah et al. 2012), hungry individuals focus more on food (e.g., Radel and Clément-Guillotin 2012), and busy individuals focus more on tasks with deadlines (e.g., Karau and Kelly 1992).

Comparably, in the context of organizations, scholars find that hospitals focus on managing operating rooms when operating room capacity is scarce (e.g., Henderson et al. 2004), and resource scarcity can trigger structural and strategic adjustments within firms (e.g., Koberg 1987). Similarly, when water is scarce, manufacturing facilities will strive to better understand how water is used in the production processes. A first-order response to water scarcity is to reduce consumption or possibly find alternative sources. For example, Averyt et al. (2011) point out instances when manufacturing facilities in Texas were forced to curtail operations due to an inadequate water supply to support production, and O'Grady (2011) highlights instances in which manufacturing plants in east Texas were forced to obtain water from alternative sources (i.e., other rivers) and secure additional water usage rights to ensure continued operations. These efforts have been documented elsewhere (see e.g., Sojamo and Larson 2012, Hoekstra 2014) and are not our focus. Instead, we are interested in more indirect effects of water scarcity on waste flows.

Typically, water is used in industries for purposes such as processing, fabrication, cooling, cleaning, dilution, transporting effluents, incorporating water into a product, landscaping, sanitation, or sewage (United States Geological Survey 2019). Given the broad scope of these applications, manufacturing managers must review a wide range of production activities when they seek to understand their water usage. As a result, these managers are likely to develop a better grasp of their manufacturing processes and the organization of production activities that could cause inefficiencies in water use (see e.g., Rajaram and Corbett 2002).

In addition, a review of water usage could enable managers to identify operational factors or practices that generate waste, which in turn may require increased water for disposal. For example, Pil and Rothenberg (2003) document how improper painting operations led to increased water use for an automotive facility. An improved understanding of manufacturing processes, organization of production activities, and identification of operational factors or practices can enable managers to improve operational efficiency so that manufacturing facilities use water more effectively. A natural corollary of improving operational efficiency is that manufacturing facilities generate less waste. Because toxic releases are the result of waste discarded or discharged into the environment, a focus on water will also result in lower toxic releases into the environment.

Based on the previous theoretical discussion and the Texas-specific deliberation on water scarcity, we hypothesize the following.

Hypothesis 1. *A manufacturing unit that faces serious water scarcity will subsequently reduce its total toxic releases to the environment to a greater degree.*

Hypothesis 1 investigates the effect of water scarcity on overall toxic releases. Hypothesis 1 serves as an essential step to understand the link between environmental events (i.e., water scarcity) and their consequences for manufacturing activity (i.e., toxic releases). However, Hypothesis 1 does not illuminate whether this effect results from narrow efforts on water-related waste or whether there is a broader

mechanism that affects waste in general. If the effect is narrowly focused, then we would logically expect that manufacturing facilities will mainly reduce their toxic releases into water when they grapple with water scarcity. However, if the effect is broader, then we would expect a reduction in the toxic releases into other media (i.e., land and air) as well. Therefore, in the next pair of hypotheses, we delve deeper to examine the effect of water scarcity on the toxic releases of manufacturing facilities into water as well as into other media (i.e., land and air). We first discuss the theoretical mechanism linking water scarcity to a reduction in releases specifically to water; after that, we review the less obvious mechanism linking water scarcity to releases to other media in addition to water.

Water scarcity can draw attention to "the value of water" (Podolak and Doyle 2011), which can prompt manufacturing facilities to adopt three broad approaches to conserve water. First, manufacturing facilities can avoid wasting water—i.e., they can verify that the correct amount of water is used in production processes. These efforts could involve initiatives such as checking water lines for leaks (e.g., Federal Energy Management Program 2009), using high-pressure washers for cleaning, using flow restrictors in water lines, and using timers and overflow controls to prevent excess water intake (e.g., North Carolina Department of Environment and Natural Resources 2009).

Second, manufacturing facilities can reduce (or eliminate) the water required for specific operations. For instance, manufacturing facilities can switch to recirculating cooling systems or dry cooling systems instead of "once-through" water to cool heat-generating equipment (North Carolina Department of Environment and Natural Resources 2009, Averyt et al. 2011).

Third, manufacturing facilities can reuse water—that is, they can extract multiple functional uses from a given quantity of water. For example, manufacturing facilities could use countercurrent systems in which less contaminated water from the latter stages of a process is reused for prior stages in the process. Also, waste streams from one process (e.g., wash water in fabric processing) could be reused for other operations (e.g., equipment or color shop cleaning, cooling tower make-up), and wastewater could be treated and reused, as in paper mills (e.g., North Carolina Department of Environment and Natural Resources 2009).

When manufacturing facilities avoid wasting water or when they reduce (or eliminate) the water required for specific operations, there will also be a corresponding reduction in the overall amount of toxic chemicals and solvents used to maintain water at the desired concentrations for the production processes. Consequently, we expect that, overall, lesser quantities of solvents and chemicals will be discharged along with this water.

Analogously, when manufacturing facilities reuse water, they will become more aware of the contaminants in the water because they must ensure that impurities do not affect subsequent processes. For example, Rajaram and Corbett (2002) show, in the context of a food processing facility, water conservation efforts enabled a substantial reduction in toxic discharges owing to widespread process improvements.

In sum, due to the increased conservation and reuse efforts, the increased attention to the additives or contaminants in water will ensure that lesser amounts of chemicals and solvents are discarded with water. Based on these reasons, we hypothesize the following.

Hypothesis 2 (a). *A manufacturing unit that faces serious water scarcity will subsequently reduce its toxic releases into water to a greater degree.*

The focus on water could also induce a broader effect that induces waste reduction efforts in general, which in turn also affects toxic releases into other environmental media (i.e., land and air). Two potential mechanisms can account for the prospective effect on other media. The first mechanism relates to the idea generated in the total quality management movement that improving efficiency leads to lower waste (Juran and De Feo 2010). In other words, when a manufacturing process becomes more efficient, it also reduces waste. Since water conservation involves avoiding water wastage, reducing water consumption, and reusing water for multiple functions, the increased focus on water means that manufacturing processes become more efficient, which means that less waste is generated overall.

The second mechanism draws on the research that finds that proenvironmental actions in one domain induce broader proenvironmental shifts in other domains (Truelove et al. 2014, Dhanorkar and Muthulingam 2020). Thus, when decision makers focus on environmental issues (e.g., conserving water), they are also likely to review their production processes to improve the overall efficiency of their operations (Corbett and Klassen 2006, Plambeck 2013). For instance, Pil and Rothenberg (2003) find that studying water usage enabled an automotive facility to identify excess paint and solvent use. Similarly, Mani and Muthulingam (2019b) find that a review of operations led to a reduction in water-based waste as well as solid waste in unconventional well operations. Finally, studies on the EPA's TRI program have found evidence that operational improvements can spur reduction in toxic releases (Florida 1996, King and Lenox 2001b).

Overall, we expect that greater water scarcity will mean that lower quantities of waste are generated in production processes, which in turn will result in lower discharges to all environmental media (i.e., water, land, and air). For the broader effect that we describe here to hold, we must specifically find a reduction in releases to media other than water. Based on these discussions, we hypothesize the following.

Hypothesis 2 (b). *A manufacturing unit that faces serious water scarcity will subsequently reduce its toxic releases into other media (besides water) to a greater degree.*

4. Data

4.1. Data Sources

We use a facility–chemical-level panel data set to examine the longitudinal relationship between firm-level toxic chemical releases and water scarcity. We constructed our data set using information from multiple sources.

First, we collected data on toxic chemical releases from the EPA's TRI program for the state of Texas from 2000 to 2016. These data from the TRI program include information on the 508 toxic chemicals that were released across the 3,092 manufacturing facilities in Texas. On average, these manufacturing facilities reported releasing 6.50 chemicals, yielding 13,854 facility–chemical and 108,966 facility–chemical–year observations. We note that our data does not include the universe of manufacturing firms in Texas because the TRI program requires firms to report their toxic releases only if they have more than 10 employees or if they cross some thresholds for the use of chemicals (from one to 25,000 pounds based on the specific chemical).

Second, we collected information on water scarcity recorded for counties within Texas from two sources. The first source is the United States Drought Monitor (USDM), which prepares data on water scarcity through a collaborative effort between the National Drought Mitigation Center at the University of Nebraska–Lincoln, the United States Department of Agriculture, and the National Oceanic and Atmospheric Administration. The second source is the Texas Commission on Environmental Quality (TCEQ), which records water restrictions imposed by local public water authorities in all the counties in Texas.

Finally, we match the data from these sources to create a longitudinal facility–chemical-level panel data set from 2000 to 2016 that constitutes the core data for our analysis.

Next, we describe the dependent, independent, and control variables used in our analysis.

4.2. Dependent Variables

We use three measures of toxic releases:

a. $Ln(Toxic\ Releases)_{cit}$. This measures the total toxic releases of chemical c in pounds by manufacturing facility i in year t. We measure the total toxic chemical releases using TRI's definition (see TRI documentation (Environmental Protection Agency 2020)), which is the sum of the total onsite releases and total offsite releases. We use the logarithmic transformation of *Toxic Releases* to reduce skew (i.e., we take the natural logarithm of [*Toxic Releases* + 1]). Our measure is aligned with prior work (Dutt and King 2014).

The next two variables decompose the total toxic releases into two components: the toxic releases into water and the toxic releases into other media.

b. $Ln(Toxic\ Releases\ to\ Water)_{cit}$. This measures the toxic releases of chemical c into water by manufacturing facility i in year t (i.e., the amount of chemical c released into water).

c. $Ln(Toxic\ Releases\ to\ Other)_{cit}$. This measures the toxic releases of chemical c into media other than water (i.e., land or air) by manufacturing facility i in year t (i.e., the amount of chemical c released into media other than water).

4.3. Independent Variables to Measure Water Scarcity

The variable $Ln(Total\ Weeks)_{it}$ measures water scarcity in terms of the total number of weeks of drought experienced by facility i in year t.

The USDM estimates the number of weeks of drought that each county experiences in a year based on climatological inputs, satellite-based assessments of vegetation health, indicators of soil moisture, and hydrologic data. Additionally, the USDM utilizes a network of more than 450 observers across the country to synthesize and interpret the various sources of information. This network of observers includes state climatologists, National Weather Service staff, and hydrologists.

The USDM uses a five-category system to classify drought. These categories are: D0 (abnormally dry) (i.e., a precursor to drought, but not an actual drought), D1 (moderate drought), D2 (severe drought), D3 (extreme drought), and D4 (exceptional drought) (United States Drought Monitor 2019). The D2 classification corresponds to drought conditions when water shortages are common, when water use restrictions are imposed by affected regions, and when water levels result in crop damage. Our discussions with a water data scientist at the United States Geological Survey (USGS) indicated that the D2 classification represents the first level of drought that could affect economic activity. Therefore, we calculate the total number of weeks of drought experienced by each county as the sum of weeks in D2, D3, and D4 drought.

We perform a logarithmic transformation to reduce skew. This variable, $Ln(Total\ Weeks)_{it}$, allows us to examine Hypotheses 1, 2(a), and 2(b). In other words, we can examine whether water scarcity leads to lower overall toxic releases, lower toxic releases that are

discharged into water, and lower toxic releases that are discharged into environmental media other than water. In our regression models (shown in Section 5.2), if the coefficients of *Ln(Total Weeks)*$_{it}$ are negative and significant, then we can infer that water scarcity is associated with lower toxic releases.

We also define the variables *Ln(Total Weeks in Extreme Drought)*$_{it}$, which represents the log transformation of the weeks of extreme drought (i.e., the sum of weeks in D3 and D4 drought), and *Ln(Total Number of Rationings in County)*$_{it}$, which represents the log transformation of the number of water rationing events in a county (obtained from TCEQ).

In our analysis, we lag the independent variables as appropriate to avoid simultaneity.

4.4. Control Variables

The control variables (i.e., *Ln(Production Ratio)*, *Ln(Toxicity Ratio)*, *EMS*, *Tenure of Technical Personnel*, and *Tenure of Certifying Manager)* used in our analysis are described next.

The variable *Ln(Production Ratio)*$_{cit}$ represents changes in production activity related to chemical c for facility i in year t. This variable controls for changes in the toxic releases of chemical c that can be attributed to changes in production output relevant for chemical c. Often, use of a toxic chemical depends on the production volume of the final product (e.g., toluene use in painting refrigerators). Then the relevant production ratio is calculated as the ratio of the current year production to the previous year production. However, in many instances, use of a toxic chemical depends on auxiliary activities (e.g., toluene use for cleaning of stamping molds) that are not necessarily governed by the production volumes of the final product. In such instances, the relevant production ratio is calculated as the ratio of the current year activity to the previous year activity. Detailed information on the calculation of the production ratio are provided in the EPA's Toxic Chemical Release Inventory Reporting Forms and Instructions (Environmental Protection Agency 2018). Dutt and King (2014) point out that there could be several reporting issues for the production ratios, consequently we winsorize 1% of both tails to account for the potential errors in the reporting of production ratio and to account for potential outliers.

The variable *Ln(Toxicity Ratio)*$_{it}$ controls for the changes in toxin intensity for facility i in year t. To calculate this variable, we obtain the toxicity details for each chemical in the TRI data from the EPA's Risk-Screening Environmental Indicators (RSEI) model. We use the RSEI toxicity information to weight each chemical release of a facility. The toxicity ratio for a facility in a given year is calculated as the total toxicity-weighted chemical releases of the facility in a given year divided by the prior year's total toxicity-weighted chemical releases.

The toxic releases could be lower for facilities that use an Environmental Management System (EMS). We adopt Dutt and King's (2014) methods to infer the presence of an EMS at a facility. This involves checking whether the facility reports source reduction activities attributable to an EMS in the last three years. We use an indicator variable, $EMS_{it,}$ to identify facilities that use EMS. This variable takes a value of 1 if a facility has reported such source reduction activity and is 0 otherwise.

We follow Dutt and King (2014) to measure how long (in years) a specific technical person completes the TRI form for a particular facility. We represent this measure as *Tenure of Technical Personnel*$_{it}$. This allows for the possibility that continuity in tenure of technical personnel might help facilities achieve lower toxic releases.

We follow Dutt and King (2014) to measure how long (in years) a specific manager signs off on the TRI forms for a particular facility. We represent this measure as *Tenure of Certifying Manager*$_{it}$. This allows for the possibility that continuity in the tenure of the certifying manager might help facilities achieve lower toxic releases.

A key issue involved in calculating the *Tenure of Technical Personnel*, and *Tenure of Certifying Manager* relates to inconsistencies in the names reported in the TRI data. For instance, a certifying manager could be recorded as "Jaccci Church" one year and as "Jacci Church" the other years, or a technical person could be recorded as "Mike Miller/Plant Manager" in some years and as "Mike Miller" in other years. To address these issues, we created a program to identify discrepancies and then we rechecked the data to identify and rectify any such errors.

4.5. Fixed Effects

Our study includes the following fixed effects:

a. *Facility Three-Digit NAICS Code* ($NAICS_i$). Indicator variables that identify the three-digit primary North American Industry Classification System (NAICS) code for each facility. These indicators control for potential industry-level factors that may affect toxic releases.

b. *Facility–Chemical Fixed Effects* (FC_{ci}). Our regression models include facility–chemical pair fixed effects. Thus, we have fixed effects for each facility as well as fixed effects for each toxic chemical released by the facility. These variables control for potential factors related to the facility and the specific chemicals that may affect toxic releases. Furthermore, since a facility is located in a county, the facility fixed effects control for factors specific to the county (or geography) that might impact results.

c. *Year Fixed Effects* (YR_t). Indicator variables that identify the relevant year of our data. These indicators control for potential factors that may change over time.

Table 1 presents the summary statistics. (Table A1 in the online appendix shows the correlations.)

5. Methodology

5.1. Empirical Approach

Our empirical approach to evaluate our hypotheses encompasses three sets of interrelated analyses. First, we examine the impact of water scarcity on toxic chemical releases for all manufacturing facilities in Texas. Second, we expect that the effect of water scarcity on toxic chemical releases will be higher for the 802 firms in our data that released toxic chemicals to water, since this would indicate a higher reliance on water for manufacturing operations. Therefore, we repeat our analyses only for those manufacturing facilities that released toxic chemicals to water anytime during 2000–2016. Third, we expect that the impact of water scarcity on toxic chemical releases will be lower for the 2,290 firms in our data that did not release toxic chemicals to water during 2000–2016, due to their relatively low reliance on water as an input resource. Therefore, we also examine the effect of water scarcity for those manufacturing facilities that did not release toxic chemicals to water during 2000–2016. All the analyses were performed using Stata version 16.1.

5.2. Model Specification

Hypothesis 1 examines the impact of water scarcity on the toxic chemical releases of a manufacturing facility. We evaluate Hypothesis 1 using the following specification:

$$Ln(Toxic\ Releases)_{cit} = \propto_0 + \beta_1 Ln(Total\ Weeks)_{i(t-1)} + \gamma \boldsymbol{X}_{ci(t-1)} + \delta_1 NAICS_i + \delta_2 FC_{ci} + \delta_3 YR_t + \varepsilon_{cit}, \quad (1)$$

where $Ln(Toxic\ Releases)_{cit}$ represents the total toxic releases, $\boldsymbol{\alpha_0}$ denotes the intercept, ε_{cit} indicates the error terms, and the independent variables are lagged as appropriate to avoid simultaneity. The variable $Ln(Total\ Weeks)_{i(t-1)}$ indicates the log of the number of weeks of drought experienced by the facility in the prior year. The vector $\mathbf{X}_{ci(t-1)}$ encompasses the control variables, including $Ln(Production\ Ratio)_{ci(t-1)}$, $Ln(Toxicity\ Ratio)_{i(t-1)}$, $EMS_{i(t-1)}$, $Tenure\ of\ Technical\ Personnel_{i(t-1)}$, and $Tenure\ of\ Certifying\ Manager_{i(t-1)}$. The fixed effects include the three-digit primary NAICS code for each facility ($NAICS_i$), facility–chemical pair fixed effects (FC_{ci}), and year fixed effects (YR_t).

Hypothesis 2(a) seeks to examine the effect of water scarcity on the toxic chemical releases discharged to water. We evaluate Hypothesis 2(a) using the following specification:

$$Ln(Toxic\ Releases\ to\ Water)_{cit} = \propto_0 + \beta_1 Ln(Total\ Weeks)_{i(t-1)} + \gamma \boldsymbol{X}_{ci(t-1)} + \delta_1 NAICS_i + \delta_2 FC_{ci} + \delta_3 YR_t + \varepsilon_{cit}. \quad (2)$$

Hypothesis 2(b) seeks to examine the impact of water scarcity on the toxic chemical releases discharged into environmental media other than water. To test Hypothesis 2(b), we use the following specification:

$$Ln(Toxic\ Releases\ to\ Other)_{cit} = \propto_0 + \beta_1 Ln(Total\ Weeks)_{i(t-1)} + \gamma \boldsymbol{X}_{ci(t-1)} + \delta_1 NAICS_i + \delta_2 FC_{ci} + \delta_3 YR_t + \varepsilon_{cit}. \quad (3)$$

We use a panel data regression with standard errors clustered at the facility–chemical level to estimate models (1), (2), and (3) for all the manufacturing facilities in our data set. These results are shown in columns (1), (2), and (3) of Table 2. Next, we estimate models (1), (2), and (3) for the population of manufacturing facilities that released toxic chemicals into water during 2000–2016. These results are shown in columns (4), (5), and (6) of Table 2. Finally, we estimate model (1) for the population of manufacturing facilities that did not release toxic chemicals into water during 2000–2016. These results are shown in column (7) of Table 2. (Note that model (2) is not relevant for facilities with no toxic chemical releases into water, and models (1) and (3) are equivalent.) Across all models, the Variance inflation factor are within acceptable limits. We find that more severe drought is associated with a reduction in releases to

Table 1. Summary Statistics

Variable	Mean	S.D.	Min	Max	N
ln(Toxic Releases) – pounds	5.596	3.900	0	16.920	108,964
ln(Toxic Releases to Water) – pounds	0.604	1.819	0	16.580	108,964
ln(Toxic Releases to Other) – pounds	5.448	3.926	0	16.920	108,964
ln(Total Weeks)	1.794	1.513	0	3.970	108,964
ln(Production Ratio)	0.635	0.298	0	1.825	108,964
ln(Toxicity Ratio)	0.878	1.363	0	25.950	108,964
Environmental Management System	0.259	0.438	0	1	108,964
Tenure of Technical Personnel – years	3.451	2.745	1	16	108,964
Tenure of Certifying Manager – years	3.818	2.977	1	16	108,964

other media, but not to water. We discuss this finding later.

6. Results and Robustness Checks

Next, we present our results with their associated effects. Additionally, we discuss the analyses using propensity score matching and alternative measures of water scarcity that serve as robustness tests to validate our results. We also provide confidence intervals (CIs) and estimates of magnitude wherever applicable. This methodology is in line with recent suggestions (Amrhein et al. 2019, Haaf et al. 2019). Next, we present our results in a logical sequence to facilitate understanding and later (in Section 7) we present an overall picture of our main results in Figure 2.

6.1. Results

We examine column (1) of Table 2 to evaluate Hypothesis 1, which seeks to assess the impact of water scarcity on toxic chemical releases. We see that the coefficient of *Ln(Total Weeks)* is negative (−0.0167) and significant ($p < 0.01$), with a 95% CI [−0.0283, −0.0050]. This result supports Hypothesis 1 because it indicates that manufacturing facilities reduced their toxic chemical releases when they experienced a drought in the previous year.

In column (1) of Table 2, a one standard deviation increase in *Ln(Total Weeks)* from 1.794 to 3.307 lowers the average toxic releases of a chemical at a facility by 2.49% across all chemicals reported. We use the method proposed in Cameron and Trivedi (2009, pp. 103–104) for log-linear models of the general form $\ln(\boldsymbol{y}) = \boldsymbol{x}'\boldsymbol{\beta} + \boldsymbol{\epsilon}$, where $\boldsymbol{E}(y_i/\mathbf{x}_i) = \exp(\boldsymbol{x}_i'\boldsymbol{\beta})\boldsymbol{E}[\exp(\epsilon_i)]$, to evaluate toxic releases when *Ln(Total Weeks)* takes values of 1.794–3.307. Thus, we obtain $\frac{(3{,}677.38 - 3{,}585.81)}{3{,}677.38} \times 100 = 2.49\%$.

Additionally, when we examine the results shown in column (4) of Table 2 for manufacturing facilities that released toxic chemicals to water anytime during 2000–2016, we observe that the coefficient of *Ln(Total Weeks)* is negative (−0.0220) and significant ($p < 0.01$), with a 95% CI [−0.0370, −0.0070]. By contrast, when we examine column (7) of Table 2, for manufacturing facilities that did not release toxic chemicals to water anytime during 2000–2016, we observe that the coefficient of *Ln(Total Weeks)* is not significant.

Table 2. Main Regression Results

	All plants			Plants with water releases			Plants without water releases
Dependent variable →	*Ln(Toxic Releases)* (1)	*Ln(Toxic Releases to Water)* (2)	*Ln(Toxic Releases to Other)* (3)	*Ln(Toxic Releases)* (4)	*Ln(Toxic Releases to Water)* (5)	*Ln(Toxic Releases to Other)* (6)	*Ln(Toxic Releases)* (7)
Lag. Ln(Total Weeks in Drought) – β_1	−0.0167**	0.0008	−0.0197**	−0.0220**	0.0022	−0.0273***	−0.0143
	(0.006)	(0.003)	(0.006)	(0.008)	(0.004)	(0.008)	(0.010)
Lag. Ln(Production Ratio) – β_2	0.5175***	0.0236	0.5074***	0.4892***	0.0446+	0.4702***	0.5354***
	(0.032)	(0.014)	(0.032)	(0.041)	(0.025)	(0.041)	(0.050)
Lag. Ln(Toxicity Ratio) – β_3	0.0434***	0.0050**	0.0423***	0.0219**	0.0112**	0.0194**	0.0614***
	(0.005)	(0.002)	(0.005)	(0.007)	(0.004)	(0.007)	(0.008)
Lag. EMS used in last 3 years – β_4	-0.0159	0.0245	-0.0226	-0.0059	0.0300	-0.0132	-0.0270
	(0.026)	(0.017)	(0.026)	(0.031)	(0.026)	(0.031)	(0.044)
Lag. Tenure of Certifying Officer – β_5	(0.000)	(0.002)	0.001	0.001	(0.003)	0.0037	0.005
	(0.004)	(0.002)	(0.004)	(0.005)	(0.003)	(0.005)	(0.006)
Lag. Tenure of Technical Person – β_6	0.002	(0.002)	0.001	0.007	(0.004)	0.0054	(0.006)
	(0.004)	(0.002)	(0.004)	(0.005)	(0.004)	(0.005)	(0.006)
Constant	5.5132***	0.7364+	5.2105***	7.4201***	1.2412*	6.8996***	5.9560***
	(0.474)	(0.410)	(0.480)	(0.632)	(0.617)	(0.647)	(0.485)
Controls							
Facility Three Digit NAICS Code	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Facility-Chemical Pair Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.878	0.847	0.876	0.870	0.836	0.870	0.882
Adusted R^2	0.860	0.825	0.858	0.854	0.815	0.853	0.861
Facility-Chemical Pairs	13,854	13,854	13,854	7,390	7,390	7,390	6,463
Number	108,964	108,964	108,964	66,508	66,508	66,508	42,456

Note. We report coefficient estimates with standard errors clustered at the facility–chemical level in parentheses.
$+p < 0.10$; $*p < 0.05$; $**p < 0.01$; $***p < 0.001$.

Figure 2. Summary of Main Results

Hypothesis & Research Question	Geographical Scope of Analysis	Summary of Main Results		
		All Facilities	Facilities with releases to water	Facilities with no releases to water
H1: Does water scarcity lower toxic releases?	All Counties	**Yes**	**Yes**	Not Significant
H2a: Does water scarcity lower toxic releases to water?	All Counties	Not Significant	Not Significant	Not Applicable
	Counties with highest drought	**Yes**	**Yes**	
H2b: Does water scarcity lower toxic releases to other media?	All Counties	**Yes**	**Yes**	Not Significant

Thus, our results indicate that the impact of water scarcity is observed mainly for those manufacturing facilities that released toxic chemicals to water—that is, for those facilities that rely more heavily on water as an input resource in their manufacturing operations.

Next, Hypothesis 2(a) seeks to assess the effect of water scarcity on the toxic releases to water. To evaluate Hypothesis 2(a), we refer to columns (2) and (5) of Table 2 and observe that the coefficients of *Ln(Total Weeks)* are not significant. We also note that the magnitude of these coefficients (i.e., 0.0008 and 0.0022) are much smaller than the corresponding coefficients observed in columns (1) and (4) (i.e., −0.0167 and −0.0220), which suggests that the effect of water scarcity on toxic releases to water is lower than the effect of water scarcity on total toxic releases to all media combined. These results indicate that water scarcity had no discernible impact on the toxic chemicals that were released to water. Thus, we do not find support for Hypothesis 2(a). (Later, in the post hoc analysis (i.e., Section 6.3), we will discuss this seemingly counterintuitive result in detail.)

Hypothesis 2(b) seeks to assess the impact of water scarcity on toxic chemical releases into media other than water. To test this hypothesis, we examine column (3) of Table 2. We observe that the coefficient of *Ln(Total Weeks)* is negative (−0.0197) and significant ($p < 0.01$), with a 95% CI [−0.0315, −0.00784]. This result supports Hypothesis 2(b) because it indicates that water scarcity lowers toxic chemical releases into media other than water. In column (3) of Table 2, a one standard deviation increase in *Ln(Total Weeks)* lowers the average of those toxic releases of each chemical at a facility by 2.93%.

Additionally, from the results in column (6) of Table 2 for releases to other media by manufacturing facilities that released toxic chemicals into water during 2000–2016, we see that the coefficient of *Ln(Total Weeks)* is negative (−0.0273) and significant ($p < 0.001$), with a 95% CI [−0.0427, −0.0119]. Thus, the evaluation of Hypothesis 2(b) shows that the effect of water scarcity manifests itself mainly in the form of reductions in toxic chemicals that are released into media other than water.

6.2. Robustness Tests

A common concern in empirical studies relates to the endogeneity of the treatment. But endogeneity is not a concern in our setting because the treatment (i.e., drought) results from natural circumstances, which makes the treatment exogenous. Similarly, reverse causality is also not a concern because a single firm's toxic releases would hardly have any bearing on regional water scarcity. Nevertheless, other factors could bias our results, and to alleviate some of these threats to our analysis, we describe select tests that provide additional confirmatory evidence for our results.

6.2.1. Propensity to Be Affected by Water Scarcity. Manufacturing facilities that release toxic chemicals into water may rely more on water as an input resource than manufacturing facilities that do not release toxic chemicals into water. Moreover, these two classes of manufacturing facilities could differ along dimensions such as industry classification, production volume, processes, and products.

To ensure that our results are not driven by systematic differences between facilities that release toxic chemicals into water and those that do not release any toxic chemicals into water, we use a propensity score matching (PSM) approach with the nearest three neighbor (NN3) algorithm to minimize the differences

between such manufacturing facilities (using the nearest five neighbor (NN5) algorithm also provides similar results). The idea behind this matching approach is that each facility that releases toxic chemicals to water is matched with three similar facilities that did not (Heckman et al. 1997).

We generate a matched sample of manufacturing facilities that did not release toxic chemicals to water but are otherwise similar (with respect to their observed characteristics) to manufacturing facilities that did release toxic chemicals into water (Heckman et al. 1997). For the PSM, we use *Ln(Production Ratio)*, *Facility Three-Digit Primary NAICS Code*, chemical, and *EMS* as the matching variables. The reduction in bias across these covariates ranges between 37.3% and 66.4%. (Figure A1 in the online appendix illustrates the standardized reduction in bias.) We repeat the analyses conducted in Section 5.2 and present the results in Table A2 in the online appendix. These results are essentially similar to our main results reported in Table 2, which provides additional validity for our findings.

6.2.2. Robustness of the Water Scarcity Measure. We measured water scarcity as the total number of weeks of D2, D3, and D4 drought experienced by facility i in year t. As a robustness check, we use two alternative measures of water scarcity.

First, we use the D3 and D4 categories that indicate extreme drought and exceptional drought based on the typology used by USDM. The D3 and D4 categories correspond to drought with widespread water shortages or restrictions and with water levels that result in economic losses in the affected regions. We measured water scarcity as the total number of weeks in D3 and D4 drought experienced by facility i in year t and repeat our analysis. These results are shown in Table 3 and they are essentially similar to our main results in Table 2.

We also examined whether the coefficients for the weeks in extreme drought (Table 3) are significantly different from the coefficients for weeks in severe drought (Table 2). To do so, we use the methods developed by Clogg et al. (1995) for comparing regression coefficients between models, which has also been used in several other studies (see e.g., Klingebiel and Rammer 2014, Jeziorski and Moorthy 2018), and find that there is no significant difference between the coefficients.

Second, we use data from TCEQ on the water rationing mandates issued by public water systems (PWSs) in Texas. The PWSs work with the

Table 3. Regression Results for Water Scarcity Measured in Weeks of D3 and D4 Drought

	All plants			Plants with water releases			Plants without water releases
Dependent variable →	*Ln(Toxic Releases)* (1)	*Ln(Toxic Releases to Water)* (2)	*Ln(Toxic Releases to Other)* (3)	*Ln(Toxic Releases)* (4)	*Ln(Toxic Releases to Water)* (5)	*Ln(Toxic Releases to Other)* (6)	*Ln(Toxic Releases)* (7)
Lag. Ln(Total Weeks in Extreme Drought) – β_1	−0.0146*	0.0014	−0.0184**	-0.0204*	0.0033	−0.0273**	−0.0106
	(0.007)	(0.003)	(0.007)	(0.009)	(0.005)	(0.010)	(0.010)
Lag. Ln(Production Ratio) – β_2	0.5174***	0.0236	0.5073***	0.4891***	0.0447+	0.4701***	0.5353***
	(0.032)	(0.014)	(0.032)	(0.041)	(0.025)	(0.041)	(0.050)
Lag. Ln(Toxicity Ratio) – β_3	0.0434***	0.0050**	0.0424***	0.0220**	0.0112**	0.0195**	0.0614***
	(0.005)	(0.002)	(0.005)	(0.007)	(0.004)	(0.007)	(0.008)
Lag. EMS used in last 3 years – β_4	-0.0150	0.0244	-0.0215	-0.0047	0.0298	-0.0116	-0.0263
	(0.026)	(0.017)	(0.026)	(0.031)	(0.026)	(0.031)	(0.044)
Lag. Tenure of Certifying Officer – β_5	(0.000)	(0.002)	0.001	0.001	(0.003)	0.0033	0.005
	(0.004)	(0.002)	(0.004)	(0.005)	(0.003)	(0.005)	(0.006)
Lag. Tenure of Technical Person – β_6	0.002	(0.002)	0.001	0.006	(0.004)	0.0051	(0.006)
	(0.004)	(0.002)	(0.004)	(0.005)	(0.004)	(0.005)	(0.006)
Constant	5.4678***	0.7382+	5.1574***	7.3597***	1.2469*	6.8249***	5.9129***
	(0.474)	(0.410)	(0.479)	(0.632)	(0.617)	(0.647)	(0.484)
Controls							
Facility Three Digit NAICS Code	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Facility-Chemical Pair Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.878	0.847	0.876	0.870	0.836	0.870	0.882
Adusted R^2	0.860	0.825	0.858	0.854	0.815	0.853	0.861
Facility-Chemical Pairs	13,854	13,854	13,854	7,390	7,390	7,390	6,463
Number	108,964	108,964	108,964	66,508	66,508	66,508	42,456

Note. We report coefficient estimates with standard errors clustered at the facility–chemical level in parentheses.
$+p < 0.10$; $*p < 0.05$; $**p < 0.01$; $***p < 0.001$.

government bodies during periods of drought to impose water rationing mandates, to establish drought contingency plans and reporting, and to provide educational materials and emergency management services. The water rationing mandates represent the regulatory response to manage water resources (as opposed to drought, which indicates the limited local availability of water resources). TCEQ monitors and reports information on all the water rationing mandates imposed by PWSs in Texas. Since TCEQ only records the number of water rationing mandates and not the duration of each mandate, we measure water scarcity as the total number of water rationing mandates experienced by each county in year t. We repeat our analysis using this alternative measure for water scarcity. These results, shown in Table A3 in the online appendix, are similar to our main results in Table 2, which provides additional support for our findings.

For completeness, we include both the total number of weeks in drought and the total number of water rationing mandates as measures of water scarcity in our specifications and repeat our analysis. These estimation results are shown in Table 4. We observe that the impact of the total weeks in drought remains essentially similar to our main results. However, the impact of total number of rationing-related variables loses significance in several models. As a result, we continue to report our main results only with the drought-related variables.

We undertook two additional tests that include examining our regression models with first difference estimates and incorporating nonparametric facility and chemical trends. These results are presented in the online appendix Tables A4 and A5, respectively. Our results and inference remain essentially the same with these additional tests.

6.3. Post Hoc Analysis

6.3.1. Examining the Impact of Water Scarcity on Toxic Releases to Water. Our results give rise to a natural question: Why do firms fail to reduce their toxic releases to water in the presence of water scarcity even though they do reduce their releases to other media? Although we provided theoretical arguments (in the development of Hypothesis 2(b)) for why water scarcity could induce lower releases to media other than water, they do not explain the lack of an

Table 4. Regression Results for Water Scarcity Measured with Weeks in Drought and Rationing Mandates

	All plants			Plants with water releases			Plants without water releases
Dependent variable →	*Ln(Toxic Releases)* (1)	*Ln(Toxic Releases to Water)* (2)	*Ln(Toxic Releases to Other)* (3)	*Ln(Toxic Releases)* (4)	*Ln(Toxic Releases to Water)* (5)	*Ln(Toxic Releases to Other)* (6)	*Ln(Toxic Releases)* (7)
Lag. Ln(Total Weeks in Drought) – β_1	−0.0146*	0.0009	−0.0175**	−0.0177*	0.0023	−0.0229**	−0.0158
	(0.006)	(0.003)	(0.006)	(0.008)	(0.005)	(0.008)	(0.010)
Lag. Ln(Total Rationing Mandates in County) – β_2	−0.0096	−0.0009	−0.0099	−0.0194+	−0.0009	−0.0201+	0.0070
	(0.009)	(0.005)	(0.009)	(0.011)	(0.008)	(0.012)	(0.014)
Lag. Ln(Production Ratio) – β_3	0.5172***	0.0235	0.5071***	0.4890***	0.0446+	0.4700***	0.5357***
	(0.032)	(0.014)	(0.032)	(0.041)	(0.025)	(0.041)	(0.050)
Lag. Ln(Toxicity Ratio) – β_4	0.0434***	0.0050**	0.0423***	0.0220**	0.0112**	0.0195**	0.0614***
	(0.005)	(0.002)	(0.005)	(0.007)	(0.004)	(0.007)	(0.008)
Lag. EMS used in last 3 years – β_5	−0.0153	0.0245	−0.0219	−0.0043	0.0301	−0.0115	−0.0274
	(0.026)	(0.017)	(0.026)	(0.031)	(0.026)	(0.031)	(0.044)
Lag. Tenure of Certifying Officer – β_6	(0.000)	(0.002)	0.001	0.002	(0.003)	0.0038	0.005
	(0.004)	(0.002)	(0.004)	(0.005)	(0.003)	(0.005)	(0.006)
Lag. Tenure of Technical Person – β_7	0.002	(0.002)	0.001	0.006	(0.004)	0.0052	(0.006)
	(0.004)	(0.002)	(0.004)	(0.005)	(0.004)	(0.005)	(0.006)
Constant	5.5130***	0.7364+	5.2104***	7.4245***	1.2414*	6.9041***	5.9573***
	(0.475)	(0.410)	(0.480)	(0.632)	(0.618)	(0.647)	(0.485)
Controls							
Facility Three Digit NAICS Code	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Facility-Chemical Pair Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.878	0.847	0.876	0.870	0.836	0.870	0.882
Adusted R^2	0.860	0.825	0.858	0.854	0.815	0.853	0.861
Facility-Chemical Pairs	13,854	13,854	13,854	7,390	7,390	7,390	6,463
Number	108,964	108,964	108,964	66,508	66,508	66,508	42,456

Note. We report coefficient estimates with standard errors clustered at the facility–chemical level in parentheses.
$+p < 0.10$; $*p < 0.05$; $**p < 0.01$; $***p < 0.001$.

effect for releases to water (counter to the proposition of Hypothesis 2(a)). Here we explore the apparent paradox further. The rationale can be linked to the idea that water scarcity induces a scarcity mindset (Shah et al. 2012), which directs attention to the conservation of water. Because water is an essential element in many production settings, water conservation efforts can often trigger broader waste reductions or efficiency improvements across manufacturing processes. It may be possible that firms may require significant effort or investment to reduce toxic chemicals that are released to water (e.g., installing wastewater treatment, adopting countercurrent systems). Reducing releases into other media may be less costly, on average, and firms may find it valuable to exert effort to reduce releases to water only when water scarcity is persistent.

To test this notion, we undertook additional analysis to assess whether firms in more persistently drought-prone counties exhibited a stronger response to perceived scarcity than firms in less drought-prone counties. The analysis starts by identifying the top quintile of counties in terms of observations with higher drought incidence. In our data, 88 counties experienced at least 267 weeks of drought during 2000–2016, meaning that these 88 counties were in drought for more than 30% of the study period. We repeated our main analysis for the firms in these 88 counties, and the results are shown in Table 5. We observe that the coefficients of *Ln(Total Weeks)* for *Ln(Toxic Releases to Water)* in columns (2) and (5) of Table 5 are negative (−0.0143, −0.0319) and significant ($p < 0.01$, $p < 0.01$). On the other hand, we do not find any significant effects for *Ln(Toxic Releases)* and *Ln(Toxic Releases to Other).*

Next, we identified the bottom quintile of counties that had the lowest drought incidence. In our data, 24 counties experienced no more than 184 weeks of drought during 2000–2016, meaning that these 24 counties were in drought for less than 21% of the study time period. We repeated the regression analysis for these 24 counties, and these results are in Table A6 in the online appendix. We see that the coefficients of *Ln(Total Weeks)* are not significant in any of our regression models, which suggests that a low incidence of water scarcity does not spur a reduction in releases to any media.

Finally, we repeated our main analysis for the remaining data, which correspond to 63 counties with intermediate drought incidence in our data. These

Table 5. Regression Results for Counties with Higher Incidence of Drought (Top Quintile of Observations)

	All plants			Plants with water releases			Plants without water releases
Dependent variable →	*Ln(Toxic Releases)* (1)	*Ln(Toxic Releases to Water)* (2)	*Ln(Toxic Releases to Other)* (3)	*Ln(Toxic Releases)* (4)	*Ln(Toxic Releases to Water)* (5)	*Ln(Toxic Releases to Other)* (6)	*Ln(Toxic Releases)* (7)
Lag. Ln(Total Weeks in Drought) – β_1	−0.0068	−0.0143**	−0.0062	0.0028	−0.0319**	0.0054	−0.0166
	(0.013)	(0.005)	(0.013)	(0.019)	(0.011)	(0.019)	(0.017)
Lag. Ln(Production Ratio) – β_2	0.4687***	0.0480	0.4672***	0.3858***	0.1315	0.3821***	0.5168***
	(0.071)	(0.032)	(0.071)	(0.109)	(0.086)	(0.109)	(0.093)
Lag. Ln(Toxicity Ratio) – β_3	0.0450***	0.0018	0.0462***	0.0451**	0.0081	0.0483**	0.0439**
	(0.010)	(0.002)	(0.010)	(0.015)	(0.007)	(0.015)	(0.014)
Lag. EMS used in last 3 years – β_4	−0.0654	0.0295	−0.0720	−0.0737	0.0677	−0.0888	−0.0680
	(0.054)	(0.033)	(0.054)	(0.071)	(0.066)	(0.072)	(0.081)
Lag. Tenure of Certifying Officer – β_5	0.000	0.001	0.000	(0.005)	0.005	−0.0053	0.004
	(0.008)	(0.004)	(0.008)	(0.011)	(0.008)	(0.012)	(0.012)
Lag. Tenure of Technical Person – β_6	−0.0182**	0.002	−0.0210**	(0.008)	0.006	−0.0125	−0.0332**
	(0.007)	(0.004)	(0.007)	(0.010)	(0.007)	(0.010)	(0.010)
Constant	4.5979***	0.5052***	4.4516***	6.0276***	1.0090***	5.7311***	4.3336***
	(0.573)	(0.066)	(0.574)	(0.142)	(0.105)	(0.142)	(0.759)
Controls							
Facility Three Digit NAICS Code	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Facility-Chemical Pair Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R^{12}	0.902	0.879	0.898	0.886	0.866	0.880	0.909
Adusted R^{12}	0.887	0.860	0.883	0.872	0.849	0.866	0.893
Facility-Chemical Pairs	2,918	2,918	2,918	1,143	1,143	1,143	1,774
Number	22,328	22,328	22,328	10,704	10,704	10,704	11,624

Note. We report coefficient estimates with standard errors clustered at the facility–chemical level in parentheses.
$^{+}p < 0.10$; $^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$.

results are presented in Table A7 in the online appendix and they are aligned with the main results in Table 2.

Overall, the post hoc analysis confirms that facilities in counties with more frequent drought (Table 5) lowered their toxic releases into water. However, facilities with average incidence of drought (online appendix Table A7) lowered their toxic releases primarily into media other than water, and we observe no reduction in toxic releases for facilities with the lowest incidence of drought (online appendix Table A6).

An interesting feature of our results in Table 5 is that manufacturing facilities in counties with persistent water scarcity failed to lower their toxic releases into other media (i.e., land and air) as opposed to our main results presented in Table 2. These results could suggest that although persistent water scarcity draws attention to the management of water usage, persistent water scarcity also diverts attention away from other aspects of production that could affect toxic releases in general. This interpretation is consistent with Mullainathan and Shafir (2013), who point out that scarcity can drain managers' mental capacity and induce "tunneling," which is a single-minded focus on one particular problem while neglecting other matters that may actually be more important.

6.3.2. Examining Persistence of the Impact of Water Scarcity. Next, we analyze whether the reductions in toxic releases induced by water scarcity persist over time. To do so, we examine our regression models with multiple lag terms for the weeks in drought experienced by a county. The estimation results with the drought data lagged up to three years is shown in Table A8 in the online appendix. These results indicate that the effect of water scarcity persists for two years across all facilities in Texas and for three years for facilities with toxic releases to water. Additional analysis (not presented here, but can be made available on request) indicates that drought that occurred four years earlier (or more) does not have a significant impact on toxic releases.

6.4. Analysis of Mechanisms for Reduction in Toxic Releases

So far, we explored how water scarcity affects the toxic chemical releases of manufacturing facilities. Now, we turn to examine the potential mechanisms that may the drive reduction in toxic releases. Toward this end, we analyze information from the source reduction activity fields of the TRI data, which record the various modifications that facilities report having initiated to reduce specific toxic chemical releases at the source. Facilities are not mandated to report their source reduction activities (as opposed to toxic releases which are mandated by the EPA) and as a result there could be differences in the way in which facilities report their modifications. However, many papers have used this data to explore potential mechanisms (Dutt and King 2014) and likely sources (Berchicci et al. 2019) of waste reduction. The TRI data records 49 different types of modifications. We followed Dutt and King (2014) and classified the modifications into three categories:[2]

a. Management modifications involve changes to the management of manufacturing process (e.g., implemented inspection or monitoring program of potential spill or leak sources).

b. Technology modifications pertain to changes in plant equipment or product design (e.g., modified or installed rinse system).

c. Input modifications represent changes or substitution of materials used in manufacturing (e.g., changed to aqueous cleaners from solvents or other materials).

Consistent with Nelson and Winter's (1982) synthesis on the challenges of adopting more disruptive change, we anticipate that management modifications that mainly involve changes to internal routines will be easier to initiate, whereas technology modifications that may entail investments or process changes and input modifications that may have cost as well as quality implications would be more difficult to initiate. Then, we examine whether water scarcity induces facilities to undertake specific types of modifications using the following specification:

$$\begin{aligned} Ln(Modification_m)_{cit} = \alpha_0 + \beta_1 Ln(Total\ Weeks)_{i(t-1)} \\ + \gamma \boldsymbol{X}_{ci(t-1)} + \delta_1 NAICS_i \\ + \delta_2 FC_{ci} + \delta_3 YR_t + \varepsilon_{cit}, \end{aligned} \tag{4}$$

where $Ln(Modification_m)$ is the natural logarithm of the count of modification of type m (i.e., count of management, technology, or input modification). The rest of the terms are as defined in Equation (1). We estimate specification (4) for water scarcity measured as $Ln(Total\ Weeks)_{it}$ (i.e., weeks in drought at level D2, D3, and D4) and $Ln(Total\ Weeks–Extreme\ Drought)_{it}$ (i.e., weeks in drought at level D3 and D4) and these results are shown in Tables 6 and 7, respectively.

From Table 6, we observe that the coefficients of *Ln(Total Weeks)* in columns (1) and (2) are positive (0.0019, 0.0006) and significant ($p < 0.01$, $p < 0.05$). Thus, across all facilities, water scarcity seems to induce more management and technology modifications. For plants with toxic releases to water, the coefficient of *Ln(Total Weeks)* in column (5) is positive (0.0016) and significant ($p < 0.001$), which indicates that water scarcity induces such facilities to undertake more technology modifications. For plants without any toxic releases to water, the coefficient of *Ln(Total Weeks)* in column (7) is positive (0.0060) and

Table 6. Results for Impact of Water Scarcity on Modifications

	All plants			Plants with water releases			Plants without water releases		
Dependent variable →	*Ln(Management Modifications)* (1)	*Ln(Technology Modifications)* (2)	*Ln(Input Modifications)* (3)	*Ln(Management Modifications)* (4)	*Ln(Technology Modifications)* (5)	*Ln(Input Modifications)* (6)	*Ln(Management Modifications)* (7)	*Ln(Technology Modifications)* (8)	*Ln(Input Modifications)* (9)
Lag. Ln(Total Weeks in Drought) – β_1	0.0019**	0.0006*	0.0000	−0.0010	0.0016***	0.0002	0.0060***	−0.0004	−0.0002
	(0.001)	(0.000)	(0.000)	(0.001)	(0.000)	(0.000)	(0.001)	(0.001)	(0.001)
Lag. Ln(Production Ratio) – β_2	0.0031	0.0009	−0.0043**	0.0017	−0.0029	−0.0031+	0.0069	0.0061*	−0.0058**
	(0.003)	(0.002)	(0.001)	(0.004)	(0.002)	(0.002)	(0.006)	(0.002)	(0.002)
Lag. Ln(Toxicity Ratio) – β_2	0.0001	−0.0002	0.0000	0.0012+	−0.0007	0.0001	−0.0009*	0.0001	0.0000
	(0.000)	(0.000)	(0.000)	(0.001)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Lag. EMS used in last 3 years – β_3	0.0525***	0.0128***	0.0122***	0.0475***	0.0141***	0.0106***	0.0644***	0.0111***	0.0156***
	(0.004)	(0.002)	(0.002)	(0.005)	(0.002)	(0.002)	(0.006)	(0.003)	(0.004)
Lag. Tenure of Certifying Officer – β_4	(0.000)	−0.0003+	−0.0009***	0.0009*	(0.000)	−0.0009***	−0.0016*	(0.001)	−0.0008*
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.001)	(0.000)	(0.000)
Lag. Tenure of Technical Person – β_5	(0.001)	0.000	0.000	0.000	0.000	0.000	−0.0019*	0.000	(0.000)
	(0.001)	(0.000)	(0.000)	(0.001)	(0.000)	(0.000)	(0.001)	(0.000)	(0.000)
Constant	0.0699***	−0.0019	−0.0201	−0.0033	−0.0016	0.0382+	0.0322	0.0413*	0.0258+
	(0.017)	(0.015)	(0.014)	(0.025)	(0.009)	(0.020)	(0.027)	(0.021)	(0.015)
Controls									
Facility Three Digit NAICS Code	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Facility-Chemical Pair Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.557	0.419	0.422	0.507	0.363	0.444	0.598	0.475	0.398
Adusted R^2	0.492	0.335	0.337	0.445	0.283	0.374	0.526	0.379	0.289
Facility-Chemical Pairs	13,854	13,854	13,854	7,390	7,390	7,390	6,463	6,463	6,463
Number	108,960	108,960	108,960	66,507	66,507	66,507	42,453	42,453	42,453

Note. We report coefficient estimates with standard errors clustered at the facility–chemical level in parentheses.
$+p < 0.10$; $^*p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$.

Table 7. Results for Impact of Water Scarcity (D3 and D4 Level of Drought) on Modifications

	All plants			Plants with water releases			Plants without water releases		
Dependent variable →	*Ln(Management Modifications)* (1)	*Ln(Technology Modifications)* (2)	*Ln(Input Modifications)* (3)	*Ln(Management Modifications)* (4)	*Ln(Technology Modifications)* (5)	*Ln(Input Modifications)* (6)	*Ln(Management Modifications)* (7)	*Ln(Technology Modifications)* (8)	*Ln(Input Modifications)* (9)
Lag. Ln(Tot. Wks- Extreme Drought) – β_1	0.0009	0.0007*	0.0007+	−0.0006	0.0022***	0.0011*	0.0035***	−0.0008	0.0005
	(0.001)	(0.000)	(0.000)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Lag. Ln(Production Ratio) – β_2	0.0031	0.0009	−0.0043**	0.0017	−0.0029	−0.0031+	0.0069	0.0061*	−0.0058**
	(0.003)	(0.002)	(0.001)	(0.004)	(0.002)	(0.002)	(0.006)	(0.002)	(0.002)
Lag. Ln(Toxicity Ratio) – β_2	0.0001	−0.0002	0.0000	0.0012+	−0.0007	0.0001	−0.0010*	0.0001	0.0000
	(0.000)	(0.000)	(0.000)	(0.001)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Lag. EMS used in last 3 years – β_3	0.0525***	0.0127***	0.0121***	0.0475***	0.0139***	0.0105***	0.0641***	0.0111***	0.0156***
	(0.004)	(0.002)	(0.002)	(0.005)	(0.002)	(0.002)	(0.006)	(0.003)	(0.004)
Lag. Tenure of Certifying Officer – β_4	(0.000)	−0.0003+	−0.0009***	0.0008*	(0.000)	−0.0008***	−0.0017*	(0.001)	−0.0008*
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.001)	(0.000)	(0.000)
Lag. Tenure of Technical Person – β_5	(0.001)	0.000	0.000	0.000	0.000	0.000	−0.0019*	0.000	(0.000)
	(0.001)	(0.000)	(0.000)	(0.001)	(0.000)	(0.000)	(0.001)	(0.000)	(0.000)
Constant	0.0752***	−0.0002	−0.0202	−0.0059	0.0026	0.0387*	0.0515+	0.0405+	0.0246
	(0.017)	(0.015)	(0.014)	(0.024)	(0.009)	(0.019)	(0.027)	(0.021)	(0.016)
Controls									
Facility Three Digit NAICS Code	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Facility-Chemical Pair Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.556	0.419	0.422	0.507	0.363	0.444	0.598	0.475	0.398
Adusted R^2	0.492	0.335	0.337	0.445	0.283	0.374	0.525	0.379	0.289
Facility-Chemical Pairs	13,854	13,854	13,854	7,390	7,390	7,390	6,463	6,463	6,463
Number	108,960	108,960	108,960	66,507	66,507	66,507	42,453	42,453	42,453

Note. We report coefficient estimates with standard errors clustered at the facility–chemical level in parentheses.
$+p < 0.10$; $^*p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$.

significant ($p < 0.001$), which suggests that water scarcity induces such facilities to undertake more management modifications.

From Table 7, we observe that the coefficients of *Ln(Total Weeks–Extreme Drought)* in columns (2) and (3) are positive (0.0007, 0.0007) and significant ($p < 0.05$, $p < 0.10$), which suggests that extreme drought induces more technology and input modifications across all facilities. For plants with toxic releases to water, the coefficient of *Ln(Total Weeks–Extreme Drought)* in columns (5) and (6) are positive (0.0022, 0.0011) and significant ($p < 0.001$, $p < 0.05$), which suggest that extreme drought induces such facilities not only to undertake more technology modifications but also more input modifications. For plants without any toxic releases to water, the results for severe drought are similar to what we observe in Table 6.

Although the previous analysis (in Tables 6 and 7) shows the link between drought and modifications, it does not link modifications with reduction in toxic releases. Therefore, we undertook instrumental variables (IV) analysis to study the underlying potential mechanism, while accounting for the potential endogeneity of the modification variables. We instrument the modification variables for each chemical with the average number of modifications for the same chemical undertaken at all facilities within the county in the same year. We validate that our instruments satisfy the inclusion and exclusion restrictions. We present the details of the IV analysis in Tables A9 and A10 in the online appendix, which provides evidence consistent with the potential causal link between drought, modifications, and the subsequent reduction in toxic releases.

Overall, our results indicate that all facilities respond to water scarcity with some form of modifications in their manufacturing processes. Additionally, there are differences in how plants with water releases and plants without water releases respond to water scarcity—the former focus more on technology and input modifications, whereas the latter focus mainly on management modifications, which suggests that plants with water releases are willing to undertake more disruptive changes in response to water scarcity than plants without water releases.

7. Discussion and Conclusions

Many scientists have warned about the economic effects resulting from impending climate change and environmental disasters (United Nations 2017). Yet, much remains to be explored about how these shifting environmental conditions may shape manufacturing activity. Our study contributes to this stream of literature by demonstrating that water scarcity can induce manufacturing facilities to improve their environmental performance by lowering toxic releases.

Additionally, our results show that the impact of water scarcity is observed mainly at those manufacturing facilities that release toxic chemicals to water. At a more granular level, we observe that the effect of water scarcity induces manufacturing facilities to reduce their toxic releases to media other than water. Further, we observe that firms only lower the toxic releases they discharge to water when they face persistent drought. Thus, we add to the literature by illustrating the various conditions under which water scarcity can affect environmental outcomes for manufacturing facilities. In Figure 2, we summarize the main results of our study.

To understand why water scarcity induces manufacturing facilities to further reduce their toxic emissions into media other than water, we return to the notion that shortage of water can direct more attention toward water conservation. Since water is commonly used in several manufacturing activities, the conservation efforts could spur waste reductions (or efficiency improvement) across production processes that also lower toxic emissions into media other than water. Two explanations illustrate this rationale. First, water conservation can reduce energy requirements and thereby lower toxic releases from energy generation, which are often released to other media (i.e., air and land). For instance, Rajaram and Corbett (2002) analyze environmental improvements at a food processing plant in the Netherlands and observed that across eight waves of water conservation, the plant also realized significant (i.e., nearly 30%) reduction in energy consumption. Second, in the process of reducing water use, plants may institute process modifications that lower toxic releases to other media. For instance, when Woodward (an aerospace parts manufacturer) switched from an acid-based passivation system for its stainless steel parts to a citric passivation system (see FMA 2016), the firm not only realized significant reduction in water use but also obtained reductions in air emissions associated with its exhaust and cooling systems.

Our study could have implications for shaping regulatory policies. Regulatory bodies use a variety of tools (e.g., penalties, inspections, reporting mechanisms) to ensure that manufacturing facilities comply with regulations. These enforcement and monitoring approaches have garnered significant success (Gray and Shimshack 2011). For instance, the EPA maintains that these traditional regulatory approaches helped the United States prevent more than several billion pounds of emissions in 2017.[3]

However, more recently, research indicates that firm-level voluntary approaches can also complement the traditional regulatory approaches to lower

pollution (Innes and Sam 2008). Our results are relevant for policymakers because they highlight that water scarcity stimulates a broader mechanism of operational improvements that encourage reduction in toxic releases across water as well as other media. Policymakers can leverage locally relevant scarcity messaging (using social and news media) under conditions of drought to induce a scarcity mindset (Shah et al. 2012, Mani et al. 2013) that spurs wide-ranging operational improvements. For instance, communicating the scarcity of water could encourage production personnel to find ways to reduce waste in general. Although subtle, such behavioral nudges can provide a boost to environmental efforts (Thaler and Sunstein 2008, Allcott and Mullainathan 2010). Our finding that water scarcity has little effect on releases at plants with no releases to water suggests that such scarcity messaging needs to be tailored to focus on resources that are salient to the target plant. Emphasizing shortages of certain key inputs may stimulate waste reduction efforts at plants where those inputs are key. Nevertheless, we recognize that policy interventions could lead to unintended consequences (e.g., Cushing et al. 2018), and therefore suggest that scarcity-related policy interventions should be carefully evaluated before extensive adoption.

Our study is not without limitations, but we hope these could be addressed in future research. First, in our analysis, we use the total weeks of drought or the number of rationing mandates as a measure of the water scarcity faced by manufacturing firms. Although this is a reasonable initial approximation, future studies can examine water scarcity at a more granular level.

Second, our analysis used the temporal and spatial variability in the degree of water scarcity to assess the impact on toxic releases. Although these results could be relevant for regions across the world that face varying levels of water shortage over time, the impact of chronic water scarcity may be different. We believe this could be a fruitful avenue for future research.

Third, we examined whether our results hold in other states in the United States that do not experience drought-like conditions similar to Texas. We analyzed manufacturing facilities in Ohio and Florida and find that water scarcity does not significantly affect toxic releases of manufacturing facilities in either state. On average, facilities in Ohio and Florida experience 0.72 and 5.12 weeks of drought, respectively, much lower than the 12.95 weeks of average annual drought experienced by facilities in Texas. We speculate that the effect of drought on manufacturing activity may only occur once the frequency of drought exceeds some threshold. Finally, though we were able to incorporate data on local water rationings in Texas, we note that information on rationing measures is not carefully tracked across the rest of the United States. Analyzing the differences in the impact of water scarcity across different geographies can be an interesting area for further study.

Fourth, we did not observe the actual source reduction activities, the changes to production processes, or the investments made within manufacturing facilities in response to water scarcity; the TRI data on modifications are at best an imperfect proxy. We hope future studies can collect more detailed information on specific source reduction activities, modifications, and investments within production processes to provide deeper insights on how water scarcity shapes production processes and the deployment of resources in manufacturing facilities.

Fifth, our analysis uses facility–chemical and year fixed effects to control for the scarcity effects of other unobserved factors. However, if such other factors are also correlated with water scarcity, then our analysis cannot account for the impact of such correlated unobserved factors.

Finally, our investigation focuses only on water scarcity. But scarcity may also extend to other factors such as raw materials, energy, or production technologies. It remains to be seen whether the scarcity of other factors produces similar or differing implications for environmental and operational performance. We hope our study spurs further investigation on the implications of scarcity for manufacturing firms.

Acknowledgments

The authors thank S. Gopinath from SNC Lavalin for valuable inputs, and A. Appling from the U.S. Geological Survey (Data Science Branch) for inputs on data sources related to water scarcity. The authors are grateful to the three anonymous reviewers, the associate editor, and the editor for their helpful comments and suggestions. S. Muthulingam and S. Dhanorkar thank the Center for the Business of Sustainability at Penn State's Smeal College of Business for support. Author names are listed in reverse alphabetical order. All authors contributed equally.

Endnotes

[1] See https://www.cdp.net/en/research/global-reports/global-water-report-2016.

[2] Specifically, we used the following codes for management modifications: W13, W14, W15, W19, W21, W22, W23, W24, W25, W29, W31, W32, W36, W39, W54, W55, W56, W63, W64; technology modifications: W33, W35, W50, W51, W52, W53, W57, W59, W60, W65, W66, W67, W68, W71, W72, W73, W74, W75, W78, W81, W82, W83, W84, W89; and input modifications: W41, W42, W43, W49, W58, W61. For details, see Environmental Protection Agency (2018)

[3] See https://www.epa.gov/enforcement/enforcement-annual-results-analysis-and-trends-fiscal-year-2017.

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