The Effectiveness of Overlapping Pollution Regulation: Evidence from the Ban on Phosphate in Dishwasher Detergent

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Abstract

This paper examines the failure of command-and-control pollution policies in the presence of overlapping regulations. We study the case of recent bans on phosphate in household dishwasher detergent. We show that the effectiveness of the bans in reducing effluent depends critically on existing pollution regulations at receiving wastewater treatment facilities. Some facilities face limits on how much phosphorus they can emit. As cost minimizers, limit facilities face no incentive to deviate from this standard. Using novel datasets on wastewater treatment facilities, we show that bans have weak effects on phosphorous effluent, especially in the most polluted waterways.

Keywords: Environmental Regulation, Policy Interactions, Water Quality, Phosphorous

JEL Codes: Q50, Q53, Q58, H11, H23, D23

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“Although household dishwasher detergent constitutes just one source, restricting its phosphorus content to a nominal level would be a simple way to reduce the overall amount that ends up in the State's lakes, rivers, and streams.” (Michigan State Senate Fiscal Agency 2007, 2)[1]

1 Introduction

Command-and-control approaches remain the dominant form of U.S. environmental policy. This dominance continues despite several decades of theoretical and empirical evidence that challenges these approaches for failing to meet desirable criteria, such as cost-effectiveness and/or economic efficiency. A key reason for the continued use of these direct regulations is that they are often thought to provide a simple, definitive way to achieve a desired environmental quality.[2] However, the management of pollution is often complicated by a patchwork of policies crafted within and across various levels of government. In this type of setting, even the simplest command-and-control policies may not be able to achieve intended reductions in pollution.

This paper explores the effectiveness of command-and-control policies in the presence of overlapping regulation through the case of recent state-level bans on the sale of high-phosphate household dishwasher detergent. The control of nutrient pollution has become a major focus of the U.S. Environmental Protection Agency (US EPA), as well as numerous state environmental agencies. Excess phosphorous pollution in waterways can lead to noxious and unsightly algal blooms, which affect both wildlife and humans.[3] Rough estimates place damages from freshwater eutrophication, caused by excess phosphorous, at several billion dollars per year (Dodds et al. 2009). The standard logic for implementing bans is that banning household use of phosphates will provide a guaranteed reduction in phosphate loadings to waterways.

We show, both theoretically and empirically, that the effectiveness of such household-level bans critically depends upon existing pollution regulations at wastewater treatment facilities. Wastewater from households flows directly to wastewater treatment facilities (as influent), where it is treated and discharged into waterways (as effluent). Using a model of wastewater treatment

[1] This quote is from the supporting argument for Michigan Senate Bill 152 to ban the sale of phosphates in automatic dishwasher detergent.
[2] See Stavins (1998) for a more detailed discussion of command-and-control policies in the U.S.
[3] A recent “water crisis” in Toledo, Ohio, illustrates the importance of controlling phosphorous in waterways (Wines 2014). In the summer of 2014, excess phosphorous levels in portions of Lake Erie that provided drinking water for residents led to poisonous algal blooms that made tap water unsafe to drink for several days.

facility behavior, we show that facilities that face limits on how much phosphorous they can emit, will see smaller reductions in phosphorous effluent as a result of a ban, relative to facilities that do not face limits. Because it is costly to treat phosphorous, facilities that face limits choose to keep their phosphorous effluent at or just below the limit and will treat phosphorous less when phosphorous influent falls as a result of a ban.

Using a multi-state dataset, we test this prediction with a difference-in-difference approach that compares phosphorous effluent concentrations in facilities that faced phosphorous limits to those that did not before and after the ban. We find that phosphorous effluent concentration dropped two to four times as much at "no limit" versus "limit" facilities after the ban. We argue that these results are not driven by differential trends over time across limit versus no limit facilities. We do this by estimating the effect of "placebo" bans by re-defining the pre and post period as years before the ban took place. We find no differential effects in no limit versus limit facilities in these specifications, which suggests our main results are not driven by differential trends that are common over time.

To further validate our model, we utilize a unique wastewater treatment facility dataset from the state of Minnesota. These data provide both influent and effluent concentrations for individual facilities. With these data, we estimate an elasticity of effluent concentration with respect to influent concentration. Our model predicts that effluent should be more responsive to changes in influent, whether from a ban in phosphates in dishwasher detergent or any other source, at no limit facilities. As expected, facilities without limits display a much greater response to observed changes to influent. Our preferred estimates place a lower bound of the elasticity of effluent to influent for no limit facilities of approximately 0.50. For limit facilities, elasticity estimates are statistically insignificant and roughly 0.10 in magnitude. The Minnesota dataset also lets us test whether the results in the multi-state dataset are driven by differential changes in influent across limit versus no limit facilities as a result of the ban.[4] Using the Minnesota dataset, we find no evidence of a differential effect of the ban on influent across limit

[4] For example, suppose no limit facilities are more likely to treat water coming from more residential areas, which are likely to be more affected by the ban. In this case, no limit facilities will see a larger drop in effluent as a result of the ban, not because they face different incentives but simply because they see a larger drop in influent.

versus no limit facilities. Furthermore, we find that both limit and no limit facilities see a drop in influent that is within the range of engineering estimates of the effect of the ban.[5]

Finally, we use measures of the elasticity of influent to effluent and the share of influent treated by limit and no limit facilities to quantify the impact of the ban on reducing phosphorous effluent. We calculate that for a 1 percent decrease in phosphorous influent across all facilities, total phosphorous effluent falls by 0.41 to 0.76 percent. This range reflects current estimates that place 24 percent of all influent at limit facilities. However, if we focus attention on impaired waterways, the proportion of limit facilities increases. This is because facilities that have limits tend to serve those waterways where pollution is a high priority. For example, if we restrict our analysis to impaired waterways in the state of Minnesota, the share of limit facilities increases to 30 percent in 2010 and then rises substantially to 79 percent in 2014. This suggests that the ban has become even more ineffective in these areas over time. In 2014, our results suggest that for every 1 percent of phosphorus influent reduced in impaired waterways, phosphorus effluent has been reduced by just 0.18 to 0.21 percent. A key objective of influent reduction policies, such as phosphate bans, is to reduce phosphorus effluent. However, our results suggest that these types of policies are misplaced, particularly in areas that are already subject to strict phosphorus regulations.

This paper contributes to recent work that has explored unintended consequences of incomplete and overlapping pollution regulations (Becker and Henderson 2000; Copeland and Taylor 2005; Bushnell, Peterman, and Wolfram 2008; Fowlie 2009; Fowlie 2010; Goulder and Stavins 2011; Goulder, Jacobsen, and van Benthem 2012; Baylis, Fullerton, and Karney 2014).[6] We extend the literature in five important ways. First, to our knowledge, we provide the first empirical results in which an implemented policy failed to meet targeted environmental improvements due to the structure of incomplete and overlapping pollution regulation. To date, much of the literature has focused on carbon policy and relied upon theoretical models and simulations to gauge the extent of potential carbon leakage. Second, our work is different in that there is no market response generating leakage; rather, the ineffectiveness of the environmental

[5] In addition, for the Minnesota sample, the estimated effect of the ban on effluent across limit and no limit facilities is very similar to the estimated effects from the multi-state analysis.

[6] This work focuses on uncoordinated regulations that target the control of the same pollutant. A related, but distinct, literature examines the issue of co-benefits of pollution regulations, where the targeted control of one pollutant results in the production or abatement of other pollutants (see, for example, Groosman, Muller, and O'Neill-Toy 2011).

policy is purely driven by overlapping and heterogeneous regulations. In this regard, our work is also different from the local air pollution literature in that we observe a policy failure that arises from a uniform policy (the ban) that overlaps with incomplete environmental regulations (wastewater treatment limits).[7] Third, we show that this failure occurs within the context of command-and-control regulations. This result is important considering the commonly held belief that command-and-control regulations provide guaranteed means to reduce pollution. As with Goulder and Stavins (2011), we show theoretically that a price instrument may alleviate the need to coordinate the present patchwork of policies. This finding contributes to an extensive body of literature that has generally extolled the advantages of market-based instruments over command-and-control approaches (Crocker 1968; Dales 1968; Montgomery 1972; Tietenberg 1980; Baumol and Oates 1988; Muller and Mendelsohn 2009). Fourth, while the existing literature has focused primarily on interactions between state and federal policies or between countries, our case is one in which regulations are primarily set within the same state. This finding is important, since the prior literature suggests that failures due to nested regulations within the U.S. are primarily driven by state and federal interactions (Goulder and Stavins 2011). As many policies are set at the state or local level, these interactions are likely important within and across all levels of government. Fifth, we provide evidence of a failure to take into account overlapping policies in a very simple setting. The water pollution policies we study focus on one pollutant and consist of two, relatively easy-to-understand levels of regulation set within the same state. Even in this simple environment, we find evidence of a failure to coordinate policies, which suggests such failures may be extremely common.

This paper also contributes to the literature on wastewater treatment facility behavior and the impact of regulations on these facilities (e.g., Earnhart 2004, 2007; Shimshack and Ward, 2005, 2008; Chakraborti and McConnell, 2012). We extend this work by highlighting the effect of overlapping regulations on wastewater treatment facilities.

Our results have important policy implications as well. Bans on household products with phosphates have been and continue to be a widely used tool for controlling phosphorous in

[7] This differs from Becker and Henderson (2000) who observe improvements in air quality in nonattainment counties at the expense of increases in air pollution in counties previously in attainment. Heterogeneous, not overlapping regulations causes the offsetting behavior. Similar to our work, Fowlie (2010) explores a uniform policy (the NO_x trading program) that overlaps with heterogeneous regulation (regulated and deregulated coal plants). However, in Fowlie (2010), a market response is responsible for the unintended consequences of these policies—in this case, the failure to minimize abatement costs and a shift in emissions to areas with air quality problems.

waterways in the U.S. In contrast to what we find, bans on phosphates in household laundry detergent starting in the 1970s had substantial impacts on phosphorous pollution. Basic research designs that compared mean effluent levels at wastewater treatment plants pre and post bans showed decreases in phosphorus loadings from wastewater treatment facilities that were proportional to expected changes in phosphorus influent (Maki, Porcella, and Wendt 1984; Booman and Sedlak 1986). However, these early studies examined the effectiveness of bans prior to the introduction of limits on phosphorus effluent at wastewater treatment facilities (Litke 1999). Our results suggest that, now that more wastewater treatment facilities have adopted limits, the impact of phosphate bans will have a small effect on phosphorous pollution. This includes bans on high-phosphate commercial dishwasher detergent, which are already being adopted in some states (Cleanlink News 2013).[8]

The rest of the paper proceeds as follows: Section 2 describes the main costs of phosphorous pollution, highlights the primary details of the phosphate ban and provides an overview of wastewater treatment regulations within the U.S. Section 3 outlines our model of wastewater treatment facility behavior and derives empirical predictions for limit and no limit facilities. Section 4 describes the multi-state and Minnesota datasets. Section 5 uses the multi-state dataset to estimate how phosphorous effluent changed after the ban across limit versus no limit facilities. Section 6 uses the Minnesota dataset to estimate elasticity of effluent to influent at limit and no limit facilities and test for any differential effect of the ban on influent across limit versus no limit facilities. Section 7 uses the elasticity estimates to calculate the total expected reduction in effluent given similar influent reduction policies. Section 8 concludes.

2 Phosphorus Pollution, Ban Details and Wastewater Treatment Regulations

2.1 Phosphorus Pollution and Ban Details

Phosphorus is an essential nutrient for plant growth in aquatic systems and occurs naturally at varying levels throughout world. However, excess phosphorus loads from anthropogenic sources can be problematic. At high levels, a process known as cultural eutrophication occurs and is

[8] However, our results do not extend to proposed bans on high-phosphate lawn fertilizer (Sewer, 2014). Phosphorous in water coming from lawns is not directly treated by wastewater treatment facilities and therefore not affected by limits at treatment facilities.

often marked by undesirable changes to the aquatic system.[9] The ubiquitous nature of the problem makes it one of the most important water quality issues today. Other nutrients may contribute to eutrophication. However, the prominent role that phosphorus plays in freshwater eutrophication is well established (Smith and Schindler 2009).

Although eutrophication is not a new phenomenon, renewed calls to address this major determinant of water quality have gained traction with state and federal policy makers. Effective July 2010, a group of 17 states banned the sale of automatic dishwasher detergent.[10] Following suit, the American Cleaning Institute (ACI) announced a similar voluntary national ban.[11] The rationale given for the policy often centered on two main points: 1) the ability of the ban to reduce phosphorus emissions (Washington State Department of Ecology 2013) and 2) cost savings to wastewater treatment facilities from a reduction in phosphorus influent (Walsh 2010). However, there is little evidence that the policy decision process considered how current wastewater treatment regulations would affect these outcomes. Of course, a fully robust welfare analysis of the policy would need to consider the costs that the ban places on households in the form of lost utility, the cost savings to wastewater treatment facilities and the benefits from reduced phosphorus concentrations in the aquatic system. Our paper addresses a key piece of this work and shows that the reductions in phosphorus emissions depend upon the regulatory structure in place.

The timing of the ban plays an important role in our multi-state identification strategy. We assume that differences in effluent between limit and no limit facilities pre and post ban capture the responses from these facilities to the ban. Although July 2010 is often stated as the effective date of the ban, several states included exclusions that allowed the sale of inventory for up to 60 days after this date. In addition, the laws banned the sale, but not the use of, automatic dishwasher detergents with phosphates. Thus, households may have had a limited inventory of high phosphate detergent purchased prior to the ban. The potential lags in both the sale and use of phosphates drive our empirical strategy, which compares effluent in 2009 to 2011. We remove

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[9] These changes include noxious and unsightly algal blooms, increased aquatic plant growth, alternations to fish species compositions, and a host of other adverse effects (US EPA 2000; Smith and Schindler 2009).

[10] The states that instituted the ban were Illinois, Indiana, Maryland, Massachusetts, Michigan, Minnesota, Montana, New Hampshire, New York, Ohio, Oregon, Pennsylvania, Utah, Vermont, Virginia, Washington and Wisconsin. The ban outlawed dishwasher detergent that was more than 0.5 percent phosphorus by weight. With traditional detergents containing 8-9 percent phosphorus by weight, these actions were viewed as a ban on phosphates.

[11] ACI describes itself as a trade group that represents the large majority of detergent manufacturers in the U.S. (ACI 2010).

2010 as an adjustment period. In the Appendix, we perform a number of robustness checks, all of which are consistent with this strategy.

2.2 Wastewater Treatment Regulations

Effluent from wastewater treatment facilities is primarily governed by individual emissions standards. Known as secondary treatment standards, the majority of plants face limits on total suspended solids (TSS), 5-day biochemical oxygen demand (BOD5) and pH. To address waterway impairments, state regulators have the authority to place additional limits on other types of pollution, including limits on phosphorus.

Although the ban focuses on household behavior, it essentially seeks to limit phosphorus loads from wastewater treatment facilities. Recent studies have estimated that these facilities contribute approximately 60 percent of total phosphorus loads from point sources (Maupin and Ivahnenko 2011). However, to put the contribution from dish detergent use in context with the greater phosphorus pollution problem, engineering estimates typically place dish detergent's contribution at roughly 10 percent of the total phosphorus influent to treatment facilities.[12] Furthermore, it is likely that the ban is far from cost-effective. Nonpoint sources of pollution, such as fertilizer runoff from farms, have become the primary cause of water quality impairment in the US (Olmstead 2010). There are likely large cost savings by moving future abatement control efforts from heavily regulated point sources to unregulated nonpoint sources (Olmstead 2010).

3 Model

3.1 Facility Optimization Problem

To motivate our empirical approach, we propose a simple model of wastewater treatment behavior. The objective of each facility i in time period t is to minimize abatement costs, $\left(C(\bullet)\right)$, subject to limits placed on phosphorus effluent ($\overline{phos_i}$) and another representative pollutant ($\bar{q}_i$). Abatement occurs through respective abatement functions for phosphorus ($phos_{it}^R(\bullet)$) and the other pollutant ($q_{it}^R(\bullet)$). Abatement costs and abatement functions are functions of inputs

[12] New York State Department of Environmental Conservation estimates this range at 9 to 34 percent (New York State Department of Environmental Conservation 2015). Washington State Department of Ecology estimates this figure at 10 to 12 percent (Washington State Department of Ecology 2013). State of Minnesota estimates this figure at 7 to 11 percent (Barr Engineering Company 2004).

(x_{it}, y_{it}, z_{it}), where we allow for the possibility of one shared input to abatement (y_{it}). We assume a multiplicative form of abatement in which a certain percentage of influent ($phos_{it}^{I}$ and q_{it}^{I}) is removed through the abatement process. The facility's objective function and constraints are:

$$\min_{x_{it}, y_{it}, z_{it}} C(x_{it}, y_{it}, z_{it}) \tag{1}$$

$$s.t. \quad phos_{it}^{E} \equiv phos_{it}^{I} phos_{it}^{R}(x_{it}, y_{it}) \leq \overline{phos}_{i} \tag{2}$$

$$q_{it}^{E} \equiv q_{it}^{I} q_{it}^{R}(y_{it}, z_{it}) \leq \bar{q}_{i}. \tag{3}$$

3.2 Predictions

The model predicts that while changes in phosphorous influent will affect phosphorous effluent at no limit facilities, they will have a muted effect on phosphorous effluent at limit facilities.

Limit facilities find it optimal to set effluent equal to the individual standard in each time period $\left(phos_{it}^{E*} = \overline{phos}_{i}\right)$. Thus, we should see no change in effluent given an exogenous change in influent $\left(\frac{d\ phos_{it}^{E}}{d\ phos_{it}^{I}} = 0\right)$ when the limit on phosphorous binds. In particular, a ban on phosphate in dishwasher detergent, which lowers phosphorous influent, will have no effect on effluent when the limit on phosphorous binds. For no limit facilities, phosphorus effluent in any time period is determined by phosphorus influent and the complementary pollutant, since there is no incentive to abate phosphorous $\left(phos_{it}^{E*} = phos_{it}^{I} phos_{it}^{R}(x_{it}^{*}, y_{it}^{*})\right)$.

We will use a multi-state dataset to test this prediction. Specifically, we compare the change in phosphorous effluent before and after the ban across limit vs. no limit facilities. Note that the change in phosphorus effluent over time is described by the total derivative of phosphorus effluent with respect to time:

$$\frac{d\ phos_{it}^{E}}{dt} = phos_{it}^{R}(x_{it}, y_{it}) \frac{d\ phos_{it}^{I}}{dt} + phos_{it}^{I} \frac{d\ phos_{it}^{R}}{dt} \tag{4}$$

For no limit facilities, this equation highlights the important point that changes in influent, changes in the complementary input, and any change in the abatement function over time will affect phosphorus effluent levels. To attribute the change we see in effluent levels over this time period to the ban $\left(\frac{d\ phos_{it}^{E}}{dt}\right)$, we must assume that there are no other reasons for a change in phosphorus influent $\left(\frac{d\ phos_{it}^{I}}{dt}\right)$, no changes to the removal function $\left(\frac{d\ phos_{it}^{R}}{dt} = 0\right)$, and no changes in the level of the complementary input, (y_{it}). For limit facilities, we would expect no change in phosphorus effluent over time, $\left(\frac{d\ phos_{it}^{E}}{dt} = 0\right)$.

It is important to note that there may be reasons a priori why our empirical results may deviate slightly from these theoretical predictions for limit facilities. Facilities' actual decision problem may be more complicated than our simple model. For example, limit facilities may take time to learn about reductions in phosphorous influent, or they may "overcomply" with regulations by setting influent below effluent standards (Earnhart 2007, Bandyopadhyay and Horowitz 2006, Shimshack and Ward 2008, Chakraborti and McConnell 2012), which could lead to more flexible responses to drops in influent. In these circumstances, our identification strategy will still reveal the differential response by limit and no limit facilities to the ban as long as influent dropped similarly across limit and no limit facilities and there are no differential changes in the removal function. For example, there may be differential changes in the removal function if no limit facilities are upgrading their removal technology more rapidly than limit facilities over the pre and post ban period or if limit facilities are seeing a larger increase in other pollutants. We return to this issue in Section 5.

We then use a dataset from Minnesota, which provides data on phosphorous influent, to provide a more direct test of the model. The model predicts no change in effluent with respect to a change in influent levels $\left(\frac{d\ \ phos_{it}^{E}}{d\ \ phos_{it}^{I}} = 0\right)$ for limit facilities. This implies an elasticity of zero for these facilities:

$$\frac{\partial\ phos_{it}^{E}}{\partial\ phos_{it}^{I}} \frac{phos_{it}^{I}}{phos_{it}^{E}} = 0. \tag{5}$$

For no limit facilities, from (2) we see that the change in effluent with respect to influent equals the percentage removed as given by the abatement function:

$$\frac{\partial\, phos_{it}^{E}}{\partial\, phos_{it}^{I}} = phos_{it}^{R}(x_{it}, y_{it}). \tag{6}$$

Since $phos_{it}^{R}(x_{it}, y_{it}) = \frac{phos_{it}^{E}}{phos_{it}^{I}}$, this implies an elasticity of 1 for no limit facilities:[13]

$$\frac{\partial\, phos_{it}^{E}}{\partial\, phos_{it}^{I}} \frac{phos_{it}^{I}}{phos_{it}^{E}} = 1. \tag{7}$$

We test these predictions directly by regressing phosphorous effluent on influent, using the Minnesota dataset.

As with the multi-state analysis, we may be concerned that changes in influent are correlated with changes in the removal function or changes in other pollutant influent, which will bias our estimates. We return to this issue in Section 6.

3.3 Current Framework vs. Market-Based Instruments

Before we proceed to our data and empirical results, we note an important result for how facilities respond to individual standards versus market-based approaches to managing effluent. Under binding individual standards, the optimal solution implies that facilities will set phosphorus effluent equal to the standard. This implies that with an influent ban, there should be no change in effluent, given that the constraint still binds.

If the regulator's goal is to reduce phosphorus emissions, a tax on phosphorus effluent passes through these influent reductions. Prior to a ban, facilities will abate phosphorus up to the level at which their marginal cost of abatement is set equal to the tax and then pay a tax on the remaining

[13] We also see that if facilities remove a certain quantity rather than percentage of influent, our predictions would change slightly. Equation (2) would now result in $\frac{\partial\, phos_{it}^{E}}{\partial\, phos_{it}^{I}} \frac{phos_{it}^{I}}{phos_{it}^{E}} = 1$. Since $\frac{phos_{it}^{I}}{phos_{it}^{E}} \geq 1$, the elasticity would be greater than or equal to 1.

units of emissions.[14] With a reduction in phosphorus influent from the ban, each facility continues to abate up to the level of the tax. Influent reductions are passed through as emissions reductions.

If instead a quantity based trading market had been established, there would be no reductions in total emissions without a corresponding reduction in the total phosphorus cap. How the reductions in influent were spread throughout the market would determine what particular facilities would emit more versus less than before the ban. The alleviation of coordination issues with a tax, but not a quantity instrument, is similar to the theoretical exercise for federal-state interactions as discussed in Goulder and Stavins (2011).[15]

4 Data

We use two datasets for our analysis. The first is a multi-state emissions dataset, which we use to estimate the effect of the ban on phosphate in dishwasher detergent across limit versus no limit facilities. The second is an emissions dataset from Minnesota, which provides detail on influent as well as effluent. Influent data lets us test additional predictions of the model and provide further support for the multi-state analysis by estimating the effect of the ban on both influent and effluent.

4.1 Data Sources

The multi-state emissions dataset is provided by the US EPA (US EPA 2007-2011) and captures phosphorus emissions from the majority of large wastewater treatment facilities in the U.S. In addition, we link these facilities with additional facility characteristics captured by the 2008 US EPA Clean Water Needs Survey (US EPA 2008). We limit our sample to control for potential unobserved differences between limit and no limit facilities that could be changing more or less for one type of facility over our time period. Our sample includes only major

[14] This discussion assumes an interior solution to the abatement problem. Corner solutions where facilities abate everything or pay a tax on all emissions can theoretically exist. If a facility abates all emissions prior to the ban, its behavior will not change and it will realize a cost savings equal to the reduction in corresponding abatement costs. The result of the ban on facilities that pay a tax on all emissions will be similar to the interior solution. If marginal abatement costs are still greater than the tax, the facility will continue to emit everything, but will see a reduction in effluent that corresponds to the reduction in influent. Otherwise, the facility will behave as other interior solution facilities.

[15] Accordino and Rajagopal (2015) show that there may be circumstances where the result of a tax alleviating coordination issues may not hold. However, the reshuffling of pollution that is key to their results would not likely play an important role in this analysis since a key objective of these bans is to reduce pollution locally.

facilities[16] and publicly owned treatment works. We also drop facilities that change limit status or limit level over time out of concern that these changes may capture misreporting and not actual changes in regulations. Furthermore, we keep facilities that report only one observation per month out of concern that it will be more difficult to identify the effect of the ban at facilities with multiple effluent pipes. We limit our sample to facilities that report at least once in 2009 and again in 2011 so that we do not capture changes in effluent due to changes in the composition of facilities being surveyed. To remove unreasonable average concentrations, we exclude the top one percent of limit and no limit average effluent concentrations. In practice, we find that these controls have little effect on the results, as demonstrated in our robustness checks in the Appendix.

The Minnesota dataset is obtained directly from the state of Minnesota (Minnesota Pollution Control Agency 2007-2013). We link total phosphorus effluent to total phosphorus influent by facility, month and year. As with the multi-state dataset, we limit our sample to publicly owned facilities, facilities where industrial waste is not the primary influent, facilities with only one effluent pipe and those that discharge to surface waters and facilities that do not change limit status or limit level over the time period. For purposes of comparison to the multi-state ban regressions, we limit our sample for ban regressions to facilities that report at least once in 2009 and once in 2011. For our elasticity estimates, we take advantage of a larger sample size and limit our sample to those facilities that report at least once over the period 2007 to 2013. We also exclude outlier observations for the top one percent of effluent and influent concentrations. While the Minnesota dataset does not provide a signifier for major facilities, we do observe the total design flow of facilities, which is a good indicator of major status, since major facilities have higher flow. In the multi-state dataset, the lowest flow we observe for facilities labeled "major" is 0.3 million gallons per day. Thus, we only include facilities with a flow of 0.3 million gallons per day or greater in this sample.[17] In addition, the Minnesota data provide influent concentrations for pollutants that all treatment facilities are required to treat. These include TSS, BOD5, and minimum and maximum levels of pH. We limit the top 1 percent of outlier

[16] We limit our analysis to what are described as "major" facilities, due to differences in reporting requirements at the state and federal level for "minor" facilities.
[17] Generally, major facilities are those with a flow of 1 million gallons per day. However, when we limit the Minnesota dataset to only those with 1 million gallons per day, we are only left with six facilities and the estimates become imprecise.

concentrations for these observations. [18] As with the multi-state dataset, we discuss the consequences of relaxing these restrictions on the sample in the Appendix.

4.2 Summary Statistics

For both datasets, we define an observation as the phosphorus effluent or influent concentration for each individual facility, month, and year. Table 1 presents summary statistics for three estimating samples. Panel A shows summary statistics for the sample we use to estimate the effect of the ban on effluent across limit versus no limit facilities using the multi-state dataset. The sample includes data from 2009 (the pre ban period) and 2011 (the post ban period), since we exclude 2010 as an "adjustment year." Panel B shows summary statistics for the sample we use to estimate the effect of the ban on influent and effluent across limit versus no limit facilities using the Minnesota dataset. As with the multi-state analysis, the sample includes only 2009 and 2011. Panel C shows summary statistics for the sample we use to estimate the elasticity of phosphorous effluent to influent using the Minnesota dataset. This sample includes 2007 to 2013.

Table 1 highlights a few important summary statistics from these datasets. First, we are interested in how well the Minnesota data represent the larger national dataset. The biggest difference between the two datasets is that limit facilities make up the majority of facilities in the multi-state dataset. This is likely due to differences in reporting requirements that increase the number of limit facilities relative to no limit facilities. However, importantly, both datasets show limit facilities emitting at phosphorus levels significantly lower than no limit facilities. In addition, for each type of facility, mean effluent concentrations are roughly the same magnitude across samples.

Second, the Minnesota dataset also provides an important statistic to support our identification strategy. Table 1 shows that the mean phosphorus influent levels at limit and no limit facilities are fairly close in magnitude. Implicit in our analysis is the idea that limit facilities are similar to no limit facilities. We assume that limit facilities would react to influent shocks in the same manner as no limit facilities if they no longer faced a phosphorus standard. We assume the reverse is also true.

[18] For minimum pH, we exclude the bottom 1 percent of concentrations.

Table 1. Summary Statistics

Panel A. Multi-State Dataset: 2009 and 2011			
	No Limit	Limit	Total
Effluent (mg/L)	2.09	0.53	1.46
	(1.70)	(0.33)	(1.54)
Obs.	3,880	2,629	6,509
Facilities	182	118	300

Panel B. Minnesota Dataset (Ban Regressions Sample): 2009 and 2011			
	No Limit	Limit	Total
Effluent (mg/L)	2.40	0.47	1.95
	(1.93)	(0.26)	(1.88)
Influent (mg/L)	5.91	5.41	5.79
	(2.44)	(2.42)	(2.44)
Obs.	1,840	557	2397
Facilities	85	26	111

Panel C. Minnesota Dataset (Elasticity Regressions Sample): 2007 - 2013			
	No Limit	Limit	Total
Effluent (mg/L)	2.40	0.47	1.94
	(1.95)	(0.25)	(1.89)
Influent (mg/L)	6.21	5.44	6.03
	(2.51)	(2.52)	(2.54)
Obs.	6,571	2,088	8,659
Facilities	99	32	131

Notes: Standard errors in parentheses.

5 Results: Multi-state Analysis

We first use the multi-state dataset to estimate how phosphorous effluent changed after the ban, relative to before, in limit vs. no limit facilities. We employ a differences-in-differences approach to capture the differential effect of the ban on limit and no limit facilities, using the multi-state dataset. To allow for an adjustment period for the ban to take hold, we remove observations from 2010 from our analysis and compare effluent levels from 2009 to 2011 at limit and no limit facilities.

The main specification is

$$\ln phos_{it}^{E} = \beta_0 + \beta_1(post_t * nolimit_i) + \beta_2 nolimit_i + \beta_3 post_t + \epsilon_{it}, \tag{8}$$

where $post_t$ is equal to 1 if the year is 2011, $nolimit_i$ is equal to 1 if the facility does not have a limit on phosphorous emissions.[19]

Our parameter of interest, β_1, captures the percentage difference in emissions between limit and no limit facilities after the ban, relative to before. Our theory tells us that this parameter should be negative and significant since the ban is anticipated to cause a larger relative drop in emissions at no limit facilities than limit facilities. Although theory doesn't dictate a magnitude for this parameter, our expectations from the engineering estimates would place $\beta_1 \approx 0.10$, with a range of 0.09 to 0.34. We also expect $\beta_3 = 0$ since this parameter captures the average effect of the post ban period on limit facilities.

We also run specifications with facility fixed effects and month fixed effects. For no limit facilities, facility fixed effects capture variables like removal technology, influent and cost of treatment for other pollutants, which may affect phosphorous effluent but which we do not observe in the multi-state dataset. For limit facilities, the only facility characteristic that should reflect phosphorous effluent is the limit on phosphorous, assuming the limit is binding. Thus, for limit facilities, the facility fixed effect captures any variation in the level of the limit. Month fixed effects capture any unobserved shocks to effluent that are common across limit and no limit facilities. Month fixed effects might capture differences in measured effluent concentration due to unusually high flow of water due to increased rainfall or snow during certain times of the year.

Table 2 reports estimates of (8) for states that instituted a ban in July 2010. As expected, the interaction of dummies for post and no limit is negative and significant. The estimates without fixed effects indicate that phosphorous effluent dropped 18 percentage points more at no limit facilities from 2009 to 2011, relative to limit facilities. This magnitude is within range of our engineering estimate of dish detergent's contribution to influent at wastewater treatment facilities. Adding facility and month fixed effects do not change the coefficient estimates significantly.

Although we do not pick up a significant effect of the post variable in OLS models, it is important to note that we pick up a negative and significant effect of the post variable in facility and month fixed effects specifications. This indicates that total phosphorous effluent dropped at

[19] We estimate this model in logs since limit facilities, on average, have lower effluent levels. If we use levels instead, we would naturally expect to see a smaller change in limit facilities relative to no limit facilities.

Table 2. Effect of Ban on Limit versus No Limit Facilities (Ban States)

	Log Effluent (1)	Log Effluent (2)	Log Effluent (3)	Log Effluent (4)
No Limit x Post	-0.180***	-0.178***	-0.179***	-0.178***
	(0.0464)	(0.0464)	(0.0441)	(0.0441)
No Limit	1.329***	1.328***		
	(0.0806)	(0.0806)		
Post	-0.0459	-0.0457	-0.0683**	-0.0681**
	(0.0326)	(0.0327)	(0.0302)	(0.0303)
Constant	-0.813***	-0.774***	-0.00953	0.0302
	(0.0546)	(0.0602)	(0.0115)	(0.0247)
Facility FE?	No	No	Yes	Yes
Month FE?	No	Yes	No	Yes
Obs.	6,509	6,509	6,509	6,509
Facilities	300	300	300	300
R^2	0.361	0.377	0.790	0.805

Notes: Standard errors, clustered at the facility level, in parentheses.
*** Significant at the 1 percent level.
** Significant at the 5 percent level.
* Significant at the 10 percent level.

limit facilities over the ban period. This runs counter to our model, which predicted the ban should have no effect on phosphorous effluent. As discussed in Section 2, there are a number of possible explanations for this result. If limit facilities overcomply, they may be more responsive to changes in influent than predicted. In Appendix Table A1, we provide results from separate regressions for limit facilities that significantly overcomply (by reducing effluent by more than 50 percent below the limit), those that overcomply but remain closer to their limit, and a few facilities that, on average, violate their limits. We see that facilities that overcomply show a negative and significant drop in effluent over the ban period with a drop in phosphorus effluent of 9 to 12 percent. Facilities that overcomply, but remain closer to their limits show a negative, but insignificant drop in effluent over the ban period with a magnitude of approximately 4 percent. The four facilities that are on average violators of their limits show an increase in phosphorus effluent of approximately 12 to 25 percent after the ban. These results point to heterogeneity in limit facilities with some overcomplying facilities being more responsive to drops in influent. Nonetheless, we find strong evidence that the effect on phosphorous effluent concentration is significantly stronger in no limit facilities, with the ban leading to 2 to 4 times as much of a drop in effluent in no limit facilities relative to limit facilities.

Table 3. Effect of "Placebo Bans" on Limit versus No Limit Facilities (Ban States)

	2007-2008		2008-2009		2007-2009	
	Log Effluent	Log Effluent	Log Effluent	Log Effluent	Log Effluent	Log Effluent
	(1)	(2)	(3)	(4)	(5)	(6)
No Limit x Post	0.0151	0.0403	-0.0363	-0.0278	-0.00649	0.0156
	(0.0410)	(0.0330)	(0.0358)	(0.0326)	(0.0528)	(0.0482)
No Limit	1.487***		1.417***		1.477***	
	(0.0819)		(0.0809)		(0.0830)	
Post	-0.0739***	-0.0666***	-0.0161	-0.000958	-0.0972***	-0.0711**
	(0.0254)	(0.0215)	(0.0263)	(0.0251)	(0.0334)	(0.0302)
Constant	-0.729***	-0.128***	-0.822***	-0.111***	-0.717***	-0.114***
	(0.0491)	(0.0275)	(0.0522)	(0.0236)	(0.0486)	(0.0269)
Facility FE?	No	Yes	No	Yes	No	Yes
Month FE?	No	Yes	No	Yes	No	Yes
Obs.	5,820	5,820	6,691	6,691	5,530	5,530
Facilities	270	270	310	310	257	257
R^2	0.475	0.841	0.413	0.840	0.482	0.826

Notes: Standard errors, clustered at the facility level, in parentheses.
*** Significant at the 1 percent level.
** Significant at the 5 percent level.
* Significant at the 10 percent level.

The main identification assumption for the difference-in-difference approach is that there are no differential trends in unobservables across no limit and limit facilities over time. This assumption would fail if removal technology were improving more or phosphorous influent were falling more at no limit facilities relative to limit facilities from 2009 to 2011. We provide evidence in support of the no-differential-trends assumption by estimating (8) using "placebo" pre and post years. Table 3 shows estimates of (8) using 2007 to 2008, 2008 to 2009 and 2007 to 2010 as the pre and post years. Across all specifications the interaction term is not statistically different from zero. These results suggest that the results in Table 2 are not driven by differential trends in phosphorus effluent across limit versus no limit facilities.

6 Results: Minnesota Analysis

In this section, we provide further support for our model by testing whether limit facilities are less responsive to changes in phosphorus influent, using the dataset from Minnesota. We then use this influent data to provide additional support for the difference-in-difference specification in the previous section by testing whether those results were driven by differential changes in influent as a result of the ban.

6.1 Elasticity of Effluent to Influent

We start by estimating the elasticity of phosphorous effluent with respect to influent by estimating the following equation:

$$\ln phos_{it}^{E} = \gamma_0 + \gamma_1(\ln phos_{it}^{I} * nolimit_i) \\ + \gamma_2 \ln phos_{it}^{I} + \gamma_3 nolimit_i + \nu_{it}, \tag{9}$$

where γ_2 is the elasticity of effluent with respect to influent for limit facilities and γ_1 is the difference in elasticity for no limit facilities. Our theory predicts that $\gamma_1 > 0$ and $\gamma_2 = 0$.

Estimating (9) using OLS may lead to a biased coefficient on influent if there are unobserved characteristics, such as removal technology, that affect effluent and are correlated with changes in influent. To control for any unobserved characteristics that are time-invariant, we use facility fixed effects. Our model suggests that other pollutant influent, which may be time-varying and thus not captured by a facility fixed effect, may also bias our estimates. Specifically, unobserved non-phosphorous influent may lead to a downward bias in our estimate of the elasticity of effluent with respect to influent. Recall from Section 3 that the elasticity of phosphorus effluent with respect to phosphorus influent for no limit facilities equals 1. Now, relaxing the assumption that only phosphorus influent changes, equation (2) from Section 3 gives the total derivative of effluent with respect to influent as:

$$\frac{d\, phos_{it}^{E}}{d\, phos_{it}^{I}} = phos_{it}^{R}(x_{it}, y_{it}) + phos_{it}^{I} \frac{d\, phos_{it}^{R}}{d\, phos_{it}^{I}} \tag{10}$$

multiplying both sides by $\frac{phos_{it}^{I}}{phos_{it}^{E}}$ yields:

$$\frac{d\, phos_{it}^{E}}{d\, phos_{it}^{I}} \frac{phos_{it}^{I}}{phos_{it}^{E}} = 1 + phos_{it}^{I} \frac{d\, phos_{it}^{R}}{d\, phos_{it}^{I}} \frac{phos_{it}^{I}}{phos_{it}^{E}}. \tag{11}$$

Suppose changes in phosphorous influent are correlated with changes in the other pollutant influent. This changes the facility’s use of the common treatment input and, hence, changes

Table 4. Elasticity of Effluent to Influent

	Log Effluent (1)	Log Effluent (2)	Log Effluent (3)	Log Effluent (4)	Log Effluent (5)
No Limit x Log Influent	-0.0708	0.0410	0.389***	0.423***	0.407***
	(0.182)	(0.225)	(0.0894)	(0.1000)	(0.0958)
Log Influent	0.353***	0.347***	0.162**	0.147**	0.0978
	(0.108)	(0.121)	(0.0701)	(0.0675)	(0.0660)
Constant	-1.474***	-1.758**	-0.665***	-0.952***	-0.887***
	(0.181)	(0.821)	(0.0781)	(0.307)	(0.295)
Facility FE?	No	No	Yes	Yes	Yes
Year FE?	No	No	No	No	Yes
Month FE?	No	No	No	No	Yes
Other Pollutants?	No	Yes	No	Yes	Yes
Obs.	8,659	8,659	8,659	8,659	8,659
Facilities	131	131	131	131	131
R^2	0.294	0.309	0.817	0.818	0.826

Notes: Standard errors, clustered at the facility level, in parentheses.
*** Significant at the 1 percent level.
** Significant at the 5 percent level.
* Significant at the 10 percent level.

phosphorous effluent. In this case, $\frac{d\ phos_{it}^{R}}{d\ phos_{it}^{I}} < 0$, and failing to control for other pollutants leads to downward bias. The Minnesota dataset lets us address this concern by controlling for influent of conventional pollutants: TSS, BOD and pH.

Table 4 shows the elasticity of phosphorous effluent with respect to influent across limit and no limit facilities. Estimating (9) without controlling for facility fixed effects or other pollutant influent shows that no limit facilities have an elasticity of 0.28, while limit facilities have an elasticity of 0.35 (Column (1)). A significant and *larger* elasticity for limit facilities runs counter to our model. This could be driven by unobserved characteristics or unobserved pollutant influent that bias the coefficients in (9).

Columns (2)-(4) add controls for facility fixed effects and other pollutants. When we control for other pollutant influent, the elasticity for no limit facilities rises and limit facilities decreases slightly (Column (2)). Adding facility fixed effects increases the coefficients on no limit facilities and significantly decreases the elasticity for limit facilities. Column (5) controls for facility fixed effects, other pollutants, and month fixed effects. With this full set of controls, the elasticity of effluent to influent at no limit facilities is 0.50 and significant. The elasticity for limit facilities is 0.10, but insignificant. The greater responsiveness of no limit facilities vs. limit facilities to changes in influent is consistent with our theoretical predictions. The large differences between the fully specified model and OLS appear to be primarily explained by the addition of a facility fixed effect that properly controls for unobserved fixed facility characteristics that would otherwise bias our parameter estimate on phosphorous influent downwards. This fully specified model also has appeal given how elasticity measures are defined. The facility fixed effect allows us to estimate elasticity by examining how individual facilities alter effluent in response to changes in influent. This contrasts with OLS models that look at correlations between effluent and influent levels across facilities.

Although the relative responsiveness of no limit versus limit facilities to changes in influent are consistent with our theory, the magnitudes of the responses differ from our predictions. For no limit facilities, one possible explanation is that controlling for facility fixed effects exacerbates attenuation bias arising from measurement error. Ideally, we would like to account for both measurement error and unobserved characteristics, for example, using an instrument that is correlated with influent but uncorrelated with all other characteristics that affect effluent. In Appendix Table A5, we present results from an an instrumental variables approach similar to Arellano and Bond (1991) that uses lagged values of influent to instrument for first differences. Using both forward orthogonal deviations and two-step difference GMM models, the elasticity coefficient for no limit facilities rises very close to our predicted elasticity of 1. These models also estimate an elasticity for limit facilities that generally remains insignificant and roughly equivalent to the fully specified model in Table 4. However, we find that these results are very sensitive to the number of lags used as instruments (Appendix Table A6). In sum, we believe 0.5 represents a feasible lower bound on the elasticity for no limit facilities.

Similar to the exercises we performed for the multi-state analysis, we also examine the elasticity for limit facilities that significantly overcomply on average versus facilities that remain closer to the limit. As with the multi-state analysis, we find that limit facilities that significantly overcomply, have a greater response to changes in influent than those that don't (see Appendix Table A7). However, it is important to note that no elasticity estimate for limit facilities is greater than 0.16 when controlling for facility fixed effects, and none of these estimates are significant. As with the multi-state analysis, we find that this overcompliance behavior yields some response to changes in phosphorus influent, but the key finding that no limit facilities are much more responsive to changes in influent remains unchanged.

6.2 Effect of Ban on Influent

In Section 5, we showed that no limit facilities saw a much larger drop in phosphorous effluent from 2009 to 2011, relative to limit facilities. We provided evidence that this effect was not driven by differential trends in effluent across limit vs. no limit facilities. One remaining concern with the results in Section 5 could be that no limit facilities saw a larger drop in influent as a result of the ban on phosphate in dishwasher detergent. For example, if no limit facilities are more likely to treat water from households, then we would expect a stronger drop in effluent at no limit facilities simply because no limit facilities saw a larger reduction in phosphorous influent as a result of the ban.

We can use the Minnesota data to test for this directly. We estimate the specification in (8) using phosphorous influent as the left-hand side variable:

$$\ln phos_{it}^{I} = \rho_0 + \rho_1(post_t * nolimit_i) + \rho_2 nolimit_i + \rho_3 post_t + \eta_{it}. \qquad (12)$$

We also estimate the difference-in-difference specification for phosphorous effluent, using (8), to show that we can replicate the multi-state results in the Minnesota dataset.

Table 5 presents estimates of (8) and (12) using both phosphorous influent and effluent. Columns (1)-(2) show that the effect of the ban on effluent in the Minnesota is similar to the effects in the multi-state analysis. No limit facilities decrease effluent 24 percentage points more than limit facilities. We also find a negative effect of the ban on limit facilities, as in the multi-state analysis. The point estimate is between -0.04 and -0.05, but is not statistically significant. Columns (3)-(4) estimate whether no limit facilities saw a differential change in influent after the ban. The estimates suggest that there were no differential changes in influent over the ban period. Moreover, there was a drop in influent over the ban period of 11 to 17 percent across all facilities, consistent with engineering estimates of the effect of the ban on phosphorous influent. These results suggest that the differential change in phosphorous effluent from before and after the ban is not driven by differential changes in influent.

Lastly, notice that we observe a larger drop in effluent (24 percent) at no limit facilities than influent (15 to 17 percent) pre and post ban. This suggests there are additional changes, other than decreases in influent, driving the drop in effluent at no limit facilities, such as changes in the removal technology, costs of inputs used to treat phosphorous or limits on other pollutants.

Table 5. Effect of Ban on Effluent in Minnesota Dataset

	Log Effluent (1)	Log Effluent (2)	Log Influent (3)	Log Influent (4)
No Limit x Post	-0.235***	-0.239***	-0.0614	-0.0422
	(0.0708)	(0.0720)	(0.0392)	(0.0389)
No Limit	1.506***		0.124	
	(0.133)		(0.0806)	
Post	-0.0473	-0.0439	-0.105***	-0.110***
	(0.0548)	(0.0566)	(0.0321)	(0.0335)
Constant	-0.891***	0.305***	1.646***	1.843***
	(0.0875)	(0.0388)	(0.0725)	(0.0186)
Facility FE?	No	Yes	No	Yes
Month FE?	No	Yes	No	Yes
Obs.	2,397	2,397	2,397	2,397
Facilities	111	111	111	111
R^2	0.302	0.839	0.037	0.680

Notes: Standard errors, clustered at the facility level, in parentheses.
*** Significant at the 1 percent level.
** Significant at the 5 percent level.
* Significant at the 10 percent level.

While such changes appear to be driving some of the drop in effluent at no limit facilities, the placebo tests we conducted with the multi-state analysis suggest differential changes in, for example, the removal technology are not driving our results.

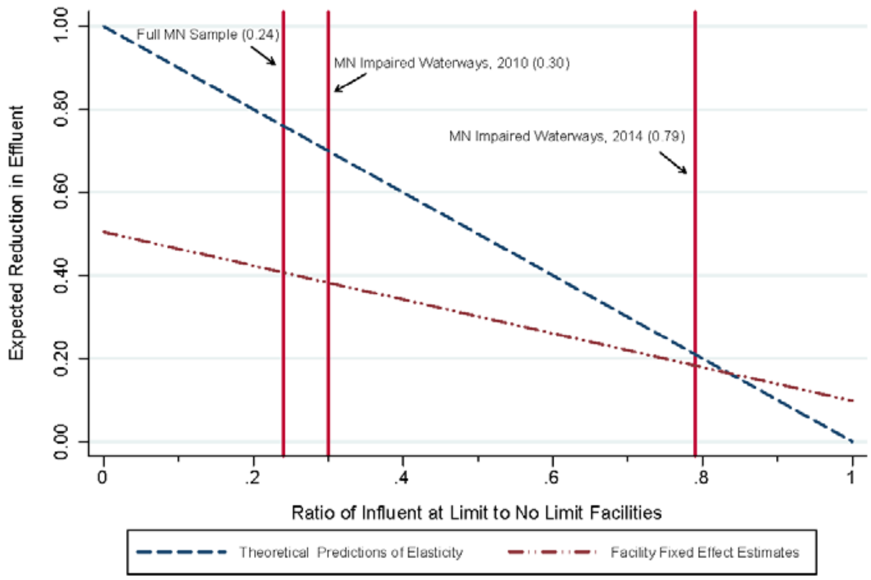
7 Quantification

Naturally, one question that arises from these results is: How effective are influent policies at reducing phosphorus effluent? This question is at the heart of policies such as the phosphate bans and other policies targeting influent reductions. The answer depends upon the composition of limit and no limit facilities in the U.S. and their corresponding elasticities.[20] Intuitively, since limit facilities have a low "pass-through" of phosphorous influent to effluent (i.e., a low elasticity), policies like bans that reduce phosphorous influent will have a weak impact on phosphorous effluent in waterways when there are many limit facilities.

Figure 1 plots the expected reduction in effluent in response to a 1 percent reduction in influent due to some policy, such as a phosphate dish detergent ban, as a function of the ratio of influent treated by limit to no limit facilities. Figure 1 plots this relationship for two sets of

[20] This also depends upon whether limits still bind for limit facilities. However, given that human waste contributes a significant portion of phosphorus influent, it is unlikely that other influent policies would drop influent below limit levels.

Figure 1. Expected Reduction in Effluent Given Unit Reduction in Influent



Notes: Share of influent for full MN sample calculated by authors using data on influent mass from 2007 to 2013. Share of influent for impaired waterways calculated by authors using counts of limit and no limit facilities provided by Minnesota Pollution Control Agency.

elasticities. The first is our theoretical predictions of elasticity at limit facilities, where our model predicts an elasticity of 0, and no limit facilities, where our model predicts an elasticity of 1. The second is the elasticity we estimated from the Minnesota data in the facility fixed-effects specifications. In the Minnesota data, we estimated an elasticity of 0.10 for limit facilities and 0.50 for no limit facilities.

Using our theoretical predictions for elasticity, we see that when all the phosphorus influent is treated by no limit facilities (a ratio of 0), reductions in phosphorus influent are passed completely through as reductions in phosphorus effluent. Phosphate laundry detergents bans in the 1970s were likely successful since the ratio of influent at limit to no limit facilities was close to 0. Likewise, when all facilities are limit facilities (a ratio of 1), influent reductions fail to reduce any effluent. Using our facility fixed-effect elasticity estimates, these predictions change slightly. We see that the upper bound on expected phosphorus effluent reductions is now 50 percent (when the ratio of limit to no limit facilities is 0) and the lower bound is approximately 10 percent (when the ratio of limit to no limit facilities is 1).

Pinning down the actual effect of policies like the ban on phosphate in dishwasher detergent requires estimating the ratio of influent treated at limit versus no limit facilities. Using the

Minnesota sample, we calculate the ratio of limit to no limit facilities equal to 0.24. If the Minnesota sample is representative of the nation as a whole, then phosphate bans (or similar influent reduction policies) yield only 41 to 76 percent of expected effluent reductions, depending on which elasticity measure we use.[21] However, the Clean Water Act requires that states develop total maximum daily loads (TMDLs) for waterbodies that are not meeting their designated uses. A critical component of a TMDL is to determine the sources of impairment and assign allowable loads of pollution to point and nonpoint sources. New or tighter limits are then developed for point sources, such as wastewater treatment facilities. Using data provided by the Minnesota Pollution Control Agency, we calculate expected reductions in nutrient impaired waterways. In 2010, expected effluent reductions (38 to 70 percent) are slightly lower than our calculation for all facilities. However, in 2014, expected effluent reductions fall dramatically to 18 to 21 percent. As seen in Figure 1, the red line shifts significantly to the right for nutrient impaired waterways. This significant shift reflects the fact that nutrients have become a major focus of state and federal regulators. This also means that the phosphate ban has become even less effective in these high priority waterways.

Overall, these calculations suggest that influent reduction policies will fall short of their intended targets for reducing phosphorous effluent. Moreover, these policies will be least effective in waterways served by limit facilities, which often serve waterways that are the most impaired by phosphorous and other nutrient pollution.

8 Conclusion

This paper examines an example of the important consequences of overlapping pollution regulations within the U.S. We consider the case of a recent ban on phosphates in household automatic dishwasher detergent. Although phosphorus emission reductions are often cited as a reason for this ban, we show that the effectiveness of this policy depended upon downstream regulations in place at wastewater treatment facilities. Our multi-state and Minnesota analyses taken together suggest that influent reductions have very little effect on effluent levels at limit facilities, but do decrease effluent at no limit facilities. Given the prevalence of limit facilities, our results suggest the bans achieved just a fraction of the intended reductions in phosphorous

[21] To estimate the share of phosphorus influent at no limit and limit facilities, we calculate the mass of influent at no limit and limit facilities using influent concentration and flow measures. We also calculate the share differently using the simple share of the count of no limit to limit facilities but find nearly identical results.

effluent in waterways. Moreover, our results suggest that such bans will have even weaker effects on effluent in the most polluted waterways, since these are more likely to be served by limit facilities. Finally, this work extends the scope of recent studies that have focused on unintended consequences of incomplete and overlapping environmental regulations. Our work challenges conventional wisdom that even simple command-and-control policies, such as bans on pollution, may fail to achieve desired environmental goals.

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Appendix: Robustness Checks

We perform a number of robustness checks to test the effects of our data and model selections. We find that our results are very robust to these restrictions.

7.1 Multi-state Analysis

For the multi-state analysis, we start by examining the effects of the ban in non-mandatory ban states. While the major manufacturers of dishwasher detergent stopped producing detergent with phosphates following the July 2010 bans in 17 states, states could still continue selling their inventory of dishwasher detergent with phosphates. We can use non-ban states to test whether differential trends are driving the results in Table 2 by testing whether the coefficient on the interaction between no limit and post is significantly different from zero in non-ban states.

Table A2 reports estimates of (8) using non-ban states. The coefficient on the interaction between no limit and post is statistically insignificant (and point estimate is actually positive for several specifications). These results suggest the results in Table 2 are not driven by a differential trend in phosphorous across limit versus no limit facilities that was common across all states.

Is this placebo test still valid if the ban had an effect in non-ban states? If the ban actually did have an effect in non-ban states, we would expect the coefficient on the interaction term to be negative and significant. Our finding that the coefficient on the interaction term is not statistically different from zero thus suggests both that there are no differential trends in phosphorous across limit versus no limit facilities outside of the ban and that the ban did not have an effect in non-ban states.

Next, we relax sample restrictions one a time by including outliers, including non-major facilities, including private facilities, including CSO facilities, implementing a balanced sample restriction, including facilities that changed limit status and/or limit level over our time frame, restricting facilities with municipal share greater than 50 percent and equal to 100 percent, and including facilities with multiple observations a month that likely represent facilities with multiple pipes. As shown in Table A3, removing these restrictions does not change the results.

However, we do find that there are two main sample restrictions that influence our results. The first is our definition of the post period. When we define the post ban period as anything after July 2010, we no longer see an effect of the ban at limit or no limit facilities (Columns (13)-(14) of Table A3). However, when we include up to July 2010 in our analysis and remove July-December 2010, we find very similar results to those presented in our main analysis (Columns (15)-(16) of Table A3). These results suggest that there was an adjustment period for the ban to take hold in ban states. This finding is not surprising given that the July 2010 date was for phosphorous purchases, not necessarily household use. In addition, several states that instituted the ban allowed inventory exclusions that may have contributed to a longer timeframe for the ban to take place.

In Table A4, we show that the results are robust to dropping each state at a time. Thus, our results are not driven by any single state.

7.2 Minnesota Analysis

For the Minnesota analysis, we first check the robustness of our results on the elasticity of phosphorous effluent with respect to influent. The results are in Table A8. We remove sample restrictions one by one by including outliers, non-major facilities, private facilities, facilities that changed limit or limit status. We also run the regressions using a balanced panel and the same sample we used in the ban regressions. Removing these restrictions does not generally affect our finding that no limit facilities have a higher elasticity of effluent with respect to influent. The only restriction that appears to be important is restricting the sample to a balanced panel from 2007 to 2013. When we restrict our sample to a balanced panel, we find no significant difference between elasticities of no limit and limit facilities. However, given that there are only 3 no limit facilities and 21 limit facilities in this sample, we feel that the sample is too small for these results to challenge our other findings.

Next, we check the robustness of our results on the effect of the ban on phosphorous influent and effluent in the Minnesota dataset. First, in Table A9, we include controls for influent of other pollutants. We find nearly identical results to those in the main analysis. Next, we test the robustness of the results to including outliers, including private facilities, using a balanced sample, including facilities that changed limit and/or limit status. As shown in Table A10, these restrictions do not change our results. We also test whether including 2010 affects the results, as we did for the multi-state analysis. We find that it does not.

The most important restriction for our ban results is excluding non-major facilities, which we define as those with a total design flow less than or equal to 0.3 million gallons per day. Including non-major facilities suggests that the ban caused a larger drop in influent at no limit facilities versus limit facilities (Columns (11)-(12) of Table A10). However, we still find very little effect of the ban on limit facilities and a much larger response at no limit facilities (Columns (9)-(10)), which is consistent with our expectations.

Appendix Table A1. Robustness Checks for Multi-state Analysis:
Ban Results by Average Overcompliance Percentage (Limit Facilities)

	Log Effluent (1)	Log Effluent (2)	Log Effluent (3)	Log Effluent (4)	Log Effluent (5)	Log Effluent (6)
Post	-0.0896*	-0.120**	-0.0385	-0.0376	0.249*	0.116
	(0.0496)	(0.0464)	(0.0399)	(0.0414)	(0.0921)	(0.131)
Constant	-1.134***	-1.181***	-0.520***	-0.485***	-1.282	-1.110**
	(0.0644)	(0.0641)	(0.0648)	(0.0345)	(0.600)	(0.258)
Facility FE?	No	Yes	No	Yes	No	Yes
Month FE?	No	Yes	No	Yes	No	Yes
Avg. Facility Overcompliance (Average % below limit)	$\geq$ 50%	$\geq$ 50%	< 50%	< 50%	Violators	Violators
Obs.	1,141	1,141	1,405	1,405	83	83
Facilities	53	53	61	61	4	4
R^2	0.005	0.502	0.001	0.667	0.013	0.771

Notes: Standard errors, clustered at the facility level, in parentheses.
*** Significant at the 1 percent level.
** Significant at the 5 percent level.
* Significant at the 10 percent level.

Appendix Table A2. Robustness Check for Multi-State Analysis: Effect of Ban on Limit vs. No Limit Facilities (Non-Ban States)

	Log Effluent (1)	Log Effluent (2)	Log Effluent (3)	Log Effluent (4)
No Limit x Post	0.0222	0.0263	-0.0317	-0.0269
	(0.0817)	(0.0821)	(0.0795)	(0.0800)
No Limit	1.590***	1.590***		
	(0.127)	(0.127)		
Post	-0.0752	-0.0768	-0.00896	-0.00954
	(0.0659)	(0.0663)	(0.0620)	(0.0626)
Constant	-0.993***	-1.015***	0.0730***	0.0355
	(0.103)	(0.112)	(0.0200)	(0.0444)
Facility FE?	No	No	Yes	Yes
Month FE?	No	Yes	No	Yes
Obs.	3,507	3,507	3,507	3,507
Facilities	195	195	195	195
R^2	0.370	0.381	0.786	0.798

Notes: Standard errors, clustered at the facility level, in parentheses.
*** Significant at the 1 percent level.
** Significant at the 5 percent level.
* Significant at the 10 percent level.

Appendix Table A3. Robustness Checks for Multi-state Analysis: Relax Sample Restrictions

	Main Sample		Include Outliers		Include Non-Major Facilities		Include Private Facilities	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
No Limit x Post	-0.180***	-0.178***	-0.185***	-0.175***	-0.202***	-0.180***	-0.193***	-0.172***
	(0.0464)	(0.0441)	(0.0454)	(0.0442)	(0.0359)	(0.0327)	(0.0464)	(0.0441)
No Limit	1.329***		1.346***		1.465***		1.304***	
	(0.0806)		(0.0817)		(0.0585)		(0.0813)	
Post	-0.0459	-0.0681**	-0.0476	-0.0691**	-0.0283	-0.0547**	-0.0459	-0.0680**
	(0.0326)	(0.0303)	(0.0324)	(0.0302)	(0.0292)	(0.0265)	(0.0326)	(0.0303)
Constant	-0.813***	0.0302	-0.811***	0.0376	-0.839***	0.223***	-0.813***	0.0195
	(0.0546)	(0.0247)	(0.0548)	(0.0246)	(0.0482)	(0.0178)	(0.0546)	(0.0245)
Facility FE?	No	Yes	No	Yes	No	Yes	No	Yes
Month FE?	No	Yes	No	Yes	No	Yes	No	Yes
Obs.	6,509	6,509	6,533	6,533	12,710	12,710	6,621	6,621
Facilities	300	300	301	301	668	668	305	305
R^2	0.361	0.805	0.358	0.802	0.380	0.782	0.342	0.804

Notes: Standard errors, clustered at the facility level, in parentheses.
*** Significant at the 1 percent level.
** Significant at the 5 percent level.
* Significant at the 10 percent level.

Appendix Table A3 (cont.). Robustness Checks for Multi-state Analysis: Relax Sample Restrictions

	Exclude CSO Facilities		Balanced Sample		Include 2010		Include 2010 Before July	
	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
No Limit x Post	-0.178***	-0.172***	-0.153***	-0.153***	-0.0570	-0.0516	-0.138***	-0.132***
	(0.0504)	(0.0487)	(0.0484)	(0.0494)	(0.0379)	(0.0364)	(0.0438)	(0.0426)
No Limit	1.387***		1.314***		1.279***		1.278***	
	(0.0903)		(0.0911)		(0.0791)		(0.0790)	
Post	-0.0468	-0.0711**	-0.0658*	-0.0658*	-0.00974	-0.0888***	-0.0333	-0.0770***
	(0.0343)	(0.0308)	(0.0338)	(0.0346)	(0.0272)	(0.0251)	(0.0312)	(0.0290)
Constant	-0.757***	0.0903***	-0.772***	-0.000101	-0.826***	-0.0482**	-0.826***	-0.0394**
	(0.0597)	(0.0269)	(0.0594)	(0.0276)	(0.0532)	(0.0186)	(0.0532)	(0.0192)
Facility FE?	No	Yes	No	Yes	No	Yes	No	Yes
Month FE?	No	Yes	No	Yes	No	Yes	No	Yes
Obs.	4,845	4,845	4,968	4,968	9,738	9,738	8,114	8,114
Facilities	223	223	207	207	299	299	299	299
R^2	0.400	0.814	0.387	0.807	0.363	0.797	0.355	0.799

Notes: Standard errors, clustered at the facility level, in parentheses.
*** Significant at the 1 percent level.
** Significant at the 5 percent level.
* Significant at the 10 percent level.

Appendix Table A3 (cont.). Robustness Checks for Multi-state Analysis: Relax Sample Restrictions

	Include Facilities That Changed Limit		Include Facilities That Changed Limit Status		Municpal Share >50%		Municpal Share =100%	
	(17)	(18)	(19)	(20)	(21)	(22)	(23)	(24)
No Limit x Post	-0.138***	-0.145***	-0.167***	-0.114**	-0.146***	-0.152***	-0.132*	-0.150*
	(0.0480)	(0.0471)	(0.0504)	(0.0516)	(0.0466)	(0.0451)	(0.0748)	(0.0762)
No Limit	1.442***		1.318***		1.301***		1.311***	
	(0.0807)		(0.0788)		(0.0858)		(0.150)	
Post	-0.0873**	-0.101***	-0.0595*	-0.110***	-0.0618*	-0.0744**	-0.0864	-0.0857
	(0.0348)	(0.0345)	(0.0359)	(0.0350)	(0.0323)	(0.0316)	(0.0595)	(0.0605)
Constant	-0.926***	-0.113***	-0.840***	0.0199	-0.795***	0.0151	-0.879***	0.178***
	(0.0547)	(0.0265)	(0.0541)	(0.0258)	(0.0577)	(0.0253)	(0.122)	(0.0390)
Facility FE?	No	Yes	No	Yes	No	Yes	No	Yes
Month FE?	No	Yes	No	Yes	No	Yes	No	Yes
Obs.	7,540	7,540	6,901	6,901	6,001	6,001	2,590	2,590
Facilities	347	347	326	326	277	277	121	121
R^2	0.398	0.807	0.345	0.786	0.349	0.810	0.278	0.805

Notes: Standard errors, clustered at the facility level, in parentheses.
*** Significant at the 1 percent level.
** Significant at the 5 percent level.
* Significant at the 10 percent level.

Appendix Table A3 (cont.). Robustness Checks for Multi-state Analysis: Relax Sample Restrictions

	Multiple Observations	
	(25)	(26)
No Limit x Post	-0.174***	-0.174***
	(0.0447)	(0.0420)
No Limit	1.371***	
	(0.0754)	
Post	-0.0584*	-0.0754**
	(0.0310)	(0.0294)
Constant	-0.822***	0.0666***
	(0.0529)	(0.0231)
Facility FE?	No	Yes
Month FE?	No	Yes
Obs.	7,063	7,063
Facilities	318	318
R^2	0.388	0.804

Notes: Standard errors, clustered at the facility level, in parentheses.

*** Significant at the 1 percent level.

** Significant at the 5 percent level.

* Significant at the 10 percent level.

Appendix Table A4. Robustness Checks for Multi-state Analysis: Drop One State at a Time

	Main Sample		Drop IL		Drop IN		Drop MD	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
No Limit x Post	-0.180***	-0.178***	-0.187***	-0.185***	-0.178***	-0.172***	-0.183***	-0.181***
	(0.0464)	(0.0441)	(0.0464)	(0.0440)	(0.0481)	(0.0446)	(0.0469)	(0.0445)
No Limit	1.329***		1.337***		1.283***		1.335***	
	(0.0806)		(0.0801)		(0.0898)		(0.0811)	
Post	-0.0459	-0.0681**	-0.0459	-0.0681**	-0.0467	-0.0734**	-0.0435	-0.0647**
	(0.0326)	(0.0303)	(0.0326)	(0.0303)	(0.0348)	(0.0309)	(0.0331)	(0.0307)
Constant	-0.813***	0.0302	-0.813***	0.0305	-0.770***	0.149***	-0.815***	0.0338
	(0.0546)	(0.0247)	(0.0546)	(0.0248)	(0.0672)	(0.0260)	(0.0552)	(0.0248)
Facility FE?	No	Yes	No	Yes	No	Yes	No	Yes
Month FE?	No	Yes	No	Yes	No	Yes	No	Yes
Obs.	6,509	6,509	6,461	6,461	5,744	5,744	6,447	6,447
Facilities	300	300	298	298	266	266	296	296
R^2	0.361	0.805	0.366	0.805	0.315	0.795	0.362	0.806

Notes: Standard errors, clustered at the facility level, in parentheses.
*** Significant at the 1 percent level.
** Significant at the 5 percent level.
* Significant at the 10 percent level.

Appendix Table A4 (cont.). Robustness Checks for Multi-state Analysis: Drop One State at a Time

	Drop MA		Drop MI		Drop MN		Drop MT	
	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
No Limit x Post	-0.181***	-0.178***	-0.182***	-0.178***	-0.168***	-0.171***	-0.178***	-0.179***
	(0.0470)	(0.0445)	(0.0472)	(0.0449)	(0.0470)	(0.0445)	(0.0466)	(0.0443)
No Limit	1.326***		1.336***		1.279***		1.333***	
	(0.0809)		(0.0817)		(0.0810)		(0.0807)	
Post	-0.0455	-0.0694**	-0.0469	-0.0695**	-0.0422	-0.0640**	-0.0459	-0.0681**
	(0.0330)	(0.0304)	(0.0336)	(0.0312)	(0.0331)	(0.0308)	(0.0326)	(0.0303)
Constant	-0.805***	0.0326	-0.811***	0.0441*	-0.811***	-0.00172	-0.813***	0.0332
	(0.0538)	(0.0249)	(0.0559)	(0.0250)	(0.0552)	(0.0254)	(0.0546)	(0.0246)
Facility FE?	No	Yes	No	Yes	No	Yes	No	Yes
Month FE?	No	Yes	No	Yes	No	Yes	No	Yes
Obs.	6,390	6,390	6,407	6,407	6,267	6,267	6,470	6,470
Facilities	293	293	293	293	288	288	298	298
R^2	0.361	0.808	0.360	0.805	0.350	0.798	0.364	0.806

Notes: Standard errors, clustered at the facility level, in parentheses.
*** Significant at the 1 percent level.
** Significant at the 5 percent level.
* Significant at the 10 percent level.

Appendix Table A4 (cont.). Robustness Checks for Multi-state Analysis: Drop One State at a Time

	Drop NH		Drop NY		Drop OH		Drop OR	
	(17)	(18)	(19)	(20)	(21)	(22)	(23)	(24)
No Limit x Post	-0.178***	-0.174***	-0.159***	-0.165***	-0.203***	-0.207***	-0.177***	-0.176***
	(0.0467)	(0.0443)	(0.0481)	(0.0461)	(0.0644)	(0.0633)	(0.0468)	(0.0444)
No Limit	1.329***		1.308***		1.185***		1.321***	
	(0.0811)		(0.0834)		(0.117)		(0.0813)	
Post	-0.0459	-0.0681**	-0.0515	-0.0681**	-0.0489	-0.0709**	-0.0459	-0.0681**
	(0.0326)	(0.0303)	(0.0347)	(0.0327)	(0.0327)	(0.0304)	(0.0326)	(0.0303)
Constant	-0.813***	0.0240	-0.803***	0.0439*	-0.810***	-0.306***	-0.813***	0.0213
	(0.0546)	(0.0247)	(0.0564)	(0.0263)	(0.0550)	(0.0317)	(0.0546)	(0.0248)
Facility FE?	No	Yes	No	Yes	No	Yes	No	Yes
Month FE?	No	Yes	No	Yes	No	Yes	No	Yes
Obs.	6,456	6,456	6,055	6,055	4,369	4,369	6,438	6,438
Facilities	297	297	280	280	204	204	294	294
R^2	0.361	0.807	0.352	0.801	0.295	0.797	0.359	0.804

Notes: Standard errors, clustered at the facility level, in parentheses.
*** Significant at the 1 percent level.
** Significant at the 5 percent level.
* Significant at the 10 percent level.

Appendix Table A4 (cont.). Robustness Checks for Multi-state Analysis: Drop One State at a Time

	Drop PA		Drop UT		Drop VT		Drop VA	
	(25)	(26)	(27)	(28)	(29)	(30)	(31)	(32)
No Limit x Post	-0.176***	-0.175***	-0.178***	-0.176***	-0.179***	-0.177***	-0.189***	-0.181***
	(0.0486)	(0.0476)	(0.0466)	(0.0442)	(0.0468)	(0.0444)	(0.0463)	(0.0431)
No Limit	1.362***		1.324***		1.331***		1.374***	
	(0.0829)		(0.0807)		(0.0801)		(0.0782)	
Post	-0.0567*	-0.0686**	-0.0479	-0.0701**	-0.0470	-0.0688**	-0.0438	-0.0676**
	(0.0309)	(0.0304)	(0.0326)	(0.0303)	(0.0329)	(0.0306)	(0.0332)	(0.0308)
Constant	-0.801***	-0.0210	-0.810***	0.0283	-0.804***	0.0402	-0.792***	0.0647***
	(0.0539)	(0.0247)	(0.0545)	(0.0247)	(0.0544)	(0.0248)	(0.0523)	(0.0242)
Facility FE?	No	Yes	No	Yes	No	Yes	No	Yes
Month FE?	No	Yes	No	Yes	No	Yes	No	Yes
Obs.	5,787	5,787	6,488	6,488	6,466	6,466	6,214	6,214
Facilities	267	267	298	298	298	298	287	287
R^2	0.397	0.810	0.360	0.805	0.364	0.804	0.396	0.808

Notes: Standard errors, clustered at the facility level, in parentheses.
*** Significant at the 1 percent level.
** Significant at the 5 percent level.
* Significant at the 10 percent level.

Appendix Table A4 (cont.). Robustness Checks for Multi-state Analysis: Drop One State at a Time

	Drop WA		Drop WI	
	(33)	(34)	(35)	(36)
No Limit x Post	-0.180***	-0.178***	-0.206***	-0.188***
	(0.0464)	(0.0441)	(0.0606)	(0.0569)
No Limit	1.329***		1.522***	
	(0.0806)		(0.101)	
Post	-0.0459	-0.0681**	-0.0195	-0.0575
	(0.0326)	(0.0303)	(0.0507)	(0.0469)
Constant	-0.813***	0.0302	-1.006***	0.201***
	(0.0546)	(0.0247)	(0.0816)	(0.0284)
Facility FE?	No	Yes	No	Yes
Month FE?	No	Yes	No	Yes
Obs.	6,509	6,509	5,176	5,176
Facilities	300	300	243	243
R^2	0.361	0.805	0.346	0.809

Notes: Standard errors, clustered at the facility level, in parentheses.
*** Significant at the 1 percent level.
** Significant at the 5 percent level.
* Significant at the 10 percent level.

Appendix Table A5. Robustness Check for Minnesota Analysis: Elasticity of Effluent to Influent (Forward Orthogonal Deviations)

	Log Effluent (1)	Log Effluent (2)	Log Effluent (3)	Log Effluent (4)
No Limit x Log Influent	0.163	0.373**	0.788***	0.197
	(0.159)	(0.186)	(0.192)	(0.206)
Log Influent	0.645***	0.133	-0.229*	0.445**
	(0.157)	(0.144)	(0.125)	(0.177)
No Limit x Log Effluent_{t-1}				0.114
				(0.0858)
Log Effluent_{t-1}				0.0313
				(0.0778)
Year FE?	No	Yes	Yes	Yes
Month FE?	No	Yes	Yes	Yes
Other Pollutants?	No	No	Yes	Yes
Arellano-Bond test for AR(2) in first differences (p-value)	p = 0.263	p = 0.556	p = 0.450	p = 0.695
Hansen J-Stat (p-value)	0.999	1.000	1.000	1.000
Obs.	8,528	8,528	8,528	7,444
Facilities	131	131	131	131

Notes: Standard errors, clustered at the facility level, in parentheses. First-differences are instrumented using collapsed lag levels.
*** Significant at the 1 percent level.
** Significant at the 5 percent level.
* Significant at the 10 percent level.

Appendix Table A5 (cont.). Robustness Check for Minnesota Analysis: Elasticity of Effluent to Influent (Two-step Difference GMM)

	Log Effluent (5)	Log Effluent (6)	Log Effluent (7)	Log Effluent (8)
No Limit x Log Influent	0.639***	0.598***	0.575***	0.645***
	(0.183)	(0.188)	(0.188)	(0.152)
Log Influent	0.170	0.0250	0.0811	0.106
	(0.144)	(0.135)	(0.146)	(0.0919)
No Limit x Log $Effluent_{t-1}$				0.142
				(0.0928)
Log $Effluent_{t-1}$				-0.117
				(0.0794)
Year FE?	No	Yes	Yes	Yes
Month FE?	No	Yes	Yes	Yes
Other Pollutants?	No	No	Yes	Yes
Arellano-Bond test for AR(2) in first differences (p-value)	p = 0.411	p = 0.579	p = 0.412	p = 0.277
Hansen J-Stat (p-value)	0.999	0.998	1.000	1.000
Obs.	7,575	7,575	7,575	6,755
Facilities	131	131	131	127

Notes: Standard errors, clustered at the facility level, in parentheses. First-differences are instrumented using collapsed lag levels.
*** Significant at the 1 percent level.
** Significant at the 5 percent level.
* Significant at the 10 percent level.

Appendix Table A6. Robustness Check for Minnesota Analysis: Elasticity of Effluent to Influent (Lags 2-2)

	Forward Orthogonal Deviations		Difference GMM	
	(1)	(2)	(3)	(4)
No Limit x Log Influent	0.243	-3.247	5.748	3.441
	(0.656)	(7.550)	(5.121)	(29.44)
Log Influent	-0.170	0.907	-1.780	-1.244
	(0.389)	(2.599)	(3.179)	(22.90)
No Limit x Log Effluent$_{t-1}$		0.778		2.796
		(1.636)		(10.21)
Log Effluent$_{t-1}$		-0.484		-2.793
		(1.082)		(9.268)
Year FE?	No	Yes	No	Yes
Month FE?	No	Yes	No	Yes
Other Pollutants?	No	Yes	No	Yes
Arellano-Bond test for AR(2) in first differences (p-value)	0.887	0.482	0.234	0.818
Hansen J-Stat (p-value)	-	-	-	-
Obs.	8,528	7,444	7,575	6,755
Facilities	131	131	131	127

Notes: Standard errors, clustered at the facility level, in parentheses. First-differences are instrumented using collapsed lag levels.

*** Significant at the 1 percent level.
** Significant at the 5 percent level.
* Significant at the 10 percent level.

Appendix Table A6 (cont.). Robustness Check for Minnesota Analysis: Elasticity of Effluent to Influent (Lags 2-4)

	Forward Orthogonal Deviations		Difference GMM	
	(5)	(6)	(7)	(8)
No Limit x Log Influent	0.0392	0.477	2.320	0.634
	(0.493)	(0.726)	(3.320)	(0.588)
Log Influent	0.00903	0.0739	1.261	-0.0358
	(0.357)	(0.623)	(1.118)	(0.488)
No Limit x Log Effluent$_{t-1}$		0.172		0.547**
		(0.273)		(0.271)
Log Effluent$_{t-1}$		-0.108		-0.466*
		(0.274)		(0.247)
Year FE?	No	Yes	No	Yes
Month FE?	No	Yes	No	Yes
Other Pollutants?	No	Yes	No	Yes
Arellano-Bond test for AR(2) in first differences (p-value)	0.959	0.061	0.121	0.193
Hansen J-Stat (p-value)	0.055	0.315	0.267	0.726
Obs.	8,528	7,444	7,575	6,755
Facilities	131	131	131	127

Notes: Standard errors, clustered at the facility level, in parentheses. First-differences are instrumented using collapsed lag levels.
*** Significant at the 1 percent level.
** Significant at the 5 percent level.
* Significant at the 10 percent level.

Appendix Table A6 (cont.). Robustness Check for Minnesota Analysis: Elasticity of Effluent to Influent (Lags 2-6)

	Forward Orthogonal Deviations		Difference GMM	
	(9)	(10)	(11)	(12)
No Limit x Log Influent	-0.126	0.408	-0.153	0.528
	(0.488)	(0.451)	(0.781)	(0.746)
Log Influent	-0.129	-0.108	0.624*	0.612
	(0.365)	(0.316)	(0.375)	(0.392)
No Limit x Log Effluent$_{t-1}$		-0.0166		0.311
		(0.172)		(0.323)
Log Effluent$_{t-1}$		0.0668		-0.293
		(0.166)		(0.281)
Year FE?	No	Yes	No	Yes
Month FE?	No	Yes	No	Yes
Other Pollutants?	No	Yes	No	Yes
Arellano-Bond test for AR(2) in first differences (p-value)	0.83	0.480	0.502	0.06
Hansen J-Stat (p-value)	0.108	0.030	0.094	0.416
Obs.	8,528	7,444	7,575	6,755
Facilities	131	131	131	127

Notes: Standard errors, clustered at the facility level, in parentheses. First-differences are instrumented using collapsed lag levels.
*** Significant at the 1 percent level.
** Significant at the 5 percent level.
* Significant at the 10 percent level.

Appendix Table A6 (cont.). Robustness Check for Minnesota Analysis: Elasticity of Effluent to Influent (Lags 2-8)

	Forward Orthogonal Deviations		Difference GMM	
	(13)	(14)	(15)	(16)
No Limit x Log Influent	0.650**	1.001***	0.602*	0.614*
	(0.308)	(0.328)	(0.347)	(0.327)
Log Influent	-0.0941	-0.0955	0.188	0.124
	(0.262)	(0.264)	(0.316)	(0.241)
No Limit x Log Effluent_{t-1}		0.139		0.168
		(0.0915)		(0.121)
Log Effluent_{t-1}		-0.0921		-0.225**
		(0.0702)		(0.103)
Year FE?	No	Yes	No	Yes
Month FE?	No	Yes	No	Yes
Other Pollutants?	No	Yes	No	Yes
Arellano-Bond test for AR(2) in first differences (p-value)	0.753	0.034	0.419	0.008
Hansen J-Stat (p-value)	0.000	0.000	0.075	0.586
Obs.	8,528	7,444	7,575	6,755
Facilities	131	131	131	127

Notes: Standard errors, clustered at the facility level, in parentheses. First-differences are instrumented using collapsed lag levels.

*** Significant at the 1 percent level.
** Significant at the 5 percent level.
* Significant at the 10 percent level.

Appendix Table A6 (cont.). Robustness Check for Minnesota Analysis: Elasticity of Effluent to Influent (Lags 2-10)

	Forward Orthogonal Deviations		Difference GMM	
	(17)	(18)	(19)	(20)
No Limit x Log Influent	0.417*	0.773**	0.669**	0.832***
	(0.218)	(0.333)	(0.336)	(0.304)
Log Influent	0.161	-0.0916	0.188	0.0296
	(0.178)	(0.273)	(0.305)	(0.251)
No Limit x Log Effluent$_{t-1}$		0.181*		0.138
		(0.104)		(0.112)
Log Effluent$_{t-1}$		-0.126		-0.122
		(0.0830)		(0.0950)
Year FE?	No	Yes	No	Yes
Month FE?	No	Yes	No	Yes
Other Pollutants?	No	Yes	No	Yes
Arellano-Bond test for AR(2) in first differences (p-value)	0.617	0.043	0.367	0.063
Hansen J-Stat (p-value)	0.000	0.000	0.026	0.880
Obs.	8,528	7,444	7,575	6,755
Facilities	131	131	131	127

Notes: Standard errors, clustered at the facility level, in parentheses. First-differences are instrumented using collapsed lag levels.
*** Significant at the 1 percent level.
** Significant at the 5 percent level.
* Significant at the 10 percent level.

Appendix Table A6 (cont.). Robustness Check for Minnesota Analysis: Elasticity of Effluent to Influent (Lags 2-12)

	Forward Orthogonal Deviations		Difference GMM	
	(21)	(22)	(23)	(24)
No Limit x Log Influent	0.392*	0.931***	0.697**	0.800***
	(0.220)	(0.302)	(0.331)	(0.303)
Log Influent	0.185	-0.0516	0.162	0.0447
	(0.177)	(0.243)	(0.302)	(0.229)
No Limit x Log Effluent$_{t-1}$		0.145		0.132
		(0.0960)		(0.105)
Log Effluent$_{t-1}$		-0.0493		-0.126
		(0.0912)		(0.0869)
Year FE?	No	Yes	No	Yes
Month FE?	No	Yes	No	Yes
Other Pollutants?	No	Yes	No	Yes
Arellano-Bond test for AR(2) in first differences (p-value)	0.606	0.169	0.374	0.059
Hansen J-Stat (p-value)	0.000	0.000	0.082	0.986
Obs.	8,528	7,444	7,575	6,755
Facilities	131	131	131	127

Notes: Standard errors, clustered at the facility level, in parentheses. First-differences are instrumented using collapsed lag levels.

*** Significant at the 1 percent level.
** Significant at the 5 percent level.
* Significant at the 10 percent level.

Appendix Table A7. Robustness Checks for Minnesota Analysis:
Elasticity of Effluent to Influent by Average Overcompliance Percentage (Limit Facilities)

	Log Effluent (1)	Log Effluent (2)	Log Effluent (3)	Log Effluent (4)
Log Influent	0.153	0.119	0.0690	0.0559
	(0.114)	(0.0726)	(0.0715)	(0.142)
Constant	-1.404***	-0.521	-0.663***	-1.372**
	(0.178)	(0.975)	(0.122)	(0.472)
Facility FE?	No	Yes	No	Yes
Year FE?	No	Yes	No	Yes
Month FE?	No	Yes	No	Yes
Other Pollutants?	No	Yes	No	Yes
Avg. Facility Overcompliance (Average % below limit)	$\geq$ 50%	$\geq$ 50%	< 50%	< 50%
Obs.	1,207	1,207	881	881
Facilities	19	19	13	13
R^2	0.013	0.344	0.005	0.247

Notes: Standard errors, clustered at the facility level, in parentheses. No observations of facilities that averaged effluent levels greater than their limit.
*** Significant at the 1 percent level.
** Significant at the 5 percent level.
* Significant at the 10 percent level.

Appendix Table A8. Robustness Checks for Minnesota Analysis: Elasticity Regressions

	Main Sample		Include Outliers	
	(1)	(2)	(3)	(4)
No Limit x Log Influent	-0.0708	0.407***	-0.00142	0.368***
	(0.182)	(0.0958)	(0.167)	(0.0877)
Log Influent	0.353***	0.0978	0.314***	0.0805
	(0.108)	(0.0660)	(0.101)	(0.0570)
Constant	-1.474***	-0.887***	-1.387***	-0.427***
	(0.181)	(0.295)	(0.168)	(0.147)
Facility FE?	No	Yes	No	Yes
Year FE?	No	Yes	No	Yes
Month FE?	No	Yes	No	Yes
Other Pollutants?	No	Yes	No	Yes
Obs.	8,659	8,659	9,481	9,154
Facilities	131	131	157	131
R^2	0.294	0.826	0.271	0.820

Notes: Standard errors, clustered at the facility level, in parentheses.
*** Significant at the 1 percent level.
** Significant at the 5 percent level.
* Significant at the 10 percent level.

Appendix Table A8 (cont.). Robustness Checks for Minnesota Analysis: Elasticity Regressions

	Include Non-Major Facilities		Include Private Facilities	
	(5)	(6)	(7)	(8)
No Limit x Log Influent	0.270*	0.373***	-0.0706	0.411***
	(0.156)	(0.0892)	(0.182)	(0.0959)
Log Influent	0.0644	0.115	0.353***	0.0983
	(0.124)	(0.0794)	(0.108)	(0.0660)
Constant	-1.089***	-0.591**	-1.474***	-0.906***
	(0.190)	(0.233)	(0.181)	(0.296)
Facility FE?	No	Yes	No	Yes
Year FE?	No	Yes	No	Yes
Month FE?	No	Yes	No	Yes
Other Pollutants?	No	Yes	No	Yes
Obs.	14,059	14,058	8,676	8,676
Facilities	208	208	131	131
R^2	0.355	0.821	0.294	0.826

Notes: Standard errors, clustered at the facility level, in parentheses.
*** Significant at the 1 percent level.
** Significant at the 5 percent level.
* Significant at the 10 percent level.

Appendix Table A8 (cont.). Robustness Checks for Minnesota Analysis: Elasticity Regressions

	Balanced Panel (2007 - 2013)		Include Facilities That Changed Limit	
	(9)	(10)	(11)	(12)
No Limit x Log Influent	-0.713	0.129	-0.0814	0.409***
	(0.464)	(0.615)	(0.196)	(0.0947)
Log Influent	1.127***	0.337	0.365***	0.0999
	(0.382)	(0.597)	(0.129)	(0.0638)
Constant	-2.672***	-1.721***	-1.571***	-0.951***
	(0.776)	(0.497)	(0.230)	(0.295)
Facility FE?	No	Yes	No	Yes
Year FE?	No	Yes	No	Yes
Month FE?	No	Yes	No	Yes
Other Pollutants?	No	Yes	No	Yes
Obs.	1,992	1,992	8,957	8,957
Facilities	24	24	136	136
R^2	0.195	0.834	0.331	0.839

Notes: Standard errors, clustered at the facility level, in parentheses.
*** Significant at the 1 percent level.
** Significant at the 5 percent level.
* Significant at the 10 percent level.

Appendix Table A8 (cont.). Robustness Checks for Minnesota Analysis: Elasticity Regressions

	Include Facilities That Changed Limit Status		Ban Regression Sample	
	(13)	(14)	(15)	(16)
No Limit x Log Influent	0.0506	0.414***	-0.0315	0.631***
	(0.163)	(0.0935)	(0.222)	(0.164)
Log Influent	0.290***	0.116**	0.370***	-0.0616
	(0.0820)	(0.0587)	(0.140)	(0.124)
Constant	-1.351***	-0.988***	-1.504***	-1.590***
	(0.153)	(0.295)	(0.238)	(0.533)
Facility FE?	No	Yes	No	Yes
Year FE?	No	Yes	No	Yes
Month FE?	No	Yes	No	Yes
Other Pollutants?	No	Yes	No	Yes
Obs.	10,079	10,079	2,397	2,397
Facilities	154	154	111	111
R^2	0.310	0.807	0.309	0.853

Notes: Standard errors, clustered at the facility level, in parentheses.
*** Significant at the 1 percent level.
** Significant at the 5 percent level.
* Significant at the 10 percent level.

Appendix Table A9. Effect of Ban on Effluent in Minnesota Dataset

	Log Effluent (1)	Log Effluent (2)	Log Effluent (3)	Log Effluent (4)
No Limit x Post	-0.240***	-0.240***	-0.215***	-0.214***
	(0.0723)	(0.0725)	(0.0691)	(0.0688)
No Limit	3.498	3.527		
	(2.325)	(2.345)		
Post	-0.0387	-0.0408	-0.0286	-0.0321
	(0.0499)	(0.0499)	(0.0529)	(0.0522)
Constant	-1.863	-1.727	-2.262***	-2.255***
	(1.269)	(1.293)	(0.508)	(0.512)
Facility FE?	No	No	Yes	Yes
Month FE?	No	Yes	No	Yes
Other Pollutants?	Yes	Yes	Yes	Yes
Obs.	2,397	2,397	2,397	2,397
Facilities	111	111	111	111
R^2	0.320	0.323	0.844	0.846

Notes: Standard errors, clustered at the facility level, in parentheses.
*** Significant at the 1 percent level.
** Significant at the 5 percent level.
* Significant at the 10 percent level.

Appendix Table A10. Robustness Checks for Minnesota Analysis: Ban Regressions

	Main Sample				Include Outliers			
	Log Effluent	Log Effluent	Log Influent	Log Influent	Log Effluent	Log Effluent	Log Influent	Log Influent
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
No Limit x Post	-0.235***	-0.239***	-0.0614	-0.0422	-0.261***	-0.238***	-0.0193	-0.0493
	(0.0708)	(0.0720)	(0.0392)	(0.0389)	(0.0688)	(0.0683)	(0.0515)	(0.0433)
No Limit	1.506***		0.124		1.479***		0.136	
	(0.133)		(0.0806)		(0.122)		(0.0829)	
Post	-0.0473	-0.0439	-0.105***	-0.110***	-0.0210	-0.0216	-0.157***	-0.116***
	(0.0548)	(0.0566)	(0.0321)	(0.0335)	(0.0536)	(0.0547)	(0.0438)	(0.0348)
Constant	-0.891***	0.305***	1.646***	1.843***	-0.863***	0.320***	1.663***	1.887***
	(0.0875)	(0.0388)	(0.0725)	(0.0186)	(0.0781)	(0.0385)	(0.0741)	(0.0232)
Facility FE?	No	Yes	No	Yes	No	Yes	No	Yes
Month FE?	No	Yes	No	Yes	No	Yes	No	Yes
Other Pollutants?	No	No	No	No	No	No	No	No
Obs.	2,397	2,397	2,397	2,397	2,911	2,911	2,656	2,656
Facilities	111	111	111	111	145	145	132	132
R^2	0.302	0.839	0.037	0.680	0.285	0.820	0.044	0.622

Notes: Standard errors, clustered at the facility level, in parentheses.
*** Significant at the 1 percent level.
** Significant at the 5 percent level.
* Significant at the 10 percent level.

Appendix Table A10 (cont.). Robustness Checks for Minnesota Analysis: Ban Regressions

	Include Non-Major Facilities				Include Private Facilities			
	Log Effluent	Log Effluent	Log Influent	Log Influent	Log Effluent	Log Effluent	Log Influent	Log Influent
	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
No Limit x Post	-0.239***	-0.214***	-0.0811**	-0.0780**	-0.235***	-0.239***	-0.0614	-0.0422
	(0.0722)	(0.0742)	(0.0331)	(0.0329)	(0.0708)	(0.0720)	(0.0392)	(0.0389)
No Limit	1.801***		0.150*		1.506***		0.124	
	(0.115)		(0.0846)		(0.133)		(0.0806)	
Post	-0.0571	-0.0523	-0.101***	-0.103***	-0.0473	-0.0439	-0.105***	-0.110***
	(0.0641)	(0.0674)	(0.0265)	(0.0266)	(0.0548)	(0.0566)	(0.0321)	(0.0335)
Constant	-0.993***	0.490***	1.578***	1.808***	-0.891***	0.305***	1.646***	1.843***
	(0.0900)	(0.0324)	(0.0798)	(0.0189)	(0.0875)	(0.0388)	(0.0725)	(0.0186)
Facility FE?	No	Yes	No	Yes	No	Yes	No	Yes
Month FE?	No	Yes	No	Yes	No	Yes	No	Yes
Other Pollutants?	No	No	No	No	No	No	No	No
Obs.	3,907	3,907	3,907	3,907	2,397	2,397	2,397	2,397
Facilities	176	176	176	176	111	111	111	111
R^2	0.354	0.832	0.034	0.635	0.302	0.839	0.037	0.680

Notes: Standard errors, clustered at the facility level, in parentheses.
*** Significant at the 1 percent level.
** Significant at the 5 percent level.
* Significant at the 10 percent level.

Appendix Table A10 (cont.). Robustness Checks for Minnesota Analysis: Ban Regressions

	Balanced Sample				Include 2010			
	Log Effluent	Log Effluent	Log Influent	Log Influent	Log Effluent	Log Effluent	Log Influent	Log Influent
	(17)	(18)	(19)	(20)	(21)	(22)	(23)	(24)
No Limit x Post	-0.317***	-0.317***	-0.0621	-0.0621	-0.187***	-0.181***	-0.0562*	-0.0415
	(0.0853)	(0.0875)	(0.0505)	(0.0518)	(0.0520)	(0.0518)	(0.0337)	(0.0338)
No Limit	1.226***		-0.0378		1.493***		0.111	
	(0.185)		(0.101)		(0.128)		(0.0776)	
Post	-0.00193	-0.00193	-0.106**	-0.106**	-0.0289	-0.0691*	-0.0772***	-0.122***
	(0.0594)	(0.0609)	(0.0426)	(0.0437)	(0.0388)	(0.0373)	(0.0289)	(0.0292)
Constant	-0.943***	0.0232	1.726***	1.813***	-0.932***	0.275***	1.627***	1.828***
	(0.121)	(0.0554)	(0.0901)	(0.0227)	(0.0818)	(0.0317)	(0.0686)	(0.0164)
Facility FE?	No	Yes	No	Yes	No	Yes	No	Yes
Month FE?	No	Yes	No	Yes	No	Yes	No	Yes
Other Pollutants?	No	No	No	No	No	No	No	No
Obs.	1,296	1,296	1,296	1,296	3,620	3,620	3,620	3,620
Facilities	54	54	54	54	111	111	111	111
R^2	0.230	0.797	0.036	0.661	0.297	0.843	0.026	0.684

Notes: Standard errors, clustered at the facility level, in parentheses.
*** Significant at the 1 percent level.
** Significant at the 5 percent level.
* Significant at the 10 percent level.

Appendix Table A10 (cont.). Robustness Checks for Minnesota Analysis: Ban Regressions

	Include 2010 Before July				Include Facilities That Changed Limit			
	Log Effluent	Log Effluent	Log Influent	Log Influent	Log Effluent	Log Effluent	Log Influent	Log Influent
	(25)	(26)	(27)	(28)	(29)	(30)	(31)	(32)
No Limit x Post	-0.230***	-0.221***	-0.0497	-0.0306	-0.225***	-0.229***	-0.0685*	-0.0442
	(0.0577)	(0.0586)	(0.0334)	(0.0327)	(0.0652)	(0.0665)	(0.0380)	(0.0369)
No Limit	1.495***		0.109		1.579***		0.138*	
	(0.128)		(0.0790)		(0.137)		(0.0752)	
Post	-0.00488	-0.0330	-0.0898***	-0.119***	-0.0588	-0.0551	-0.101***	-0.111***
	(0.0423)	(0.0430)	(0.0274)	(0.0274)	(0.0477)	(0.0498)	(0.0304)	(0.0309)
Constant	-0.932***	0.273***	1.630***	1.826***	-0.960***	0.253***	1.636***	1.840***
	(0.0817)	(0.0307)	(0.0700)	(0.0153)	(0.0937)	(0.0377)	(0.0665)	(0.0180)
Facility FE?	No	Yes	No	Yes	No	Yes	No	Yes
Month FE?	No	Yes	No	Yes	No	Yes	No	Yes
Other Pollutants?	No	No	No	No	No	No	No	No
Obs.	3,012	3,012	3,012	3,012	2,487	2,487	2,487	2,487
Facilities	111	111	111	111	115	115	115	115
R^2	0.302	0.846	0.028	0.690	0.338	0.850	0.040	0.676

Notes: Standard errors, clustered at the facility level, in parentheses.
*** Significant at the 1 percent level.
** Significant at the 5 percent level.
* Significant at the 10 percent level.

Appendix Table A10 (cont.). Robustness Checks for Minnesota Analysis: Ban Regressions

	Include Facilities That Changed Limit Status			
	Log Effluent	Log Effluent	Log Influent	Log Influent
	(33)	(34)	(35)	(36)
No Limit x Post	-0.278***	-0.150*	-0.107**	-0.0740**
	(0.0757)	(0.0784)	(0.0477)	(0.0351)
No Limit	1.484***		0.110	
	(0.119)		(0.0719)	
Post	-0.0524	-0.162**	-0.0571	-0.0828***
	(0.0569)	(0.0685)	(0.0398)	(0.0290)
Constant	-0.822***	0.268***	1.674***	1.864***
	(0.0732)	(0.0392)	(0.0638)	(0.0181)
Facility FE?	No	Yes	No	Yes
Month FE?	No	Yes	No	Yes
Other Pollutants?	No	No	No	No
Obs.	2,785	2,785	2,785	2,785
Facilities	128	128	128	128
R^2	0.320	0.817	0.028	0.669

Notes: Standard errors, clustered at the facility level, in parentheses.
*** Significant at the 1 percent level.
** Significant at the 5 percent level.
* Significant at the 10 percent level.