Sized-based Regulation and Environmental Quality: Evidence from the US Livestock Industry

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Size-Based Regulation and Environmental Quality: Evidence from the US Livestock Industry

Chen-Ti Chen,[*] Gabriel E. Lade,[†] John M. Crespi,[‡] and David A. Keiser[§]

Abstract. The growing prevalence of animal feeding operations (AFOs) in the United States raises concerns among the public and regulators about their impact on local environmental quality. This paper studies the effects of Clean Water Act regulations that targeted water pollution from the largest hog AFOs. We compile a novel dataset linking historical regulatory records of AFOs in Iowa to downstream surface water pollution monitors. The regulation decreased ammonia concentrations downstream of large AFOs by 6 to 9 percentage points and modestly improved dissolved oxygen concentrations, but did not reduce phosphorus concentrations. Pollution reductions are largest during heavy precipitation months, consistent with the regulations reducing on-site spills and nutrient runoff from local fields. However, we find that pollution increased downstream from mid-sized AFOs, which were exempt from the regulations. Given the growth in the number of mid-sized facilities relative to large AFOs, we estimate that the regulation had little discernible impact on overall water quality.

Keywords: Iowa, Clean Water Act (CWA), concentrated animal feeding operations (CAFOs), size-based regulation, livestock water quality.

JEL Codes: C10, Q15, Q18, Q53, Q58

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1. Introduction

Agriculture is a primary source of surface water pollution in the United States. However, the Environmental Protection Agency (EPA) classifies most agricultural pollution as “nonpoint” under the Clean Water Act (CWA), exempting most agricultural producers from permitting requirements (Kling 2011). Large animal farms, known as concentrated animal feeding operations (CAFOs), are among the few exceptions and are classified as point-source polluters.

The US animal agricultural industry has experienced dramatic structural changes over the last three decades (MacDonald and McBride 2009). A notable feature has been the growing prevalence of animal feeding operations (AFOs) concentrated in Midwestern states. AFOs specialize in both animal-type and lifecycle stages, raising a large number of animals on relatively limited amounts of land. Specialization allows AFOs to achieve greater efficiency and operate at a lower cost. However, concentrated operations also concentrate pollution externalities. Manure, a byproduct of AFOs, contains high nutrient contents, especially nitrogen and phosphorus. If not stored on-site correctly and properly applied to nearby cropland, manure can spill or run off into local waterways, contributing to downstream water pollution. Nutrient pollution consistently ranks as one of the leading causes of water quality impairments in the United States (Del Rossi 2023).

Historical responses to these environmental concerns have been to tighten regulations on the largest AFOs, known as concentrated animal feeding operations (CAFOs), under the authority of the CWA. A significant update to the CWA occurred in 2003 when the EPA increased the stringency of pollution controls and permitting requirements of CAFOs. However, recent literature shows that such size-based regulations can have unintended consequences. Size-based rules incentivize existing and new operations to restrict their operation sizes to avoid compliance

(Sneeringer and Key 2011), raising doubts about the regulations' effectiveness (Eller 2017; Guess 2018).

This paper studies the impacts of the 2003 CWA updates on water quality downstream of large, regulated hog AFOs and exempt, mid-sized AFOs in Iowa.[1] Iowa is the largest US hog-producing state, raising around one-third of the nation's hogs (USDA-NASS 2023). We examine the impacts of the regulation on downstream ammonia, total phosphorus, and dissolved oxygen concentrations. Ammonia and total phosphorus have been a focus of other recent research on CAFOs (Raff and Meyer 2021; Palandri 2023). Dissolved oxygen is a broad measure of overall water quality affected by nutrient pollution and other pollutants (Hribar 2010). We match monthly monitor-level pollution concentration readings to more than 7,000 upstream animal feeding operations in Iowa from 2000 to 2012. Our research design leverages the time-varying regulatory status and entry of upstream AFOs to identify the impacts of the 2003 updates on mid-sized and large AFOs.

Our empirical results show that the 2003 CWA updates reduced ammonia levels downstream of large hog CAFOs by approximately 6 to 9 percentage points. We find modest improvements in dissolved oxygen and no evidence of changes in phosphorus pollution. The greatest pollution reductions occurred during high precipitation months, consistent with the regulation reducing on-site spills and local field runoff of nutrient pollutants.

However, we also find worse pollution downstream of mid-sized AFOs. These AFOs were not subject to the same stringency as larger operations under the 2003 CWA regulations,

[1] We refer to large animal feeding operations as CAFOs in this paper, as it is the terminology used in the CWA. We refer to medium-sized operations, operations that are large enough to be tracked and monitored by Iowa but smaller than CAFO size limits specified by the CWA, as "mid-sized AFOs" or "MMPs" for reasons detailed in section 2.

incentivizing firms to sort just below the regulatory cutoff (Sneeringer and Key 2011). Correspondingly, the number of mid-sized AFOs increased substantially relative to CAFOs after the 2003 updates, as did the average number of animals kept on each operation. The overall benefits of the 2003 CWA updates were, in turn, undermined by this strategic sorting. Accounting for the growth in mid-sized operations and the increase in pollution downstream of them after 2003, we estimate the net effect of the regulation on water quality was not statistically different from zero.

We contribute to a large and growing literature studying the effects of agri-environmental regulations. Prior research using USDA survey data finds evidence that CAFO regulations spur the adoption of nutrient management practices (Savage and Ribaudo 2013; Sneeringer et al. 2018). Others find that CWA compliance costs in the agricultural sector, particularly nonpoint source pollution requirements, are inefficiently high (Fleming et al. 1998, Ribaudo et al. 2003; Wang and Baerenklau 2014). Wang and Baerenklau (2014) show that input regulations like requiring producers to develop comprehensive nutrient management plans (CNMPs) are inefficient relative to quantity-based emission controls. Mullen and Centner (2004) opine that, in theory, the effect of CAFO regulations on environmental quality can be ambiguous and show that the effectiveness of policies like the CWA updates depends critically on monitoring efforts. Related literature has shown that animal operations such as those we study here actively avoid regulation. Roe et al. (2002) and Isik (2004) find operations migrate to locations with looser environmental regulations. Sneeringer and Key (2011) document substantial sorting around the CAFO threshold after the passage of the 2003 CWA updates. While these papers all study the consequences of environmental regulations on the livestock industry, none calculate net environmental benefits.

A related empirical literature studies the impacts of AFOs on local water quality. Both economics literature (Sneeringer 2009; 2010; Raff and Meyer 2021; Hochard et al. 2023, Palandri 2023) and those in other disciplines (Burkholder et al. 2007; Zirkle et al. 2016) highlight a strong association between CAFOs and degraded nearby water and air quality and resultant negative human health impacts. Closely related to our work, Raff and Meyer (2021) use an empirical strategy similar to ours and find that CAFOs increase ammonia and phosphorus concentrations in surface water in Wisconsin. Palandri (2023) similarly studies the impacts of AFOs on downstream water quality in Iowa and North Carolina. Our research extends this literature, using novel river streamflow data combined with historical pollution monitor data and historical regulatory records to test whether regulations can improve these detrimental impacts of AFOs.

Our work has several implications for local, state, and national policymakers. While regulatory authority over CAFOs ultimately resides with the EPA, the federal government delegates much of the design and enforcement to states. Thus, while our study focuses on one state, our findings may guide CAFO policies in other states. In particular, we document the suite of regulations used in Iowa following the 2003 CWA updates were effective, but only for operations covered under the most stringent form of the regulation. Changing or eliminating size limits under existing rules may be a practical first step to further addressing water quality concerns from these operations.

The paper proceeds as follows. Section 2 provides background information on the federal and state regulations on CAFOs and the livestock industry in Iowa. Section 3 describes our data and presents summary statistics. Section 4 outlines our empirical strategy, and Section 5 presents the results. Section 6 concludes and discusses future work.

2. Background

EPA CAFO Regulations

The EPA defines AFOs as farms that keep and raise animals in confined spaces.[2] The EPA designated AFOs that keep more than 1,000 animal units (AU) as CAFOs in 1976, defining them as point source polluters under the CWA.[3] Animal unit measurements standardize the regulation across different types of animal operations — for example, one finished steer and 2.5 market hogs count as one AU. Thus, the relevant regulatory cutoff for our paper is 2,500 hogs, which is equivalent to 1,000 AUs. Beyond the strict size thresholds, smaller AFOs may also be designated as CAFOs if they have the potential to significantly pollute waterways.

CAFOs are a large nutrient pollution source in the US. A 2003 study estimated that CAFOs, which accounted for only 5% of all AFOs in the US, were responsible for half of the more than 500 million tons of manure produced by animal agriculture annually. Annual CAFO manure production is three times greater than human sanitary waste in the US (EPA 2003).[4] Initially, the CWA required only CAFOs discharging into local waterways to obtain National Pollutant Discharge Elimination System (NPDES) permits. However, reports suggested that manure runoff and pollution discharge problems persisted around CAFOs due to inadequate enforcement (EPA 2003).

[2] Specifically, the EPA defines an AFO as a lot or facility in which animals are confined for at least 45 days in a year where no crops, vegetation, forage growth, or post-harvest residues are sustained in the facility during the normal growing season.

[3] The size threshold was first proposed by Senator Muskie when the CWA was enacted, and was subsequently adopted by the EPA based on both the amount of animal waste generated by facilities above 1,000 AUs and the number of operations above the threshold.

[4] The estimates of human sanitary waste were based on assuming a total U.S. population of 285 million and an average of 0.518 tons/year wastes generated for each person (EPA 2003).

The EPA responded to these and other concerns, updating the CWA in 2003. The updates included two new requirements. First, all CAFOs were required to apply for NPDES permits, known as duty-to-apply requirements, regardless the intent to discharge into waterways. Second, the EPA required CAFOs to submit CNMPs to ensure proper manure management. CNMPs included requirements that CAFOs secure or contract with local farms to apply manure on sufficient acreage so that there is no excessive application.

The EPA revised the CAFO rules in 2008 in response to issues brought forward by industries and environmental groups. The EPA relaxed duty-to-apply requirements since most facilities did not discharge into waterways and NPDES permits were costly. After 2008, only facilities proposing to or deemed unable to avoid discharging had to apply for NPDES permits. The EPA concurrently strengthened nutrient management requirements, requiring state regulators to review and approve CNMPs as part of their permitting requirements.

Iowa's Hog Industry

Iowa is a national leader in livestock production by many measures. Hog sales accounted for $9.4 billion in 2021, the largest state for the category (USDA-NASS 2023). Where other large hog-producing states, such as North Carolina and Minnesota, have seen modest increases or even declines in hog inventories over time, Iowa inventories have steadily increased since 1982. Iowa hog inventories were 23.9 million head in 2021, one-third of the total hogs produced in the US (USDA-NASS 2023). As Iowa's hog industry has grown, the size composition of producers also shifted. In 1982, only 9 percent of hogs were produced on farms with more than 2,000 hogs. In 2017 more than 50 percent of hog farms had at least 2,000 head, accounting for around 90 percent of inventories in the state (USDA-NASS 2017). Not surprisingly, Iowa is also the leading state in the number of CAFOs. As of 2022, Iowa had 4,203 CAFOs, more than the second and the third top states combined (NPDES CAFO Permitting Status Report 2023).[5]

Iowa AFO Rules

The EPA delegates most CWA enforcement to state agencies. States must adhere to federal minimum reporting and enforcement guidelines but may increase the stringency of their regulations beyond EPA guidance.[6] As a result, there is substantive variation in the implementation of CWA rules for CAFOs across states (GAO 2003).

The Department of Natural Resources (DNR) enforces AFO standards in Iowa. The Iowa DNR designates two AFO facility types: (i) confinements (roofed facilities) and (ii) open feedlots. Since nearly all hog AFOs in Iowa are confinements, our paper focuses on confinement requirements.

The DNR regulates both large- and mid-sized confinements. Mid-sized facilities, defined as those with between 500 and 1,000 AUs, must submit annual manure management plans (MMP). MMP requirements for mid-sized confinements have been in effect since 1995 and, unlike the CAFO rules, were not updated in 2003.

Confinements with over 1,000 AUs are defined as CAFOs and face additional regulations. In anticipation of the 2003 CWA updates, Iowa revised CAFO rules via Senate File 2293 in 2002, which became effective in March 2003. The rules required any confinement constructed or expanded to raise more than 1,000 AUs to apply for a construction permit and, in most counties,

[5] The second and third leading states have been Minnesota and Nebraska since 2019.
[6] The only states not authorized by the EPA to implement their own CAFO rules are Alaska, Idaho, Massachusetts, New Hampshire, and New Mexico (EPA 2017).

complete a form known as the Master Matrix.[7] The Master Matrix is a scoring system evaluating confinements based on their proposed location (e.g., distance from water sources), practices (e.g., covered liquid manure storage structures), and size. A proposed site is approved if it scores at least 50 percent of available points and 25 percent for each of the three subcategories (water, air, and community impact). The DNR adopted an interim Matrix soon after passing the updated CAFOs rules in 2002, which went into effect starting July 23, 2002, and remained in effect until the updated requirements became effective in 2003.[8]

Since 2003, the Iowa DNR has not required confinements meeting these standards to apply for an NPDES permit since meeting the requirements means an operation should not discharge into waterways.[9] Accordingly, the DNR did not update its regulations in 2008 when the EPA updated federal guidelines, as it considered the existing laws to have already conformed with the updates.

3. Data and Summary Statistics

We combine several data sources to create a monitor-level, longitudinal surface water quality database from 2000 to 2012 to evaluate the effectiveness of the 2003 CWA update. Here, we

[7] Similar to the federal CAFO rules, confinements smaller than 1,000 AUs can still be required to apply for a construction permit prior to building/expanding a facility, based on the manure storage structure. Confinements that do not use (or do not propose to use) the formed storage structure will need to apply for a construction permit if it is between 500 and 1,000 AUs.
[8] The interim Matrix was similar to the Master Matrix, except it required proposed confinements to score only half of what the latter would require for approval.
[9] The number of CAFOs covered under the NPDES permit programs in each state varies, as states may have their own permitting requirements that substitute for the CWA NPDES permit programs. As of 2022, Iowa had 4,203 CAFOs, but only 167 had an NPDES permit (EPA 2023). The 167 CAFOs are mostly open feedlots that do not need a Master Matrix. Most of these facilities are located in the northwest Iowa. In Nebraska there is also only a small fraction of its total number of CAFOs covered by the NPDES permit. On the other hand, most CAFOs in Minnesota have a NPDES permit.

describe the key datasets used in our analysis, discuss our data matching procedure, and present summary statistics.

Data Descriptions and Matching Procedure

Animal Feeding Operations (AFOs). Iowa DNR maintains several operation-level databases, primarily of facilities with 500 or more AUs.[10] We combine two DNR databases for our analysis. First, we downloaded a cross-section of all active AFOs in Iowa as of mid-2018. The data track facility-level characteristics for 11,121 operations, including the operation type, size, geographic coordinates, and first survey date.[11] Second, we use a longitudinal database of all pre-2018 construction permitting and MMP approval dates. While we track all types of AFOs, we focus on hog operations given the limitations of historical permitting records for other AFO types discussed below.[12]

Ideally, we would observe every CAFO's initial construction and entry date. This information, however, is not directly observable. We instead proxy for facilities' entry using permit/management plan approval dates. We designate a facility's entry date as the earliest date that (i) the DNR issued a construction permit, (ii) the DNR approved a manure management plan, or (iii) the earliest date the DNR documented the facility (i.e., first survey date).[13]

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[10] AFOs smaller than 500 AUs are included in the DNR database if they are deemed a potential contributor to a nearby water body. Information for some small AFOs are also collected by the DNR.

[11] The first survey date refers to either the first date the DNR discovered the facility, or the date the DNR first recorded the facility into the publicly available digital database.

[12] We follow the definition by Sneeringer and Key (2011) to assign operations with at least 40 AUs of hog as hog AFOs. 40 AUs are equivalent to 100 hogs weighing over 55 pounds (EPA 2003). 8,091 out of the cross-section of 11,121 AFOs from the DNR sample are assigned as hog AFOs following the definition.

[13] Using this rule, 661 facilities are assigned entry dates using the construction permit issued dates, 7,108 facilities are assigned using the manure/nutrient management plan approved dates, and 3,352 facilities are assigned using the first survey dates.

The DNR data have several limitations. First, we do not observe historic facility sizes. We instead proxy for facility size using historical regulatory status, binning facilities into those between 500 and 1000 AUs (MMPs) and those above 1000 AUs (CAFOs). The DNR also only records status changes when facilities expand to exceed the regulatory thresholds, but not the other way around, preventing us from observing facilities' exits. As such, we limit our sample to active AFOs only. Thus, our source of variation comes from the expansion/entry of AFOs. Finally, permitting records for other animal operations are less comprehensive than for hogs. For example, entry dates for most cattle AFOs are in 2008 when the DNR first collected data on these facilities.[14] We, therefore, focus on hog AFOs and, to the best extent possible, control for the presence of other AFOs in an area.

Surface Water Quality. We obtain surface water quality data from the EPA STOrage and RETrieval (STORET) repository and the Iowa DNR AQuIA databases. Our first pollutant of interest is surface water ammonia, which mostly comes from animal waste discharge or manure runoff from croplands. High ammonia concentrations are toxic to aquatic life, and long-term exposure to water containing ammonia can harm human health (Hribar 2010). We also examine dissolved oxygen and phosphorus. Dissolved oxygen is an important indicator of surface water quality, with higher levels indicating a healthier water body. Phosphorus is another primary nutrient from animal and human waste (EPA 2013). Lower levels of ammonia and phosphorus and higher levels of dissolved oxygen would suggest better water quality.

We collect daily historical surface water pollution concentration measurements from all monitoring stations in Iowa and process the data in several ways. Both ammonia and phosphorus

[14] See Figure A1 in the appendix for the histogram of entry dates for hog and cattle AFOs.

concentrations come in different forms. We convert all ammonia values to ammonia-nitrogen and limit phosphorus forms to total phosphorus.[15] Several observations are labeled as false detections, typically because concentrations are below detectable levels. We replace these values with half the minimum detection limit. We drop observations that are false detections but do not have corresponding detection limits.

Hydrological System. We use the National Hydrography Dataset (NHD) to construct a network of rivers and streams in Iowa with flow directions. The data consist of nodes (i.e., latitude and longitude points) along every river and stream in the state and include the upstream-downstream relationship and distance between any two nodes along the same river/stream. We overlay the river data with GIS boundary data at hydrologic unit code (HUC) levels from the United States Geological Survey (USGS). A HUC consists of a 2- to 12-digit number identifying a unique drainage area based on surface hydrologic features. HUC classifications are nested. For example, Iowa includes two HUC2 regions, the Upper Mississippi and Missouri. Within these two HUC2s are 56 HUC8 subbasins, 389 HUC10 watersheds, and 1,713 HUC12 sub-watersheds.[16]

Crop Production. Local land use also contributes to nutrient pollution. Animal manure is a common fertilizer, and CAFOs contract with local farmers to apply manure only to nearby croplands due to its high transportation cost. As such, the number of AFOs and their respective sizes should correlate with the amount of local land in crop production. We, therefore, include annual, county-level data on corn and soybean planted acres from the USDA National Agricultural Statistics Service (NASS) as controls.

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[15] Ammonia (NH_3) uses the weight of the entire molecular ammonia, while ammonia as nitrogen (NH_3-N) uses only the weight of the nitrogen atoms. Weight conversion: $NH_3 = NH_3\text{-}N * 1.12589$.

[16] A HUC that consists of 8 digits or more is under the fourth level of hydrologic classification. The average size of a HUC8, HUC10, and HUC12 region in our database is around 1433, 191, and 35 square miles, respectively.

Weather. We use historical weather data from PRISM, developed by researchers at Oregon State University, as additional control variables and to explore the regulation's heterogeneous impacts. We construct monthly measures of average temperature (˚C) and average and maximum precipitation (millimeters) at the HUC12 level, the finest available level in the hydrologic system hierarchy. We designate maximum precipitation as the highest accumulated precipitation in any grid cell within each HUC12.

Data Matching. We match the latitude and longitude of every AFO facility and water quality monitoring station to the nearest river node in the NHD data.[17] From this, we construct upstream-downstream relationships between AFOs and water quality monitoring stations. We then calculate the distances between all AFOs and monitoring stations along the same river/stream and count the number of AFOs by facility type within 15, 20, 25, and 30 miles of the monitor, respectively.[18,19] We overlay all other GIS data with our monitoring stations to identify their respective HUCs and counties to merge with weather and crop production datasets.

Not all AFOs are matched to a downstream monitoring station. We thus limit our sample for analyses to matched facilities. In addition, monitoring station observations are unbalanced, varying from year to year. We have very few monitor-AFO matches before 2000, and monitoring observations have declined steadily since 2011. As such, we limit our sample period to 2000-2012. We assume monitoring station reporting is uncorrelated with nearby water quality outcomes.[20]

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[17] We keep only AFOs and monitoring stations that are within 1 kilometer of a river or stream segment in the NHD data.

[18] We calculate the distance between the upstream and downstream river nodes matched to an AFO and a monitoring station, respectively. We use the routing program developed in Keiser and Shapiro (2019) to establish spatial links.

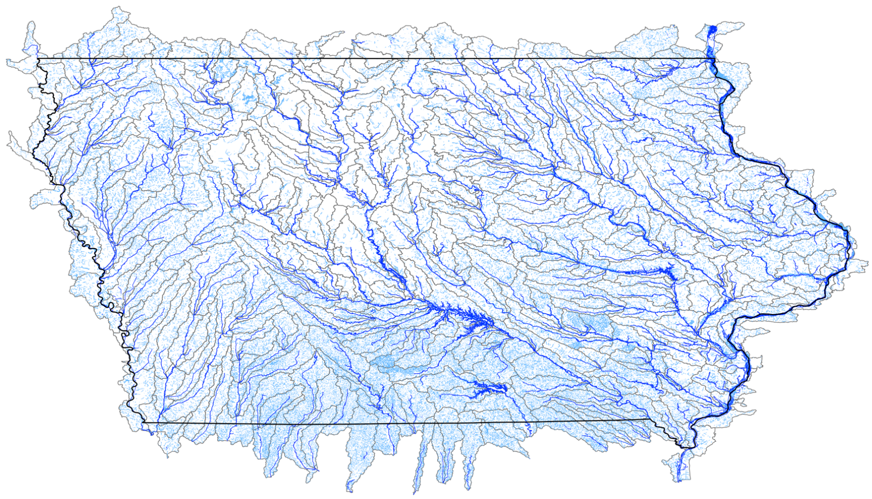
[19] The number of AFOs far exceeds the number of water quality monitoring stations. Whereas we can pair almost all AFOs with downstream monitoring stations, few are paired with a corresponding upstream monitoring station within the distance bins we consider. Given this, we are unable to pursue an upstream-downstream empirical strategy as used by Keiser and Shapiro (2019).

[20] In Appendix A we present details on the number of observations and monitoring stations over time and the decision process on defining the sample period.

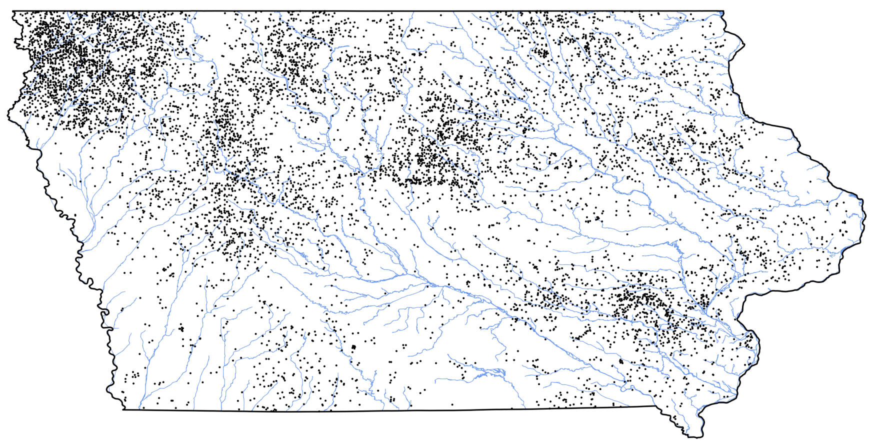
After these restrictions, the water quality monitors in our final dataset are matched to over 5,800 hog AFOs and 1,800 other-animal AFOs (e.g., cattle or poultry) in Iowa.[21]

Figure 1 presents a visualization of our primary data. Figure 1(a) overlays Iowa's major river system and HUC10 watersheds. Figure 1(b) shows the location of active hog AFOs in mid-2018. Figure 1(c) shows a snapshot of all surface water quality monitoring sites. The solid black circles are sites that monitor ammonia, hollow red triangles monitor dissolved oxygen, and hollow green diamonds monitor phosphorus. Most sites monitor more than one water quality indicator.

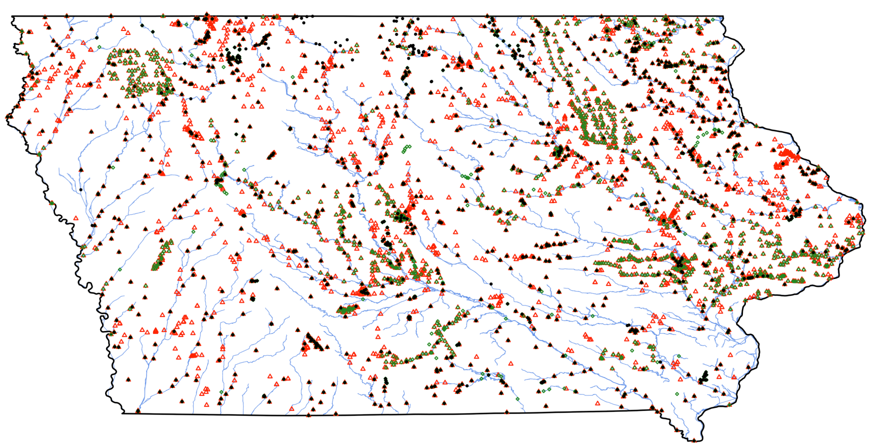
[21] Among matched monitoring stations, 1,384 have ammonia readings, 3,187 have dissolved oxygen readings, and 2,260 have phosphorus readings.



1(a) Rivers, Streams Network and Watershed Boundaries



1(b) Hog Animal Feeding Operations



1(c) Surface Water Quality Monitoring Sites

Figure 1: Iowa Hydrology, Hog AFOs, and Surface Water Pollution Data

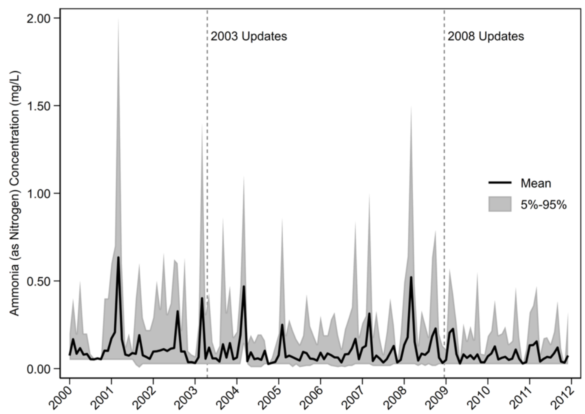
Notes: Figure 1(a) displays the river and stream network (blue) and HUC10 watershed boundaries (light brown). Figure 1(b) displays all hog AFOs and CAFOs (black dots). In Figure 1(c), solid black circles, hollow red triangles, and hollow green diamonds are sites that monitor surface water ammonia, dissolved oxygen, and phosphorus concentrations, respectively.

Summary Statistics

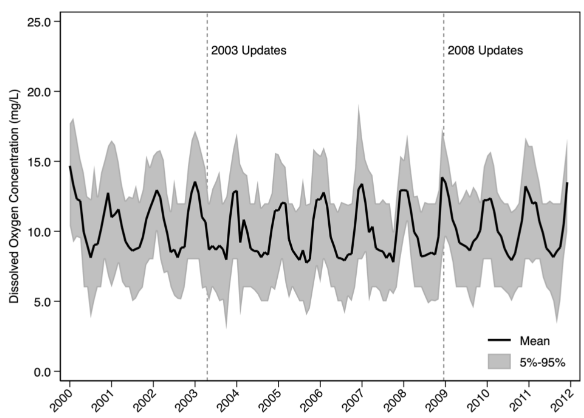
In this section, we document trends in surface water pollutant concentrations from pollution monitors downstream of AFOs and CAFOs in Iowa. We also present statistics on the number and size distribution of hog AFOs over our estimation sample period from 2000 to 2012. Appendix A contains more detailed summary statistics.

Figure 2 shows the time-series variation in pollutant concentrations for ammonia (2a), dissolved oxygen (2b), and total phosphorus (2c). All pollutants exhibit substantial temporal variation, particularly across seasons. The largest increases in concentrations and decreases in dissolved oxygen occur in spring and summer, respectively. Further, there were more frequent spikes in ammonia pollution before the 2003 major CAFO rule updates, though we do not see a similar pattern for phosphorus or dissolved oxygen. Figure 2 suggests there was little improvement in overall water quality downstream from CAFOs and AFOs in Iowa over this period. The average concentration levels for ammonia and phosphorus are modestly lower after the 2003 regulatory updates. Meanwhile, mean dissolved oxygen concentrations are lower after 2003, suggesting poorer quality.[26]

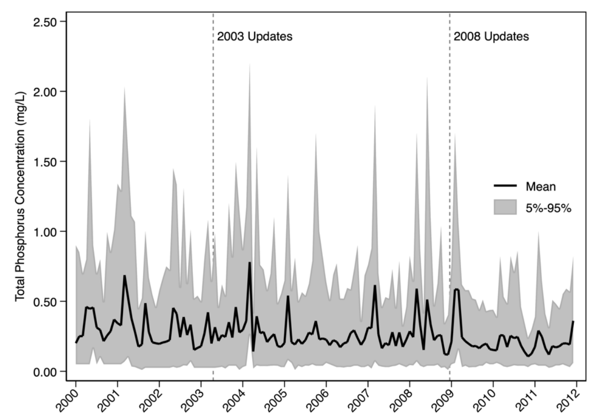
[26] The differences in means for all three pollutants are statistically significant. Table A1 in Appendix A presents the mean values of concentrations before and after the CWA updates.



2(a) Ammonia (as nitrogen)



2(b) Dissolved Oxygen



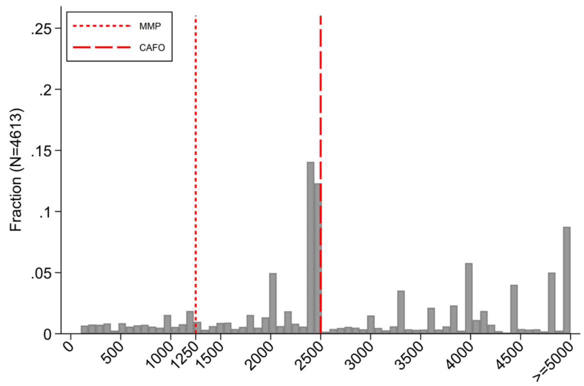
2(c) Total Phosphorus

Figure 2: Pollutant Concentrations (2000-2012)

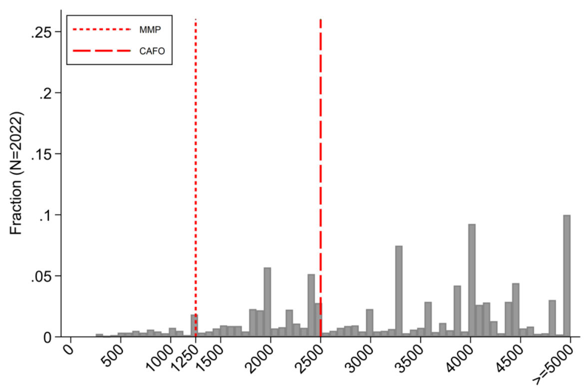
Notes: The solid line is the average concentration from 2000 to 2012. The shaded area shows the 5^{th} to 95^{th} percentiles of each pollutant concentration.

Figure 3(a) shows the size distributions of active hog AFOs in mid-2018. Several features of the data are apparent. First, facilities cluster at specific sizes. This is due to a distinct industry feature – hog barns are sized in fixed intervals. Standard single barns are designed to hold 1,000 to 1,200 head and double-long or double-wide barns to hold 2,400 head. The single-barn design has been around since the late 1990s. The 2,400 double-long/double-wide design became popular after 2002, likely since it is just below the CAFO threshold (2,500 hogs or 1,000 AUs). Second, conditional on being above the CAFO limit, most operations are quite large. The second-largest cluster in the histogram is at 4,800 hogs, twice the CAFO limit.

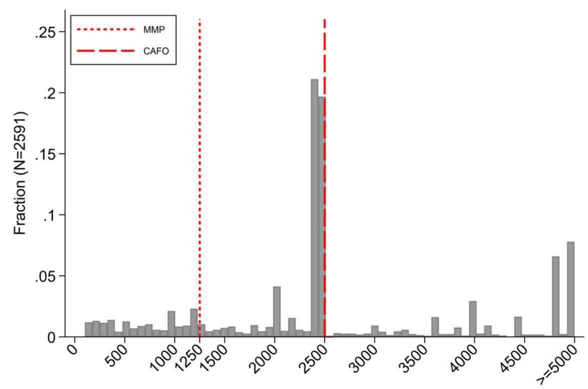
Figures 3(b) and 3(c) split the sample into facilities that entered before and after 2003, respectively. Recall that all size statistics represent sizes as of mid-2018, so the figures may not represent actual historical facility sizes. Nonetheless, we see far less evidence of strategic sorting for facilities that entered before 2003, consistent with Sneeringer and Key (2011). Figure 3(b) shows a relatively even distribution of facility sizes around standard hog barn sizes. In contrast, Figure 3(c) shows a large mass of facilities just below the CAFO limit, another large mass at 5,000 hogs, and some evidence of a mass at 1,250 hogs (500 AUs) where facilities must file an MMP with the DNR.



3(a) All AFOs



3(b) AFOs Established Before 2003



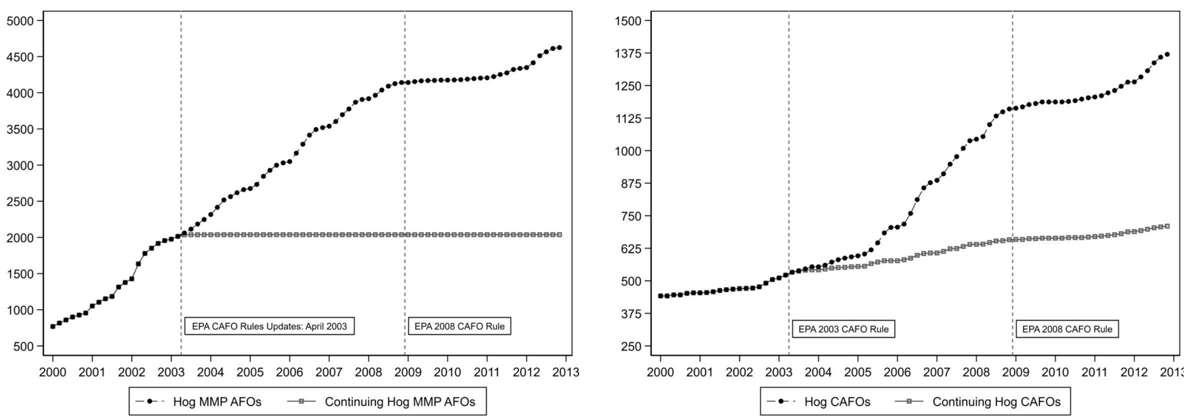
3(c) AFOs Established After 2003

Figure 3: Hog AFOs Size Distribution

Notes: Figure 3 graphs the size distribution of hog AFOs from our main sample. Figure 3(a) includes all AFOs in our sample. Figures 3(b) and 3(c) show the distribution of hog AFOs that entered before and after April 2003, respectively. The y-axis is the fraction of AFOs in each bin, and the total number of AFOs is indicated in parentheses. The vertical short-dashed line is the size threshold for MMP requirements (1,250 hogs or 500 AUs), and the vertical long-dashed line is the size threshold for CAFO requirements (2,500 hogs or 1,000 AUs). All AFOs larger than 5,000 hogs are grouped in the right-most bin.

Figure 4 shows the number of hog AFOs with an MMP (4(a)) and CAFO permit (4(b)) from 2000 to 2012. Based on our findings in Figure 3, we distinguish AFOs that entered before and after 2003, denoting pre-2003 entrants as 'Continuing (C)AFOs.' There are no new 'Continuing' AFOs in Figure 4(a) since we do not observe any very small AFOs expanding to be covered by an MMP. However, the increase in 'Continuing CAFOs' in Figure 4(b) is driven by AFOs with MMPs increasing the size of their facilities post-2003.

Figure 4(a) shows a stable and large increase in AFOs with an MMP through mid-2008. By the end of our sample, Iowa had 4,625 mid-sized AFO operations compared to 2,035 in April 2003, shown by the hollow gray squares. Figure 4(b) shows slower growth in the number of AFOs with a CAFO permit from 2000 to 2005, followed by more rapid growth from 2005 to 2009. The number of facilities established before 2003 with CAFO permits also grew, reflecting AFOs expanding their operation size. The figure highlights the primary source of variation in our data, specifically variation in the number of AFOs requiring an MMP and CAFO permit over time.



4(a) AFOs with MMPs 4(b) AFOs with CAFO Permit

Figure 4: Hog AFO Variation Over Time (2000-2012)

Notes: Figures 4(a) and 4(b) show the total number of AFOs with manure management plans and CAFO permits, respectively. Solid black circles are the total AFOs, and gray hollow gray squares are operations that were established before April 2003. The difference between the circles and hollow squares is the number of hog AFOs established after April 2003. The hollow squares are flat in Figure 4(a) given the entry cutoff but gradually increase in Figure 4(b), reflecting AFOs with MMPs that upgrade their size and acquire a CAFO permit.

4. Empirical Strategy

We use a difference-in-differences research design to examine the effects of the 2003 federal CAFO regulations on surface water ammonia, phosphorus, and dissolved oxygen concentrations in Iowa waterways.[27] We leverage rich spatial controls and estimate our treatment effects using variation in the number of regulated mid-sized AFOs and CAFOs upstream of monitoring stations before and after the 2003 CWA updates.

We estimate the following regression at the monitor-station level:

$$\begin{aligned} N_{iym} = {} & \beta_0 + \beta_1 MMP_{iym} + \beta_2 CAFO_{iym} + \beta_3 \mathbf{1}[Post03] + \\ & \beta_4 (MMP_{iym} \times \mathbf{1}[Post_{03}]) + \beta_5 (CAFO_{iym} \times \mathbf{1}[Post_{03}]) + \\ & X'_{iym}\gamma + \eta_y + \eta_m + \eta_i + \tau_{hy} + \varepsilon_{iym}. \end{aligned} \tag{1}$$

N_{iym} is the natural log pollutant concentration at monitoring station i in year y month m. MMP_{iym} and $CAFO_{iym}$ are monthly counts of upstream hog AFOs with an MMP and hog CAFOs, respectively.[28] As such, instead of binary indicators, MMP_{iym} and $CAFO_{iym}$ are treatment-intensity variables. $\mathbf{1}[Post03]$ is an indicator for post-April 2003 when the CWA updates were passed. The vector X_{iym} includes upstream monthly counts of unregulated hog AFOs and other-animal AFOs, monthly temperature and precipitation controls, and annual corn and soybean acreage. X_{iym} also controls for the monthly count of upstream hog MMPs and CAFOs between July 2002 and April 2003 to control for potential anticipation effects after the passage of Senate File 2293 but before the law became effective.[29]

We include fixed effects to account for unobservables that may be correlated with the number of upstream AFOs and surface water pollution. Year (η_y) and month-of-year fixed effects (η_m) flexibly control for time effects common to all monitors, such as seasonality or enforcement

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[27] The recent literature on differences-in-differences (e.g., Goodman-Bacon 2021) with variation in treatment timing is irrelevant in our setting since we have a single treatment that applies to all treated units after a single year.

[28] Hog CAFO refers to an AFO with both a construction permit and completed Master Matrix.

[29] The approach is similar to Malani and Reif (2015), who study the impacts of anticipated tort reforms on physician practices.

efforts. Monitor fixed effects (η_i) control for time-invariant unobservables unique to each monitor. Because we have an unbalanced panel of monitors, our estimates rely on "within" variation at the monitor to identify the regulatory impacts, where our treatment intensity variables exploit the counts of hog AFOs upstream of a monitoring station over time to identify our coefficients of interest. In some specifications, we include watershed-specific annual trends (τ_{hy}) to account for unobserved factors that result in differential pollutant concentration growth trajectories within a HUC10.[30]

Our parameters of interest are β_4 and β_5, the coefficients on the interactions between the post-2003 indicator and the MMP- and CAFO-count variables, respectively. The coefficients estimate whether, conditional on our controls, water pollution changed at monitors downstream from hog AFOs with an MMP and hog CAFOs after the 2003 updates. For ammonia and phosphorus, a negative coefficient on the CAFO interaction (β_5) would suggest that the EPA requirements led to less manure runoff from CAFO facilities or nearby farm fields due to, for example, better manure management or on-site infrastructure. A positive β_5 coefficient for dissolved oxygen would suggest the updates improved downstream water quality. Our research design relies on the assumption that, absent the 2003 CWA updates and corresponding changes in DNR policies, an additional upstream hog AFO with an MMP or hog CAFO after 2003 would, on average, have the same impact on downstream pollution as an additional facility before the regulatory updates.

[30] A HUC10 is the second finest hydrological unit next to a HUC12. In our dataset the average size of a HUC12 sub-watershed is 35 square miles. As such, controlling for HUC12-specific trends is essentially identical to station-specific trends. An alternative to flexibly control for time-variant unobserved shocks that vary across watersheds is to include watershed-by-year fixed effects. However, identification then comes solely from variation within a watershed and year. In Appendix B, we present additional results allowing trends to differ by larger regions at HUC8-level, or alternatively absorb HUC8- or -HUC10-by-year fixed effects.

We also estimate a flexible difference-in-differences model to estimate the regulation's impact over time. We estimate a flexible form of equation (1), interacting the treatment variables MMP_{iym} and $CAFO_{iym}$ with indicators for each year before and after the regulation. All other controls and fixed effects are still included in the model, except we also interact our antipation controls with a year indicator.

We also test for heterogeneous effects of the CWA updates. Extreme weather, especially heavy rainfalls, can exacerbate surface pollution runoff or lead to overflow and equipment failures. If the regulations improved on-site manure management, it could reduce the chances of runoffs during extreme weather events. As such, we would expect differential impacts of the regulation during dry months versus wet months. We, therefore, test whether the regulation had greater impacts during high-precipitation months. Specifically, we categorize monthly maximum precipitation into five quintiles and interact treatment with each quintile.[31]

Two additional empirical considerations are worth noting. First, equation (1) includes hog AFOs that entered before and after 2003. Our identifying assumption may be violated if unobserved factors influence operations' regulatory status and water quality. A priori, we believe the identifying assumption is more likely to hold for operations established before 2003 that upgraded their facilities. Operations established before 2003 are less likely to choose their location or size strategically since changing on-site infrastructure is costly, given asset specificity.[32] Sneeringer and Key (2011) and Figure 3 suggest that newer AFOs are more likely to select their

[31] In the Appendix A, we show the distribution of monthly maximum precipitation and the respective quintiles. While we argue maximum precipitation is more appropriate than mean precipitation to capture extreme weather events, we show that the distributions of the two variations are similar. We obtain similar results using monthly mean precipitation.
[32] Figure 3(b) supports this hypothesis, as well as the development of 2,400 double-long/double-wide hog barns after 2002. Over two-thirds of hogs are procured through production contracts, many of which require the purchase of specific assets, see Crespi and Saitone (2018).

regulatory status. We, therefore, examine whether our results are sensitive to this concern by estimating a model similar to equation (1) but separating regulatory impacts for hog AFOs that entered before and after 2003.

Second, we use county-level corn and soybean production data to account for any correlation between crop production, the number of CAFOs in an area, and downstream water quality. Local crop production might be affected by treatment if the regulations change the relationship between CAFOs and the amount or composition of local land in corn or soybean production. As such, these may be "bad controls," mediating the treatment effect and attenuating our estimates (Angrist and Pischke 2009). We investigate this by estimating models with and without crop controls and comparing the results. Details on the regressions from these alternative specifications are presented in Appendix B.

5. Results

Table 1 presents our main estimation results. Column (1) includes station and time fixed effects. Column (2) adds HUC10 watershed linear trends. In columns (3) and (4), we follow the same specifications as columns (1) and (2), except that we additionally include post-2008 interactions to test whether differential regulatory impacts exist after 2008. In all specifications, we limit the sample to AFOs no more than 20 miles upstream of a monitoring station.[33] Our coefficients of interest are MMPxPost03 and CAFOxPost03, estimating the change in average downstream

[33] Keiser and Shaprio (2019) use a 25-mile bandwidth to study impacts of treatment plants on downstream water quality. We use a 20-mile buffer since the average size of a HUC10 is around 200 mi^2 and follows a fan or fern shape. A 20-mile bandwidth ensures that most of our identifying variation comes from within HUC10 changes in the number of CAFOs/AFOs before and after the CWA updates. Appendix B1 presents results using alternative bandwidths, including 25 miles.

pollution concentrations resulting from adding one more regulated hog AFO or CAFO, respectively, after the regulatory updates.

We first discuss the effects on surface water pollution downstream of CAFOs, the operations targeted by the regulation. The first panel in Table 1 shows that the 2003 updates decreased ammonia concentrations by 5.6% on average in column 1. The magnitude increases to 7.8% when we include HUC10-by-year linear trends in column 2. Columns 3 and 4 show no differential regulatory impacts post-2008 (columns 3 and 4). The finding is unsurprising since the DNR did not revise its regulations in response to the 2008 EPA rule updates. The second panel shows that the 2003 CWA updates modestly improved downstream dissolved oxygen. We observe a 1% increase in dissolved oxygen concentrations downstream of CAFOs across specifications after 2003. The third panel shows a 1.5% to 3.2% decrease in phosphorous pollution downstream of CAFOs. The estimates for phosphorus are statistically insignificant.

Next, we turn to mid-sized AFOs with MMPs. Table 1 shows that the 2003 CWA updates had positive and statistically significant impacts on ammonia and total phosphorus concentrations at monitors downstream of AFOs with MMPs. The magnitudes are smaller than the corresponding CAFO estimates. The estimates may seem surprising since there were no regulatory updates for mid-sized AFOs in 2003. However, facilities' strategic sorting plausibly explains this finding. The average MMP facility size is around 2,000 hogs in Figure 3(b) versus over 2,300 in Figure 3(c), i.e., strategic sorting likely increased the average number of hogs on mid-sized operations by as much as 15%.

Table 1: Effect of 2003 CAFOs Regulation on Water Pollution

	(1)	(2)	(3)	(4)
Dependent Variable: ln(Ammonia-Nitrogen)				
MMP x Post03	0.0306***	0.0333***	0.0284***	0.0262***
	(0.0074)	(0.0090)	(0.0075)	(0.0096)
CAFO x Post03	-0.0566***	-0.0788***	-0.0561***	-0.0899***
	(0.0179)	(0.0196)	(0.0179)	(0.0217)
MMP x Post08			-0.0132***	-0.0118
			(0.0041)	(0.0072)
CAFO x Post08			-0.0066	-0.0127
			(0.0141)	(0.0198)
R-Squared	0.2922	0.3163	0.2936	0.3174
Observations	22670	22670	22670	22670
Stations	1049	1049	1049	1049
Dependent Variable: ln(Dissolved Oxygen)				
MMP x Post03	-0.0016	-1.18E-5	-0.0017	-0.0002
	(0.0031)	(0.0032)	(0.0032)	(0.0032)
CAFO x Post03	0.0105**	0.0103*	0.0107**	0.0103*
	(0.0053)	(0.0060)	(0.0054)	(0.0060)
MMP x Post08			-0.0006	-0.0005
			(0.0009)	(0.0010)
CAFO x Post08			-0.0015	0.0008
			(0.0029)	(0.0035)
R-Squared	0.4671	0.4777	0.4671	0.4777
Observations	41129	41129	41129	41129
Stations	2594	2594	2594	2594
Dependent Variable: ln(Total Phosphorus)				
MMP x Post03	0.0226***	0.0190***	0.0237***	0.0207***
	(0.0078)	(0.0073)	(0.0078)	(0.0075)
CAFO x Post03	-0.0328	-0.0240	-0.0390*	-0.0157
	(0.0238)	(0.0177)	(0.0232)	(0.0178)
MMP x Post08			-0.0010	0.0012
			(0.0032)	(0.0046)
CAFO x Post08			0.0180	0.0192
			(0.0125)	(0.0179)
R-Squared	0.5502	0.5620	0.5510	0.5629
Observations	31283	31283	31283	31283
Stations	1861	1861	1861	1861
Time-varying controls	Yes	Yes	Yes	Yes
Month-of-year FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Station FE	Yes	Yes	Yes	Yes
Watershed x year trend	No	Yes	No	Yes

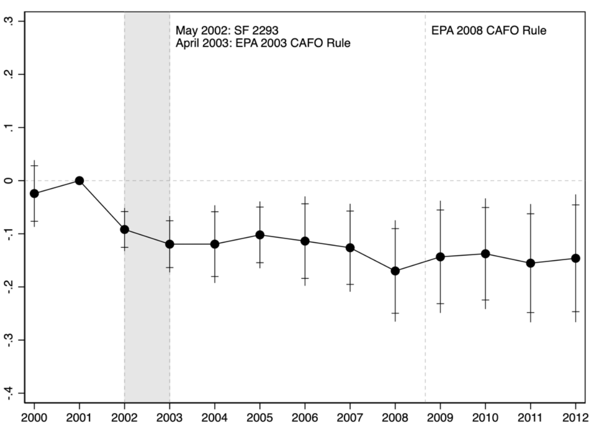
Note: *, **, and *** denote significance at the 10%, 5%, and 1% level. The dependent variables are station-level log-transformed pollution concentrations. For all columns the max distance AFOs to station is restricted to 20 miles. Time-varying controls include annual corn and soybean acreage, monthly max precipitation and mean temperature, and monthly other-animal AFOs. Columns (2) and (4) are our main specifications, where we include HUC10-by-year trends. Standard errors (in parenthesis) in all regression equations are clustered at the station level.

Figure 5 presents the flexible difference-in-differences results.[34] The regressions include the same control variables and fixed effects as in column 2. We use the year before the DNR passed its updated CAFOs rules in 2002 as the reference year to account for the possibility that producers started complying with the regulations after the DNR began using the interim Matrix.

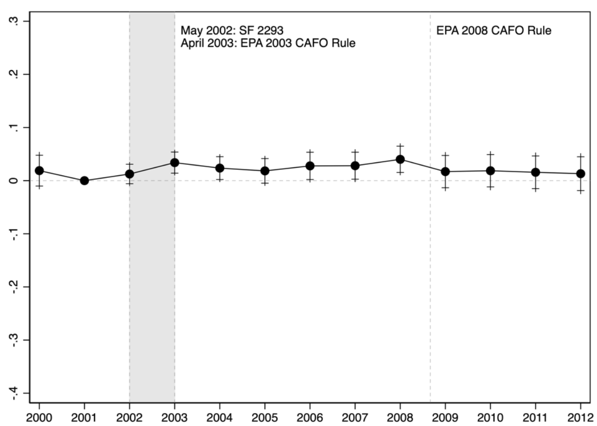
Figures 5(a), 5(c), and 5(e) show the year-by-year effects of the EPA updates on pollution downstream of hog CAFOs for ammonia, dissolved oxygen, and total phosphorus, respectively. Following the regulatory updates, we see a steady decline in ammonia concentrations downstream of CAFOs, with more modest improvements in dissolved oxygen and total phosphorus. These results support the findings in Table 1. We also find suggestive evidence of an anticipation effect in ammonia and dissolved oxygen. The former decreased while the latter increased between 2002 and 2003 when the DNR introduced the interim Matrix and the updated CAFO rules passed.

Figures 5(b), 5(d), and 5(f) show corresponding effects for mid-sized AFOs with MMPs. We observe a modest but persistent and statistically significant increase in ammonia and phosphorus concentrations after the 2003 updates. After the updates, we observe no statistically detectable change in dissolved oxygen levels.

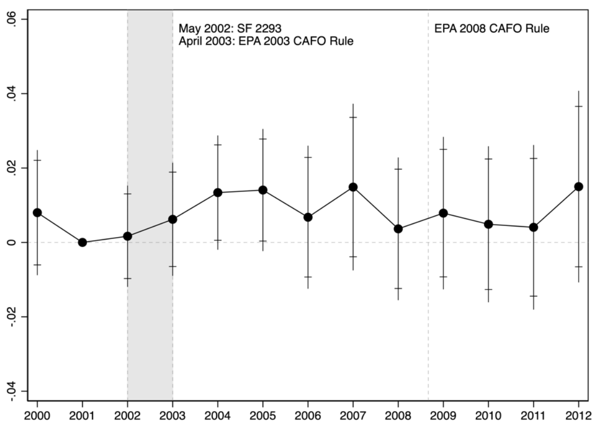
[34] We do not observe large differential trends prior to regulation, but due to limited historical data, we are not able to assess the assertion rigorously.



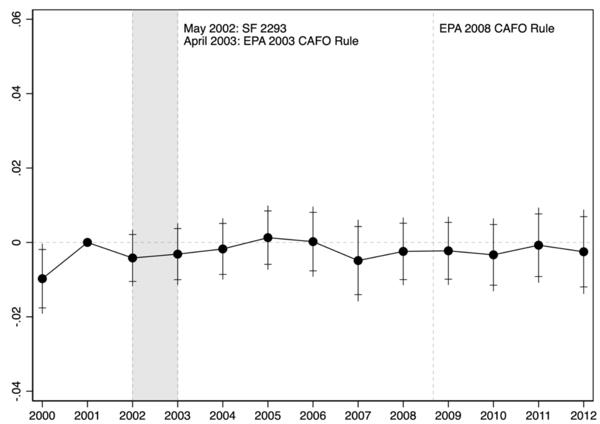
5(a) Ammonia: Hog CAFOs



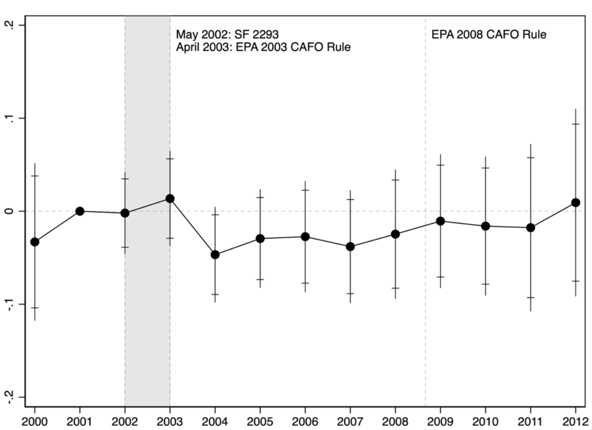
5(b) Ammonia: Hog AFOs with MMP Permit



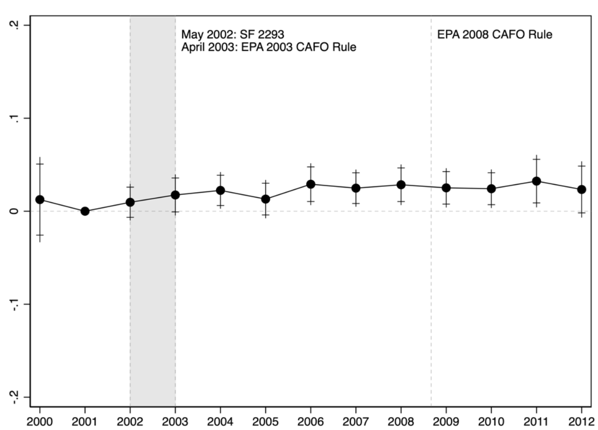
(c) Dissolved Oxygen: Hog CAFOs



5(d) Dissolved Oxygen: Hog AFOs with MMP Permit



5(e) Phosphorus: Hog CAFOs



5(f) Phosphorus: Hog AFOs with MMP Permit

Figure 5: Treatment Effect of 2003 EPA CWA Regulations by Year

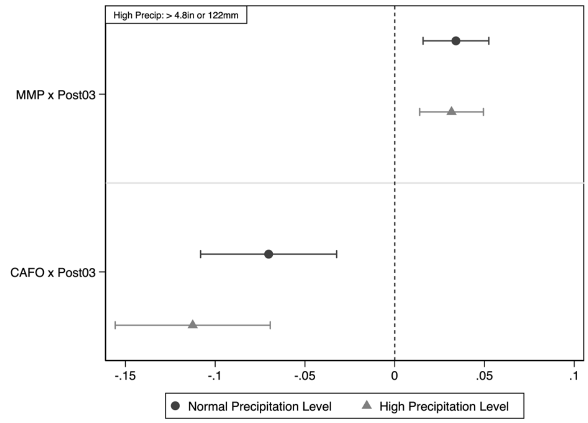
Notes: In each sub-figure, the extended vertical lines are 90 percent confidence intervals, and the bars are 95 percent confidence intervals. The gray shaded areas span from May 2002 to April 2003. The gray vertical dashed lines indicate December 2008.

Heterogeneous Effects and Robustness Checks

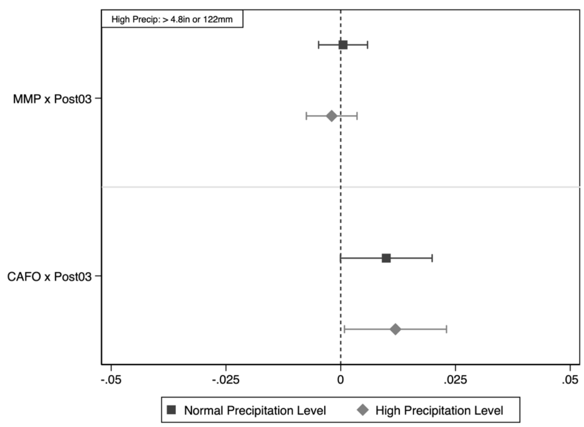
Figure 6 explores treatment effect heterogeneity, dividing our sample into months with higher and lower precipitation. We interact the relevant treatment indicators with a single 'high precipitation' indicator, defined as months where precipitation falls in the fifth quintile, estimating a triple-difference regression.[35] We include the same controls as column 2 of Table 1 in regressions for all three outcomes.

We find a positive impact of the regulation on ammonia pollution downstream of hog AFOs with MMPs, both during normal precipitation and high precipitation months, relative to their impacts before 2003. During high precipitation months, we estimate the ammonia concentrations downstream of hog CAFOs decreased by over 11 percentage points relative to similar months before the regulation. The finding is consistent with reduced manure runoff or equipment failure being one mechanism underlying our treatment effect. We observe similar patterns for dissolved oxygen and total phosphorus during high precipitation months, though the differences are much smaller and are not statistically significant for the latter.

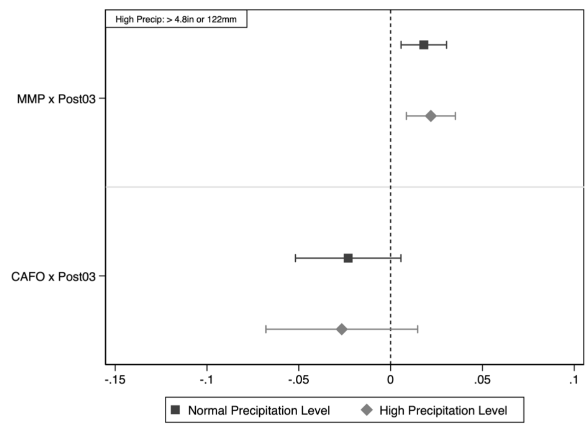
[35] High-precipitation level is defined as the monthly maximum precipitation level that falls into the fifth quintile with the precipitation level higher than 4.8 inches or 122 mm. Appendix B presents results interacting treatment with every precipitation quintile. We still see that largest treatment effect during months with precipitation in the fifth quintile, although results are noisier.



6(a) Ammonia



6(b) Dissolved Oxygen



6(c) Total Phosphorus

Figure 6: Heterogeneous Effect of 2003 EPA CWA Regulation

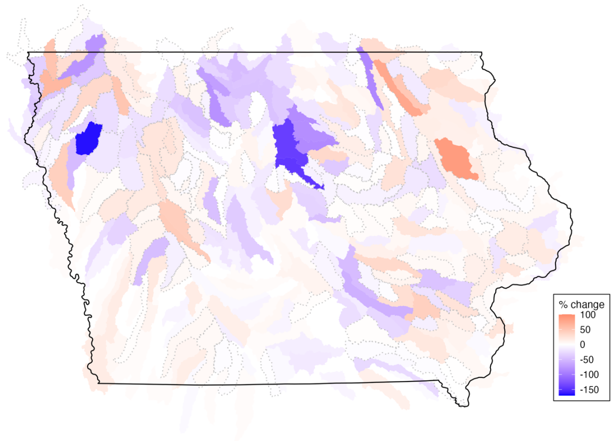
Notes: All sub-figures show the heterogeneous effects by precipitation levels following the main specification (Table 1 column 2). Bars indicate 95% confidence intervals.

Appendix B examines the robustness of our results, explores alternative specifications of the model, and conducts falsification regressions. We first estimate similar regressions as equation (1) but separate hog AFOs that were established before and after 2003. We find quantitatively similar results for the regulatory effects for CAFOs established before 2003, suggesting selection into treatment does not substantively bias our preferred estimates. We also show that our results are not sensitive to the inclusion or exclusion of local crop production controls, suggesting potential changes in local crop choices induced by the regulation were not substantive. Third, we re-estimate our models using alternative upstream distance criteria (15, 25, and 30 miles). Impacts are smaller as we extend the maximum distance upstream, highlighting the local nature of pollution from animal agriculture operations. Finally, we run falsification regressions, re-estimating the models using monitors for pollutants for which we would not expect differential impacts by CAFOs after the regulatory updates. Concentrations of atrazine and metribuzin, herbicides commonly used in corn and soybean production, were unaffected by the 2003 updates, supporting the credibility of our research design.

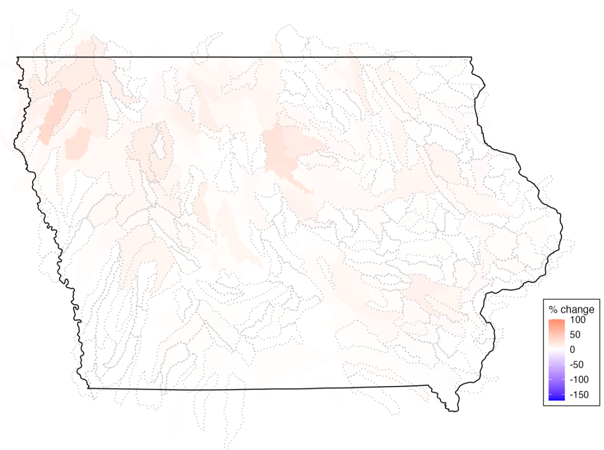
Overall impacts of the CWA updates

We use the estimates from our regression model to predict the overall impact of the 2003 CWA updates on average surface water quality downstream of AFOs in Iowa. In particular, we quantify the rule's effect at the HUC10 watershed level, multiplying our estimated coefficients by the observed growth in CAFOs and mid-sized AFOs in each HUC10 from 2003 to 2012 (Figure A5). We repeat this process for each of the three water quality outcomes.

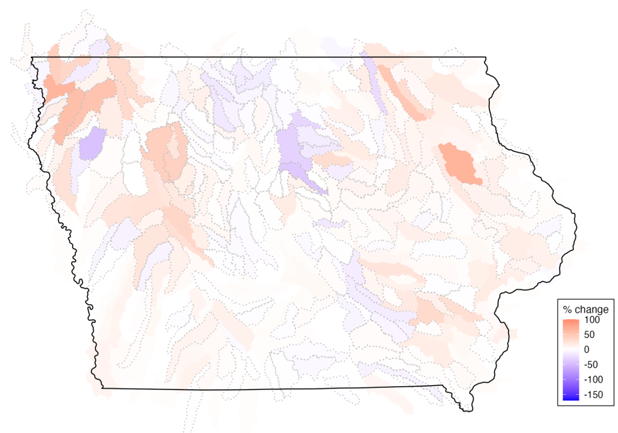
Figure 7 maps the overall effect of the CWA updates at the HUC10 level on ammonia, dissolved oxygen, and phosphorus pollution. We find substantial heterogeneity in the regulation's effects across watersheds, driven by the different magnitudes in the growth of mid-sized AFOs versus CAFOs over time. In areas with larger increases in AFOs with MMPs relative to CAFOs, we observe non-detectable or positive effects (i.e., worse water quality) of the regulation on ammonia and phosphorus concentrations. In areas with more CAFO entrants, we see substantial improvements in water quality due to the regulation.



7(a) Ammonia



7(b) Dissolved Oxygen



7(c) Total Phosphorus

Figure 7: Overall Effect of 2003 EPA CWA Regulation at HUC10-Level

Notes: Each subfigure plots the overall effect in each HUC10 as a percentage point change, using the point estimates from column 2 Table 1. A HUC10 outlined by dotted lines indicates the estimated effect is not statistically significant at the 90 percent significance level.

Table 2 presents the average statewide effects.[36] On average, we estimate that the regulation decreased ammonia concentrations by 3.3%, increased dissolved oxygen by 2.9%, and increased total phosphorus by 4.1%. However, the ammonia and phosphorus results are statistically insignificant. The findings suggest that the regulation had little discernible impact on

[36] We obtain very similar results when we weight the averages by HUC10 size.

the three water quality outcomes and that the improvement in water quality from more stringently regulating CAFOs was mostly offset by strategic sorting.

Table 2: Overall Effect of 2003 EPA CWA Regulation

	Coefficient	Standard Error	P-Value
Ammonia	-0.033	0.061	0.591
Dissolved Oxygen	0.029	0.015	0.051
Total Phosphorus	0.041	0.048	0.393

Note: For each water quality outcome, the coefficient is constructed by averaging the HUC10-level overall effect estimates from Figure 7.

Our results are subject to several caveats. First, data limitations on AFO entry dates may bias our estimates if mistakes in the DNR's records correlates with the onset of the regulation. Further, we cannot explicitly model facilities' sizing decisions since the DNR does not track facility sizes over time. While robustness checks suggest that our findings are robust to using a subset of facilities less likely to sort, explicitly modeling regulatory regime sorting would be preferable. Another factor that could introduce noise into our identification is grandfathering. Grandfathering practices are common in environmental regulations and can have unintended consequences (Heutel 2011). In our setting, AFOs constructed or expanded before May 31, 1985, were not required to obtain MMPs if they were under the 1,000 AU threshold. We address this issue by assigning them to the control group, but future work may consider pollution from these facilities separately. Finally, the construction of our outcome variables of interest is imperfect. Not every monitoring station records pollutant concentration in every period.

6. Conclusion

In this study, we combine facility-level data on AFO regulatory status and monitoring-level data on surface water pollutant concentrations for ammonia, dissolved oxygen, and total phosphorus to study the effects of the 2003 federal CAFO regulations on water pollution from CAFOs in Iowa.

Our results suggest that the federal regulations improved water quality downstream of hog CAFOs after 2003. These gains, though, were offset by increased pollution from mid-sized AFOs with MMPs after 2003. We attribute this to the likely increase in the size of average mid-sized AFOs after the regulation, induced by strategic avoidance of the regulation by many AFOs in the state post-2003.

Our paper serves as a step toward better understanding the benefits of regulating animal operations. As part of the regulatory review process, the EPA estimated that the compliance costs associated with the CWA updates would be about $335 million annually. In comparison, estimated benefits ranged from $204 to $355 million, yielding an ex-ante benefit-cost ratio of around one (EPA 2003). To conduct their analysis, the EPA relied on an integrated assessment model (IAM), which combined hydrological models to predict changes in water pollution from the rule with estimates of the economic benefits of surface water quality improvements.

We show that, while statistically detectable improvements in water quality downstream of CAFOs exist due to the regulations, mid-sized operations strategically sorting below CAFO size limits eroded nearly all these benefits. In this way, our paper also contributes to an important emerging literature comparing ex-ante and ex-post estimates of the effectiveness of regulations (Cropper et al. 2018; Aldy et al. 2022; Fraas and Morgenstern 2023). We highlight an important reason these estimates may differ: actors strategically avoid regulation in an unanticipated manner.

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Online Appendix for
Size-Based Regulation and Environmental Quality:
Evidence from the US Livestock Industry
Chen-Ti Chen, Gabriel E. Lade, John M. Crespi, and David A. Keiser

January 2024

A. Supplementary Data Details

1. AFOs entry dates

Figure A1 shows entry dates for hog and cattle operations in Iowa. Entry dates for most cattle operations are 2008. This is likely because Iowa cattle operations are mostly open feedlots, which were not required to register with DNR if they were smaller than the CAFO limit. Therefore, many of these operations likely already existed but showed up in our dataset in 2008 since the DNR began tracking their location that year. On the other hand, the MMP requirements for confinements, mostly hog operations in Iowa, went into effect in 1995, resulting in more accurate records of entry dates for these operations.

2. Construction of weather control variables

We construct monthly HUC12 PRISM data using data provided by researchers at Oregon State University. We aggregate daily temperature and precipitation data to month. We calculate mean temperature and precipitation using the average of all grid cells within the same HUC12. Maximum and minimum variables are similarly constructed as the maximum/minimum among all grid cells within the same HUC12. Figure A2 shows the distribution and the corresponding five quintiles for monthly maximum and mean precipitation levels.

3. Other-Animal AFOs

'Other-animal AFOs' can be AFOs with cattle, poultry, or other animals and their combinations. We control for these other animal AFOs in the same distance range in all empirical specifications. Figure A3 shows a snapshot in 2012 of the spatial distribution of other-animal AFOs, most of which are in northwest Iowa.

4. Surface Water Pollutant Reading Observations and Monitoring Stations Over Time

Figure A4 shows observations for the three pollutant concentration readings and the number of stations over the sample period from 2000 to 2012. Observations for each of the three pollutants follow a similar trend, where the number of observations peaks around 2006/07, followed by a decline in observations and a modest rebound through 2011. Monitors have decreased since 2011.

5. Summary Statistics

Table A1 presents the full summary statistics of variables used in different regression analyses. Our main specifications limit the distance of any AFOs upstream of a monitor to 20 miles. Corn and soybean planted acreage variables are annual. All other variables are monthly.

6. Growth of MMP AFOs and CAFOs in a HUC10 post-2003

Figure A5 shows the increase in hog AFOs with MMP and hog CAFOs in each HUC10 watershed since the regulatory updates. The increase in the number of facilities is the difference between March 2003 (a month before the updates went into effect) and December 2012 (the last month of the sample period).

Table A1: Summary Statistics

	Ammonia (as Nitrogen)		Dissolved Oxygen		Total Phosphorus	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
1. Outcome Variable						
Pollutant Concentrations (2000–2012)	0.102	1.173	9.398	2.687	0.254	0.511
— Pre-2003 CAFO Rule Updates	0.128	0.426	9.924	2.781	0.311	0.647
— Post-2003 CAFO Rule Updates	0.097	1.274	9.279	2.65	0.244	0.482
2. Treatment Variables						
Number of Hog AFOs with MMPs						
— upstream 15 miles	1.705	3.021	1.571	2.951	1.66	2.847
— upstream 20 miles	2.758	4.776	2.405	4.592	2.627	4.489
— upstream 25 miles	4.298	7.368	3.528	6.837	4.01	6.932
— upstream 30 miles	5.845	10.327	4.683	9.327	5.454	9.884
Number of Hog CAFOs						
— upstream 15 miles	0.437	1.017	0.392	0.967	0.418	0.945
— upstream 20 miles	0.675	1.426	0.585	1.375	0.625	1.319
— upstream 25 miles	1.086	2.035	0.88	1.939	1.008	1.93
— upstream 30 miles	1.487	2.807	1.16	2.551	1.409	2.831
3. Control Variables						
Mean Temperature (˚C)	13.243	9.888	13.596	8.926	13.558	9.172
Maximum Precipitation (Millimeter)	91.127	65.723	92.259	62.954	91.471	64.853
Corn Planted Acreage (Million Acres)	0.135	0.050	0.137	0.047	0.134	0.049
Soybeans Planted Acreage (Million Acres)	0.097	0.039	0.993	0.039	0.097	0.039
Number of other AFOs						
— upstream 15 miles	0.550	1.313	0.456	1.192	0.508	1.267
— upstream 20 miles	0.857	2.135	0.676	1.832	0.772	2.007
— upstream 25 miles	1.213	3.105	0.925	2.586	1.087	2.874
— upstream 30 miles	1.674	4.112	1.238	3.403	1.471	3.763
		N = 23,005		N = 41,722		N = 31,682

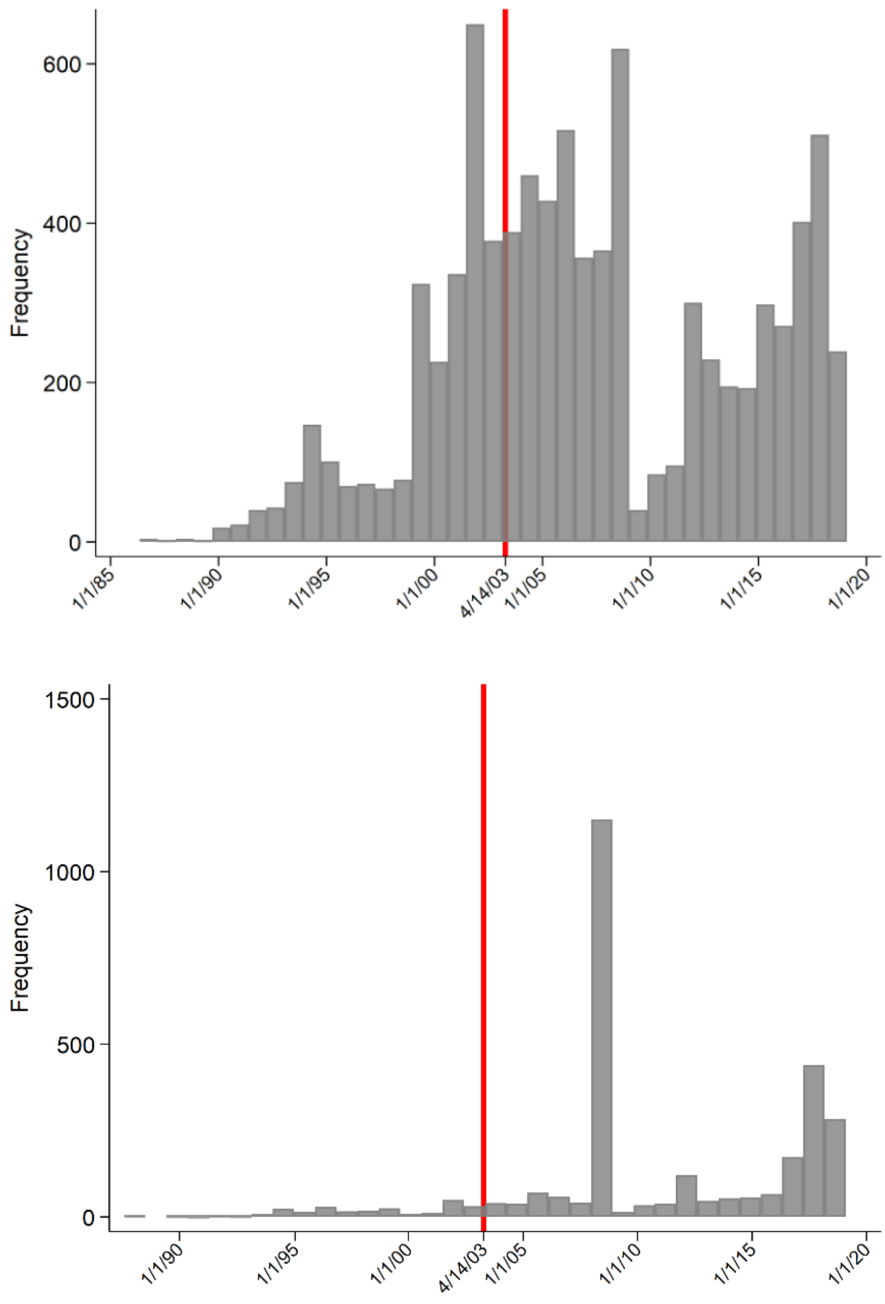


Figure A1: Hog (top) and Cattle (bottom) AFO Entry Dates

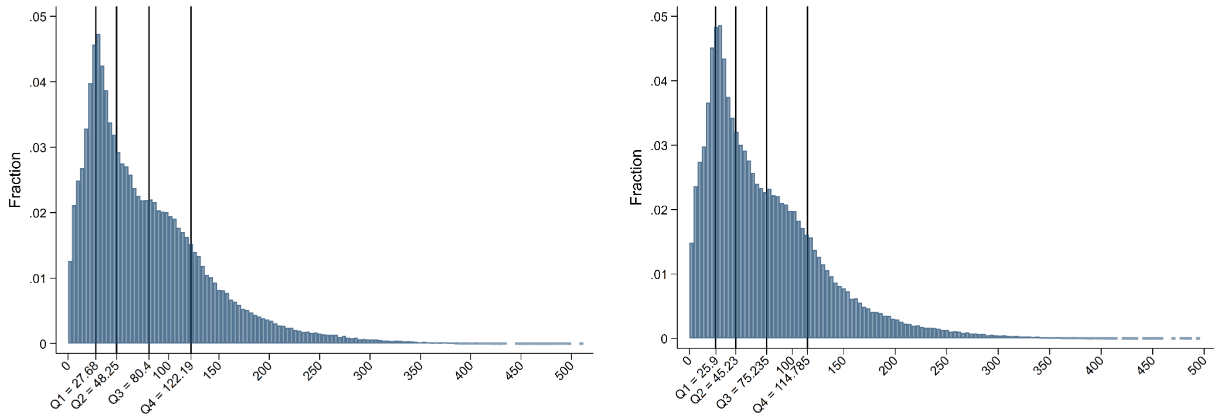


Figure A2: Monthly Maximum (left) and Mean (right) Precipitation Distribution (N = 198,396)

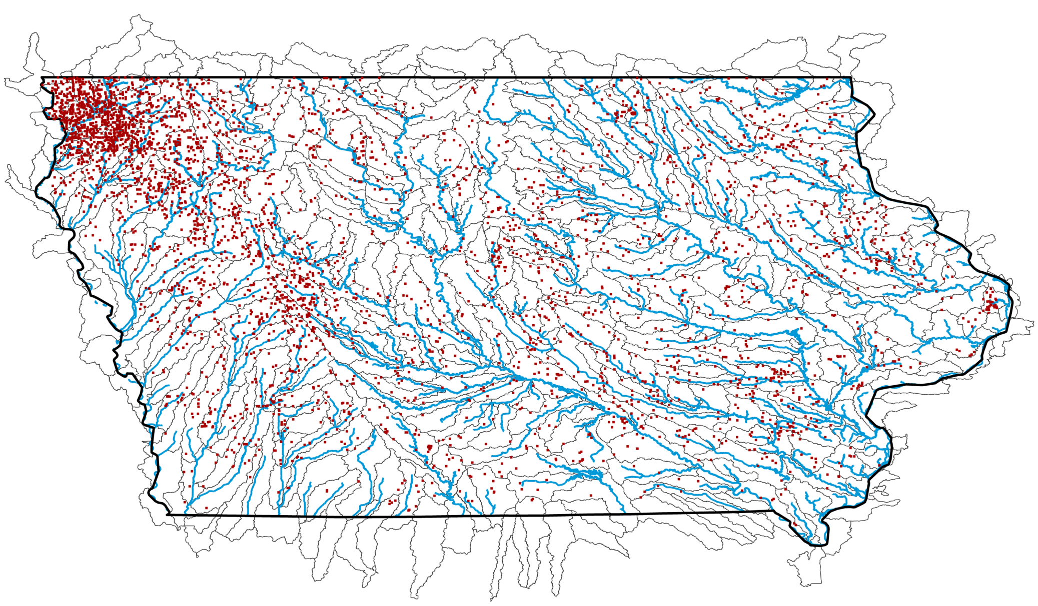
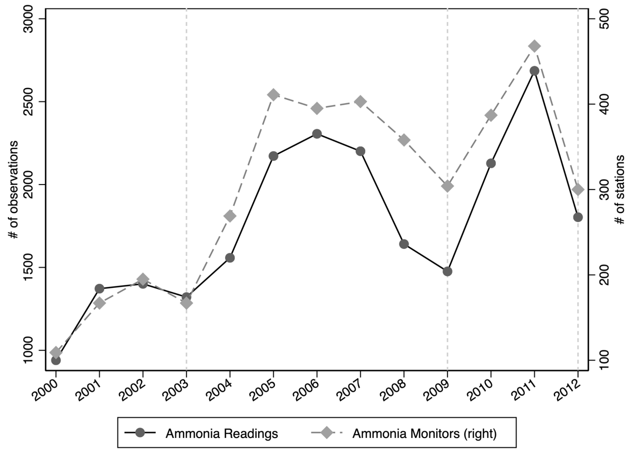
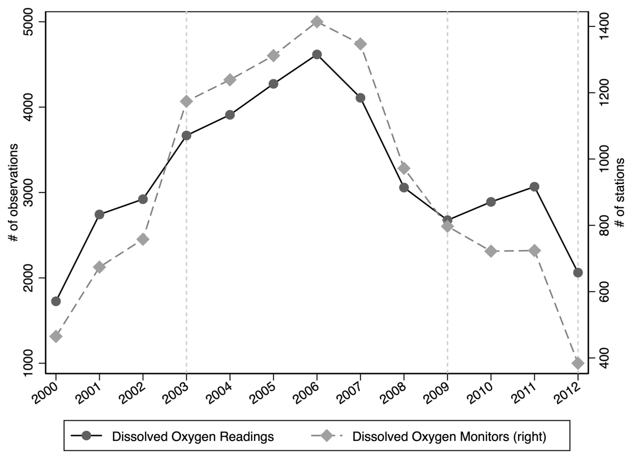


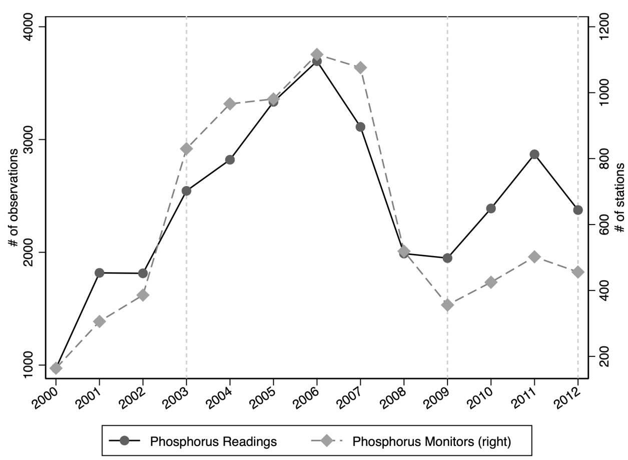
Figure A3: Other-Animal AFO Spatial Distribution.



A4(a): Ammonia

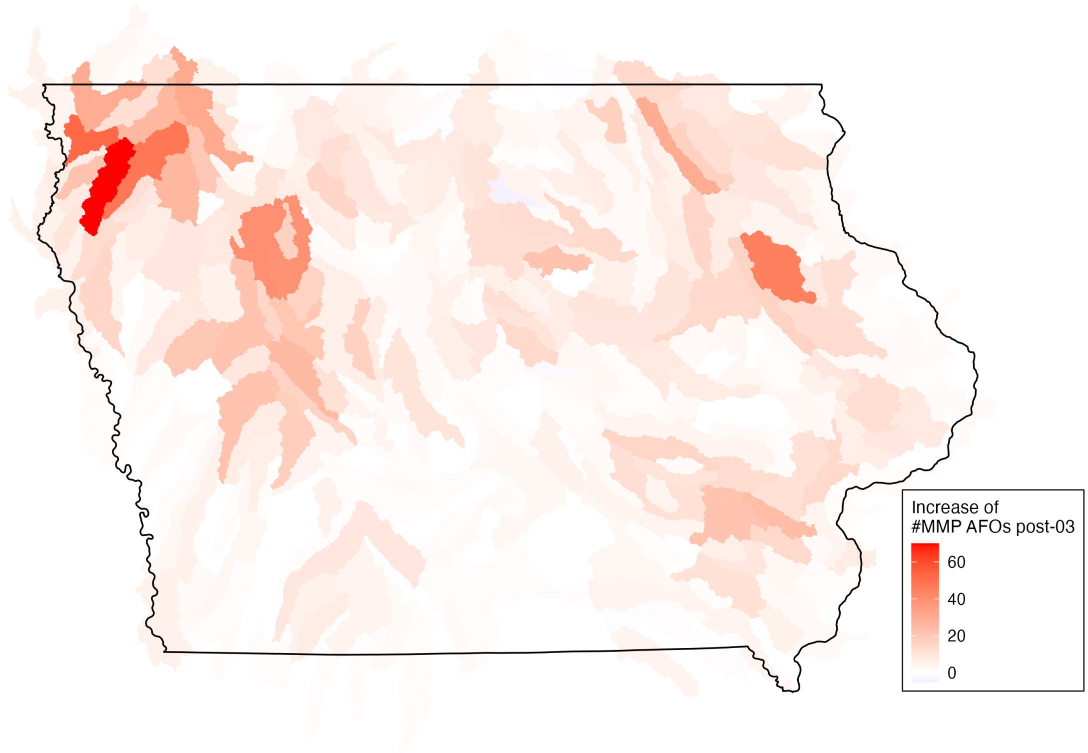


A4(b): Dissolved Oxygen



A4(c): Total Phosphorus

Figure A4: Annual Observations of Pollutant Monitors and Readings.



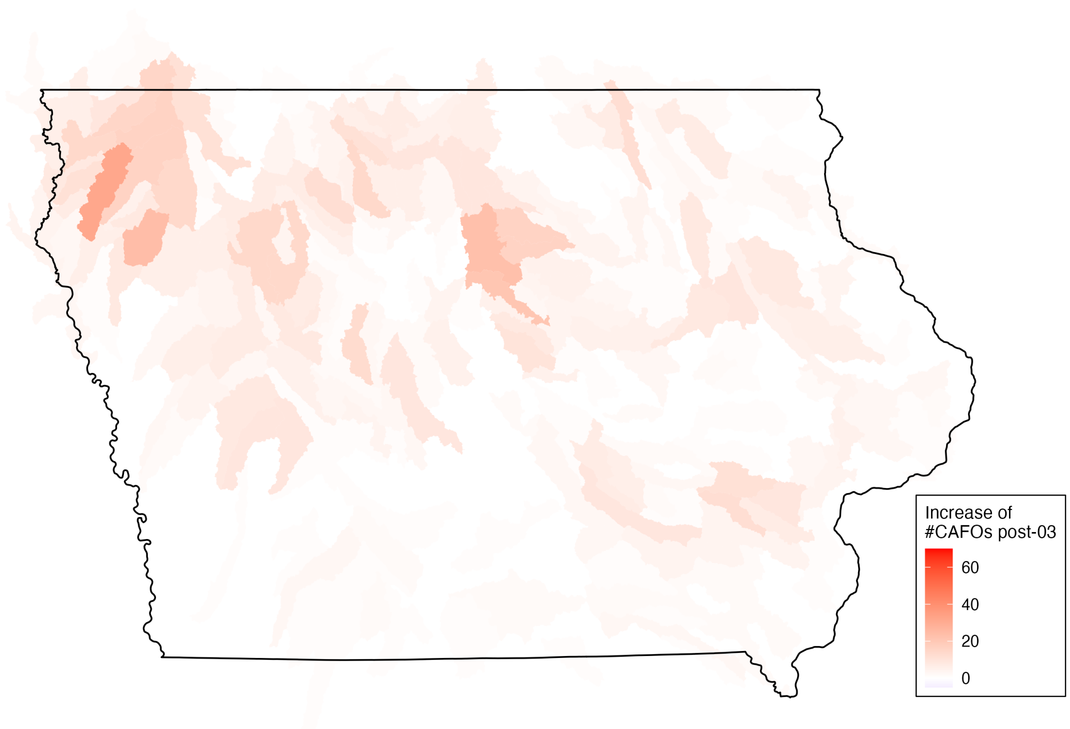


Figure A5: Increase in the number of hog AFOs with MMP (top) and hog CAFOs (bottom) since 2003

B. Additional Results

1. Robustness Checks: Difference-in-Differences

Alternative Identification Strategy. We estimate a similar equation as equation (1) but estimate separate effects for continuing (i.e., pre-2003) and new (post-2003) AFOs:

$$\begin{aligned} N_{iym} = {} & \beta_0 + \beta_1 MMP\_cont_{iym} + \beta_2 CAFO\_cont_{iym} + \beta_3 \mathbf{1}[Post03] + \\ & \beta_4 (MMP\_cont_{iym} \times \mathbf{1}[Post_{03}]) + \beta_5 (CAFO\_cont_{iym} \times \mathbf{1}[Post_{03}]) + \\ & \beta_6 MMP\_new_{iym} + \beta_7 CAFO\_new_{iym} + X'_{iym}\gamma + \eta_y + \eta_m + \eta_i + \tau_{hy} + \varepsilon_{iym}. \end{aligned} \tag{A1}$$

MMP_cont_{iym} and $CAFO\_cont_{iym}$ are the numbers of hog AFOs upstream that entered before 2003; MMP_new_{iym} and $CAFO\_new_{iym}$ are those that entered after 2003. The rest of the controls and fixed effects are identical to those in equation (1).

Our parameter of interest in this case is β_5. Identification for β_5 comes from variation in pre-existing facilities upgrading their facility sizes in the post-update period (hollow gray squares in Figure 4(b)). Importantly, while equation (A1) allows us to identify treatment effects of the policy by removing some forms of potential selection bias in our sample, we also lose the ability to causally interpret β_4 as the effect of additional continuing AFOs with MMPs on downstream pollutant concentrations. Recall that given the nature of our data, we do not observe smaller AFOs established before 2003 upgrading to mid-sized facilities and face MMP requirements. See the data section for more details. By construction, the variable ($MMP\_cont_{iym} \times \mathbf{1}[Post_{03}]$) is constant, and we do not have post-2003 identifying variation (hollow gray squares in Figure 4(a)). Therefore, we cannot conduct similar robustness checks for mid-sized AFOs with MMPs. $MMP\_cont_{iym} \times \mathbf{1}[Post_{03}]$ instead serves as a control variable. Similarly, MMP_new_{iym} and $CAFO\_new_{iym}$ are zero before 2003. As such, the coefficients β_6 and β_7 estimate the post-2003 conditional correlation between new hog AFO with MMP CAFO permits and downstream ammonia concentrations, respectively. Table B1 presents the average results. We observe quantitatively similar results to those in Table 1, our primary identification strategy.

Test Bad Controls. Table B2 presents the average regulatory effects with and without controlling for local crop production. We obtain similar estimates with and without crop controls, suggesting they do not substantively affect or meditate our treatment effects of interest.

Different Bandwidths. Table B3 presents the average regulatory effects when we allow the maximum distances between AFOs and a downstream monitor to decrease to 15 miles and extend to 25 and 30 miles. The specifications across columns for all pollutants follow those in column 2 of Table 1 in the main text. The regulatory impacts are smaller with larger maximum distances allowed, supporting our research design to focus on local pollution sources.

Different Watershed Fixed Effects/Trends. Table B4 further shows that our results are insensitive to alternative watershed-level fixed effects or linear trend specifications. We include HUC8-by-year time trends, HUC8-by-year fixed effects, or HUC10-by-year fixed effects to account for underlying unobservables that contribute to changes in water quality over time. We obtain quantitatively consistent results in all cases.

2. Heterogeneous Treatment Effect: Alternative Specification

The results presented in Figure 6 are from estimating regression models following a similar specification as in column 2 Table 1 but with interaction variables between (MMP x Post03) and (CAFO x Post03) and a dummy variable for a high precipitation month (i.e., month in the fifth total precipitation quintile). Figure B2 shows alternative specifications where we interact the treatment variables with each of the five precipitation levels. Overall, we observe similar results as in Figure 6.

3. Falsification Tests

Figure B2 presents the regression results for two outcomes of interest: atrazine and metribuzin. The regressions follow the same specification as column 2 in Table 1. Some coefficients are not estimated (2010 and 2011 for both atrazine and metribuzin) as we do not have sufficient within-year variation for those by-year treatment variables. Overall, the results show no statistically detectable differences in treatment effects relative to the reference period, supporting our research design.

Table B1: Effect of 2003 CAFOs Regulation on Water Pollution

	(1)	(2)	(3)	(4)
Dependent Variable: ln(Ammonia-Nitrogen)				
CAFO_cont x Post03	-0.056***	-0.091***	-0.0579***	-0.0983***
	(0.0186)	(0.0223)	(0.0197)	(0.0298)
CAFO_cont x Post08			0.0024	-0.0125
			(0.0158)	(0.0287)
R-Squared	0.2922	0.3057	0.2938	0.3101
Observations	22670	22670	22670	22670
Stations	1049	1049	1049	1049
Dependent Variable: ln(Dissolved Oxygen)				
CAFO_cont x Post03	0.0093*	0.0089*	0.0105**	0.0073
	(0.0051)	(0.0053)	(0.0051)	(0.0055)
CAFO_cont x Post08			-0.0043	-0.008*
			(0.0034)	(0.0045)
R-Squared	0.4671	0.4766	0.4672	0.4767
Observations	41129	41129	41129	41129
Stations	2594	2594	2594	2594
Dependent Variable: ln(Total Phosphorus)				
CAFO_cont x Post03	-0.0336	-0.0241	-0.0337	-0.0205
	(0.0259)	(0.0183)	(0.0236)	(0.0199)
CAFO_cont x Post08			0.0003	0.0177
			(0.0134)	(0.0189)
R-Squared	0.5503	0.5591	0.5512	0.5598
Observations	31283	31283	31283	31283
Stations	1861	1861	1861	1861
Time-varying controls	Yes	Yes	Yes	Yes
Month-of-year FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Station FE	Yes	Yes	Yes	Yes
Watershed x year trend	No	Yes	No	Yes

Note: *, **, and *** denote significance at the 10%, 5%, and 1% level. The dependent variables are station-level log-transformed pollution concentrations. For all columns, the max distance from AFOs to a station is 20 miles. Time-varying controls include annual corn and soybean acreage, monthly max precipitation and mean temperature, and monthly other-animal AFOs. For all regressions, "CAFO_cont" refers to the number of upstream hog AFOs that were established before 2003 and upgraded in size to become CAFOs later on. Standard errors (in parenthesis) in all regression equations are clustered at the station level.

Table B2: Effect of 2003 CAFOs Regulation on Water Pollution (w/o Crop Controls)

	(1)	(2)	(3)	(4)
Dependent Variable: ln(Ammonia-Nitrogen)				
MMP x Post03	0.0306***	0.0335***	0.0283***	0.0266***
	(0.0074)	(0.0091)	(0.0075)	(0.0097)
CAFO x Post03	-0.0584***	-0.0798***	-0.0573***	-0.0905***
	(0.0166)	(0.0199)	(0.0171)	(0.0219)
MMP x Post08			-0.0132***	-0.0116
			(0.0042)	(0.0073)
CAFO x Post08			-0.0074	-0.0124
			(0.0141)	(0.02)
R-Squared	0.2921	0.3161	0.2936	0.3172
Observations	22670	22670	22670	22670
Stations	1049	1049	1049	1049
Dependent Variable: ln(Dissolved Oxygen)				
MMP x Post03	-0.0016	-1.18E-5	-0.0017	-0.0002
	(0.0031)	(0.0032)	(0.0032)	(0.0032)
CAFO x Post03	0.01*	0.0103*	0.0103*	0.0103*
	(0.0053)	(0.006)	(0.0054)	(0.006)
MMP x Post08			-0.0006	-0.0005
			(0.0009)	(0.001)
CAFO x Post08			-0.0017	0.0008
			(0.003)	(0.0035)
R-Squared	0.4670	0.4777	0.4670	0.4777
Observations	41129	41129	41129	41129
Stations	2594	2594	2594	2594
Dependent Variable: ln(Total Phosphorus)				
MMP x Post03	0.0225***	0.0193***	0.0236***	0.0209***
	(0.0078)	(0.0073)	(0.0078)	(0.0075)
CAFO x Post03	-0.0334	-0.0242	-0.0395*	-0.0161
	(0.0236)	(0.0176)	(0.023)	(0.0176)
MMP x Post08			-0.0009	0.0011
			(0.0032)	(0.0046)
CAFO x Post08			0.0177	0.0185
			(0.0124)	(0.0178)
R-Squared	0.5502	0.5620	0.5510	0.5629
Observations	31283	31283	31283	31283
Stations	1861	1861	1861	1861
Time-varying controls	Yes	Yes	Yes	Yes
Month-of-year FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Station FE	Yes	Yes	Yes	Yes
Watershed x year trend	No	Yes	No	Yes

Note: *, **, and *** denote significance at the 10%, 5%, and 1% level. The dependent variables are station-level log-transformed pollution concentrations. For all columns, the max distance from AFOs to a station is 20 miles. All regressions follow the same specifications as in Table 1. Time-varying controls include monthly max precipitation and mean temperature, and monthly other-animal AFOs, but exclude annual corn and soybean acreage. Standard errors (in parenthesis) in all regression equations are clustered at the station level.

Table B3: Effect of 2003 CAFOs Regulation on Water Pollution (Different Bandwidths)

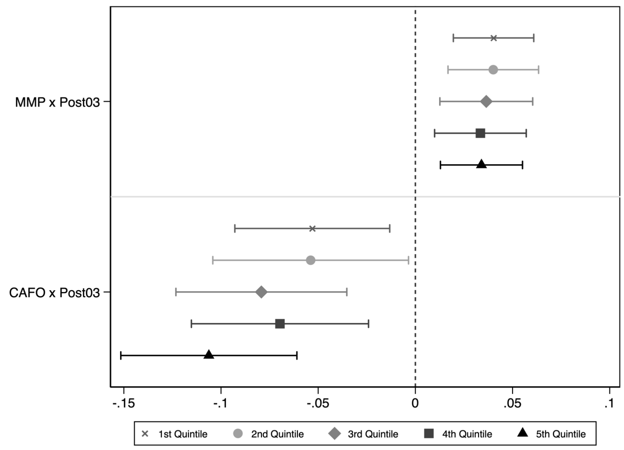
	(1)	(2)	(3)	(4)
	≤ 15mi	≤ 20mi	≤ 25mi	≤ 30mi
Dependent Variable: ln(Ammonia-Nitrogen)				
MMP x Post03	0.0446***	0.0333***	0.0166***	0.0162***
	(0.017)	(0.009)	(0.0062)	(0.0048)
CAFO x Post03	-0.1062***	-0.0788***	-0.0537***	-0.0517**
	(0.0335)	(0.0196)	(0.016)	(0.0129)
R-Squared	0.3163	0.3163	0.3162	0.3165
Observations	22670	22670	22670	22670
Stations	1049	1049	1049	1049
Dependent Variable: ln(Dissolved Oxygen)				
MMP x Post03	-0.0012	-1.18E-5	-0.0013	-0.0007
	(0.0043)	(0.0032)	(0.0021)	(0.0014)
CAFO x Post03	0.0099	0.0103*	0.0084*	0.0059*
	(0.0077)	(0.006)	(0.0045)	(0.0035)
R-Squared	0.4776	0.4777	0.4677	0.4778
Observations	41129	41129	41129	41129
Stations	2594	2594	2594	2594
Dependent Variable: ln(Total Phosphorus)				
MMP x Post03	0.0244**	0.019***	0.0142**	0.0175***
	(0.0116)	(0.0073)	(0.0067)	(0.0046)
CAFO x Post03	-0.0074	-0.0240	-0.0180	-0.0263**
	(0.0226)	(0.0177)	(0.0162)	(0.0107)
R-Squared	0.5621	0.5620	0.5620	0.5622
Observations	31283	31283	31283	31283
Stations	1861	1861	1861	1861
Time-varying controls	Yes	Yes	Yes	Yes
Month-of-year FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Station FE	Yes	Yes	Yes	Yes
Watershed x year trend	Yes	Yes	Yes	Yes

Note: *, **, and *** denote significance at the 10%, 5%, and 1% level. The dependent variables are station-level log-transformed pollution concentrations. All regressions follow the same specification as column 2 in Table 1. Time-varying controls include annual corn and soybean acreage, monthly max precipitation and mean temperature, and monthly other-animal AFOs. Standard errors (in parenthesis) in all regression equations are clustered at the station level.

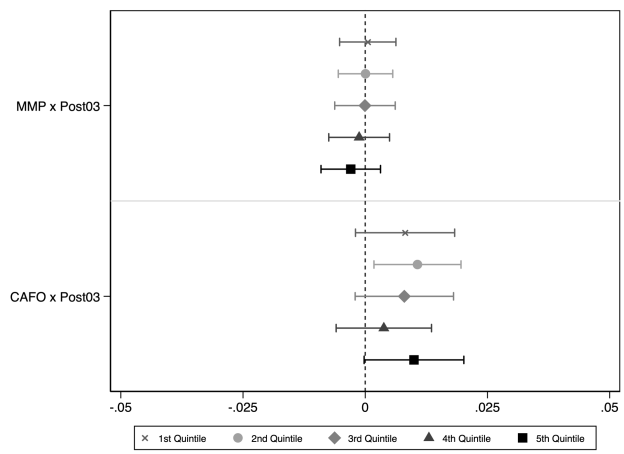
Table B4: Effect of 2003 CAFOs Regulation on Water Pollution (Different FEs/Trends)

	(1)	(2)	(3)
Dependent Variable: ln(Ammonia-Nitrogen)			
MMP x Post03	0.0277***	0.0557***	0.0654***
	(0.0093)	(0.011)	(0.017)
CAFO x Post03	-0.056***	-0.0594**	-0.1472*
	(0.0175)	(0.0298)	(0.079)
R-Squared	0.2969	0.3247	0.3842
Observations	22670	22660	22573
Stations	1049	1046	1021
Dependent Variable: ln(Dissolved Oxygen)			
MMP x Post03	-0.0008	-0.0041	0.0006
	(0.0031)	(0.0034)	(0.004)
CAFO x Post03	0.0138***	0.012**	0.0083
	(0.0053)	(0.0059)	(0.0094)
R-Squared	0.4691	0.4882	0.5350
Observations	41129	41117	40891
Stations	2594	2590	2546
Dependent Variable: ln(Total Phosphorus)			
MMP x Post03	0.0187***	0.0365***	0.0423***
	(0.0072)	(0.0087)	(0.0128)
CAFO x Post03	-0.0292*	-0.0149	-0.0002
	(0.0175)	(0.0221)	(0.0306)
R-Squared	0.5532	0.5738	0.6099
Observations	31283	31270	31084
Stations	1861	1856	1819
Time-varying controls	Yes	Yes	Yes
Month-of-year FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
Station FE	Yes	Yes	Yes
HUC8 x year trend	Yes	No	No
HUC8 x year FE	No	Yes	No
HUC10 x year FE	No	No	Yes

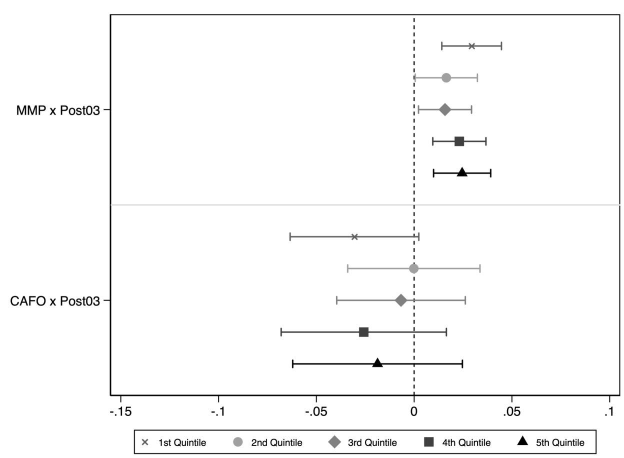
Note: *, **, and *** denote significance at the 10%, 5%, and 1% level. The dependent variables are station-level log-transformed pollution concentrations. For all columns, the max distance from AFOs to a station is 20 miles. All regressions follow the same specifications as in column 2 of Table 1, except the HUC10 linear trends are replaced with different watershed fixed effects or linear trends, depending on the specifications. Time-varying controls include annual corn and soybean acreage, monthly max precipitation and mean temperature, and monthly other-animal AFOs. Standard errors (in parenthesis) in all regression equations are clustered at the station level.



B1(a): Ammonia

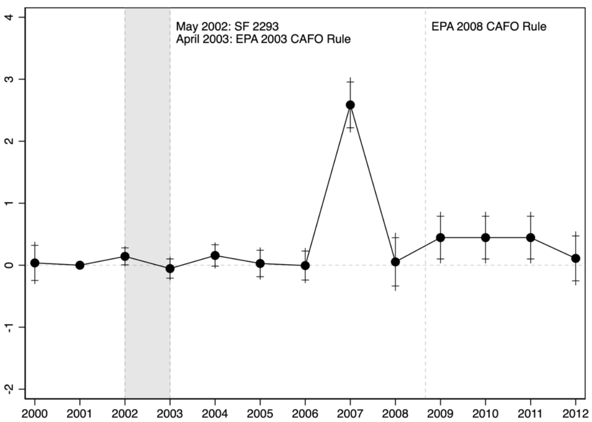


B1(b): Dissolved Oxygen

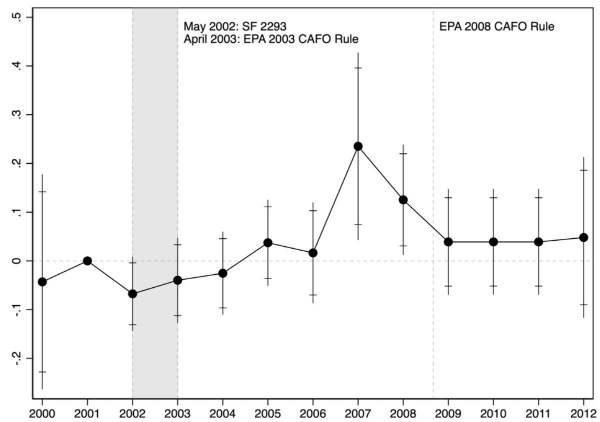


B1(c): Total Phosphorus

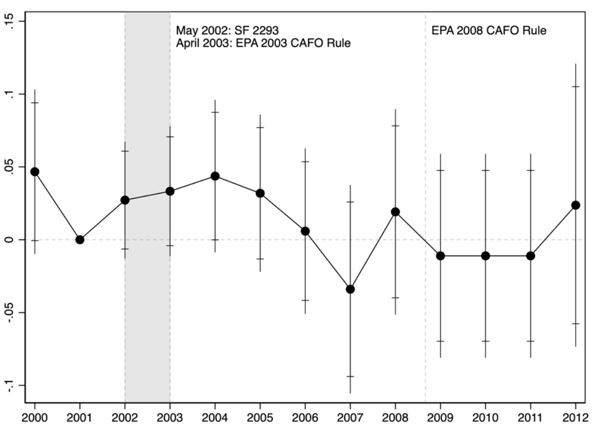
Figure B1: Heterogeneous Effect of 2003 EPA CWA Regulation



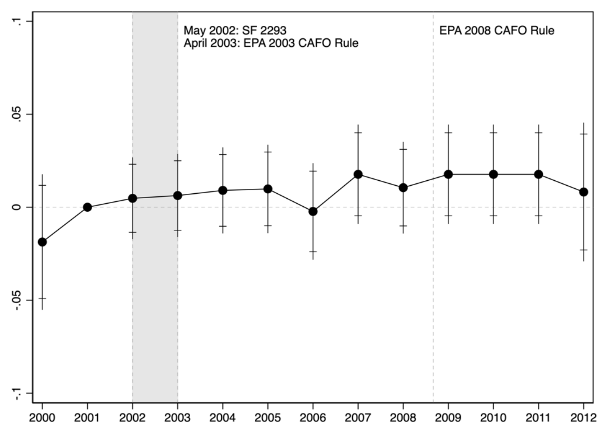
B2(a) Atrazine: Hog CAFOs



B2(b) Atrazine: Hog AFOs with MMP Permit



B2(c) Metribuzin: Hog CAFOs



B2(d) Metribuzin: Hog AFOs with MMP Permit

Figure B2: Falsification Test of Regulation on Hog CAFOs: Atrazine (a, b) and Metribuzin (c, d)