Nutrient Pollution and U.S. Agriculture: Causal Effects and Integrated Assessment

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Work in Progress–Comments are Welcome

Abstract

We study the relationship between water nutrient pollution and U.S. agriculture using data between the early 1970s and late 2010s. We document a causal positive effect of corn acreage on nitrogen concentration in the country's water bodies using alternative empirical approaches and different data aggregations. We find that a 10% increase in corn acres planted causes an increase in nitrogen concentration in water by at least 1% depending on the empirical approach and data-aggregation scheme used to estimate the effects highlighting the very important role of precipitation in the magnitude of the acreage effect. The 1% increase in the average level of nitrogen concentration in the Midwest coupled with the average streamflow of the Mississippi River at the Gulf of Mexico during this period and a damage cost of about $16 per kilogram of nitrogen implies external cost of $800 million. The results of additional integrated-assessment type of exercises, including a fully fledged welfare, analysis of a reduction in corn acreage are also reported.

Keywords: crops, environmental externalities, hypoxia, integrated assessment, nutrient pollution.

JEL codes: Q15, Q48, Q51, Q53, Q58

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1 Introduction

Nutrient pollution is one of the country's most widespread, costly, and challenging environmental problems. It is caused by excess nitrogen and phosphorus in the air and water. Although nutrients such as nitrogen and phosphorous are chemical elements that plants and animals need to grow, when too much nitrogen and phosphorus enter the environment, usually from a wide range of human activities, the air and water can become severely polluted.

Some of the largest sources of nutrient pollution include commercial fertilizers, animal manure, sewage treatment plant discharge, storm water runoff, cars, and power plants. In the Mississippi River Basin (MRB), which spans 31 states and drains 40% of the contiguous U.S. (CONUS) in the Gulf of Mexico, nutrients from row crops, large farms, and concentrated animal feeding operations account for most of the nutrient pollution. Fertilizer runoff or agricultural crops have been shown to contribute somewhere between 50% (CENR (2000)) and 76% (David et al. (2010)) of the annual and spring nitrogen riverine export from the MRB to the Gulf fueling a hypoxic ("dead") zone, with oxygen levels that are too low for fish and other marine life to survive. The Gulf hypoxic zone is the second largest in the world behind the dead zone in the Arabian Sea. By 2008, dead zones had been reported from more than 400 systems, affecting a total area of more than 245,000 square kilometers (Diaz and Rosenberg (2008)). In the summer of 2017, the areal extent of the hypoxic zone was equal to that of New Jersey (8,776 square miles)

In the U.S., according to the EPA (2016b), 46% (about 546,000 miles) of streams and rivers are in poor condition in terms of their phosphorous levels and 41% (about 495,000 miles) are in poor condition in terms of their nitrogen levels based on sampling results from almost 2,000 sites benchmarked against conditions represented by a set of least-disturbed (reference) sites. Excessive nitrogen and phosphorus in water and the air can cause health problems, damage land and water, and take a heavy toll on the economy; see CENR (2000), EPA (2007), and, more recently, Olmstead (2010), GOMNTF (2013) and Rabotyagov et al. (2014a). Unsurprisingly, there are several papers employing a variety of methodologies assessing the the cost of nitrogen pollution; see Dodds et al. (2009), Compton et al. (2011), Birch et al. (2011), Rabotyagov et al. (2014b), and Sobota et al. (2015), among others. According to Rabotyagov et al. (2014b), reducing the areal extent of the hypoxic zone to a 5-year running average of 5,000 square kilometers, a target set by the Gulf of Mexico Task Force's Action Plan, comes at a price tag of $2.7 billion a year.[1]

In this paper, we focus on water pollution and its relationship to U.S. agriculture. We use regres-

[1] EPA (2015) summarizes studies related to economic losses or costs associated with nitrogen pollution in tourism and recreation, commercial fishing, property values, human health, drinking water treatment costs, mitigation, restoration.

sion analysis to establish a causal link between nutrient pollution and farmers' decision making with respect to crop acreage. In particular, we estimate the causal effects of corn acreage on nitrogen pollution using two different estimation approaches combined with alternative aggregation schemes of publicly available data. We use panel fixed-effect and cross-sectional regressions and conduct (c)ounty-, (m)onitoring site- and (h)ydrologic unit-centric analyses. C-centric type analyses are generally common in the economics literature and have been utilized to produce estimates of climate change on agriculture (e.g., Mendelsohn et al. (1994), Deschenes and Greenstone (2007)). M-centric and h-centric analyses are common in the environmental economics and science literature (e.g., Olmstead et al. (2013) and David et al. (2010)), and probably more so in the case of h-centric analyses, employing biophysical and water-quality models like the APEX, SPARROW, and SWAT.

In the case of the c-centric analysis, we combine annual county-level data on acres planted and nitrogen pollution. Data on acres planted are readily available from the U.S. Department of Agriculture (USDA). We compile data on nitrogen pollution using U.S. Geological Survey (USGS) monitoring sites within an assumed radius from the county centroids. For the m-centric analysis, we combine monitoring-site level data with county-level acres planted using counties within the assumed radius from the sites' locations. For our h-centric analysis, we combine data on pollution and acres for monitoring sites and counties that lie in the same 8-digit hydrologic units. Both estimation approaches along with the three alternative aggregation schemes point to a causal positive relationship between corn acres planted and nutrient pollution that is statistically and economically significant. To the best of our knowledge, there is no paper in the literature that provides estimates of the causal effects we estimate in this paper with the depth and geographic scope of our analysis.

Based on our c-centric analysis with the panel fixed-effect (FE) regression approach, a *conservative* estimate of the acre elasticity of nitrogen pollution (mg/L) with respect to corn acres is about 0.1. In particular, a 3.3% increase in the average level of nitrogen concentration of about 2.5 mg/L in our sample attributed to a 28% increase in corn acres planted, entails close to 50,800 additional metric tons of nitrogen in the Gulf. This is the increase in nitrogen flux (concentration $\times$ streamflow) implied by an increase in acres planted equal to 1 within-county standard deviation coupled with the average streamflow of the Mississippi River in the Gulf for the time spanned by our data. Using the median potential damage costs of nitrogen due to declines in fisheries and estuarine/marine life of \$15.84 per kilogram (2008\$) from Sobota et al. (2015), the implied external cost is about \$805.5 million.

For our h-centric analysis, the acreage effect is 3.6% implying an elasticity of 0.1 based on the assumed in acreage of about 27% using the panel FE regression approach. The m-centric analysis points to an acreage effect of 1.4% based on an assumed increase of acreage of about 18% implying

an elasticity of 0.08. The cross-section regression based on pooled data across all years point to an effect that is 1.5 times as large as its panel FE counterpart in the case of the c-centric analysis. For the h-centric and m-centric analyses, the effects are close to 2.7 and 6 as large as their panel FE counterparts, respectively.

Based on our review of the economics/agricultural economics literature regarding acreage effects on nutrient pollution, Taylor (1973) is the paper that is closest to ours. Taylor studies the relationship between nitrate concentration in Illinois streams and the acreage of field crops and fertilizer sales using watershed-level data in the late 1960s/early 1970s employing both cross-sectional as well as pooled cross-sectional and time-series regressions. In other words, Taylor's analysis had a much more limited spatial and temporal scope compared to ours.

In terms of the environmental science literature, our approach for estimating the effects of crop acreage on nitrogen concentration is most closely related to a strand employing regression models that link nutrient concentrations to inputs (e.g., fertilizer, manure, municipal sewage effluent, crop fixation, atmospheric deposition), nutrient uptake, denitrification, volatilization, land drainage (e.g., tillage and subsurface tile drainage), environmental (precipitation, temperature), and hydrologic (e.g., streamflow) conditions, as well as watershed properties related to water and nutrient transport at various spatial and time scales and, generally involving nonlinear specifications.

To the best of our knowledge, there is no work in the economics literature aiming to identify the causal effects of farmers' decision making regarding acreage we identify in this paper using OLS regressions with few and transparent assumptions. However, we have to acknowledge recent work by Paudel and Crago (2020), who estimate the effects of fertilizer use on nitrogen pollution using an h-centric analysis for the CONUS. We discuss extensively the implications of controlling for fertilizer use for our estimated effects. The main message is that our estimated effects when we control for fertilizer use are essentially *indistinguishable* from their baseline counterparts when we don't control for fertilizer use.

The remainder of the paper is organized as follows. Section 2 provides background on nutrient pollution, the role of agriculture in nutrient pollution, as well as a discussion on federal regulations of water pollution. In Section 3, we describe the empirical approach for estimating the causal effects of acres planted on nutrient pollution. Subsequently, having discussed the data in Section 4, and provided some descriptive analysis in Section 5 and Section 6, we present the results from our regressions in Section 7. We next discuss a series of additional results and sensitivity checks in Section 8, and perform integrated-assessment type of exercises in Section 9. We finally conclude. All tables and figures are located in the end of the paper. We delegate part of our discussion in an on-line Appendix.

2 Background

In this section, we provide some background on nitrogen pollution emphasizing the role of agriculture. We also discuss possible approaches for controlling nitrogen pollution and discuss federal regulation of nutrient pollution from agriculture.

The fundamental problem behind nitrogen pollution. Nitrogen is a naturally occurring element that is essential to plant growth and crop production along with phosphorous and potassium. Using too little nitrogen for a highly responsive crop such as corn entails lower yields, poorer grain quality, and reduced profits. When too much nitrogen is applied, crop yields and quality are not affected, but profit can be reduced somewhat and negative environmental consequences are very likely. Thus, many farmers choose to err on the liberal side when making decisions on nitrogen rates. This extra nitrogen is often called "insurance" nitrogen; see Mitsch et al. (1999) and CENR (2000), among others. Overall, nitrogen use efficiency (uptake) and the "4Rs" in nutrient management—right source, rate, time, and place for plant nutrient application based on local agronomic recommendations—in order to minimize nitrogen losses to the environment are of paramount importance for addressing nitrogen pollution.[2]

Nitrogen pollution. Nitrogen inputs to the ecosystem from both anthropogenic and natural sources, are transported via atmospheric, surface flow, drain flow, and groundwater pathways. Nitrate-nitrogen concentrations in the Mississippi River that drains most of the country's cropland increased dramatically in the second half of the last century, especially between the early 1960s and the mid 1980s, largely coinciding with the surge in commercial-fertilizer use for row crops in the MRB states (e.g., see Capel et al. (2018)). The corn-and-soybeans cropping system that dominates the Corn Belt is an inherently "leaky" system—some nitrogen loss to subsurface drainage water is inevitable (McLellan et al. (2015)). In fact, the majority of agricultural nitrogen loss occurs via subsurface drainage water, either as seepage through soils and shallow geologic units or in engineered drainage structures such as drainage tiles and ditches.

Setting aside oscillations in the river's streamflow, artificial drainage and other changes to the hydrology of the Midwest (e.g., dams and reservoirs), atmospheric deposition of nitrates within the MRB, non-point discharges from urban and suburban areas, and point discharges, particularly from domestic wastewater treatment systems and feedlots, all contribute to the nutrients that reach the Gulf of Mexico (Goolsby et al. 1999). Between 1980 and 2016, close to 1.5 million metric tons of nitrogen (about 63% in the form of nitrate) per year were discharged, on average, to the Gulf. From 1968–2016, the average annual Mississippi streamflow was close to 21,500 cubic meters

[2] Ribaudo et al. (2011) and Christianson et al. (2016) offer a very informative discussion on nutrient management and its role in nitrogen pollution.

per second.[3] During this time, there was a strong positive relationship between streamflow and nitrogen flux in the Gulf.

Nitrate-nitrogen, which is an inorganic form of nitrogen, is highly soluble and mobile and can be lost from the soil by leaching, and, as we already discussed, it is also the major contributor to the hypoxic zone in the Gulf.[4] Transport of nitrate-nitrogen to surface waters occurs primarily through subsurface drainage (tile lines) or ground water. Subsurface drainage is a common water management practice in highly productive agricultural areas of the MRB like the Corn Belt, where poorly drained soils have seasonally perched water tables or shallow ground water. Very little nitrate–nitrogen is lost from the agricultural landscape via surface runoff. Several studies on rivers of different stream order draining widely different scales of watershed basins all point to the fact that agricultural practices do affect the nitrate–nitrogen concentrations in river water.[5] In general, intensive agricultural practices that enhance mineralization of soil nitrogen, coupled with subsurface artificial drainage, have been shown to be major contributors of nitrate–nitrogen to streams and rivers of the Midwest.

Dairy, cattle, hog, poultry, and aquaculture systems can also cause significant discharges of nutrients to streams and rivers. Untreated wastewater from these systems generally has very high concentrations of nitrogen, most often as ammonia–nitrogen, although high concentrations of nitrate–nitrogen are also possible. Urban and suburban areas have significant runoff from lawns, parking lots, rooftops, roads, highways, and other impervious sources.[6] The major point sources of direct discharges of nutrients, particularly nitrogen-nitrogen, appear to be domestic wastewater treatment plants (WWTPs).[7] Fossil-fuel combustion in car engines and electric generating plants

[3]We refer to the average flow and total Mississippi-Atchafalya nitrogen flux (sum of NO_3+NO_2, TKN, and NH_3) AMLE estimates using data from here.

[4]The mid-summer areal extent of the Gulf dead zone was close to 4,000 square miles in 1985, which is the the first year the zone was measured. In 2017, the last year in our sample, the hypoxic zone was close to 8,800 square miles, which is much larger than the Hypoxia Task Force (HTF) goal for a 5-year moving average of 5,000 square kilometers (1,931 square miles), indicating that nutrients from the MRB continue to affect coastal resources and habitats in the Gulf; see here.

[5]For example, Goolsby et al. (1999) cite studies showing that nitrate-nitrogen concentrations in stream water collected for a portion of the upper MRB were significantly greater from rivers that drain a large percentage of agricultural land (2–6 mg/L) compared to rivers that drain a larger percentage of forested land (0.1–0.5 mg/L); as a benchmark for these numbers, the national drinking water standard of nitrates is 10 mg/L. Alexander et al. (2008) show that agricultural sources in the MRB watersheds contribute more than 70% of the delivered nitrogen and phosphorous in the Gulf. Corn and soybean cultivation is the largest contributor of nitrogen (52%), followed by atmospheric deposition sources (16%).

[6]In the MRB, concentrations and fluxes of nutrients, particularly nitrogen and phosphorus from such non-point sources, are generally low compared to non-point agricultural sources. Concentrations of total nitrogen are generally half or less in urban runoff compared to agricultural land runoff, and fertilized agricultural land covers a much greater area in the MRB than urban and suburban land.

[7]Conventional wastewater treatment, through secondary treatment, involves removal of suspended materials, pathogens, and oxygen-demanding organics. Organic matter is converted into inorganic forms, including ammo-

also contributes to airborne nitrates that return to the earth's surface with rain, snow, and fog (wet deposition) or as gases and particulate (dry deposition). This nitrogen then enters streams and rivers and/or is retained in terrestrial systems in the same pathways as nitrate–nitrogen fertilizer.[8]

Controlling nitrogen pollution from agricultural sources. Setting aside environmental regulations, preventing nutrient pollution, particularly in the form of nitrate–nitrogen, can be accomplished through a number of general approaches and specific techniques, ranging from modification of agricultural practices to the construction and restoration of riparian zones and wetlands as buffer systems between agricultural lands and waterways.[9] To provide some examples, on-site control of agricultural drainage is possible via adoption of one or a combination of the following: nitrogen fertilizer application rates, management of manure spreading, timing of nitrogen application, the use of nitrification inhibitors, the change of plowing (tillage) methods, and increasing drainage tile spacing. Wetlands and riparian buffers can be effective means of off-site control—see Section 4.1 of topic 5 in Mitsch et al. (1999), among others.

The Clean Water Act and non-point source water pollution. Prior to 1987, the Clean Water Act (CWA), which was enacted in 1972 and it is the primary federal law governing water pollution, focused exclusively on the regulation of point sources (PS). Major environmental disasters such as the Cuyahoga River fire in Cleveland in the late 1960s, concerns regarding toxic pollution water, and growing eutrophication problems steered all levels of government towards controlling PS pollution from sewage and from industrial discharges. Neither the 1972 CWA, nor its 1977 amendments provided any funds for non-point source (NPS) pollution. During the 1970s and 1980s, significant progress was made towards reducing water pollution as both industrial discharges and WWTPs complied with regulatory requirements. Throughout this period, the U.S. Environmental Protection Agency (EPA), which is in charge of the federal enforcement of CWA, did not implement a national NPS program and did not provide any funds to states to implement NPS programs. Moreover, very few states implemented NPS programs on their own (EPA (2011)).

By the mid-1980s, and despite the progress in addressing PS pollution, it became increasingly apparent that NPS pollution would continue to cause water quality impairment unless it was properly controlled as well. The 1990 National Water Quality Inventory Report identified agriculture as a leading source of impairment in rivers and lakes assessed (EPA (1990)). Agricultural runoff was by far the most excessive source of pollution accounting for 60% of impaired river miles. Agricul-

nia–nitrogen, nitrate–nitrogen, and orthophosphates.

[8] Intensive agricultural practices, particularly feedlots, where ammonia-nitrogen concentrations are high, also result in ammonia volatilization, which increases local nitrogen (in the form of ammonia) concentrations in the atmosphere. These emissions also return to earth through precipitation and dry fallout.

[9] EPA (2007), Ribaudo et al. (2011), NRCS (2017b), and Capel et al. (2018), among others, offer a very informative discussion on controlling nitrogen pollution from agricultural sources.

ture also accounted for 57% of impaired lake acres. In response to the increased recognition of the significance of NPS pollution as the emerging leader of water quality impairment in the country, Congress enacted Section 319 of the CWA in 1987, which called on states to develop NPS assessment and management programs. These programs introduced a variety of activities including both regulatory and non-regulatory programs, technical assistance, financial assistance, education, training, technology transfer, watershed projects and monitoring, to assess the success of specific NPS implementation projects. According to EPA (2016a), over 6,000 miles of stream waters and over 164,000 acres of lakes have been restored as a result of this collective work since EPA began tracking progress in 2005. In all, although the CWA's regulatory programs include enforceable provisions that are directed at PS pollution, the NPS Program addresses NPS pollution primarily through non-regulatory means.

As of this writing, the major federal response to nutrient pollution from agriculture continues to be through research, education, outreach, and voluntary technical and financial incentives. A number of USDA agencies provide support through education, outreach, and research, while federal funds are provided through conservation programs to help agricultural producers, who participate voluntarily, to adopt best management practices in crop production to achieve nutrient pollution reduction. At a very high level, the USDA programs are distinguished between land-retirement and working-land programs with the spending on conservation programs having increased substantially since the 2002 Farm Security and Rural Investment Act.[10] In the case of the land-retirement programs, landowners receive payments in exchange for taking land out of active agricultural production and putting the land into perennial grasses, trees, or wetland restoration. Landowners or producers participating in working-land programs receive payments to cover part or all of the costs of making changes in conservation practices and management decisions on their land that remains in agricultural production.

Progress addressing nitrogen pollution. According to the USDA CEAP national nitrogen loss report (NRCS (2017b)), 29% of nitrogen applied as commercial fertilizer or manure was lost from the fields through various pathways based on survey data for 2003–2006. The mean of the average annual estimates of total nitrogen loss was 34 pounds per acre per year. The amount varied considerably, however, among cultivated cropland acres. Total nitrogen losses were highest for acres receiving manure (56 pounds per acre per year).

Based on simulations performed using the APEX model in the report, the use of conservation practices during 2003–2006 reduced total nitrogen loss (all loss pathways) by 14.9 pounds per acre per year, on average, representing a 30% reduction. The average annual amount of total nitrogen

[10]We refer to this link and Capel et al. (2018) for a succinct and very informative discussion of the various USDA conservation programs.

loss would have been 49.3 pounds per acre for the no-practice scenario, compared to an average of 34.4 pounds per acre for the baseline scenario, which includes a mix of fully treated, partially treated, and untreated acres. Reductions in total nitrogen loss due to conservation practices are much higher for some acres than others, reflecting both the level of treatment and the inherent erodibility of the soil.

Sprague et al. (2011) estimate changes in nitrate concentration and flux during 1980–2008 at 8 sites in the MRB using the WRTDS model, which produces flow-normalized (FN) estimates of nitrate concentration and flux. Their results show that little consistent progress had been made in reducing riverine nitrate since 1980, and that FN concentration and flux had increased in some areas. Murphy et al. (2013), who extended the analysis in Sprague et al., show that trends in FN nitrate concentration and flux were increasing or near-level at all sites for 1980–2018. The do note, however, that trends at some sites began to exhibit decreases or greater increases during 2000–2008.

Damage costs and abatement of nitrogen pollution. Estimating the economic value of the damages associated with nutrient pollution can be challenging.[11] The social cost of pollution in the context of water quality has received less attention than the social cost of carbon in the context of climate change.[12] Keeler et al. (2012) describe the multiple biophysical and economic pathways that link actions to changes in water quality-related ecosystem goods and services and provide guidance on valuing these changes. The authors present a valuation template that integrates biophysical and economic models, links actions to changes in service provision and value estimates, and considers multiple sources of water quality-related valued goods and services. In Table 1, we provide a summary of studies related to damage costs associated with nitrogen pollution. We provide a summary of studies related to nitrogen abatement costs in Table 2. For the less familiar

[11] EPA (2015) provides estimates of external costs associated with nutrient pollution impacts on tourism and recreation, commercial fishing, property values, human health, drinking water treatment costs, mitigation, restoration. According to Keiser et al. (2019), the U.S. has invested more than $1.9 trillion ($2014) since 1960 to abate surface water pollution, which is close to $140 per person per year. The investment costs come from both the 1972 Clean Water Act and the largely voluntary efforts to control pollution from agriculture and urban runoff. They review the methods and conclusions of about 20 recent evaluations of these policies. For most analyses, the benefits are much smaller than the costs. The benefit-cost ratio from the median study is 0.37. This provocative fact—that most analyses, including those from EPA, estimate *negative* net benefits from surface water quality regulations leads to the critical question whether the costs of current U.S. water quality regulations actually exceed their benefits, or whether existing analyses substantially understate true benefits or overstate true costs. Available evidence is insufficient to answer this question, although it is clear that current analyses exclude potentially important benefits.

[12] Gourevitch et al. (2018) argue that quantifying the social cost of nitrogen is challenging due to multiple loss pathways associated with damages to water quality, air quality, and climate change that occur over heterogeneous spatial and temporal scales. The diversity of nitrogen loss pathways and endpoints at which damages occur makes it challenging to construct a single cost metric. The impacts are largely driven by the location where the nitrogen is emitted and applied, the transport and transformation of nitrogen into different forms, and the expected damages along the flow path (Keeler et al. (2018)).

reader, additional details for these studies are available in Section A.1.

3 Empirical Approach

We employ two types of OLS regressions to study the relationship between corn acres planted and nitrogen pollution: panel fixed effects (FE) regressions and cross-section regressions. We perform our analysis using data aggregated at the county, hydrologic unit, and monitoring-site levels. Additional details follow.

3.1 Panel Regressions

We estimate panel fixed-effect (FE) OLS regressions of the form:

$$y_{it} = \delta_i + \beta_1 a_{it} + \beta_2 a_{it} p_{it} + \mathbf{z}'_{it}\gamma + g_i(t) + \varepsilon_{it}. \tag{1}$$

In terms of notation, i denotes the cross-sectional unit and t denotes the time (year). Depending on the cross-sectional unit of analysis employed, i denotes a county, an 8-digit hydrologic unit, or a USGS water quality monitoring site. The dependent variable y_{it} is nitrogen concentration (mg/L), a_{it} denotes acres planted, p_{it} denotes precipitation, and $\mathbf{z}_{it}$ is a vector of weather-related controls. The weather controls include precipitation, squared precipitation, moderate heat, and extreme heat. Furthermore, $g_i(t)$ denotes alternative functions of time (e.g., time trend, year FE, etc.). Finally, ε_{it} is the error term.

In what we call *county-centric* empirical analysis, i denotes a county, y_{it} is the average nitrogen concentration using sites within 50 miles of each county, and a_{it} are the acres planted in county i at time t (Figure 1). For the *hydrologic unit-centric* analysis, i denotes an 8-digit hydrologic unit, y_{it} is the average nitrogen concentration using sites located in the unit, and a_{it} are acres planted planted in counties that lie in the unit weighted by their area. Finally, for the *monitoring site-centric* analysis, y_{it} is the concentration for monitor i and a_{it} are the acres planted in counties within a 50-mile radius from the site. In the remainder of our discussion, we adopt the terminology, *c-centric*, *h-centric*, and *m-centric* analysis (e.g., we refer to c-centric regression results in a subsequent section).

Regarding the weather-related variables, in the case of the m-centric analysis, p_{it} and $\mathbf{z}_{it}$ are averages across counties within the assumed radius of site i. For the h-centric analysis, we use averages

of the same variables weighted by the area of the counties that lie within the hydrologic-unit polygons.

Our specifications aim to capture the most salient factors that are both in the control and out of the control of U.S. farmers and that influence the nitrogen concentration of waters draining cropland (Goolsby et al. 1999). Factors outside farmers' control include climate and hydrologic conditions, as well as terrain properties of the cropland (e.g., slope and elevation), and soil properties (e.g., depth, texture, mineralogy, capacity to support crop growth, and susceptibility to erosion). Factors in farmers' control include agricultural management practices used to boost profits, such as cropping systems, rate of and timing of nitrogen application, use and type of drainage and tillage systems, deployment of non-point source programs by the EPA and conservation programs administered by the USDA, among others.

In more detail, regarding the controls included in $\mathbf{z}_{it}$, precipitation and temperature generally affect the farmers' decision making during the spring planting season (e.g.,when and what to plant, and how much to fertilize). During the growing season, which is somewhere between March and September for most of the U.S., both temperature and precipitation have an effect on crop growth and, hence, on the plants' nutrient uptake. In the absence of robust crop growth rates, nutrients such as nitrogen that that are not absorbed by the plants can be carried over to streams, rivers, and lakes, depending on soil characteristics and precipitation.

In general, concentrations in a basin like the MRB that drains most of the cropland where corn is grown and is characterized by an abundant supply of nitrogen in the soil tend to peak in the late winter and spring when streamflow is highest, and lowest in the late summer and fall when streamflow is low. This strong positive relationship between concentration and streamflow has been well documented in the Midwest; see Goolsby et al. (1999) and the references cited. Importantly, the same strong positive relationship implies that nitrogen pollution is predominantly due to non-point sources.[13] Nitrogen concentrations generally decrease in the summer and fall as streamflow and agricultural drainage decrease. Assimilation of nitrate by agricultural crops on the land and aquatic plants in streams also helps decrease nitrogen concentrations in streams during the summer. Moreover, in-stream denitrification rates also increase during the summer due to increased temperatures and longer residence times of water in the streams. Hence, temperature and precipitation are correlated with both acres planted and nitrogen concentration.

The fixed effects δ_i aim to capture time invariant spatial attributes such as soil properties and

[13] If pollution were predominantly from point sources, concentrations would decrease as streamflow increases due to dilution. Instead, concentrations in streams increase in response to rainfall or snow melt leaching nitrogen that has accumulated in the soil. Nitrogen levels can build up in soils during dry years from mineralization processes and reduced uptake by crops, and can be flushed out in larger than normal amounts in subsequent wet years.

texture, and water infiltration rates that affect both the farmers' planting decisions and levels of nitrogen in the water due to, say, transport and attenuation. For example, soil texture—the proportions of sand, clay, and silt— influences the ease with which the soil can be worked, the amount of water and air the soil holds, and the rate at which the water can enter and move through the soil. Fine-grained (clayey) solid can hold more water than coarse-grained (sandy) soils.

Finally, $g_i(t)$ allows us to model in a flexible way trends in fertilization rates, and land management practices, such as tillage, and subsurface tile drainage, for which data with good spatial and time coverage are not available. They also allow us to account for farmers' participation in conservation programs administered by the USDA and other unobservables that may exhibit spatially differentiated trends and affect both the corn acreage and nitrogen concentration.

In a subsequent section pertaining to robustness checks, we consider a long list of additional controls to capture factors that may be correlated with both acres planted and nitrogen concentration as discussed above to ensure we obtain unbiased estimates of the effects we are interested in. We also explore alternative ways to capture the temporal variation in weather, alternative radii from county and site centroids in constructing measures of nitrogen concentration and explanatory variables of interest, as well as alternative ways to perform statistical inference, among other checks.

3.2 Cross-Section Regressions

We estimate year-specific OLS regressions of the form:

$$y_{it} = \delta_i + \beta_1 a_{it} + \beta_2 a_{it} p_{it} + \mathbf{z'}_{it}\gamma + \varepsilon_{it}. \tag{2}$$

We also estimate pooled ("across-years") OLS regressions of the form:

$$\bar{y}_i = \delta_i + \beta_1 \bar{a}_i + \beta_2 \overline{a_i p_i} + \overline{\mathbf{z}'}_i\gamma + \varepsilon_i. \tag{3}$$

We use δ_i to denote various spatial fixed effects such as state fixed effects, and fixed effects for hydrologic units of different size. The pooled cross-sectional regressions, which provide a way to assess the long-term impacts of agriculture on nitrogen pollution, resemble models used in hydrology (e.g., David et al. (2010)), and the Ricardian approach in accessing agricultural damages due to climate change (e.g., Mendelsohn et al. (1994)) taking into account adaptation. The similarity with the hydrology models is mainly due to the cross-sectional nature of the regressions and the controls considered keeping in mind that the hydrology models tend to employ non-linear specifi-

cations often aiming to identify factors that best describe variation in nitrogen pollution as opposed to estimating causal effects.

The validity of the cross-sectional approach hinges on the assumption that there are no omitted variables correlated with both planting decisions and pollution that our spatial fixed effects fail to account for, in which case our estimates will be biased; a classical example of omitted variable bias (OVB). For example, if counties that grow a lot of corn also tend to adopt more conservation efforts, for which, say, the spatial fixed effects fail to account for, our cross-sectional regressions will be understating the true effect of acreage on nitrogen pollution.[14] Numerous of our robustness checks in a subsequent section involve additional controls aiming to alleviate concerns related to the OVB.

3.3 Short Digression on Hydrologic Accounting

The U.S. is divided into successively smaller hydrologic units which are classified into four levels: regions, subregions, accounting units, and cataloging units (Figure A1). The hydrologic units are arranged or nested within each other from the largest geographic areas (regions) to the smallest geographic areas (cataloging units). Each hydrologic unit is identified by a unique hydrologic unit code (HUC) consisting of 2–8 digits based on the four levels of classification in the hydrologic unit system (Figure A2). It is common to refer to hydrologic units as watersheds and what we describe here as hydrologic accounting is also described as watershed delineation. The word watershed is sometimes used interchangeably with drainage basin or catchment. In the remainder of our discussion, we will use frequently the shortcuts HUC2, HUC4, and HUC8 to refer to 2-, 4- and 8-digit hydrologic units.

4 Data

Water quality. The data on nitrogen concentration are from the Water Quality Portal (WQP). The WQP is a cooperative service sponsored by the USGS, the EPA, and the National Water Quality Monitoring Council. It serves data collected by over 400 state, federal, tribal, and local agencies

[14] As an example of how the OVB can emerge in this context, Sprague and Gronberg (2012) study the relation between nitrogen load (riverine export) from 130 or so large agricultural watersheds in the U.S. and factors affecting nutrient transport using OLS cross-sectional regressions. Controlling for anthropogenic inputs and other landscape factors affecting nutrient transport the relation between export and the area in the USDA Conservation Reserve Program (CRP) is positive. The authors provide several possible explanations, including unobserved variables such as the higher baseline level of agricultural activity in areas with higher conservation practices due to the CRP, which may lead to a spurious correlation between conservation efforts and pollution.

with more than more than 297 million water quality records. Simply put, and borrowing from Read et al. (2017), the WQP is "big data" for water quality users.

We accessed WQP data on sites and sample results (physical/chemical metadata) associated with the parameter code 00600, which is described as "total nitrogen [nitrate + nitrite + ammonia + organic-N], water, unfiltered, milligrams per liter" without imposing any other of the additional filters available in the portal in December 2019. There were close to 754,000 observations in the sample results data and 41,800 observations in the site data.[15]

The site data contain information regarding the site's location such as longitude and latitude, county, and the 8-digit hydrologic unit. The site data also contain information on the agency operating the site (e.g., "USGS-IL") and the site type (e.g., "stream," "facility," "lake," "well," etc.) The sample results data contain a long list of variables related to water quality measures, such as the date, time, and method, of the water sample collection. Linking the site to the sample results data is possible using the site location identifier field, which is present in both datasets.[16]

We measure nitrogen pollution (concentration) in milligrams per liter (mg/L).[17] We limit the data to those for sites in the CONUS using the state information in the sites data and for which we track "surface water" and "ground water" concentration in the sample results data.[18] Furthermore, we limit the sample results data to 1970–2018.[19] For the interested reader, some additional information regarding the WQP data used in the paper is available in the on-line Appendix Section A.2.

Crops. Annual county-level data on corn acres planted are available from the National Agricultural Statistics Service (NASS) of the USDA. Following Schlenker and Roberts (2009) and Annan and Schlenker (2015), among others, in a long stream of literature in agricultural economics, and to focus on rain-fed agriculture, we limit our sample to counties east of the 100th meridian and exclude Florida. This is the part of the country that accounts for more than 95% of the corn produced

[15]The WQP data can be accessed here using web service calls. A parameter code is a 5-digit number used in the National Water Information System (NWIS) to uniquely identify a water quality characteristic. Water quality refers to physical, chemical, radiological, and biological variables that impact the fitness of use of water for ecological, biotic, human, or other purposes. Water quality characteristic groups include physical conditions, chemical and bacteriological water analyses, chemical analyses of fish tissue, taxon abundance data, toxicity data, habitat assessment scores, and biological index scores, among others. For more information on the parameter codes, see here. Read et al. (2017) provide a succinct and very informative overview of the WQP data. The USGS has developed a series of R-based routines (e.g., `dataRetrieval`) for accessing and manipulating the WQP data.

[16]Sites consist of unique `OrganizationIdentifier` and `MonitoringLocationIdentifier` combinations, while results for each sampling activity at a site have a unique `ActivityIdentifier`. Linking the site to the sample results data is possible using the `MonitoringLocationIdentifier` field, which is present in both datasets.

[17]We use the `ResultMeasureValue` field in the sample results data to track nitrogen pollution.

[18]These are the sites for which the `ActivityMediaSubdivisionname` is either "surface water" or "ground water" in the sample results data.

[19]We use the `ActivityStartDate` field in the sample results data to identify the relevant observations.

during the time relevant for our analysis; in a subsequent section, we expand the geographic scope of our analysis to the CONUS.[20]

Weather. We use updated temperature and precipitation data from Schlenker and Roberts (2009), which are available for each county during the growing season for 1970–2017 and are based on PRISM gridded weather data. The data from Schlenker and Roberts have been used extensively in the literature on the effects of climate change on U.S. agriculture and are discussed in great detail elsewhere (Roberts et al. 2012). Following this stream of the literature, we use precipitation, the square of precipitation, cumulative degree days between 10°C and 29°C (moderate heat), and cumulative degree days above 29°C (extreme heat). The precipitation is measured in meters, the moderate heat is measured in 1,000 degree days, and the extreme heat is measured in 100 degree days.

Hydrologic Units. We use the USDA Natural Resources Conservation Service (NRCS) watershed boundary dataset (WBD) to identify 4- and 8-digit hydrologic units.[21] We use 4-digit hydrologic units to cluster the standard errors in our regressions. We use 8-digit hydrologic units to identify watersheds in our h-centric analysis.

National hydrography dataset plus V21. As in Keiser and Shapiro (2018), we use the NHD Plus flow line network to follow water pollution upstream and downstream. In particular, we use the National Seamless Geodatabase built on NHD Plus to identify upstream counties in the case of the m-centric analysis and downstream monitors in the case of c-centric analysis.[22] The NHD, which serves as the foundation of NHDPlus, is a comprehensive set of digital spatial data representing the surface water of the U.S. and includes common water features such as streams, rivers, and lakes. The NHD flow direction network traces the water downstream or upstream. It also uses a reach addressing system that allows the user to link water information, such as wastewater discharges or water-quality monitoring sites, to specific locations along the stream network so they can be discovered and processed in up or downstream order. The NHD is the dataset used by the WQP upstream-downstream service to search along the network (Read et al. (2017)).

[20] Table A1 in the on-line Appendix shows corn production and acres by state.

[21] The GBD files are available here.

[22] We did so using the R package `nhdplusTools` developed by the USGS and it is available here. The NHD plus flow line network is a publicly available digital geospatial framework (database) that depicts the network of streams and rivers within the CONUS (Moore and Dewald (2016)).

5 Data Overview and Descriptive Statistics

Preamble. We use data for 1970–2017, east of the 100th meridian excluding Florida (EAST-100) for our baseline results. In the case of the counties and 8-digit hydrologic units, we use the latitude and longitude of their centroids to identify the relevant "eastern" counties and watersheds, which we obtain from the CENSUS TIGER and the USDA NRCS WBD shape files, respectively. In the case of monitors, we use their latitude and longitude that are readily available in the WQP data. As we discussed earlier, we calculate nitrogen concentration and acres planted assuming a radius of 50 miles in the case of the c-centric and m-centric analyses. For the h-centric analysis, we use monitoring sites and counties that lie within the HUC8 boundaries.

Table 3 shows basic summary statistics of nitrogen concentration, our measure of pollution, and corn acres planted. These are the dependent and main explanatory variable of interest in the regression models discussed next. The table shows summary statistics for total annual (January–December) precipitation in meters too. Precipitation plays an important role in our assessment of the effects of agriculture on nutrient pollution based on our earlier discussion regarding the tight connection between nitrogen pollution and rainfall. Figure A3 shows the spatial and temporal variation of pollution and acres with year-specific box plots. The choropleth maps in Figures A4 and A5 offer alternative visualizations of the spatial variation for the two variables pointing to a strong positive correlation. In general, we see more pollution in watersheds in southern Minnesota, Iowa, Illinois, Indiana, and Ohio that drain large areas of agricultural land.

Tables A2–A4 summarize the conditional distribution of the acres planted and the weather-related controls used in our c-, h-, and m-centric analyses, respectively, by quartile of the distribution of nitrogen pollution. For all three analyses, we see more acres planted for higher levels of nitrogen pollution. We also see lower precipitation for higher pollution levels for each month in the first quarter of the year, as well as for November and December.

C-centric analysis. We have about 64,000 observations and 2,200 counties in the case of the c-centric analysis for which we aggregate the data at the county level (Table 3). On average, we track a county for 29 years during the 48-year period 1970–2017. The mean nitrogen concentration is about 2.5 mg/L and both the between-counties and within-county standard deviation (SD) are around 1.65 mg/L. Hence, pollution exhibits similar variation across counties and within a county over time. On average, 37,800 acres of corn are planted per year in a county. Contrary to nitrogen pollution, the variation in acres is much larger across counties (48,400 acres) than within a county over time (10,500 acres). As a benchmark for the acres planted, the mean (median) county land area is 603 (556) square miles or 386,187 (355,969) acres. The total annual precipitation is, on average, close to 1.1 meters and varies more across counties than within a county over time.

H-centric analysis. For the h-centric analysis, which is based on data aggregated at the 8-digit hydrologic unit (HUC8) level, we have close to 1,000 units and about 18,000 observations. As a result, we track a unit for about 18 years, on average. The average nitrogen concentration is 2.1 mg/L and exhibits more variation across units than within a unit over time. The between-units SD is 1.9 mg/L while its within-unit counterpart is 1.5. On average, about 29,600 corn acres are planted in a year across counties lying in a HUC8 and the between-units SD (45,400) is close to 5 times as large as its within-HUC8 counterpart. To benchmark acres planted against the size of the hydrologic units, the mean (median) unit area is 1,432 (1,270) square miles or 916,422 (812,504) acres. Similar to the c-centric analysis, the precipitation is, on average, close to 1.1 meters and its between-HUC8 variation exceeds its within-HUC8 counterpart.

M-centric analysis. In the case of the m-centric analysis that is based on data aggregated at the monitoring site level, we have about 56,500 observations for almost 9,600 monitoring sites. Hence, we track a site for almost 6 years. The nitrogen concentration is 2.4 mg/L, on average, and exhibits 3 times as large variation across sites (3.7 mg/L) than within a site over time. On average, close to 292,000 corn acres are planted within the assumed 50-mile radius from a site. The acres' variation across monitors, which is close to 50,000 acres is 9 times as large as the acres' variation within a monitor over time. This feature in acres' variation can be explained by the fact that a large number of sites are located in Northeast states, such as New Jersey, New York, Maryland, and Pennsylvania, that account for only a small fraction of corn acreage in our sample. Many of these sites also have some of the longest track records in our data (Figure A6). The precipitation-related statistics are comparable to those for the c- and h-centric analyses.

6 Trends in Nitrogen Pollution

Before we discuss our results from the panel FE and cross-section regressions using the three alternative aggregation schemes we described, we present some descriptive analysis regarding overall trends in nitrogen pollution for the period that is relevant in our analysis similar to Keiser and Shapiro (2018).

Figure 2, which we constructed using monitoring-site level data on average daily nitrogen concentrations (mg/L), shows the progress that has been made in ambient water quality following the passage of the Clean Water Act. In panel A, we plot the year FE and associated 95% confidence intervals (CIs) from a regression of nitrogen concentration on monitoring-site FE, year FE, day (values 1–31), day squared, day cubed, month (values 1–12), month squared, and month cubed. The standard errors are clustered by HUC8. We also show flow-normalized annual nitrogen con-

centration in the Gulf using data from the USGS National Water Quality Network in panel B. Panels C–F provide information related to fertilizer use, acreage, and EPA CWA 319 grants, all of which are important in understanding the relationship between agriculture and nitrogen pollution.

The use of nitrogen fertilizer increased from about 2,500 metric tons in 1964 to 11,800 tons in 2015; it reached its peak of 12,250 tons in 2013. Most of the almost 5-fold increase took place before the early 1980s (panel C). By 1981, nitrogen use had steadily increased to 10,800 tons.[23] The expansion of nitrogen use during this time was due to expanded acreage (see panel D for corn), increase in application rates, and a higher share of acres receiving fertilizer (from 85% to 97%); the percent of U.S. corn acreage receiving nitrogen fertilizer has been 95%, on average, in the last 50 years or so.[24] Since then fertilizer use has fluctuated over time following changes in cropping system implementation and fertilizer crop prices, but has shown no persistent trend (Hellerstein et al. (2019)). The application rates in the major corn producing states (Corn Belt plus Minnesota) follow similar trends with a notable increase between the mid-1960s and early 1980s.[25] The fertilizer costs have oscillated somewhere between 14% and 27% of the corn gross value of production averaging close to 20%.[26]

The general pattern in Figure 2 is an increase in concentration between the early 1970s and early to mid 1980s from about 2 mg/L to a peak of about 3 mg/L. This pattern is consistent with the increase in corn acreage, nitrogen use, and nitrogen application rate discussed above. Despite some oscillations, there is a downward trend that plateaus at about 2.3 mg/L in the most recent years. These are roughly the concentration levels in the early days of the CWA (early 1970s). A similar trend emerges in the flow-normalized annual nitrogen concentration in the Gulf using data from the USGS National Water Quality Network.

[23] See Table 9 (percent of corn acreage receiving nitrogen fertilizer) in this link.

[24] The acreage of major crops (corn, cotton, soybeans, wheat, and rice) follows a pattern over time that is very similar to that for corn shown in panel C of Figure 2. The dip in corn acreage in 1981 is well documented as farmers took land out of production under the Payment-in-Kind (PIK) program and other acreage limitation programs initiated against a backdrop of serious and worsening farm surpluses during Reagan administration.

[25] During the 45-year period 1964–2018, nitrogen was applied, on average, to 94% of the corn acres in each of the 6 states. For corn, nitrogen use efficiency or recovery, which is the ratio of the amount of nitrogen in harvested crop to the amount of nitrogen applied, increased from 58% in 1997 to 76% in 2015. Nutrient use efficiency increases can be tied to the improved varieties of crops grown—ones that have been bred for higher nutrient use efficiencies—as well as to improved crop management practices that enable more efficient uptake of the applied nutrients (e.g., more farmers follow the "4Rs"). Over time, farmers have reduced the share of planted acres with excess nutrient use. For corn, the share of planted acres with excess nitrogen (above 125 percent of the crop's needs) decreased from 53 percent in 1997 to 28 percent in 2015.

[26] In general, the sensitivity of fertilizer demand to fertilizer price is very small and fertilizer prices are highly dependent on prices determined in the international market, including the price of natural gas, which accounts up to 90% total costs of manufacturing nitrogen fertilizer (GAO (2003)). The relationship between gas prices and fertilizer prices is the strongest for anhydrous ammonia, which has the highest (80%) concentration of the three fertilizer products (the other two are urea, and urea ammonium nitrate).

The downward trend in nitrogen pollution largely coincides with an upward trend in the USDA Conservation Reserve Program (CRP) acreage in panel E and the EPA Clean Water Act (CWA) 319 grants in panel F. Recall from our earlier discussion that the CRP is a land retirement program with farmers voluntarily removing environmentally sensitive land from agricultural production and plant species that will improve environmental health and quality. The EPA CWA grants fund the implementation of programs aiming to combat non-point source pollution.

The CRP acres (cumulative enrollment) increased sharply from 2 million acres in 1986 to about 35 million acres in the mid 1990s. Following a decline to about 30 million acres by 1998, cumulative enrollment continued to grow up until 2007 reaching a peak of 36.8 million acres in 2007. Since then, cumulative enrollment has steadily decreased reaching 23.4 million acres in 2017 (USDA (2020)). EPA CWA 319 grants increase from 38 million in 1990 to 200 million in 1999. After a short-lived increase to about 240 million during 2001–2004, they remained around 200 million up until 2010. For the next few years, there was a significant drop to about 160 by 2015 before a recovery in the more recent years.[27] The plateau in nitrogen pollution also coincides with the decrease in both CRP acreage and EPA CWA 319 grants.

7 Baseline Estimates

7.1 Panel Fixed-Effect Regressions

Preamble. Tables 4–6 show detailed results of the panel fixed-effect (FE) regressions associated with the three different analyses that are based on the alternative data aggregations described earlier. Table 7 summarizes our preferred specification for each of the three analyses. There are three panels in the first three of these tables. In panel A, we report results from regressing nitrogen pollution on corn acres planted without controlling for weather. In panel B, we control for weather. In particular, we use 12 control variables (one for each month) for precipitation, squared precipitation, moderate heat, and extreme heat, for a total of 48 variables. In panel C, we add the interaction of acres with total annual (January–December) precipitation to the set of explanatory variables.

The columns in the same set of tables correspond to specifications with different sets of FE and time-related controls with the simplest specification (column 1) having neither FE nor time-related controls. The richest specification (column 8) includes spatial FE, year FE, and spatially-differentiated time trends. The standard errors are clustered at the HUC4 level (124 clusters) accommodating arbitrary correlation of the unobservables across time and space. In the bottom of

[27] See here.

each of the three panels, we report elasticities along with their standard errors and t-statistics. We calculate the elasticities using the percentage change in nitrogen pollution relative to its mean and precipitation equal to the 75% percentile of its empirical distribution. We calculate the percentage change in corn acreage assuming an increase in corn acreage equal to its within SD relative to its mean.

According to Table 3, the average nitrogen concentration is 2.5 mg/L, 2.1 mg/L, and 2.4 mg/L in the case of the c-, h-, and m-centric analysis, respectively. The assumed increase in acres is about 10,500 and 8,100 acres in the first two analyses. For the m-centric analysis, the assumed increase is 52,900 acres. Expressed in percentage terms relative to the mean acreage reported in Table 3, the assumed increase in acreage is 28%, 27%, and 18%, respectively. For all three analyses, the 75% percentile of precipitation is about 1.3 meters. Based on these values, an estimated increase in pollution of 10% translates into elasticities of about of 0.4 for the c-centric and h-centric analyses, and about 0.6 for the m-centric analysis.

C-centric analysis. For the models without weather-related controls (panel A), the adjusted R-squared ($\overline{R}^2$) is 0.26–0.53 depending on the specification with most of the fit improvement attributed to the county FE as shown in Table 4. Setting aside the specifications with county-specific linear trends in columns A7 and A8, the acres coefficient is statistically significant at 5% level with values between 3.9 (column A5) and 23.6 (column A1). According to these estimates, the implied elasticities are 0.025–0.03. The implied elasticities are about 0.03 for the models with county FE.

In the presence of weather controls (panel B), we see a notable change in the acres coefficient from 23.6 (column A1) to 18.4 (column B1) for the specification without county FE. The model fit improvements, however, are relatively minor. As it was the case for the models in panel A, the acres coefficients fail to be statistically significant at conventional levels for the specifications with county-specific trends in columns B7 and B8. Setting aside the specification without county FE in column B1, the elasticity of nitrogen pollution with respect to corn acreage is between 0.06 (column B5) and 0.09 (column B6).

The interaction of acres with precipitation (panel C) implies effects that are significant at 5% level even in the presence of county-specific trends. Once again, setting aside the specification without county FE that implies an elasticity of about 0.3, we see elasticities between 0.07 (column C7) and 0.18 (column C6). Hence, the county FE seem to be more important than the time-related controls for the magnitude of the effects of interest. For the richest specification in column C8 that includes county FE, county-specific trends, and year FE, the implied elasticity is 0.12 and it is significant at 1% level. The 95% confidence interval (CI) of this elasticity is 0.05 to 0.19.

H-centric analysis. For the models without weather-related controls, the $\overline{R}^2$ is 0.26–0.64 depend-

ing on the specification with most of the fit improvement attributed to the HUC8 FE (Table 5). The acres coefficient is significant at conventional levels only in the absence of the HUC8 FE (column A1) implying an elasticity of 0.38. The same is true for the acres coefficient in the presence of weather-related controls (column B1) implying an elasticity of 0.35. Similar to the c-centric results, the presence of weather-related controls implies essentially no improvements in model fit. In the presence of the weather and acres interactions in panel C, the elasticities are significant at 1% level. Excluding the simplest specification in column C1 that does not include spatial FE and time-related controls, the elasticities are between 0.11 (column C7) and 0.16 (columns C2 and C4), which highlights that the role of the time-related controls is less important than the role of the spatial FE for the size of the estimated effects. The richest specification (column C8) with HUC8 FE, year FE, and HUC8-specific trends, implies an elasticity of 0.13 that is significant at 1% level with a 95% CI of 0.05 to 0.21.

M-centric analysis. The $\overline{R}^2$ of the models without weather-related controls is 0.12– 0.82 depending on the specification with the monitoring site FE accounting for almost the entirety of the improvement in the model fit (Table 6). Similar to the h-centric analysis, the acres coefficient is statistically significant at conventional levels only in the absence of monitoring site FE implying an elasticity of 0.29 (column A1). In the presence of the weather-related controls, the simplest specification (column B1) is the only one that implies an elasticity that is significant at conventional levels with a value of 0.25. Similar to the c- and h-centric results, the acreage elasticities are significant at 1% level in the presence of the weather controls and the acres interactions (panel C). Excluding the simplest specification that does not include spatial FE and time-related controls, the elasticities are 0.05 (column C6)–0.08 (column C8). Actually, the largest of these elasticities (0.08) with a 95% CI of 0.02 to 0.13 is implied by the richest specification with site FE, year FE, and county-specific trends.[28]

Statistical significance. In all, we see positive and statistically significant effects of corn acreage on nitrogen pollution using data aggregated at at the county, 8-digit hydrologic unit, and monitoring-site levels. The specifications of the panel FE regressions that control for weather and contain an interaction of corn acreage with precipitation generally imply larger effects than their counterparts that do not contain such interactions. Spatial FE matter more than time-related controls for the magnitude of the effects. According to our preferred specifications, the elasticities associated with a roughly 30% (1 within-county SD) increase in corn acreage when evaluated at the 75% percentile of the precipitation distribution are 0.12 and 0.13 using data at the county and 8-digit hydrologic unit levels. Using data aggregated at the monitoring-site level, the percentage increase in nitrogen

[28] We also estimated the models in Table 6 using the average of corn acres as opposed to the sum of corn acres within the assumed radius of 50 miles from the monitoring sites. The C8 elasticity is statistically indistinguishable from the one reported in Table 6.

pollution for an approximately 20% (also equal to 1 within SD) is such that the implied elasticity is 0.08. All three elasticities are significant at 1% level.

Economic significance. A natural question to ask is whether the statistically significant effects reported above are also economically meaningful. To answer this question, we perform a back-of-the-envelope (BOE) calculation that utilizes the (median) potential damage costs of nitrogen due to declines in fisheries and estuarine/marine life of $15.84 per kilogram in 2008$ from Table 1 in Sobota et al. (2015). A 3% increase in the average level of nitrogen concentration of about 2.5 mg/L in our sample, entails close to 50,852 additional metric tons of nitrogen in the Gulf. This is the increase in nitrogen flux (concentration $\times$ streamflow) implied by an increase in corn acres planted equal to 1 within-county SD coupled with the average streamflow ($\approx$ 21,500 cubic meters per second) of the Mississippi River in the Gulf for the time spanned by our data. Hence, our estimated increase in nitrogen concentration of 3% implies an external cost of $805.5 million per year.[29]

7.2 Cross-Section Regressions

Preamble. We show our year-specific and pooled (across-years) elasticity estimates based on the cross-sectional regressions using data for 1975–2017 in Figures 4–6. We report only the pooled estimates in Table 8. Our year-specific elasticities are based on (2). Their pooled analogs are based on (3). Hence, we report 43 year-specific estimates and a single pooled estimate. We start our analysis in 1975 as opposed to 1970 due to the small number of observations in the early years of our sample for the year-specific regressions. The four panels in the figure show elasticity estimates along with 95% CIs based on the same calculations as in the case of the panel FE regressions to allow for meaningful comparisons. In other words, the difference between the elasticities reported in the bottom of panel C of, say, Table 4 and the elasticities shown in Figure 4 is only due to coefficient estimates. The same holds when we compare the elasticities in, say, 1980, to the elasticities in, say, 1995 in Figure 4. We use the four panels to report results from four specifications that differ in the set of spatial FE included: no spatial FE (panel A), state FE (panel B), 2-digit hydrologic unit FE (panel C), and 4-digit hydrologic unit FE (panel D). We will be referring to the last two sets of FE, as HUC4 and HUC2 FE. All four specifications control for weather and contain an interaction of acres with total annual precipitation. The standard errors are clustered at the HUC4 level. The reader should keep in mind the substantial variation in the number of observations, as well as in the number of counties, hydrologic units, and monitoring sites across years in Figure A7 and Figure A8 when we discuss our year-specific estimates.

[29] We use the average flow for years 1970–2016 from column F (Total Mississippi-Atchafalaya River) here.

C-centric analysis. Starting with the pooled estimates for the specification with spatial FE, we see elasticities of nitrogen pollution with respect to corn acreage between 0.17 for the specification with HUC4 FE and 0.26 for the specification with HUC2 FE (Table 8, panel A). In the absence of spatial FE, the estimated elasticity is 0.27. The pooled elasticities are all significant at 1% level. For a given specification, there is notable variation in the elasticities of the year-specific effects most of which are significant at 5% level. For a given year, the estimated elasticities tend to be comparable in terms of their magnitude across specifications. For our preferred specification with the HUC4 FE that most probably account best for spatial unobservables, the magnitude of significant (at 5% level) year-specific elasticities is between 0.10 for 1990 and 0.44 for 1999 (Figure 4).

H-centric analysis. The estimated elasticities are between 0.30 for the specification without spatial FE and 0.36 for the specification with HUC4 FE (Table 8, panel B). Similar to the c-centric regressions, these elasticities are significant at 1% level. Also similar to the c-centric analysis, for a given specification, the year-specific estimated elasticities exhibit substantial variation in their magnitude and most of them are significant at 5% level. For a given year, the estimated elasticities are generally similar across specifications. Our preferred specification with the HUC4 FE implies year-specific elasticity estimates, which are significant at 5% level, between 0.40 for 1990 and 1.40 for 2014 (Figure 5).

M-centric analysis. The estimated elasticities of nitrogen pollution with respect to corn acreage are between 0.32 for the specification without spatial FE and 0.46 for the specification with HUC4 FE based on the pooled estimates (Table 8, panel C). These effects are significant at 1% level. Similar to the c- and h-centric estimates, there is substantial variation in the magnitude of the year-specific elasticities for a given specification, and close to half of all year-specific elasticities are significant at 5%. Furthermore, the effects tend to be quite similar across specifications for a given year. Our preferred specification with the HUC4 FE implies year-specific elasticities, which are significant at 5% level, between 0.33 for 2002 and 1.32 for 1987 (Figure 5).

Summary. For all three analyses, the cross-section regressions imply positive and significant elasticities of nitrogen pollution with respect to corn acreage that exhibit some variation depending on the set of spatial FE that enter their specifications when pooling data across all years. There is also notable variation in the magnitude of the year-specific elasticity estimates with many of them being statistically significant without exhibiting a particular pattern (e.g., it is hard to discern a trend over time). The pooled estimates and many of the year-specific estimates based on the cross-section regressions are larger than their counterparts based on the panel FE regressions. For our preferred specification with HUC4 FE, the pooled c-centric elasticity is 0.17 while its year-specific counterparts are 0.10–0.44. For the same specification, the h-centric elasticities are 0.36 (pooled), and 0.40–1.40 (year specific), while the m-centric ones are 0.46 (pooled), and 0.33–1.32

(year-specific).

7.3 Summary of Baseline Estimates

C-centric analysis. Our c-centric analysis is based on data aggregated at the county level as it is common in the agricultural economics literature. The elasticity of nitrogen concentration with respect to corn acres is 0.12 for our preferred specification of the panel FE regressions (column C8, Table 4). Our preferred specification of the cross-section regressions implies an elasticity equal to 0.17 when we pool data across years (panel A, Table 8). The same specification implies year-specific elasticities in the range 0.10–0.44.

H-centric analysis. In the case of h-centric analysis, the data are aggregated at the HUC8 level as it is common in the environmental science literature. The elasticity is 0.13 for our preferred specification of the panel FE regressions (column C8, Table 5). Our preferred specification of the cross-section regressions implies an elasticity equal to 0.36 when we pool data across years (panel B, Table 8). The same specification implies year-specific elasticities in the range 0.40–1.40.

M-centric analysis. For the m-centric analysis, the data are aggregated at the monitoring site level as it is also common in the environmental science literature. The elasticity is 0.08 for our preferred specification of the panel FE regressions (column C8, Table 6). Our preferred specification of the cross-section regressions implies an elasticity equal to 0.46 when we pool data across years (panel C, Table 8). The same specification implies year-specific elasticities in the range 0.33–1.32.

In all three analyses, there is a notable variation in the number of observations across years, which is something that the reader should keep in mind when we discuss our year-specific estimates. In a subsequent section of the paper, we present a set of results based on an alternative dataset aiming to reduce such variation.

7.4 Reconciling Our Baseline Estimates

Table 4 in Hendricks et al. (2014) gives the average nitrogen loss (pounds per acre) from the edge-of-field (EoF) as predicted by the SWAT water-quality model—coupled with an econometric model—for different land uses in Iowa, Illinois, and Indiana based on USDA CDL data for 2000–2010. Nitrogen losses are the sum of nitrate and organic nitrogen loss. Corn after corn generates the largest nitrogen losses (mean: 34.7 pounds per acre, SD: 11.4 pounds per acre) because more fertilizer is applied to corn after corn since there is no nitrogen carry-over from a previous soybean crop. The mean loss of 34.7 pounds per acre reported by the authors is similar to the average

estimate of total nitrogen loss of 34 pounds per acre per year in the USDA CEAP national nitrogen loss report (NRCS (2017b)).

Assuming the mean annual EoF loss of about 35 pounds per acre from Hendricks et al. and 79,384,857 corn acres per year (average of national corn acres planted during the same period according to the USDA historical track records), we have 1,260,294 metric tons of total nitrogen per year. This calculation assumes that the EoF losses translate to an equivalent nitrogen loadings in the Gulf, which may not hold as only a portion of nitrogen in the field reaches the Gulf. Note that the average annual total nitrogen flux of the Mississippi and the Atchafalaya rivers to the Gulf between 1968 and 2016 is 1,460,419 metric tons.[30]

In our case, the average nitrogen concentration is 2.5 mg/L. According to the USGS, the mean annual flow of the Mississippi plus Atchafalaya to the Gulf (Ibid) is about 21,376 cubic meters per second for 1968–2016. This mean annual flow implies 1,685,245 metric tons of total nitrogen per year, which translates to 46.8 lbs per acre using the average annual corn acreage for 1968–2016. However, a comparison of 46.8 lbs per acre with 35 lbs per acre from Hendricks et al. hinges on the assumption that all nitrogen pollution recorded at the USGS monitoring sites is due to fertilizer loss from corn fields but it is not. A better, albeit still imperfect comparison, is to assume that 70% of the 1,685,245 metric tons are attributed to agriculture (David et al. (2010)) in which case we have 32.8 lbs per acre (see Wu and Tanaka (2005) for a similar approach). This loss of 32.8 lbs per acre calculated using our estimates is highly comparable to the average loss of 34.7 lbs per acre in Hendricks et al..

Finally, according to our estimates in column C8 of Table 4, a 28% increase in acres planted implies a a 3.3% increase in nitrogen concentration when evaluated at the mean concentration of 2.5 mg/L. A 3.3% increase in mean concentration of 2.5 mg/L implies an increase in flux equal to 55,613 metric tons. Assuming that this 3.3% increase in concentration is associated with a 28% increase in 79,384,857 corn acres, the implied increase is 5.52 lbs per acre.

8 Additional Estimates

8.1 Overview

The discussion that follows pertains to various robustness checks on the panel-FE and the cross-sectional regressions. We start by motivating the various robustness checks. We then discuss our

[30] See the USGS link here.

findings noting that the discussion of our findings does not necessarily the order of the discussion motivating the various robustness checks. Some of the figures and tables that pertain to the robustness checks considered are relegated to the on-line Appendix.

Alternative datasets and extended geographic scope. In our baseline results, we use the WQP data on parameter code 00600 to measure nitrogen pollution in the Eastern part of the country (east of the 100th meridian excluding Florida). We will refer to these data as the "USGS-NWIS" data. In what follows, we will use the term "EAST-100" to refer to the analysis pertaining to the Eastern U.S.. We also present results for the CONUS using the USGS-NWIS data. Moreover, we present results for the CONUS based on two additional datasets. The first dataset ("USGS-NWQN"), which is discussed in more detail in Section A.3, is based on imputation methods developed by the USGS. The second ("USGS+EPA") dataset, which is discussed in more detail in Section A.4, is based on a combination of the USGS-NWIS and EPA-STORET data and allow us to increase coverage in the later years of our analysis.

Flexible modeling of precipitation. In our baseline results, we estimate acreage effects using the 75th percentile of the precipitation empirical distribution when we interact corn acres with precipitation. As an additional check, we consider a specification in which instead of interacting corn acres with a linear precipitation term, we interact corn acres with a cubic spline in precipitation.

Alternative radii. Our baseline results are based on 50-mile radii for USGS monitoring sites and county centroids. We explore the sensitivity of our estimates to 100- and 200-mile radii in the case of the c-centric and m-centric regressions. Setting aside the effect on (potentially) altering the number of USGS monitoring sites and corn acreage used in the analysis, increasing the radii may alter (e.g., due to attenuation/removal) the share of the EoF nutrient losses that reaches the monitoring sites where nitrogen concentration is measured. In general, nutrient removal rates increase with transport distance and nutrient sources that are further upstream deliver smaller nitrogen loads (Marshall et al. (2018) and Robertson and Saad (2006)). As Kling (2011) discusses, the degree of attenuation depends not only on physical features but also on the land use choices that gives rise to non-constant diffusion coefficients. We maintain the mean level of pollution, the level of precipitation, and the assumed increase in corn acreage the same as the ones used for our baseline elasticities in tables 4–6. Hence, any changes in our elasticity estimates are due to changes in the parameter estimates.

Other Sources of Nitrogen

Economic activity. We use the BEA series SAEMP25 (total employment, number of jobs) and SAGDP2 (GDP by state, all industry total) to control for economic activity as a potential source of

nitrogen pollution (e.g., urban non-point pollution). Both series exhibit variation by state and year. We also use three BEA series that exhibit variation by county and year, namely, CAINC30110 (per capita personal income, dollars), CAINC45190 (fertilizer and lime, incl. ag. chemicals 1978-fwd.), and CAINC45370 (farm earnings). The last economic series is the county-level monthly unemployment rate from the BLS Local Area Unemployment Statistics, which starts in 1990. We deflate all dollars using the GDP deflator (BEA Table 1.1.9. Implicit Price Deflators for Gross Domestic Product).

Fossil-fuel combustion. We also consider controls related to nitrogen pollution from fossil fuels. Fossil-fuel combustion releases nitrogen into the atmosphere, which is then redeposited on land and water through the water cycle—rain and snow. The first control is fossil-fuel consumption from the EIA State Energy Data Systems that exhibits variation by state and year. The second control is NO_x emissions from fuel combustion (electric utilities, industrial, and other) from the EPA Air Pollutant Emissions Trends data. The data on NO_x emissions exhibit variation by state and year and are available beginning in 1996.

Atmospheric deposition. Atmospheric deposition is a significant non-point source of nitrogen pollution. Using a SPARROW model for the Mississippi River Basin (MRB), Alexander et al. (2008) have shown that atmospheric deposition accounts for about 16% of the total nitrogen flux delivered to the Gulf from the basin's watersheds (see their Table 2). More recently, Robertson and Saad (2006) have shown that atmospheric deposition accounts for 34% of the mean annual yields of total nitrogen (kilograms per square kilometer per year) in the Mississippi river (see their Table 6). To control for atmospheric deposition, we use the average watershed precipitation-weighted (wet) deposition of nitrogen (kilograms per hectare) for 1985–2012 from Dataset 1 in Falcone (2018).[31]

Animal manure. Animal manure can be a significant source of nitrogen and other nutrients needed for crop growth. Improper use or disposal of manure can lead to the buildup of nitrogen in soils and the loss of nitrogen to surface or ground water. The nutrient content of manure is highly variable and depends on such factors as type of feed, type and age of livestock, type of bedding material, and storage and handling practices. Livestock inventory estimates from the Census of Agriculture and manure nutrient content estimates can be combined to estimate nitrogen voided in

[31] Falcone et al. have compiled a dataset containing consistent time-series measurements of anthropogenic activities potentially affecting stream quality across the CONUS and summarize the most noteworthy trends from 61 variables in 16 categories. Data include measures of atmospheric deposition, agricultural production, livestock, urbanization, irrigation, land use, nutrients from fertilizer, dams/reservoirs, and pesticide use, among others. The time span of the data is from 10 to 40 years, mainly for the period 1970–2012. Shape files of ecoregions, counties, and HUC-10s are also provided for user convenience. Values are given for HUC-10 areas for all variables and additionally, for land use variables values are given for counties EPA Level IV ecoregions.

animal manure.[32] We control for animal manure using data from the USDA on cattle in feedlots that exhibit variation by state and year. Alternatively, we control for manure using Dataset 2 from Falcone (2018) on animal concentration built from information from the USDA Census of Agriculture (CoA) for 1974–2012; see Falcone et al. (2018) for additional details.

Point sources of nitrogen pollution. Waste water treatment plants (WWTPs) and commercial and industrial point sources that discharge directly to streams are major contributors to surface-water nitrogen loads. We use data on the nitrogen yields (kilograms per square kilometer) for WWTPs in the EPA Clean Water Needs Survey (CWNS) from Dataset 16 in Falcone (2018) to control for point sources. As an alternative way to control for point sources, we use data on the number of CWNS WWTPs (also from Falcone (2018)). The data are available for approximately two-year intervals between 1978 and 2012.

Conservation Programs and Agricultural Management

Conservation programs. Agricultural conservation programs, which range from voluntary technical assistance only to payment-based voluntary and cross-compliance programs, have been implemented since the Food Security Act of 1985 with an early focus on the viability of agricultural production through soil conservation. The Farm Security and Rural Investment Act of 2002 substantially increased the level of public funding for conservation and initiated the goal of maximizing environmental benefit. Subsequently, the Conservation Effects Assessment Project (CEAP) was established to provide science-based guidance on the best use of funding for conservation and to facilitate the alignment of conservation programs with national environmental protection priorities such as the restoration of the Gulf of Mexico (Garcia et al. (2016)). We control for conservation programs using dataset 3 from Falcone (2018) that tracks the proportion of acres in the Conservation Reserve Program (CRP) to total cropland acres for 1986–2012.

Agricultural best management practices. Agricultural best management practices (BMPs) are designed to minimize the environmental impacts of agriculture while sustaining crop productivity (Dubrovsky et al. (2018)). BMPs reduce nutrient losses to streams through management of nutrient inputs on the land surface and through curtailment of erosion and runoff of nutrients from the land surface to streams. As we discussed earlier, three common BMPs are conservation tillage

[32] McIsaac et al. (2002) report nutrients excreted in animal manure in their Table 4. Goolsby et al. (1999) provides estimates of nitrogen (kilograms per day) voided in animal manure in their Table 5.5. Some parts of the Southeast and Southern Plains receive high loads of nitrogen in the form of manure, but such areas of high manure applications are not as extensive as those of high applications of commercial fertilizers (Dubrovsky et al. (2018)). Manure from animals that are restricted to confined feeding operations, such as at dairies or feedlots, is usually stored onsite for later use on adjacent agricultural land. Manure from free-ranging livestock is not recovered, but rather is distributed across the grasslands, shrub lands, and forests used for grazing.

(see below), nutrient management plans, and conservation buffers. Comprehensive nutrient management plans help guide decisions on the placement, rate, timing, form, and method of nutrient application to avoid inputs in excess of crop requirements and to minimize loss to streams, groundwater, or the atmosphere. Nutrient management plans can incorporate a variety of agronomic tests to balance the amount of nutrients currently available in the soil against the amount required for crop production, and to identify the ideal timing for crop growth and irrigation to minimize runoff and leaching. Conservation buffers are areas of permanent vegetation often planted adjacent to streams, lakes, ponds, and wetlands or along the edges of agricultural fields to help reduce runoff or leaching of nutrients by filtering out nutrients and sediments, enhancing infiltration, and increasing plant uptake. We believe the spatial FE and spatially differentiated trends in our specifications adequately control for agricultural BMPs.

Tillage. Tillage is used to control weeds, incorporate crop residue, and prepare land for planting, but minimizing soil disturbance and maintaining soil cover are critical to improving soil health (Claassen et al. (2018)). Conservation tillage, particularly no-till or strip-till, used in conjunction with soil cover practices, such as conservation crop rotations and cover crops, entail numerous benefits, such as improved agricultural productivity, greater drought resilience, and better environmental outcomes. To name a few examples, compared to conventional tillage, conservation tillage increases water infiltration, and reduces water runoff and sediment yield (Capel et al. (2018)). Similar to the best management practices discussed above, we believe the spatial FE and spatially differentiated trends in our specifications adequately control for tillage practices.

Drainage. Drain flow is water that moves off the landscape through artificial subsurface drains following rainfall or irrigation. Information on the location and areal extent of artificial drainage networks is crucial to understanding and quantifying their potential effects on water quality (Capel et al. (2018)). For example, subsurface tile drainage can provide both economic benefits for crop production through the removal of excess water from the soil column, and environmental improvements in soil and water quality through reductions in runoff, erosion, and phosphorous transport. Unfortunately, tile drains also transport nitrogen from fertilizer and other sources in water-soluble nitrate form more readily from the field to surface water.

The locations of surface drainage ditches are well known, because they are easily observable on the landscape. The extent of subsurface drainage systems, however, is poorly known in most areas because of their distributed nature, the extended period of installation, incomplete location maps, and a general lack of recent, systematic surveys of their spatial distributions. In addition to the lack of drainage information in recent decades, the lack of a consistent data collection method has resulted in great uncertainty as to the locations of subsurface drains throughout the country. Networks of subsurface drainage systems have been installed beneath agricultural fields in the last

few decades. In many cases, these systems have been installed as patterned drainage to improve control over soil water and thus increase crop yield. Landowners, however, are not required to report the installation of subsurface drainage systems or keep track of their locations. As a result, the locations of these networks are largely unknown.

The drainage-related datasets that we are aware off exhibit only spatial variation. Two datasets have been compiled by USGS and are 30-meter resolution rasters. The first is for the CONUS in the early 1990s (Nakagaki et al. (2016)). The second is for 12 Midwest states in 2012 (Nakagaki and Wieczorek (2016)). Both datasets are built using information from the State Soil Geographic Database Version 2 (STATSGO2), the National Land Cover Dataset (NLCD), and Sugg (2007). The latter dataset also uses information on state-level acreages of agricultural land drained by tiles from the 2012 Census of Agriculture. The third dataset is from Sugg (2007), who combines information from the USDA STATSGO database and the 1992 NLCD to calculate the percent of cropland with subsurface drainage at the county level for 18 states, which include the Corn Belt and Lakes states. We believe the spatial FE and spatially differentiated estimates of the effects of corn acreage on nitrogen pollution adequately control for drainage practices.

Heterogeneous Effects

Temporal and spatial variation in acreage effects. We first check whether the acreage effect on nitrogen concentration exhibits temporal variation by reporting decade-specific elasticities. These decade-specific elasticities are estimated by interactions with appropriate dummy variables. We also explore the possibility for spatial variation in the acreage effects by first distinguishing between effects that pertain to the top 10 corn-producing states and those that pertain to other states via interactions with appropriate dummy variables too. Finally, we perform a spatial-variation exercise allowing the effects to differ by water regions (2-digit hydrologic units).

Seasonality. Transport of nutrients to streams and groundwater varies seasonally, in large part following seasonal patterns in human activities, such as fertilizer application in the beginning of the growing season. The transport of nutrients to streams also varies as precipitation and runoff change; loads and water discharge are usually highest during the late winter, spring, and early summer when runoff is highest (CENR (2000)).

We consider several alternative windows during the year to measure nitrogen concentration. We start with the following windows: April–September, March–August, May–October, and January–June. The first three time windows are around the typical U.S. crop growing season. In the case of the 6-month window of January to June, we aim to capture the effects of spring runoff (Mitsch et al. (1999)). We also consider the April–June window, which stimulates spring and summer

algae blooms directly influencing the hypoxic zone in the Gulf (Murphy et al. (2013)), and the June–September window, which overlaps with the hypoxic season in the Gulf (CENR (2000)).

Other Checks

Runoff. Runoff is water that flows over the landscape and directly into the surface waters that drain the watershed (for example, streams). The importance of runoff as a water flow path is affected by precipitation, vegetation, topography, and soil characteristics. Precipitation in excess of what the landscape can assimilate at a given time produces runoff (Capel et al. (2018)).[33] We use data from Wolock and McCabe (2018) based on a water-balance model in Mccabe and Wolock (2011).

Streamflow. We refine the measurement of pollution and acreage in the case of the c-centric and m-centric analyses to account for streamflow. Using the USGS-NHD flow lines data and R routines developed by the USGS, we are able to identify downstream monitoring sites for each county in the case of the c-centric regressions. We are also able to identify the upstream counties in the case of the m-centric regressions. In the former case, we use downstream monitoring sites to track nitrogen pollution. In the latter case, we use upstream counties for total corn acreage.

Censoring. In the main results, we exclude values of nitrogen concentration in excess of 50 mg/L noting that the 99% of the concentration empirical distribution is 20 mg/L. We also exclude values of nitrogen concentration that are identified as being lower than a reporting limit (e.g., less than 2.5 mg/L). We consider two robustness checks in terms of how we handle observations with values lower than the reporting limits. In the first, we set such values equal to zero. In the second, we set such values equal to the reporting limit.

Additional data filters. In this robustness check, we filter the nitrogen pollution data as in Keiser and Shapiro (2018). In particular, we only consider data for surface water and routine samples associated with lakes and streams. We maintain the mean level of pollution, the level of precipitation, and the assumed increase in corn acreage the same as the ones used for calculating the effects in tables 4–6. Hence, any changes in our baseline estimates of the effects are due to parameter estimates.

Clustering. We explore alternative clustering schemes for the purpose of statistical inference.

[33] According to Table 6.2. in Goolsby et al. (1999) that pertains to a regression model for total nitrogen and nitrate yields in the 42 interior basins of the MARB, runoff is included among the explanatory variables and is assumed to represent other unmeasured inputs such as atmospheric deposition, ground water discharge, soil erosion, etc..

8.2 Panel Fixed-Effect Regressions

Preamble. Tables 13–15 show the results of our robustness checks based on the additional controls listed in Table 12. These robustness checks are summarized in tables 9-11. To ease comparisons with our baseline results, the elasticities reported in these three tables are are calculated as their counterparts in column C8 in tables 4–6. Given that many of the robustness checks involve sample sizes that are different from the ones for our baseline estimates, these three tables are structured such that we take into consideration the change in the sample size in our estimated effect of corn acreage on nitrogen concentration. For this reason, we report two elasticity estimates. The first elasticity, which is reported in panel A, accounts only for the (potential) change in the sample size implied by the additional control(s) (e.g., 1996 onward in the case of NO_x emissions). The second elasticity, which is reported in panel B, accounts for both the change in the sample size and the additional control variable(s) in the specification.

C-centric analysis. In Table 13, the elasticity estimates are significant at 5% level except for models RC7–RC12, as well as for model RC16. These 7 models are based on shorter samples than the one used for our baseline estimates. For the remaining models, the elasticity estimate when we include the additional control variables falls inside the 95% CI of its counterpart in the absence of such controls. The only exception is model RC9 that controls for regional income, fossil fuel consumption, and NO_x emissions, which is estimated using data for 1996–2017. For this model, the elasticity of nitrogen pollution with respect to corn acres is 0.21 (0.13) and it is (it is not) significant at 5% level when we include (exclude) the additional control variables. When it is significant at 5% level in the presence of the additional control variables, the acreage elasticity is between 0.12 for model RC2 that controls for GDP, and 0.26 for model RC15 that controls for regional income, fossil fuel consumption, and the percent of CRP cropland acres. The higher end of the estimated elasticities in the presence of additional controls is about twice as large as the baseline elasticity (0.12) we report in column C8 of Table 4 and falls outside its 95% CI.

As for the temporal variation, the decade-specific elasticities are between 0.01 for the 1970s (DEC70) and 0.17 for the 1980s (DEC80) and 1990s (DEC90) and fall inside the 95% CI of their baseline counterpart (Table 16, panel A).

In terms of spatial variation, the acreage elasticity for the top 10 producing states (Top) is 0.15 and it is significant at 1% level falling inside the 95% CI of its baseline counterpart (Table 17, panel A). The acreage elasticity for the remaining states (Other) is both practically and statistically indistinguishable from zero.

In Table A15 and Table A16, we explore the spatial variation of our elasticity estimates by allowing

them to differ by water region (HUC2). In the first table, we present estimates based on models in which we interact the two explanatory variables of interest—corn acreage and its interaction with precipitation—with HUC2 dummies. In the second table, we estimate a different regression for each water region. Table A14 provides a list of the water regions of interest most of which span mainly the Midwest. In panel A of Table A15, the elasticity for the Tennessee Region is -0.18 and it is significant at 2%, a rather puzzling finding, while the elasticity for the Missouri Region is 0.20, it is significant at 1%, and lies outside the 95% CI of its baseline counterpart. In panel B of Table A16, we see a single significant elasticity at conventional levels (less than or equal to 10%), which is the one for the Missouri Region (0.10).

When we allow for a flexible specification of precipitation using cubic splines, we generally see larger effects for larger values of precipitation.[34] In particular, a flexible specification of precipitation implies elasticities of about 0.08–0.11 that are significant at 5% level for precipitation values that exceed their 25% percentile (Figure 3, panel A). These effects are comparable to their baseline analog and fall inside its 95% CI.

C-centric analysis (extended geographic scope plus additional data and specifications). Using USGS-NWIS data for the CONUS as opposed to the EAST-100, the observations that pertain to the c-centric analysis are 72,751 as opposed to 64,121 (Table A23). Expanding the geographic scope of our analysis to the CONUS implies an elasticity of 0.10 that is statistically indistinguishable from its baseline counterpart of 0.12 at 5% level (Table A24, column A8).

The elasticity estimates in panel A of Table A25 are based on the USGS-NWQN data for nitrogen concentration discussed in Section A.3, which allow us to increase the sample size from 72,751 to 107,994 observations, and pertain to the CONUS. The elasticity in column A8 is 0.10 and it is indistinguishable from its baseline counterpart (0.12). The elasticity estimates in panel B of Table A25 are based on USGS+EPA data for the CONUS, which allows us to further increase the number of observations to 113,372. The elasticity in column B8 is 0.16 and it is indistinguishable from its baseline counterpart (0.12) at 5% level.[35]

In Table A26, we control for CRP acres, soybean acres, and wheat acres, as well as the acres of other major crops (cotton, rice, and sorghum, lumped together and not reported in the table). Similar to the corn acres, we interact the CRP, soybean, and wheat acres with precipitation. Given that we control for the acreage of multiple crops in our models, we adjust our temperature related

[34] For this flexible specification of precipitation, we use the interaction $a_{it} f(p_{it})$ as opposed to the interaction $a_{it} p_{it}$ in Equation 1, where $f(\cdot)$ is a cubic spline in precipitation.

[35] Figure A7 and Figure A8 show the coverage in terms of monitoring site-date combinations, number of monitoring sites, number of counties, and number of hydrologic units, by year for the alternative datasets. The use of the EPA STORET data allows us to increase significantly our sample size starting in the mid-1980s.

controls and we use the following degree days: 0C°, 5C°, 8C°, 10C°, 12C°, 20C°, 25C°, 29C°, 30C°, 31C°, 32C°, 33C°, and 34C° instead of degree days based on 29C° (moderate heat) and the difference between degree days based on 29C° and 10C° (extreme heat) in our baseline specifications that include only corn acres. Moreover, we set CRP acres equal to zero during the period 1970–1985.

The elasticity of nitrogen pollution with respect to corn acres in column 8 is 0.14 and it is significant at 1%. We also see a negative elasticity with respect to CRP acres (-0.01) in column 8, which, however, is not statistically significant at conventional levels. Regarding the small effect of the CRP acres, we have to keep the following in mind. First, the specification controls for county FE, county-specific trends, and year FE, which absorb a lot of the variation in the CRP acres. The addition of county FE alone—that is, moving from column 1 to column 2—reduces the CRP elasticity from -0.019 to -0.013. Second, it takes several years before the beneficial effects of land retired under the CRP program start materializing. Finally, given that we control for the acreage of all major crops an increase in CRP acres is due to land that is not cropland (e.g., pastureland, woodland) and for which the use of commercial nitrogen fertilizer is small.

In Table A27, we use nitrogen fertilizer sales as a proxy for nitrogen fertilizer use. The sales data are from Alexander and Smith (1990) and Brakeball and Gronberg (2017) and they are available for all years in our sample excluding 1986 and 2013–2017. As a result, the number of observations drops from 113,372 in Table A26 to 97,093. In our baseline results, corn acreage is the explanatory variable of interest on the premise that acreage is not only the primary driver of nitrogen fertilizer use, but it is also influenced by the farmers' economic and regulatory environment, which will be of immediate interest in a subsequent section that pertains to counterfactual analysis. However, nitrogen fertilizer use is driven not only by acreage but also by the share of crop acres receiving fertilizer, the application rate, and the crop nutrient recovery rate.

If nitrogen fertilizer use has a strong positive effect on nitrogen pollution and is also strongly positively correlated with corn acreage, failing to account for it in our specification would overstate our estimates of the corn acreage effects. Once we include a proxy for fertilizer use, the elasticity of nitrogen pollution with respect to corn acreage in column 8 is 0.13 as opposed to 0.16 but remains significant at 1% level. The CRP elasticity drops from -0.14 in column 7 to -0.10 in column 8 and fails to be significant at conventional levels. We also see that neither fertilizer sales nor their interaction with precipitation appear to be significant at conventional levels (10% or less).

In a recent paper, Paudel and Crago (2020) study the relationship between nitrogen and fertilizer use—to be more precise, their data are for fertilizer sales as discussed above—based on a panel FE regression approach, watershed (HUC8)-level data for 1951–2005, and the CONUS. The authors'

preferred elasticity of nitrogen pollution with respect to fertilizer use is 0.15.

Table A28 shows c-centric and h-centric elasticities controlling for fertilizer use for the CONUS based on the USGS+EPA data that allow a comparison with the estimates in Paudel and Crago. We consider two model specifications. The first is identical to the one in column C8 in tables 4 and 5. In the second, we add fertilizer sales and their interaction with precipitation. The c-centric elasticity of nitrogen pollution with respect to corn acres is 0.16 and significant at 1% whether we control for fertilizer sales or not. In the later case, the elasticity is estimated more precisely. Their h-centric counterparts, which are more comparable to the estimates in Paudel and Crago, are 0.20 when we don't control for fertilizer sales, and 0.25 when we do. Both estimates are significant at 1%. The c-centric elasticities of nitrogen pollution with respect to fertilizer sales are 0.15 (0.07) in the absence (presence) of corn acres in the model, and they are significant at 1%. Their h-centric counterparts, however, fail to be significant at conventional levels.

In Table A29, we show elasticities of 0.21 to 0.27 that are based on the models in column 8 of Tables A30–A32. These elasticities are calculated assuming an increase in contemporaneous (t) and lagged ($t-1,\ldots,t-3$) acres equal to 1 within-county SD (10,000 acres), and they are notably larger than their counterpart of 0.16 for the CONUS using the USGS+EPA data. We use lagged acres in order to capture legacy acreage effects, which seem to be important based on the results of the cross-section regressions using pooled data. We opted for a relatively small number of lags in order to maintain a sufficiently large number of observations, which are now between 71,409 (3 lags) and 75,854 (1 lag) as opposed to 113,272.

Using an average of the corn acres at time t and $t-1$, the elasticity is 0.20 in Table A33, column A8). Using an average of the corn acres at time t, $t-1$ and $t-2$, the elasticity is 0.23 (column B8). Finally, using an average of the corn acres at time t and $t-1$, $t-2$, and $t-3$, the elasticity is also 0.23 (column C8). These estimates are very similar to the ones obtained using different lags of corn acres (and their interactions with precipitation) in Table A29 and may come closer to estimates of long-run effects captured by the pooled cross-section regressions.

In Table A34, we explore the effect of an increase in the corn share of total acres, which are defined as the sum of the acres of major crops plus CRP acres, on nitrogen pollution. In particular, we report the percentage change in nitrogen concentration due to an increase in corn share equal to 1 within-county SD. Since we control for the acreage of other crops we adjust the temperature-related controls following the same approach as in Table A26.

In more detail, in panel A, we control for total acres, which is the sum of acres of major crops and CRP acres. In this case, an increase in the corn share of total acres is due to a displacement of the CRP acres and/or the acres of other major crops. The effect in column A8 is 1.2% and it

is significant at 5%. In panel B, we control for total acres and the acres of other major crops. An increase in the corn share of total acres is now due to the displacement of CRP acres. The effect in column B8 is 0.3% and fails to be significant at 10% or less. Finally, in panel C, we control for total acres and CRP acres, in which case an increase in the corn share of total acres is due to the displacement of the acres of other major crops. The effect in column C8 is 1% and it is significant at 5%. In all, an increase in the corn share of crop acres matters primarily when corn displace other crops as opposed to CRP acres. A plausible explanation for this finding is that acres previously retired under the CRP require less commercial nitrogen fertilizer use when they are turned into cropland.

H-centric analysis. Table 10 summarizes the various robustness checks we performed aggregating the data at the HUC4 level. The main message of Table 14 regarding the statistical significance of the acreage effect is similar to that of Table 13 for the c-centric analysis. The elasticity of nitrogen pollution with respect to corn acreage fails to be statistically significant at conventional levels for models with smaller sample sizes than the one used in our baseline results. These are the models RC14–RC18. Additionally, the elasticity estimates when we include the additional control variables fall inside the 95% CI of their counterparts when we exclude them. When they are significant (at 5% level), the estimated elasticities are between 0.13 for model RC2 and 0.22 for model RC9 that control for regional income, fossil fuel consumption, and NO_x emissions. The largest elasticity in the presence of additional controls is about 1.7 times as large as its baseline counterpart (0.13) we report in column C8 of Table 5 and falls outside its 95% CI.

With regards to time variation in the estimated effects, the range of the decade-specific elasticities is 0.13 for the 1970s to 0.20 for the 1990s, which is the only elasticity falling outside the 95% CI of their baseline counterpart (Table 16, panel B).

In terms of spatial variation, the elasticity for the top producing states (Top) is about 0.17%, significant at 1% level, and falls inside the 95% CI of its baseline counterpart (Table 17, panel B). Similar to the c-centric analysis, the effect for the remaining states (Other) is both practically and statistically indistinguishable from zero.

In panel B of Table A15, where we explore spatial variation in elasticity estimates across water regions, there are no significant elasticities at conventional levels. In panel B of Table A16, where we also explore spatial variation across water regions, the only significant elasticities are for the Tennessee and Upper Mississippi regions (about 2.1 in both cases), which are larger by more than an order of magnitude of their baseline counterpart (0.13) and significant at 6% and 10%, respectively.

With a flexible specification in precipitation, we see elasticities of about 0.10 for precipitation val-

ues that exceed their median (Figure 3, panel B). Similar to the c-centric analysis, these elasticities are significant at 5% level. Moreover, they are essentially identical to their baseline counterpart.

For the h-centric analysis with USGS-NWIS data that pertain to the CONUS, the observations are 27,228 as opposed to 17,943 (Table A23, panel B). The elasticity is 0.07 but it is indistinguishable from its baseline counterpart of about 0.13 at 5% level (column B8).

M-centric analysis. Table 11 summarizes the various robustness checks we performed aggregating the data at the monitoring-site level. We generally see smaller elasticities compared to the ones for the c- and h-centric analyses, which are not statistically significant for smaller sample sizes. This is the case for models RC7–RC12, and models RC14–RC18 (Table 15). Moreover, the elasticity estimates when including the additional control variables are statistically indistinguishable from their counterpart when excluding them. When they are significant, the elasticities are between 0.08 for model RC4 in which we control for employment and fossil fuel consumption and 0.11 in the case of model RC20 that includes several controls (corn yield, cattle in feedlots, fossil fuel consumption, and regional income). The estimated elasticities in the presence of additional controls are similar to their baseline counterpart (0.08) reported in column C8 of Table 6 and fall inside its 95% CI.

Regarding temporally heterogeneous effects, the decade-specific elasticities are between zero (1970s) and 0.15 for the 1990s, which is almost twice as large as its baseline analog and lies outside its 95% CI (Table 16, panel C).

In terms of spatial heterogeneity in the effects, the elasticity for the top producing states (Top) is 0.10, significant at 1%, and falls inside the 95% CI of its baseline counterpart (Table 17, panel C). As it is the case for the c- and h-centric analyses, the effect for the remaining states (Other) is practically and statistically indistinguishable from zero.

In panel C of Table A15, where we explore variation in our elasticity estimates by water region, the m-centric elasticities are essentially zero with two exceptions: the one for the Upper Mississippi Region (0.10), and the one for the Lower Mississippi Region (0.05). These two elasticities are significant at 3% but they are statistically indistinguishable from their baseline counterpart. Their magnitudes are also consistent with the fact that more corn is grown in the Upper than in the Lower Mississippi Region. In panel C of Table A16, where we also explore variation in our elasticity estimates by water region, the elasticities for the Ohio Region (0.11) and the Upper Mississippi Region (0.24) are the only ones that are significant at conventional levels, namely 10% and 2%. The elasticity for the Upper Mississippi Region is about 3 times as large as its baseline counterpart. It also lies outside its 95% CI.

The flexible specification in precipitation implies elasticities between 0.04% and 0.09% that are significant at 5% for precipitation values exceeding their median (Figure 3, panel C). These elasticity estimates fall inside the 95% CI of their baseline analog.

For the m-centric analysis with USGS-NWIS data that pertain to the CONUS, the observations are 85,340 as opposed to 56,466 (Table A23, panel C). The elasticity in column C8 is 0.07 and it is indistinguishable from its baseline counterpart of 0.08 at 5% level.

Analyses that pertain to all three levels of data aggregation

Streamflow. Table 18 shows the results for the robustness checks accounting for streamflow. In the case of the c-centric analysis (panel A), the elasticity estimate that accounts for the water flow and is based on pollution measured in downstream monitors (0.10) is statistically indistinguishable from its baseline counterpart (0.11) despite the substantially smaller sample size (33,335 obs. as opposed to 64,121 obs). In the case of the m-centric elasticities (panel B), the acreage elasticity that accounts for water flow and is based on total acreage for upstream counties (0.19) is about 2.4 times as large as its baseline analog of 0.08. It also lies outside its 95% CI.

Runoff. Table 19 shows the results for the robustness checks in which we interact acres planted with runoff as opposed to precipitation. The elasticity estimates are based on the 75% percentile of the runoff empirical distribution. For all three analyses, the acreage elasticities based on the runoff are highly comparable to the their counterparts based on precipitation and fall inside their 95% CIs.

Censoring. Table 20 pertains to robustness checks regarding our handling of observations with values lower than the reporting limits, namely, setting them equal to the reporting limits or equal to zero. In the case of the c-centric analysis, the two alternative elasticity estimates in panel A are 0.14 and 0.13 and fall inside the 95% CI of their baseline counterpart of 0.12. In the case of the h-centric analysis (panel B), although the two alternative acreage elasticities are larger (about 0.16) than their baseline counterpart (0.13), they fall inside its 95% CI. Finally, in the case of the m-centric analysis in panel C, the two alternative acreage elasticities are close to 0.10 exceeding than their baseline counterpart of 0.08. However, they fall inside its 95% CI.

Radii. We see smaller elasticities for both (c- and m-centric) levels of aggregation as we expand the radii, especially in the case of the m-centric analysis (Table 21). The c-centric elasticities in panel A drop to 0.10 (100 miles) and 0.07 (200 miles) from 0.12 but they are more precise than their baseline counterpart, which is expected given an increase in the number of monitoring sites used to track nitrogen pollution. The m-centric elasticities in panel B are 0.02 (100 miles) and 0.005 (200 miles) and they are notably smaller than their baseline counterpart (0.08). Although

the former is statistically significant at 5% level, the latter fails to be significant at conventional levels.

Additional filters. When we limit our nitrogen pollution data to those for routine samples and surface water for lakes and streams as in Keiser and Shapiro (2018), the corn acreage elasticity is essentially identical to its baseline counterpart (0.12) and is significant at 1% level in the case of the c-centric analysis (Table 22, panel A). The h- and m-centric elasticities—in panels B and C—are also identical to their baseline counterparts and significant at 1% level with values of 0.13 and 0.08, respectively.

Seasonality. Table 23 shows corn acreage elasticities of nitrogen pollution when we measure average nitrogen concentration during the following time windows within a year: January–June, March–August, April–September, and May–October. Recall that our baseline elasticity estimates are based on average annual (January–December) nitrogen concentrations. Although we keep fixed the assumed increase in acres, we allow for different average concentrations, and percentiles of precipitation for each of the time windows considered. In general, we see smaller elasticities for all three levels of aggregation for time windows different than January–December, which is used in our baseline results. The c-centric elasticities in panel A are 0.06 (March–August) to 0.08 (May–October) and they are all significant at 5.3% level. The h-centric elasticities in panel B are all around 0.07. The one for May–October (0.07) is significant at 11% level while the remaining ones are significant at 6.5% level. The m-centric elasticities in panel C are 0.09 (March-August) to 0.12 (April–September). The one for January–June (0.05) is significant at 10% while the remaining ones are significant at 5% level.

Inference. Having performed inference for our baseline estimates using standard errors clustered by HUC4, we also examined the implications for the statistical significance of our estimates clustering our standard errors by HUC2, year, HUC2-year combinations, and HUC4-year combinations (Table 24). In all, our baseline c- and h-centric elasticity estimates remain significant at 1% level when we consider any of the 4 alternative clustering schemes. The baseline m-centric elasticity estimate is significant at 5% when we cluster our standard errors by HUC2, year, or HUC2-year combinations. It is significant at 2% when we cluster our standard errors by HUC4-year combinations.

8.3 Cross-Section Regressions

Eliminate acres' interaction with precipitation: Our baseline elasticity estimates are based on an interaction of corn acres with precipitation. In this sensitivity check, we eliminate such inter-

action and re-estimate the elasticities (Figure A9-Figure A11). In general, the elimination of the interaction of corn acres with precipitation entails elasticities that are much smaller for all three levels of data aggregation. Pooling the data across years (1975–2017), the c-centric elasticities are 0.10–0.14 as opposed to 0.17–0.27 (in the presence of the interaction) depending on the specification. The h-centric elasticities are 0.10–0.24 as opposed to 0.30–0.36. Finally, the m-centric elasticities are 0.24–0.32 as opposed to 0.32–0.46.

Streamflow: This analysis is motivated by the robustness check related to streamflow for the panel FE regressions, where we see similar elasticities for the c-centric results despite the large drop in the number of observations, and elasticities that are almost twice as large for the m-centric results despite the small drop in the number of observations. Adjusting for streamflow does not seem to make a material difference for the c-centric elasticities that are 0.14–0.24 as opposed to 0.15–0.25 (Figure A12). The adjustment for streamflow makes a difference for the m-centric elasticities that are 0.07–0.11 as opposed to 0.36–0.41 (Figure A13). According to panel A in Table A17, the c-centric elasticities are 0.14–0.19, as opposed to 0.17–0.26 (Table 8, panel A) using the pooled data and controlling for spatial FE. The m-centric elasticities in panel B of Table A17 are 0.39–0.54 as opposed to 0.37–0.45 (Table 8, panel C).

Average acres: This robustness check is relevant for the m-centric results only for which we use average (as opposed to total) acres within a 50-mile radius from the sites' locations. Using average as opposed to total acres, the m-centric elasticities are 0.40–0.54 as opposed to 0.36–0.41 (Table A18).

Extended geographic scope plus additional data and specifications. In a series of robustness checks that resemble those for the c-centric analysis in the panel FE regressions discussed earlier, we use additional data (USGS+EPA as opposed to the USGS-NWIS) and expand the geographic scope of our analysis from the EAST-100 to the CONUS. These additional data allow us to alleviate some of the concerns regarding the substantial variation in the number of observations used to obtain the year-specific elasticity estimates. For example, using data for all years (1975–2017), we have 3,029 counties (Table A19). Moreover, we consider several additional controls to mitigate potential concerns for confounding factors (e.g., GDP, per-capita income, population) that introduce a bias in our baseline elasticity estimates.

Table A20 provides pooled and year-specific (for selected years) elasticity estimates for 8 specifications for which detailed estimates are available in Figure A14–Figure A22. The pooled elasticity estimates are 0.08–0.31. The lower end of the estimates is for specification 4 (SPEC4) in panel D (with HUC4 FE), which controls for weather and GDP. The upper end of the estimates is for specification 2 in panel A (no spatial FE) in which the only two explanatory variables are corn acres and

their interaction with precipitation. Even for the richest specification (9) in panel D (with HUC4 FE), which controls for weather, CRP acres, population, GDP, and land area, the pooled—and the vast majority of the year-specific—elasticity estimates are significant at 1% level with values in the range 0.09–0.25. Recall that the baseline year-specific elasticity estimates are 0.10–0.44 using USGS-NWIS data for the EAST-100 in the presence of HUC4 FE (Table 8).

We also produced a set of elasticity estimates based on *cropland* acres as opposed to corn acres for the CONUS using the USGS+EPA data and a series of controls. This analysis is c-centric only and it is limited to the Census-of-Agriculture (CoA) years. The CoA is our source of cropland acres. Moreover, we adjust our weather-related controls such that we use total annual precipitation and its square and the following annual degree days: 0C°, 5C°, 8C°, 10C°, 12C°, 20C°, 25C°, 29C°, 30C°, 31C°, 32C°, 33C°, 34C°. Hence, we use 2 as opposed to 24 precipitation-related controls and a much richer set of variables capturing degree days compared to the baseline models. Finally, the elasticity estimates are based on an increase in cropland acres equal to 1 within-county SD and precipitation equal to the 75% percentile of its empirical distribution. Similar to prior calculations, we calculate these elasticities using mean cropland acres and mean nitrogen concentration and report them in Table A22, as well as in Figure A23–Figure A32.

In all, the estimates pertain to the 48 CONUS states, 18 HUC2s and 205 HUC4s. There is still variation in the number of observations for the various CoA years despite the use of the USGS+EPA data (Table A21). When we pool observations across all CoA years, we have observations for approximately 3,000 counties. When we use data for a particular CoA year, the number of observations is between 2,028 for 1997 and 2,650 for 1978 depending on the specification. The range of the pooled elasticity estimates is 0.08–0.68 depending on the set of spatial FE and the specification when we focus on estimates that are significant at 5% level. The range of their year-specific analogs is very similar (0.08–0.73).

A notable observation regarding these elasticity estimates is that additional controls (e.g., CRP acres, population, GDP, per-capita income) have a *de minimis* effect on their magnitude once we control for weather. The only exception is when we control for corn acres. For example, moving from specification 9, in which we control for CRP acres, population, GDP, and land area to specification 10, in which we *also* control for corn acres, the pooled cropland elasticity drops from 0.34 to 0.08 in panel D (with HUC4 FE). The drop in the magnitude of the cropland elasticities once we control for corn acres in the presence of HUC4 FE is also substantial in the presence of the other spatial FE considered.

9 Integrated Assessment Exercises

Preamble. The main message of the empirical analyses presented in the previous sections is that corn acreage is a major driver of nitrogen pollution. What follows is a medley of integrated-assessment type of exercises that differ in their level of complexity and the questions they can address. The common thread in these exercises is that they utilize the relationship between corn acreage and nitrogen pollution, as well as past modeling results and approaches in the literature resembling a benefit-transfer approach. First, we link nutrient loads to the areal extent of the hypoxic zone in the Gulf and we discuss mitigation costs. Second, we explore the implications of agricultural policies for nitrogen pollution using the example of the ethanol boom triggered by the renewable fuel standard (RFS) program aiming to reduce greenhouse gas emissions and expand the renewable fuels sector while reducing reliance on imported oil.[36] Third, we discuss mitigation practices and costs using the examples of land retirement similar to the one of the USDA CRP program, riparian buffers, and wetlands. Finally, we perform a fully-fledged welfare analysis for a 20% reduction in corn acreage, the magnitude of which is similar (but of the opposite sign) to the one shown in the USDA HTR data for 2006–2007.

Nitrogen load and the size of the hypoxic zone. Using data for spring (91-day May–June period) nitrogen flux (load) from Murphy et al. (2013) and the quadratic regression equation in Whittaker et al. (2015), we estimate that a 25% increase in the spring nitrogen flux of the Mississippi river at St. Francisville, Louisiana from its mean level of 361,139 metric tons implies an increase in the areal extent of the hypoxic zone equal to 768 square kilometers (Table 25).[37] During the period 1982–2010 used to estimate the relationship between the areal extent of the hypoxic zone in the Gulf and the nitrogen flux, the average areal extent of the zone is close to 13,100 square kilometers. Hence, the implied increase is 6% when it is benchmarked against the average extent of the zone. Therefore, the elasticity of the average areal extent of the hypoxic zone with respect to the spring nitrogen flux of the Mississippi river at St. Francisville, Louisiana is $6/25 \approx 0.2$.

Our elasticity estimate of about 0.2 is smaller than–albeit not directly comparable to—others in the literature. Kling et al. (2014) estimate a regression model to study the relationship between the areal extent of the hypoxic zone and May nitrate-nitrogen (see their Table 5). According to their estimates, a 1% increase in May nitrate-nitrogen implies an increase of about 146.5 square kilometers. When we benchmark this increase in the areal extent of the hypoxic zone against its average of about 13,500 square kilometers, the implied increase is about 1% and the elasticity is 1.

[36] For the less familiar reader, the program was authorized under the Energy Policy Act of 2005 and expanded under the Energy Independence and Security Act of 2007.

[37] The same table includes information for additional outlets along the Mississippi river, which also account for major tributaries such as the Missouri and Ohio rivers.

Taylor and Heal (2021) find that a 1,000-ton increase in upstream nitrogen adds 4 square kilometers to the hypoxic zone in the Gulf. The average areal extent of the hypoxic zone during the period they analyze (1984-2019) is 14,000 square kilometers. In log form, a 1% increase in nitrogen is associated with about a 6% increase in the hypoxic zone—see their Table 5, which reports the results from a time-series regression of the summer hypoxic zone areal extent on nitrogen measured in 1,000 tons of farm use. Hence, the implied elasticity of the areal extent of the hypoxic zone with respect to upstream nitrogen is 6.

Given that flux is equal to concentration times streamflow, an increase in nitrogen concentration of 1% implies a 1% in the spring flux of the Mississippi river at St. Francisville, holding streamflow constant. Assuming an elasticity of nitrogen concentration with respect to corn acres equal to 0.1, a 1% increase in the spring flux is consistent with a 10% increase in corn acreage. In other words, a 10% increase in corn acres implies a 0.2% increase in the areal extent of the hypoxic zone, which translates to an increase of approximately 31 square kilometers.

Using the data from Figure 2 in Rabotyagov et al. (2014a) that were kindly provided to us by the authors, we estimated total, marginal, and average cost curves associated with the reduction in the size of the Gulf hypoxia (Figure 8). Based on our estimated average cost curve, the average cost per square kilometer of reduction when the reduction is less than approximately 1,700 square kilometers is $290,909. Therefore, the total cost associated with an increase of 31 square kilometers in the areal extent of the hypoxic zone is equal to $\$290{,}909 \times 31 = \$9{,}185{,}280$.

The ethanol boom and nitrogen pollution. Hendricks et al. (2014) assume that every billion gallons of ethanol increases the price of corn by 5.5%. Using the nitrogen loss elasticity of 0.05 in column (1) of their Table 5, a 5.5% increase in the price of corn and a 3.5% increase in the price of soybeans implies a 0.23% increase in nitrogen loss. Based on the regression in equation 13 of Obenour et al. (2012) that links the areal extent of the hypoxic zone in the Gulf to the aggregated bottom-water dissolved oxygen depletion due to salinity and temperature stratification, and May nitrogen concentration, a 0.23% increase in nitrogen concentration translates to an increase of 25 square miles (64.7 square kilometers) in the areal extent of the hypoxic zone. An inherent assumption in this analysis is the reduction in nitrogen delivery to the Gulf is proportional to the EoF nitrogen losses. This is justified on the basis of the relatively small fraction of in-stream removal for tile-drained watersheds with nutrient concentration during periods of high flows.

Using a supply elasticity of of 0.196 from our previous work in Metaxoglou and Smith (2020) that is discussed in more detail below, a 5.5% increase in the price of corn for every billion gallons of ethanol implies a 1.08% increase in corn acres. Assuming an elasticity of nitrogen concentration with respect to corn acres equal to 0.1, an additional billion gallons of ethanol implies an

increase in nitrogen concentration equal to $1.08 \times 0.1 \approx 0.11\%$. This increase in nitrogen concentration translates to an increase in the areal extent of the hypoxic zone equal to approximately $(0.11/0.23) \times 25 \approx 11.7$ square miles (30.5 square kilometers).

Carter et al. (2016) estimate that the 2007 expansion of the RFS (an additional 5.5 billion gallons of ethanol) increased the price of corn by 34% leading to a 6.7% increase in corn acres based on the supply elasticity of 0.196, which translates to a $6.7\% \times 0.1 = 0.67\%$ increase in nitrogen concentration. The implied increase in the areal extent of the hypoxic zone is $(0.67/0.23) \times 25 \approx$ 72.4 square miles (188.3 square kilometers). During 1985–2007, the average size of the hypoxic zone is about 14,000 square kilometers. Hence, when evaluated at the average size of 14,000 square kilometers, the 0.67% increase in nitrogen concentration implies a 1.35% increase in the areal extend of the hypoxic zone. Therefore, the elasticity of the areal extent of the hypoxic zone with respect to nitrogen concentration is about $1.35/0.67 \approx 2$.

Land retirement. Panel A in Figure 9 shows total cost curves for CRP acres by year for upstream counties within 100 miles from the USGS-05587455 monitoring site in Grafton, IL, which is located in the Upper Middle Mississippi River (see the schema in Figure 7). We constructed these total cost curves via linear approximation by sorting CRP acres in ascending order of the average CRP payment per acre using annual county-level data on CRP acres and payments from the USDA. Table 26 shows that $12.48 million dollars ($2016) of CRP payments secured 120,000 CRP acres, which is equal to 20% of corn acres planted in 2000.

Maintaining the elasticity of nitrogen concentration with respect to corn acres of 0.1, the implied increase in concentration is $0.1 \times 20\% = 2\%$ and the annual flux in the outlet of the Mississippi river in Grafton, IL increases from 238,000 to 242,717 metric tons if the CRP acres were converted into corn acres. The cost of nitrogen reduction achieved via the CRP acres is about $2,650 per ton, which is much lower than the damage cost of of $15,840 per metric ton of nitrogen from Sobota et al. (2015). Equivalently, the cost of reduction is about $1.2 per pound of nitrogen, which is substantially lower than the cost of permits in the Ohio River Basin Water Quality Program currently trading between $12 and $14 per pound of nitrogen.[38] A closer look at the table shows that the cost of nitrogen reduction in $2016 is 750–4,690 per ton depending on the year. The same table also provides calculations of farmer producer surplus following the same approach as in panel B of Figure 9, which is equal to $4.19 million in 2000.[39] Of course, these are back-of-the envelope calculations as they don't account for any partial-equilibrium effects that the additional

[38] For more information on the credits, see here.

[39] The calculations here are in the spirit of Figure 2 in Wu and Tanaka (2005), where a reduction in nitrogen concentrations requires A_c acres adopting the conservation practice with an associated payment P_c. The area under the supply curve between A_0 and A_c is the social cost of achieving the targeted level of reduction in concentrations. The difference between the total government payment $P_c \times A_c$ and the social cost is the producer surplus.

corn acreage may have in the agricultural sector, as well as any benefits to the consumers associated with the water quality. Moreover, we assume that nitrogen reductions take effect immediately.

Riparian Buffers. Farmers may install riparian buffers and wetlands to mitigate nitrogen pollution. In this case, instead of managing nutrients on the field to reduce nutrient loads to surface waters from cropland, farmers can intercept nutrient-laden runoff and filter out the nutrients before they reach surface waters. For example, wetlands can act as buffers, trapping nitrogen contained in runoff and "processing" it through plant uptake or denitrification to the atmosphere.[40] According to CENR (2000), the filtering capacity of riparian buffers is 4 grams of nitrogen per square meter per year, which translates into $4{,}046.86 \times 4/453.592 = 35.7$ pounds per acre per year. This is roughly equal to the EoF nitrogen loss from cropland in the CEAP studies assuming the 2003–2006 conservation practices are in place. The filtering capacity of wetlands is 15 grams of nitrogen per square meter per year, which translates into $4{,}046.86 \times 15/453.592 = 133.8$ pounds per acre per year.

According to the scenarios for the NRCS conservation practice 391 (Riparian Forest Buffer) in FY2021, the cost per acre associated with riparian forest buffers ranges from $322 (trees and/or shrubs planted through direct broadcast seeding, incorporated with light tillage in Kansas) to $4,879 (tree and/or shrub poles and live stakes (whips) available from a nearby off-site location are planted by hand in Minnesota); see Table 27. In the case of scenario 1 (trees or shrubs planted through direct seeding), the cost is $1,143–$1,258. For scenario 2 (machine-planted bare-root shrubs and trees at spacings recommended in a tree/shrub planting plan or machine planted bare-root shrubs, evergreen, and deciduous trees in rows), the cost is $1,285–$1,712.

Based on the NRCS practice documentation, scenario 1 entails establishing a buffer of trees and/or shrubs to restore riparian plant communities and associated benefits.[41] The payment includes tree seed, equipment and labor to seed, and foregone income for the land taken out of crop production to install the riparian buffer. Scenario 2 entails establishing a buffer of trees and shrubs into a suitably prepared site to restore riparian plant communities and associated benefits. The payment includes trees, equipment and labor to plant, and foregone income for the land taken out of crop production to install the riparian buffer. In both scenarios, the buffer is located adjacent to and up-gradient from a watercourse or water body and extends the minimum required width. Site preparation is implemented through associated practice 490 (tree/shrub Site Preparation). Additional associated practices may include practice 315 (herbaceous weed control) 660 (tree/shrub pruning), and 484 (mulching). The cost per acre of scenarios for NRCS practice 490 (tree/shrub preparation) is $58–$595 depending on the scenario and state. The cost of scenarios for practice 315 is $16-$365. The

[40] Wetlands can provide additional environmental benefits, including habitat for wildlife.

[41] Here, we focus on scenarios 1 and 2.

cost of scenarios for practice 660 is \$181–\$404. Finally, the cost of for NRCS practice 484 is \$65–\$6,389.

Wetlands. The construction of wetlands according to the NRCS practice 656 entails costs roughly in the range \$5,000–\$14,000 per acre in Table 28 noting that there are several associated practices with practice 656.[42] The lower end of these costs is related to earthwork only, namely, basic earthwork needed to to construct a wetland to treat storm water runoff or outflow from a subsurface drainage system high in nutrients with hydrophytic vegetation established through natural regeneration in Iowa and Illinois. The higher end of the costs pertains to scenarios that includes the basic earthwork and vegetation needed to construct a wetland at a medium site (0.5 acres or less) in Kansas and Nebraska. An interesting observation is the presence of scale economies in the construction of wetlands in the plains (Kansas and Nebraska). In particular, sites smaller than 0.5 acres cost about \$14,000/acre, sites between 0.5 and 1.0 acre cost cost about 9,700/acre, while larger sites (exceeding 1 acre) cost 7,500 per acre. Moreover, a medium site (0.1–0.5 acres) in Minnesota costs 5,400, which is substantially lower than the cost of a comparable site (0.5 acres or less) in the plains.

Fully-fledged welfare analysis for a reduction in corn acreage. The exercise that follows is in the spirit of the REAP-based analysis of the USDA CEAP in Marshall et al. (2018) and the analysis in Whittaker et al. (2015). In particular, Table 29 contains estimates of the welfare effects associated with a decrease in corn acreage of 20% following our approach in Metaxoglou and Smith (2020).

A key component of our welfare analysis are demand and supply elasticities for corn, which we obtain using a modified version of Roberts and Schlenker (2013). Roberts and Schlenker estimate the global demand and supply elasticities for a calorie-weighted index of corn, wheat, soybeans and rice. Using their publicly available code and data from the American Economic Review website, we limit their sample to corn and soybeans for the U.S. only and estimate the same models as in their table 1. Thus, we obtain supply and demand elasticities for an index of U.S. corn and soybeans. We use the instrumental variables estimates for the model with four knots in the cubic spline trend and obtained a supply elasticity $\eta_s = 0.196$ and a demand elasticity $\eta_d = -0.295$. With the demand and supply elasticity estimates in hand, we perform a welfare analysis assuming constant elasticity demand and supply curves of the form $Q = a_d P^{\eta_d}$ and $Q = a_s P^{\eta_s}$. We calibrate

[42] In the case of scenario 01 for Iowa, associated practices include the following: structure for water control (587); Sediment Basin (350); Dike (356); Pond Sealing or Lining, Compacted Soil Treatment (520); Pond Sealing or Lining, Geomembrane or Geosynthetic Clay Liner (521); Fence (382); Grade Stabilization Structure (410); Pumping Plant (533); Waste Transfer (634); Critical Area Planting (342); Filter Strip (393). In the case of scenario 01 for Kansas and Nebraska, associated practices include: Structure for Water Control (587); Sediment Basin (350); Dike (356); Pond Sealing or Lining, Compacted Clay Treatment (521D); Pond Sealing or Lining, Flexible Membrane (521A); Fence (382); Grade Stabilization Structure (410); Pumping Plant (533); Waste Transfer (634).

the values of a_d and a_s using the 2014–2016 U.S. prices and quantities (bushels) shown in Table 29. Next, we calculate the counterfactual prices and quantities that would have been realized in 2014–2016 following the decrease in acreage.

According the USDA HTR data, our assumed decrease of 20% in acreage is roughly equal (and of the opposite sign) to the increase in all corn planted acres between 2006 and 2007, which coincides with the beginning of the ethanol boom. As Table 29 shows, there is a drop in total surplus equal to $28.36 billion per year following the assumed decrease in acreage. Roughly 70% of the loss in total surplus is due to the loss in consumer surplus ($19.68 billion), while the remaining 30% is attributed to the loss in producer surplus ($8.68 billion). The former is a loss attributed to consumers of U.S. corn while the latter is a loss attributed to U.S. farmers. Moreover, these calculations exclude the gains from improved environmental outcomes because of the reduction in nitrogen pollution attributed to the reduced acreage.[43]

In order to evaluate the gains due to reduced nitrogen pollution, we repeat an earlier calculation that utilizes the damage costs of $15.84 per kilogram of nitrogen in ($2008) from Table 1 in Sobota et al. (2015). Based on our estimates for the elasticity of nitrogen concentration with respect to corn acres, the assumed decrease in acreage of 20% implies a decrease in nitrogen concentration of 2%. The 2% decease in the average level of nitrogen concentration of about 3.06 mg/L in our sample during 2014–2016 (these are the years used in our welfare calculations), entails 43,967 fewer metric tons of nitrogen in the Gulf. This is the decrease in nitrogen flux (concentration $\times$ streamflow) implied by a decrease in acres planted equal to 1 within-county SD coupled with the average streamflow (22,800 cubic meters per second) of the Mississippi River in the Gulf during 2014–2016. Using the damage cost of $15.84 per kilogram, this decrease in concentration implies a gain of $696.4 million per year. Using the GDP deflator, the implied gain is about 765.4 million in $2014.

10 Conclusion

We the study the relationship between water nutrient pollution and U.S. agriculture using data between the early 1970s and late 2010s. We document a strong causal positive effect of corn acreage on nitrogen concentration in the country's water bodies using alternative empirical approaches and different data aggregations. We find that a 10% increase in corn acres planted increase nitrogen concentration in water by up to 1% depending on the empirical approach and data-aggregation scheme used to estimate the effects. The 1% increase in the average level of nitrogen concentra-

[43] The same calculations are repeated for alternative scenarios regarding acreage reductions.

tion in the Midwest coupled with the average streamflow of the Mississippi river at the Gulf of Mexico during this period' and a damage cost of about $16 per ton of nitrogen, implies external cost of $800 million. We also perform a series of additional integrated-assessment type of exercise based on the relationship between nitrogen pollution and corn acreage identified in the data.

As a final word, in our thorough empirical analysis, precipitation has been shown to be a very important factor for the magnitude of the effect of corn acreage on nitrogen pollution. Sinha et al. (2017) show that climate change-induced precipitation changes alone will increase substantially riverine total nitrogen loading within the CONUS by the end of the century for their business-as-usual scenario. The impacts, driven by projected increases in both total and extreme precipitation, will be especially strong for the Northeast and the Corn Belt. Our analytical framework is particularly suitable for evaluating effects of the sort discussed in Sinha et al. and could be part of research agenda worth pursuing.

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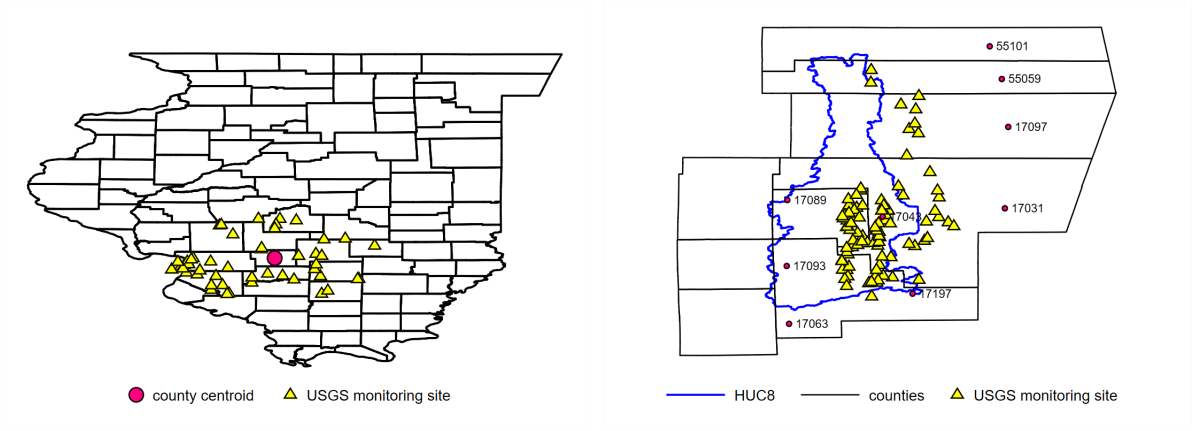
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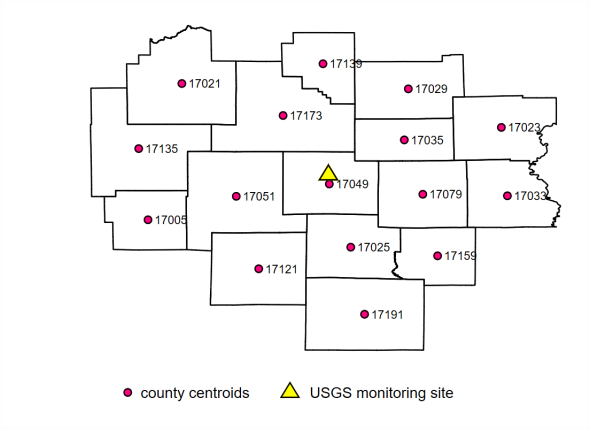
11 Figures

Figure 1. Alternative approaches used to study the relationship between nitrogen pollution and corn acres planted



A. county (c-centric)

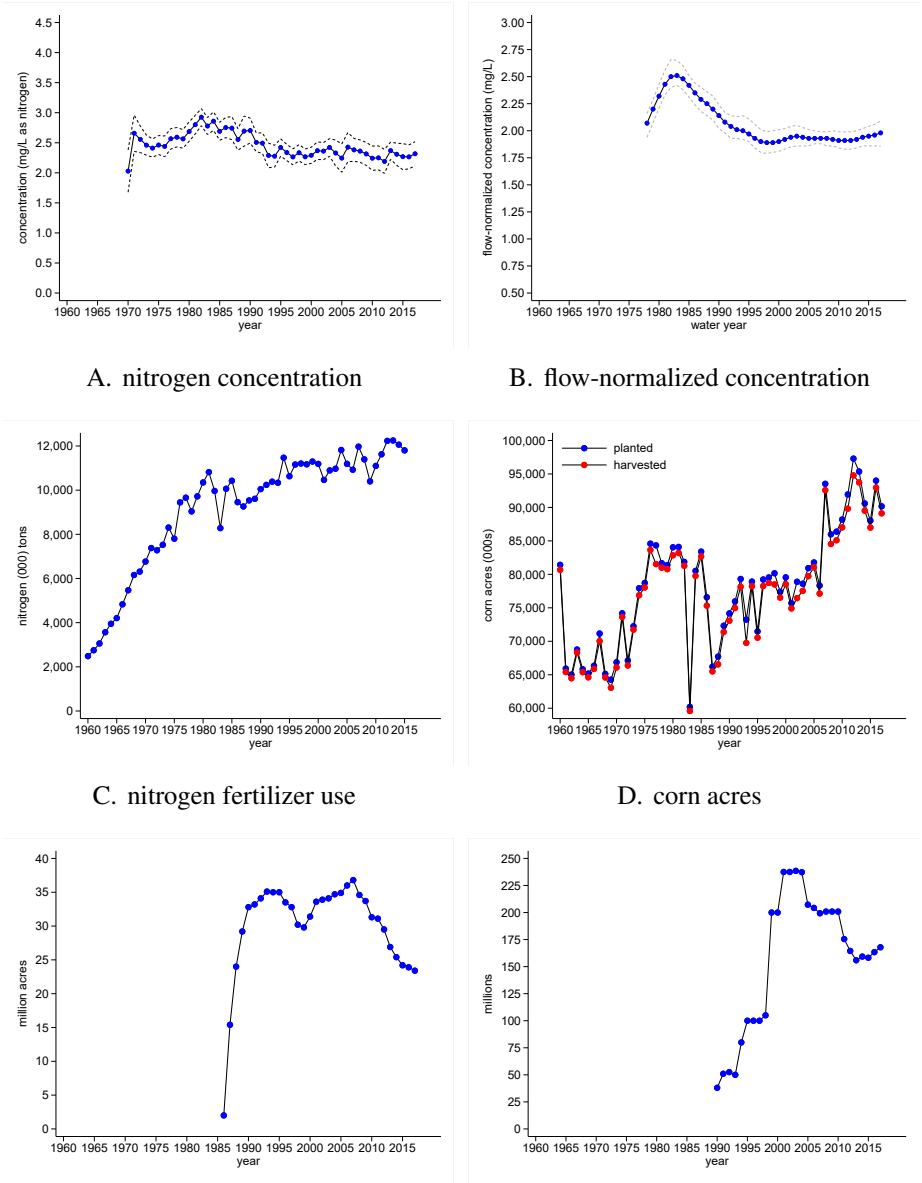
B. hydrologic unit (h-centric)



C. monitoring site (m-centric)

Note: The figure provides a graphical illustration of the three alternative approaches we use to study the relationship between nitrogen pollution and acres planted. Panel A shows the centroid of `Bond County` in Illinois along with USGS monitoring sites within a 50-mile radius from the county's centroid. Panel B shows the 8-digit `Des Plaines` hydrologic unit that stretches in parts of Illinois and Wisconsin along with the USGS monitoring sites and the counties that lie in the hydrologic unit. Panel C shows the `USGS-03378635` monitoring site in Little Wabash River near Effingham, Illinois, along with the counties whose centroids lie within a 50-mile radius from the site. For additional details, see Section 3.

Figure 2. Nitrogen pollution and related factors



A. nitrogen concentration

B. flow-normalized concentration

C. nitrogen fertilizer use

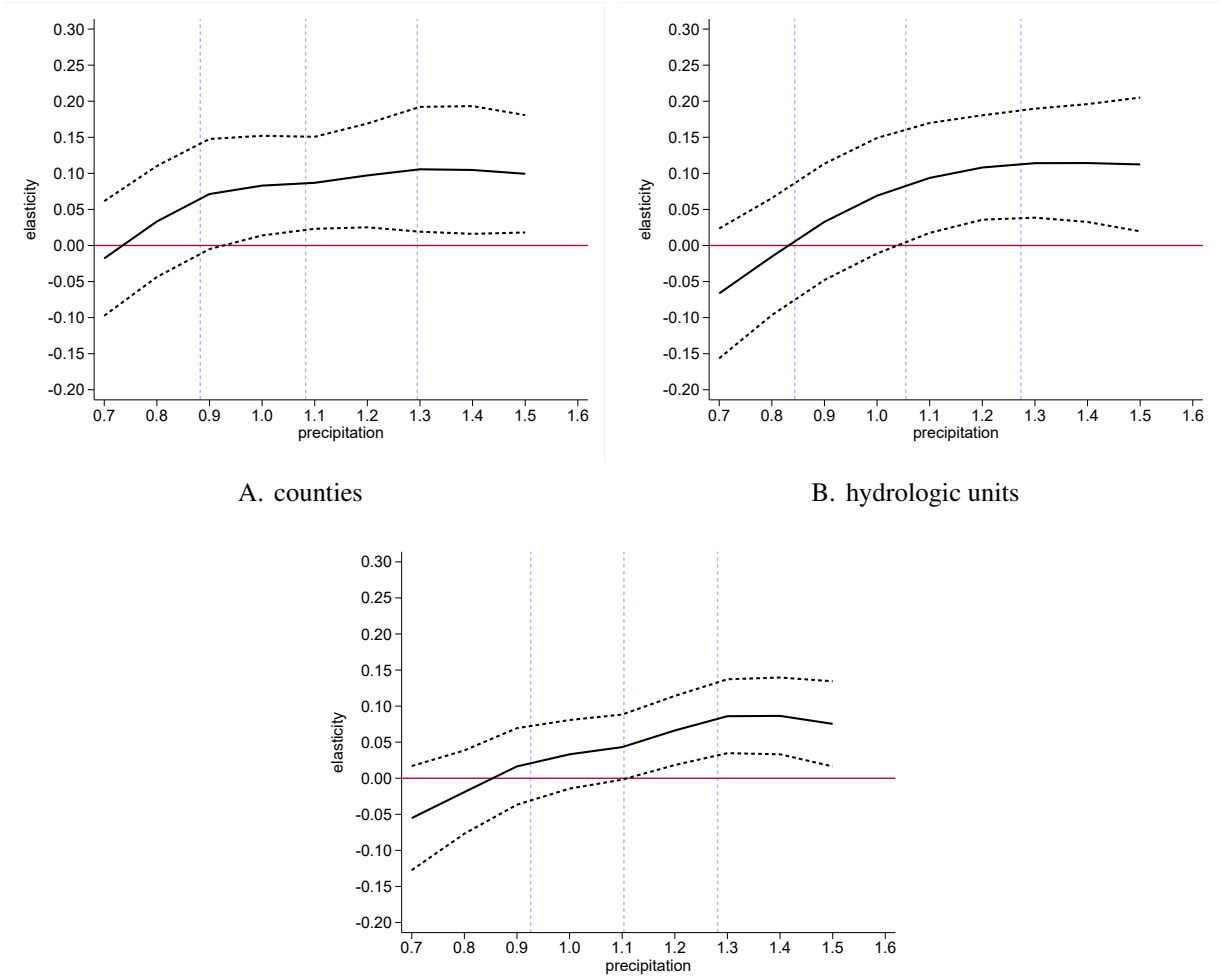
D. corn acres

E. CRP acres

F. EPA CWA 319 grants

Note: In panel A, we regress the average daily nitrogen concentration at the monitoring-site level for the CONUS on site FE, year FE, day, day squared, day cubed, month, month squared, month cubed, and report the estimated year FE. The 95% confidence intervals shown are constructed using standard errors clustered by HUC8. Additional details regarding the flow-normalized total nitrogen concentration in the Gulf in panel B are available in the following USGS link. In panel C, we show U.S. consumption of nitrogen from Table 1 in the USDA ERS report on fertilizer use and price. In panel D, we show planted and harvested corn acres from the USDA Historical Track Records. In panel E, we show cumulative enrollment in the USDA CRP from USDA (2020). In panel F, we show EPA CWA 319 grants based on information in this link. For additional details, see Section 6.

Figure 3. Flexible precipitation modeling in panel FE regressions



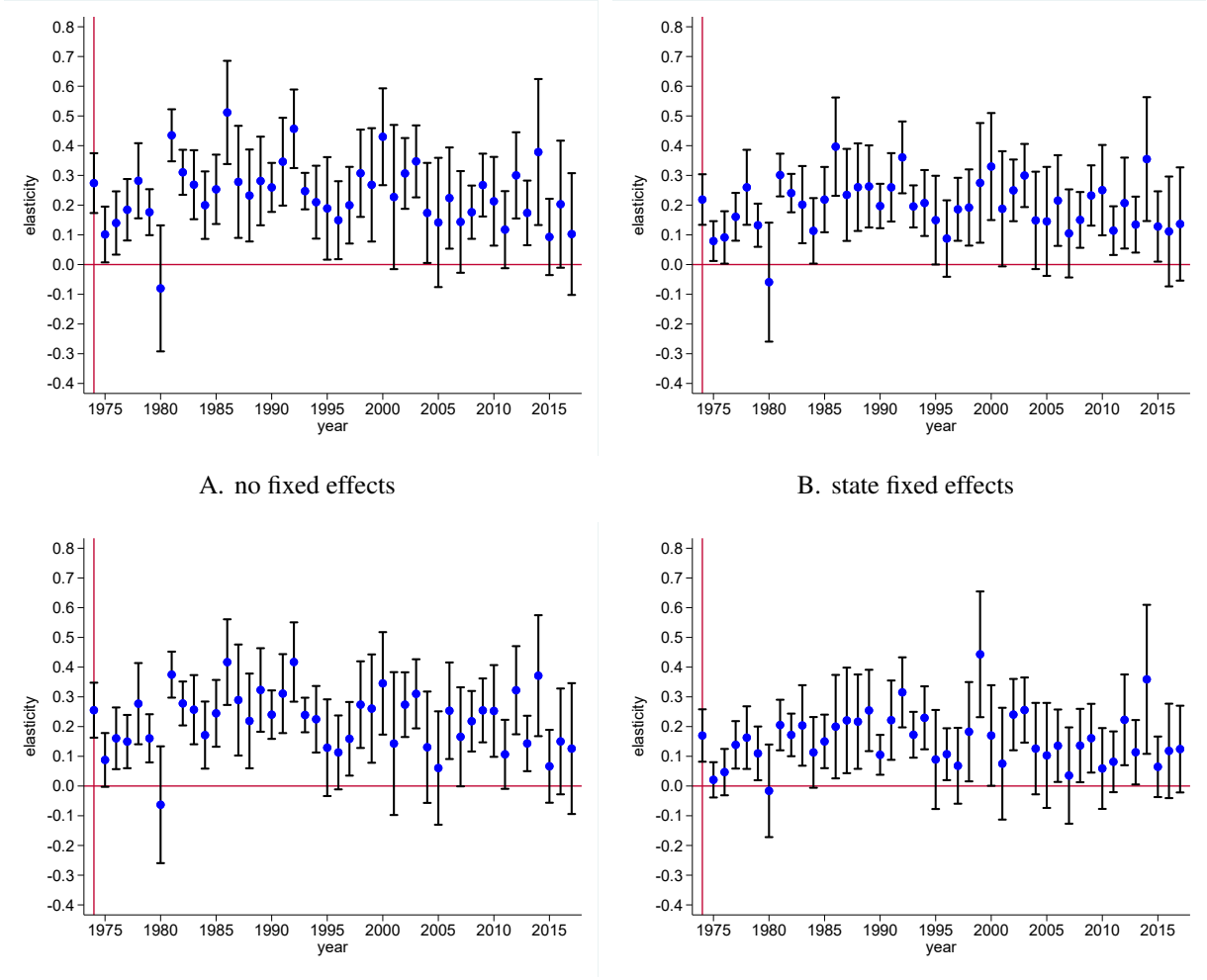
A. counties

B. hydrologic units

C. monitoring sites

Note: The figure shows point estimates and 95% confidence intervals for the elasticity of nitrogen concentration with respect to corn acres. The standard errors are clustered by 4-digit hydrologic unit. The blue dashed lines indicate the 25%, 50%, and 75% percentiles of precipitation used as knots in the precipitation spline.The estimates pertain to the EAST-100 (U.S., east of the 100th meridian) and are based on USGS-NWIS data for nitrogen concentration. For additional details, see the discussion related to flexible precipitation modeling in Section 8.

Figure 4. Cross-section regressions, counties



A. no fixed effects

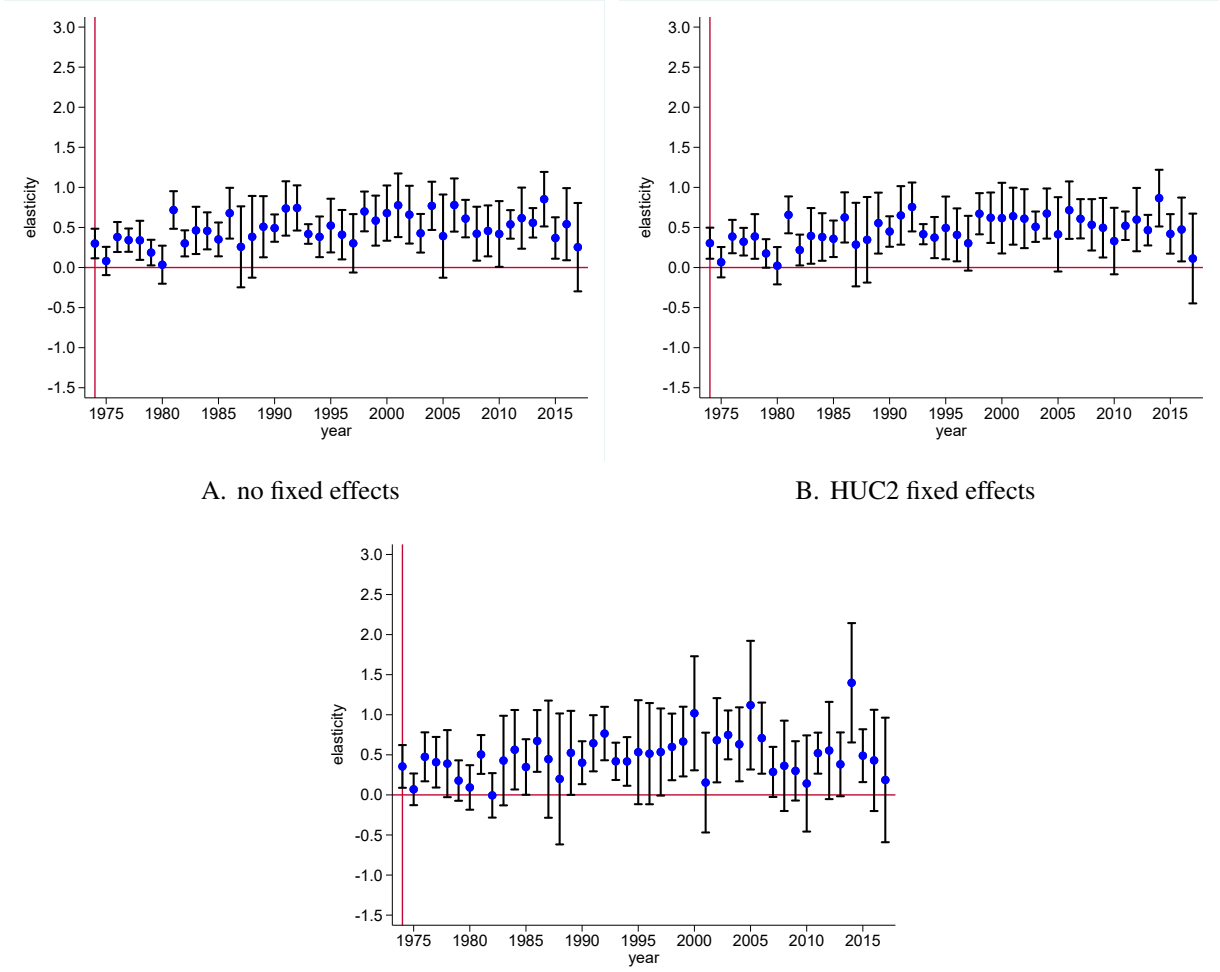
B. state fixed effects

C. HUC2 fixed effects

D. HUC4 fixed effects

Note: The figure shows point estimates and 95% confidence intervals for the elasticity of nitrogen concentration with respect to corn acres as discussed in Section 7.2. The year-specific estimates for 1975–2017 are based on OLS regressions as in equation (2). The left-most point estimate and associated confidence interval are based on the pooled ("across-years") OLS regressions as in equation (3). The standard errors are clustered by 4-digit hydrologic unit. All four specifications control for weather and contain an interaction of acres with precipitation. The estimates pertain to the EAST-100 (U.S., east of the 100th meridian) and are based on USGS-NWIS data for nitrogen concentration.

Figure 5. Cross-section regressions, hydrologic units



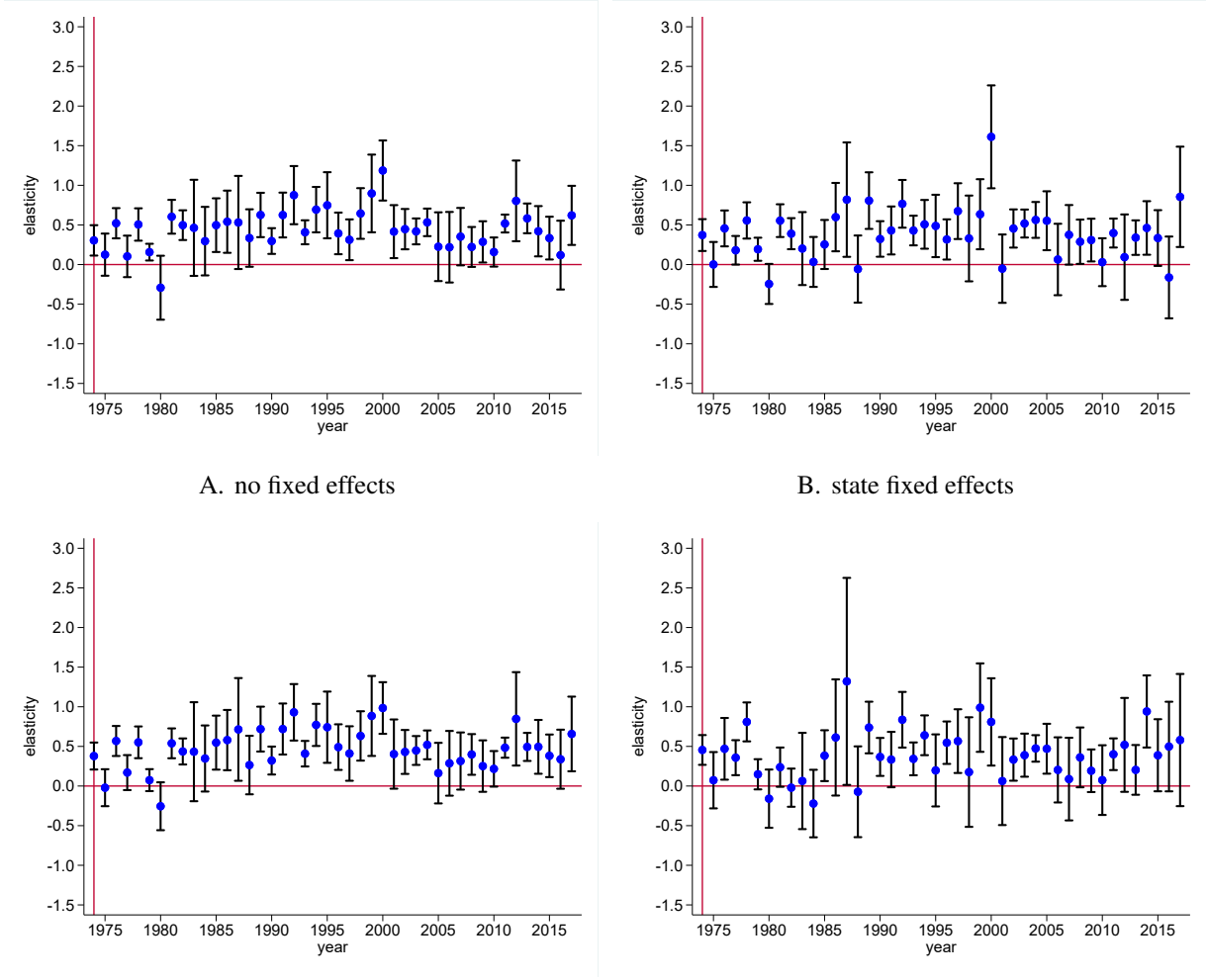
A. no fixed effects

B. HUC2 fixed effects

C. HUC4 fixed effects

Note: The figure shows point estimates and 95% confidence intervals for the elasticity of nitrogen concentration with respect to corn acres as discussed in Section 7.2. The year-specific estimates for 1975–2017 are based on OLS regressions as in equation (2). The left-most point estimate and associated confidence interval are based on the pooled ("across-years") OLS regressions as in equation (3). The standard errors are clustered by 4-digit hydrologic unit. All four specifications control for weather and contain an interaction of acres with precipitation. The estimates pertain to the EAST-100 (U.S., east of the 100th meridian) and are based on USGS-NWIS data for nitrogen concentration.

Figure 6. Cross-section regressions, monitoring sites



A. no fixed effects

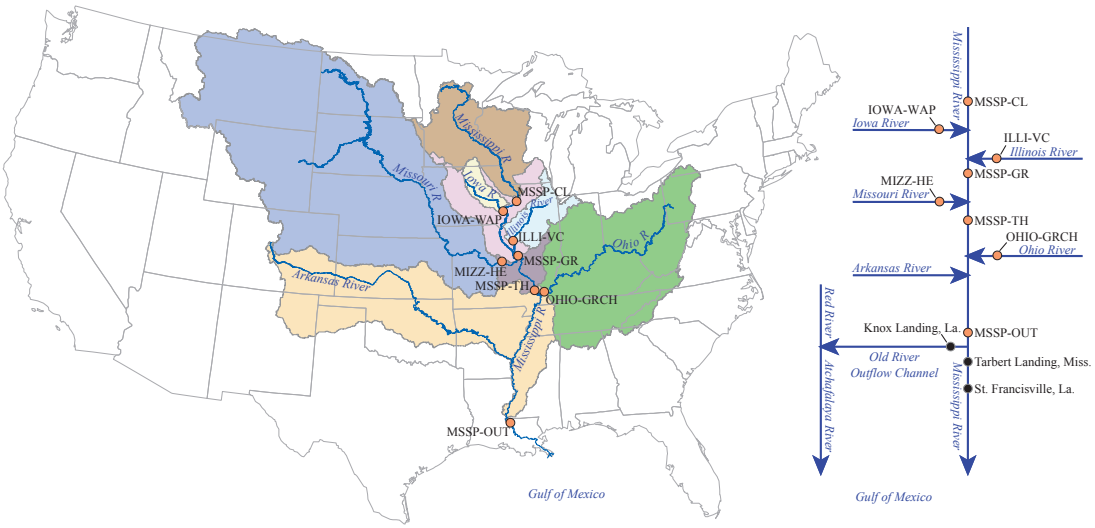
B. state fixed effects

C. HUC2 fixed effects

D. HUC4 fixed effects

Note: The figure shows point estimates and 95% confidence intervals for the elasticity of nitrogen concentration with respect to corn acres as discussed in Section 7.2. The year-specific estimates for 1975–2017 are based on OLS regressions as in equation (2). The left-most point estimate and associated confidence interval are based on the pooled ("across-years") OLS regressions as in equation (3). The standard errors are clustered by 4-digit hydrologic unit. All four specifications control for weather and contain an interaction of acres with precipitation. The estimates pertain to the EAST-100 (U.S., east of the 100th meridian) and are based on USGS-NWIS data for nitrogen concentration.

Figure 7. Schematic of the Mississippi river and its tributaries from Murphy et al. (2013)

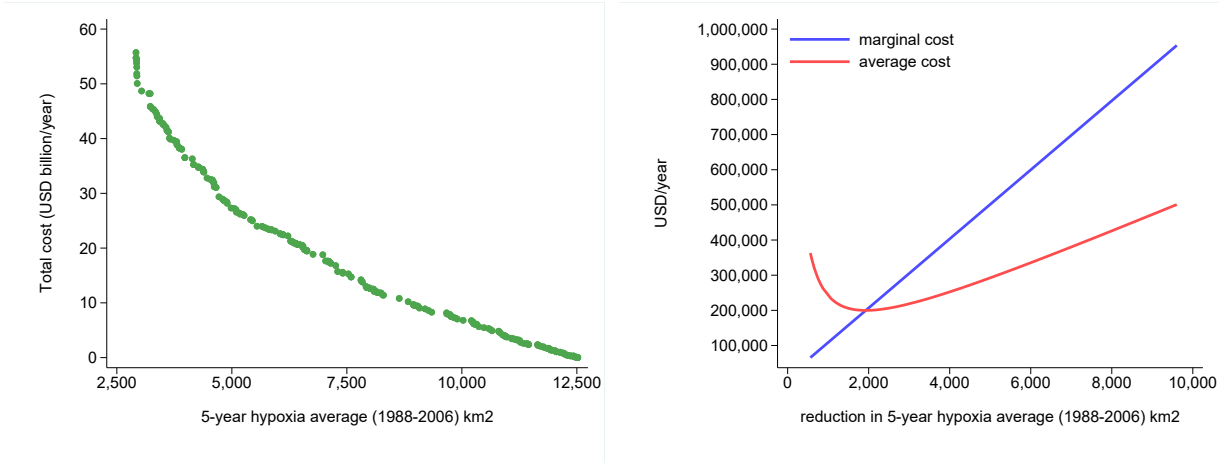


[km², square kilometers; USGS, U.S. Geological Survey]

Site abbreviation	Site number	Site name	Basin area (km²)	Model calibration		Number of samples
				Start date	End date	
MSSP-CL	05420500	Mississippi River at Clinton, IA	221,703	11/12/1974	8/16/2011	363
IOWA-WAP	05465500	Iowa River at Wapello, IA	32,375	11/10/1977	9/1/2011	333
ILLI-VC	05586100	Illinois River at Valley City, IL	69,264	12/12/1974	8/24/2011	428
MSSP-GR	05587455[1]	Mississippi River below Grafton, IL	443,665	1/27/1975	9/14/2011	362
MIZZ-HE	06934500	Missouri River at Hermann, MO	1,353,269	10/28/1969	9/29/2011	527
MSSP-TH	07022000	Mississippi River at Thebes, IL	1,847,180	1/30/1973	8/2/2011	511
OHIO-GRCH	03612500[2]	Ohio River at Dam 53 near Grand Chain, IL	526,027	10/11/1972	8/15/2011	466
MSSP-OUT	---[3]	Mississippi River above Old River Outflow Channel, LA	2,914,514	10/5/1967	8/22/2011	589

Note: The figure combines Figure 1 and Table 1 in Murphy et al. (2013). For additional details, see the discussion on page 44.

Figure 8. Abatement cost curves based on Rabotyagov et al. (2014a)

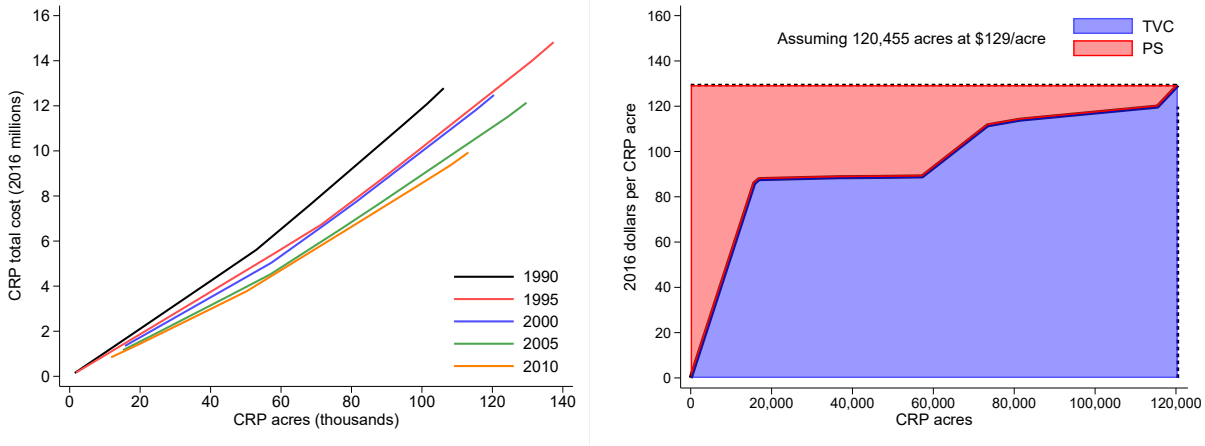


A. total cost

B. average and marginal costs

Note: The scatterplot in panel A replicates figure 2 from Rabotyagov et al. (2014a). For additional details, see the discussion on page 43.

Figure 9. Total cost of CRP acres for counties within 100 miles from USGS-05587455 in the Mississippi river below Grafron, IL



A. total cost curves

B. producer surplus calculation

Note: In panel A, we show total cost curves (based on linear approximations) for CRP acres associated with upstream counties within 100 miles from the USGS-05587455 monitoring in the Mississippi river below Grafton, IL for 5 representative years. The total cost on the vertical axis is in 2016 dollars. In panel B, we show the total variable cost (TVC) and producer surplus (PS) in 2016 dollars for a hypothetical CRP acreage in 2000. The monitoring site is located before the confluence of the Missouri River to the Mississippi River. It accounts for the confluence of the South Fork Iowa River, the Iowa River, the Des Moines River, and the Illinois River. For additional details, see the discussion on page 44.

12 Tables

Table 1. Damage costs from nitrogen pollution

Source	Damages	Additional information
Taylor and Heal (2021)	$583	U.S., per ton of nitrogen
Sobota et al. (2015)	$15,840	U.S., per ton of nitrogen
Van Grinsven et al. (2013a)	$13,338–$53,351	E.U., per ton of nitrogen
Compton et al. (2011)	$56,000	GoM fisheries decline, per ton of nitrogen
Compton et al. (2011)	$6,380	CB recreational use, per ton of nitrogen
Blottnitz et al. (2006)	$300	E.U., per ton of nitrogen
Dodds et al. (2009)	$2.2 billion	U.S., freshwater eutrophication, annually
Kudela et al. (2015)	$4 billion	U.S., algal blooms, annually
UCS (2020)	$0.552–$2.4 billion	GoM fisheries & marine habitat, annually
Anderson et al. (2000)	$449 million	U.S., algal blooms, annually

In Van Grinsven et al. (2013a), the reported cost of €25–100 billion per year implies a cost of €4.11–16.43 per lb of nitrogen using $0.6 \times 4.6 = 2.6$ million tons of nitrogen attributed to agricultural sources. At an exchange rate of $\$1.5/€$ in 2008, we have a cost of 6.05–24.20 per lb of nitrogen in 2008$. Here we report the cost per ton of nitrogen. We use "CB" to refer to the Chesapeake Bay and "GoM" to refer to the Gulf of Mexico. For additional details, see the discussion in Section A.1.

Table 2. Abatement costs from nitrogen pollution

Source	Abatement Cost	Additional Information
Xu et al. (2021)	$6 billion	MRB
Tallis et al. (2019)	$2.6 billion	MRB
Marshall et al. (2018)	$1.9–$3.3 billion	MRB
McLellan et al. (2016)	$1.48 billion	MRB
Whittaker et al. (2015)	$9.25 billion	MRB
Rabotyagov et al. (2014a)	$2.6 billion	MRB
USEPA (2001)	$<$ $1–$4.3 billion/year (TMDL)	US, national
Ribaudo et al. (2001)	$0.1–$7.91 billion	MRB
Doering et al. (1999)	−$0.1–$17.95 billion	MRB

Note: Table IV-1 in USEPA (2001) shows the leading causes of water impairment (nutrients account for 11.5%) and leading sources (agriculture accounts for 24.6%). See Table 6.1 in Doering et al. (1999), where the numbers are reported as net social benefits. See Table 2 in Ribaudo et al. (2001), where the numbers are reported as net social benefits too. For additional details, see the discussion in Section A.1.

Table 3. Summary statistics

A. counties							
variable	panel	obs	years	mean	s.d. B	s.d. W	median
nitrogen	2232	64121	28.7	2.4508	1.6446	1.6634	1.6833
acres planted	2232	64121	28.7	0.0378	0.0484	0.0105	0.0154
precipitation	2232	64121	28.7	1.0877	0.2591	0.1744	1.0700
B. hydrologic units							
variable	panel	obs	years	mean	s.d. B	s.d. W	median
nitrogen	986	17943	18.2	2.0999	1.9015	1.5162	1.3656
acres planted	986	17943	18.2	0.0296	0.0454	0.0081	0.0107
precipitation	986	17943	18.2	1.0968	0.2675	0.1727	1.0768
C. monitoring sites							
variable	panel	obs	years	mean	s.d. B	s.d. W	median
nitrogen	9596	56466	5.9	2.3558	3.7387	1.2399	1.3600
acres planted	9596	56466	5.9	0.2918	0.4599	0.0529	0.0900
precipitation	9596	56466	5.9	1.1206	0.2487	0.1633	1.1080

Note: an observation is a county-year (panel A), hydrologic unit-year (panel B), and a monitoring site-year (panel C) combination. The panel column indicates the number of counties, units, and sites. The years column gives the average number of observations per county, hydrologic unit, and monitoring site. We also report the between-counties (s.d. B) and within-county (s.d. W) standard deviation. Analogous definitions hold in the case of the hydrologic units and the monitoring sites in panels B and C. The acres are measured in millions and the nitrogen concentration is measured in mg/L. The precipitation is total annual (January–December) and is measured in meters.The estimates pertain to the EAST-100 (U.S., east of the 100th meridian) and are based on USGS-NWIS data for nitrogen concentration. For additional details, see Section 5.

Table 4. Panel FE regressions, counties

				A. acres				
	(A1)	(A2)	(A3)	(A4)	(A5)	(A6)	(A7)	(A8)
acres	23.581***	5.146***	4.202**	5.845***	3.862**	6.117***	-0.523	2.741
	(2.032)	(1.714)	(1.659)	(1.902)	(1.596)	(1.941)	(1.987)	(1.955)
$\overline{R}^2$	0.26	0.46	0.47	0.47	0.48	0.48	0.52	0.53
Obs.	64,121	64,121	64,121	64,121	64,121	64,121	64,121	64,121
Clusters	124	124	124	124	124	124	124	124
elast est.	0.364	0.079	0.065	0.090	0.060	0.094	-0.008	0.042
elast s.e.	0.031	0.026	0.026	0.029	0.025	0.030	0.031	0.030
elast t-stat	11.604	3.002	2.533	3.074	2.420	3.151	-0.263	1.403
				B. acres plus weather				
	(B1)	(B2)	(B3)	(B4)	(B5)	(B6)	(B7)	(B8)
acres	18.458***	5.212***	4.317***	5.490***	3.941**	6.058***	-0.678	2.477
	(1.872)	(1.669)	(1.640)	(1.864)	(1.525)	(1.970)	(1.941)	(1.942)
$\overline{R}^2$	0.30	0.47	0.47	0.48	0.48	0.49	0.52	0.53
Obs.	64,121	64,121	64,121	64,121	64,121	64,121	64,121	64,121
Clusters	124	124	124	124	124	124	124	124
elast est.	0.285	0.080	0.067	0.085	0.061	0.093	-0.010	0.038
elast s.e.	0.029	0.026	0.025	0.029	0.024	0.030	0.030	0.030
elast t-stat	9.861	3.123	2.633	2.944	2.584	3.075	-0.349	1.276
				C. acres plus weather and interaction				
	(C1)	(C2)	(C3)	(C4)	(C5)	(C6)	(C7)	(C8)
acres	0.765	-9.793**	-10.379***	-8.444**	-10.699***	-7.947**	-13.730***	-9.566**
	(3.315)	(3.968)	(3.916)	(3.602)	(3.804)	(3.542)	(4.887)	(4.495)
acres × prec	19.486***	16.342***	16.043***	15.355***	15.870***	15.277***	14.409***	13.517***
	(3.381)	(3.899)	(3.877)	(3.667)	(3.845)	(3.715)	(3.927)	(3.805)
$\overline{R}^2$	0.31	0.47	0.47	0.48	0.48	0.49	0.52	0.53
Obs.	64,121	64,121	64,121	64,121	64,121	64,121	64,121	64,121
Clusters	124	124	124	124	124	124	124	124
elast est.	0.394	0.169	0.154	0.171	0.146	0.177	0.071	0.117
elast s.e.	0.037	0.036	0.035	0.037	0.034	0.040	0.033	0.035
elast t-stat	10.568	4.678	4.447	4.584	4.353	4.412	2.148	3.353
county FE		✓	✓	✓	✓	✓	✓	✓
trend			✓					
year FE				✓		✓		✓
state × trend					✓	✓		
county × trend							✓	✓

Note: We control for weather (precipitation, squared precipitation, moderate heat, and extreme heat) in all 8 models of panels B and C. The standard errors reported in parentheses are clustered by 4-digit hydrologic unit. The elasticities in the bottom of each panel are based on percentage changes in nitrogen concentration assuming an increase in acres equal to 1 within standard deviation in Table 3 and the 75% percentile of precipitaion when applicable. We calculate the percentage change in concentration using the estimated marginal effect and the mean concentration in Table 3. We calculate the percentage change in acres using the 1 within standard deviation and the mean acreage in Table 3. The asterisks denote statistical significance as follows: 1% (***), 5% (**), 10% (*). The estimates pertain to the EAST-100 (U.S., east of the 100th meridian) and are based on USGS-NWIS data for nitrogen concentration. For additional details, see Section 7.

Table 5. Panel FE regressions, hydrologic units

				A. acres				
	(A1)	(A2)	(A3)	(A4)	(A5)	(A6)	(A7)	(A8)
acres	26.903***	3.707	3.114	3.395	2.138	2.337	0.611	0.974
	(1.914)	(2.539)	(2.434)	(2.731)	(2.704)	(2.977)	(2.444)	(2.352)
$\overline{R}^2$	0.26	0.53	0.53	0.54	0.56	0.56	0.64	0.64
Obs.	17,943	17,943	17,943	17,943	17,943	17,943	17,943	17,943
Clusters	128	128	128	128	128	128	128	128
elast est.	0.379	0.052	0.044	0.048	0.030	0.033	0.009	0.014
elast s.e.	0.027	0.036	0.034	0.038	0.038	0.042	0.034	0.033
elast t-stat	14.053	1.460	1.280	1.243	0.791	0.785	0.250	0.414
				B. acres plus weather				
	(B1)	(B2)	(B3)	(B4)	(B5)	(B6)	(B7)	(B8)
acres	24.635***	3.479	3.034	3.347	1.849	2.385	0.167	1.002
	(2.110)	(2.545)	(2.430)	(2.655)	(2.719)	(2.992)	(2.377)	(2.317)
$\overline{R}^2$	0.28	0.54	0.54	0.54	0.56	0.56	0.64	0.64
Obs.	17,943	17,943	17,943	17,943	17,943	17,943	17,943	17,943
Clusters	128	128	128	128	128	128	128	128
elast est.	0.347	0.049	0.043	0.047	0.026	0.034	0.002	0.014
elast s.e.	0.030	0.036	0.034	0.037	0.038	0.042	0.034	0.033
elast t-stat	11.674	1.367	1.248	1.261	0.680	0.797	0.070	0.432
				C. acres plus weather and interaction				
	(C1)	(C2)	(C3)	(C4)	(C5)	(C6)	(C7)	(C8)
acres	2.441	-17.101***	-17.395***	-16.455***	-19.071***	-17.746**	-20.221***	-18.535***
	(4.983)	(6.299)	(6.250)	(5.883)	(7.214)	(6.823)	(7.205)	(6.704)
acres × prec	24.790***	22.608***	22.508***	22.099***	22.886***	22.327***	22.315***	21.895***
	(5.588)	(6.353)	(6.354)	(6.225)	(6.678)	(6.572)	(6.361)	(6.168)
$\overline{R}^2$	0.29	0.54	0.54	0.54	0.56	0.56	0.64	0.64
Obs.	17,943	17,943	17,943	17,943	17,943	17,943	17,943	17,943
Clusters	128	128	128	128	128	128	128	128
elast est.	0.478	0.164	0.158	0.164	0.141	0.150	0.114	0.131
elast s.e.	0.047	0.052	0.050	0.054	0.051	0.057	0.041	0.042
elast t-stat	10.235	3.176	3.150	3.023	2.766	2.625	2.796	3.100
HUC8 FE		✓	✓	✓	✓	✓	✓	✓
trend			✓					
year FE				✓		✓		✓
HUC4 × trend					✓	✓		
HUC8 × trend							✓	✓

Note: We control for weather (precipitation, squared precipitation, moderate heat, and extreme heat) in all 8 models of panels B and C. The standard errors reported in parentheses are clustered by 4-digit hydrologic unit. The elasticities in the bottom of each panel are based on percentage changes in nitrogen concentration assuming an increase in acres equal to 1 within standard deviation in Table 3 and the 75% percentile of precipitaion when applicable. We calculate the percentage change in concentration using the estimated marginal effect and the mean concentration in Table 3. We calculate the percentage change in acres using the 1 within standard deviation and the mean acreage in Table 3. The asterisks denote statistical significance as follows: 1% (***), 5% (**), 10% (*). The estimates pertain to the EAST-100 (U.S., east of the 100th meridian) and are based on USGS-NWIS data for nitrogen concentration. For additional details, see Section 7.

Table 6. Panel FE regressions, monitoring sites

				A. acres				
	(A1)	(A2)	(A3)	(A4)	(A5)	(A6)	(A7)	(A8)
acres	2.403***	0.125	0.059	0.075	-0.142	-0.185	0.059	0.078
	(0.199)	(0.266)	(0.227)	(0.216)	(0.230)	(0.224)	(0.221)	(0.226)
$\overline{R}^2$	0.12	0.81	0.81	0.81	0.81	0.82	0.82	0.82
Obs.	56,466	56,466	56,466	56,466	56,466	56,466	56,466	56,466
Clusters	129	129	129	129	129	129	129	129
elast est.	0.292	0.015	0.007	0.009	-0.017	-0.022	0.007	0.010
elast s.e.	0.024	0.032	0.028	0.026	0.028	0.027	0.027	0.028
elast t-stat	12.078	0.471	0.262	0.350	-0.615	-0.824	0.268	0.346
				B. acres plus weather				
	(B1)	(B2)	(B3)	(B4)	(B5)	(B6)	(B7)	(B8)
acres	2.083***	0.036	-0.017	-0.023	-0.224	-0.266	0.010	-0.011
	(0.219)	(0.241)	(0.217)	(0.207)	(0.223)	(0.217)	(0.218)	(0.225)
$\overline{R}^2$	0.13	0.81	0.81	0.82	0.81	0.82	0.82	0.82
Obs.	56,466	56,466	56,466	56,466	56,466	56,466	56,466	56,466
Clusters	129	129	129	129	129	129	129	129
elast est.	0.253	0.004	-0.002	-0.003	-0.027	-0.032	0.001	-0.001
elast s.e.	0.027	0.029	0.026	0.025	0.027	0.026	0.027	0.027
elast t-stat	9.522	0.151	-0.077	-0.111	-1.004	-1.228	0.044	-0.049
				C. acres plus weather and interaction				
	(C1)	(C2)	(C3)	(C4)	(C5)	(C6)	(C7)	(C8)
acres	0.695	-1.582**	-1.609**	-1.520**	-1.787***	-1.741***	-1.416**	-1.359**
	(0.814)	(0.644)	(0.643)	(0.610)	(0.626)	(0.595)	(0.564)	(0.533)
acres × prec	1.480	1.747***	1.721***	1.667***	1.719***	1.669***	1.596***	1.566***
	(0.914)	(0.505)	(0.506)	(0.507)	(0.512)	(0.513)	(0.479)	(0.477)
$\overline{R}^2$	0.13	0.81	0.82	0.82	0.82	0.82	0.82	0.82
Obs.	56,466	56,466	56,466	56,466	56,466	56,466	56,466	56,466
Clusters	129	129	129	129	129	129	129	129
elast est.	0.313	0.077	0.070	0.073	0.048	0.046	0.074	0.077
elast s.e.	0.052	0.023	0.021	0.023	0.022	0.026	0.024	0.028
elast t-stat	6.062	3.306	3.365	3.109	2.154	1.806	3.072	2.729
monitor FE		✓	✓	✓	✓	✓	✓	✓
trend			✓					
year FE				✓		✓		✓
state × trend					✓	✓		
county × trend							✓	✓

Note: We control for weather (precipitation, squared precipitation, moderate heat, and extreme heat) in all 8 models of panels B and C. The standard errors reported in parentheses are clustered by 4-digit hydrologic unit. The elasticities in the bottom of each panel are based on percentage changes in nitrogen concentration assuming an increase in acres equal to 1 within standard deviation in Table 3 and the 75% percentile of precipitaion when applicable. We calculate the percentage change in concentration using the estimated marginal effect and the mean concentration in Table 3. We calculate the percentage change in acres using the 1 within standard deviation and the mean acreage in Table 3. The asterisks denote statistical significance as follows: 1% (***), 5% (**), 10% (*). The estimates pertain to the EAST-100 (U.S., east of the 100th meridian) and are based on USGS-NWIS data for nitrogen concentration. For additional details, see Section 7.

Table 7. Elasticity of nitrogen concentration with respect to corn acreage panel FE regression, baseline estimates

A. counties							
controls	estim	s.e.	t-stat	p-value	Δ acres	$\bar{y}$	precip.
baseline	0.117	0.035	3.353	0.001	0.010	2.450	1.270
B. hydrologic units							
controls	estim	s.e.	t-stat	p-value	Δ acres	$\bar{y}$	precip.
baseline	0.131	0.042	3.100	0.002	0.008	2.100	1.270
C. monitoring sites							
controls	estim	s.e.	t-stat	p-value	Δ acres	$\bar{y}$	precip.
baseline	0.077	0.028	2.729	0.007	0.053	2.400	1.270

Note: The estimates refer to the elasticity of nitrogen concentration with respect to corn acreage for the models in column C8 of tables 4–6. For clarity, we also show the assumed increase in acres (Δ acres) that is equal to a 10% of the average acres, the mean nitrogen concentration ($\bar{y}$), and the 75% percentile of precipitation (precip) used to evaluate the acreage effects. The estimates pertain to the EAST-100 (U.S., east of the 100th meridian) and are based on USGS-NWIS data for nitrogen concentration. For additional details, see Section 7.2.

Table 8. Elasticity of nitrogen concentration with respect to corn acreage pooled cross-section regressions, baseline estimates

A. counties							
controls	estim	s.e.	t-stat	p-value	Δ acres	$\bar{y}$	precip.
none	0.274	0.051	5.338	0.000	0.010	2.450	1.270
state FE	0.219	0.043	5.040	0.000	0.010	2.450	1.270
HUC2 FE	0.255	0.047	5.407	0.000	0.010	2.450	1.270
HUC4 FE	0.170	0.045	3.780	0.000	0.010	2.450	1.270
B. hydrologic units							
controls	estim	s.e.	t-stat	p-value	Δ acres	$\bar{y}$	precip.
none	0.300	0.094	3.185	0.002	0.008	2.100	1.270
HUC2 FE	0.304	0.099	3.069	0.003	0.008	2.100	1.270
HUC4 FE	0.355	0.136	2.614	0.010	0.008	2.100	1.270
C. monitoring sites							
controls	estim	s.e.	t-stat	p-value	Δ acres	$\bar{y}$	precip.
none	0.305	0.098	3.120	0.002	0.053	2.400	1.270
state FE	0.372	0.102	3.632	0.000	0.053	2.400	1.270
HUC2 FE	0.378	0.087	4.361	0.000	0.053	2.400	1.270
HUC4 FE	0.455	0.096	4.751	0.000	0.053	2.400	1.270

Note: The estimates refer to the elasticity of nitrogen concentration with respect to corn acreage. For clarity, we also show the assumed increase in acres (Δ acres) that is equal to a 10% of the average acres, the mean nitrogen concentration ($\bar{y}$), and the 75% percentile of precipitation (precip) used to evaluate the acreage effects. The estimates pertain to the EAST-100 (U.S., east of the 100th meridian) and are based on USGS-NWIS data for nitrogen concentration. For additional details, see Section 7.2.

Table 9. Elasticity of nitrogen concentration with respect to corn acreage
panel FE regressions, summary, counties

model	elasticity	reference
Baseline	0.12 [0.05,0.19]	Table 4, panel C
Additional controls	0.12–0.26	Table 13, panels A and B
Time variation	0.01–0.17	Table 16, panel A
Top states	0.15	Table 17, panel A
Water regions	0.10–0.20	Table A15–Table A16, panel A
Precipitation splines	0.08-0.11	Figure 3, panel A
CONUS USGS-NWIS	0.10	Table A24, panel A
CONUS USGS-NWQN	0.10	Table A25, panel A
CONUS USGS+EPA	0.16	Table A25, panel B
CONUS USGS+EPA, other acres	0.14	Table A26
CONUS USGS+EPA, fertilizer	0.13	Table A27
CONUS USGS+EPA, Paudel Crago	0.16	Table A28
CONUS USGS+EPA, lagged acres	0.21–0.27	Table A29
CONUS USGS+EPA, average acres	0.20–0.23	Table A33
Streamflow	0.10	Table 18, panel A
Runoff	0.12	Table 19, panel A
Censoring	0.12–0.14	Table 20, panel A
Alternative radii	0.07–0.10	Table 21, panel A
Data cleaning	0.12	Table 22, panel A
Seasonality	0.06–0.08	Table 23, panel A
Alternative clustering	1% level	Table 24, panel A

Note: The row for the baseline estimates includes a 95% confidence interval. For additional details, see Section 8.2.

Table 10. Elasticity of nitrogen concentration with respect to corn acreage panel FE regressions, summary, hydrologic units

model	elasticity	reference
Baseline	0.13 [0.05,0.21]	Table 5, panel C
Additional controls	0.13–0.22	Table 14, panels A and B
Time variation	0.04–0.22	Table 16, panel B
Top states	0.17	Table 17, panel B
Water regions	0.00–2.09	Table A15–Table A16, panel B
Precipitation splines	0.10	Figure 3, panel B
CONUS USGS-NWIS	0.07	Table A24, panel B
Runoff	0.12	Table 19, panel B
Censoring	0.13–0.16	Table 20, panel B
Data cleaning	0.13	Table 22, panel B
Seasonality	0.07	Table 23, panel B
Alternative clustering	1%	Table 24, panel B

Note: The row for the baseline estimates includes a 95% confidence interval. For additional details, see Section 8.2.

Table 11. Elasticity of nitrogen concentration with respect to corn acreage panel FE regressions, summary, monitoring sites

model	elasticity	reference
Baseline	0.08 [0.02,0.13]	Table 6, panel C
Additional controls	0.08–0.11	Table 15, panels A and B
Time variation	0.00–0.15	Table 16, panel C
Top states	0.15	Table 17, panel C
Water regions	0.05–0.40	Table A15–Table A16, panel C
Precipitation splines	0.04–0.09	Figure 3, panel C
CONUS USGS-NWIS	0.07	Table A24, panel C
Streamflow	0.10	Table 18, panel B
Runoff	0.12	Table 19, panel C
Censoring	0.12–0.14	Table 20, panel C
Alternative radii	0.07–0.10	Table 21, panel B
Data cleaning	0.12	Table 22, panel C
Seasonality	0.06–0.08	Table 23, panel C
Alternative clustering	1%–5%	Table 24, panel C

Note: The row for the baseline estimates includes a 95% confidence interval. For additional details, see Section 8.2.

Table 12. Additional controls used in various robustness checks of the panel FE regressions

model	additional control
RC1	BEA employment (SAEMP25)
RC2	BEA GDP (SAGDP2)
RC3	BEA REA CAINC (30110, 45190, 45370)
RC4	RC1 plus EIA-SEDS fossil fuel consumption
RC5	RC2 plus EIA-SEDS fossil fuel consumption
RC6	RC3 plus EIA-SEDS fossil fuel consumption
RC7	RC4 plus EPA NO_x from fossil fuel combustion
RC8	RC5 plus EPA NO_x from fossil fuel combustion
RC9	RC6 plus EPA NO_x from fossil fuel combustion
RC10	BLS local unemployment (BLS LAUS)
RC11	RC10 plus EIA-SEDS fossil fuel consumption
RC12	RC11 plus EPA NO_x from fossil fuel combustion
RC13	RC6 plus USDA cattle in feedlots
RC14	RC6 plus nitrogen atmospheric deposition
RC15	RC6 plus USDA CRP cropland
RC16	RC6 plus USDA CoA animal concentration
RC17	RC6 plus EPA CWNS WWTPs (number)
RC18	RC6 plus EPA CWNS WWTPs (nitrogen load)
RC19	RC6 plus corn yield
RC20	RC13 plus corn yield

Note: Models RC14–RC18 are based on the USGS NAWQA anthropogenic data for 15,458 10-digit hydrologic units in Falcone (2018). According to the data documentation, the Clean Water Needs Survey (CWNS) Wastewater treatment plants (WWTPs) represent 12,688 sites with data for 2012, of which 3,912 are major dischargers (more than 1 million gallons per day). The estimates pertain to the EAST-100 (U.S., east of the 100th meridian) and are based on USGS-NWIS data for nitrogen concentration. For additional details, see Section 8.2.

Table 13. Elasticity of nitrogen concentration with respect to corn acreage
panel FE regressions, additional controls, counties

	A. sample size				B. control(s)		C. additional info		
model	low	est	upp	t-stat	est	t-stat	Δ acres	$\bar{y}$	precip.
RC1	0.049	**0.117**	0.186	3.353	**0.118**	3.350	0.010	2.450	1.270
RC2	0.049	**0.117**	0.186	3.353	**0.117**	3.362	0.010	2.450	1.270
RC3	0.049	**0.117**	0.186	3.344	**0.154**	3.465	0.010	2.450	1.270
RC4	0.049	**0.117**	0.186	3.353	**0.120**	3.396	0.010	2.450	1.270
RC5	0.049	**0.117**	0.186	3.353	**0.119**	3.408	0.010	2.450	1.270
RC6	0.049	**0.117**	0.186	3.344	**0.153**	3.439	0.010	2.450	1.270
RC7	-0.081	0.125	0.331	1.187	0.134	1.259	0.010	2.450	1.270
RC8	-0.081	0.125	0.331	1.187	0.134	1.262	0.010	2.450	1.270
RC9	-0.080	0.126	0.333	1.200	**0.214**	2.031	0.010	2.450	1.270
RC10	-0.102	0.082	0.267	0.875	0.082	0.862	0.010	2.450	1.270
RC11	-0.102	0.082	0.267	0.875	0.084	0.885	0.010	2.450	1.270
RC12	-0.081	0.125	0.331	1.187	0.126	1.192	0.010	2.450	1.270
RC13	0.061	**0.135**	0.208	3.592	**0.175**	3.745	0.010	2.450	1.270
RC14	0.008	**0.208**	0.407	2.041	**0.240**	2.405	0.010	2.450	1.270
RC15	0.012	**0.235**	0.458	2.062	**0.264**	2.366	0.010	2.450	1.270
RC16	-0.031	0.111	0.254	1.529	0.136	1.597	0.010	2.450	1.270
RC17	0.049	**0.182**	0.315	2.675	**0.206**	2.863	0.010	2.450	1.270
RC18	0.049	**0.182**	0.315	2.675	**0.207**	2.866	0.010	2.450	1.270
RC19	0.049	**0.117**	0.186	3.342	**0.153**	3.433	0.010	2.450	1.270
RC20	0.061	**0.135**	0.208	3.588	**0.175**	3.736	0.010	2.450	1.270

Note: In this table, we examine the sensitivity of our estimated corn acreage effects to a series of additional control variables described in Table 12. We do so separating the consquences of data availability from the consequences of the control variable(s). In panel A, We show point estimates of the elasticity of nitrogen concentration with respect to corn acreage along with their 95% confidence intervals and the t statistics using the same observations as the ones for which the control variable is available in the absence of the control variable(s). In panel B, we show the point estimate and t statistic of the elasticities in the presence of the control variable(s). In panel C, we show the assumed increase in acres (Δ acres), the mean nitrogen concentration ($\bar{y}$), and the 75% percentile of precipitation (precip) used to evaluate the acreage effects. The bold-faced entries show elasticities that are significant at 5% level. The estimates pertain to the EAST-100 (U.S., east of the 100th meridian) and are based on USGS-NWIS data for nitrogen concentration. For additional details, see Section 8.2.

Table 14. Elasticity of nitrogen concentration with respect to corn acreage
panel FE regressions, additional controls, hydrologic units

	A. sample size				B. control(s)		C. additional info		
model	low	est	upp	t-stat	est	t-stat	Δ acres	$\bar{y}$	precip.
RC1	0.048	**0.131**	0.213	3.100	**0.130**	3.089	0.008	2.100	1.270
RC2	0.048	**0.131**	0.213	3.100	**0.129**	3.151	0.008	2.100	1.270
RC3	0.048	**0.131**	0.213	3.100	**0.167**	3.478	0.008	2.100	1.270
RC4	0.048	**0.131**	0.213	3.100	**0.130**	3.089	0.008	2.100	1.270
RC5	0.048	**0.131**	0.213	3.100	**0.129**	3.145	0.008	2.100	1.270
RC6	0.048	**0.131**	0.213	3.100	**0.166**	3.452	0.008	2.100	1.270
RC7	0.013	**0.169**	0.325	2.118	**0.169**	2.112	0.008	2.100	1.270
RC8	0.013	**0.169**	0.325	2.118	**0.174**	2.196	0.008	2.100	1.270
RC9	0.013	**0.169**	0.325	2.118	**0.217**	2.536	0.008	2.100	1.270
RC10	0.006	**0.134**	0.262	2.060	**0.137**	2.108	0.008	2.100	1.270
RC11	0.006	**0.134**	0.262	2.060	**0.137**	2.099	0.008	2.100	1.270
RC12	0.013	**0.169**	0.325	2.118	**0.173**	2.271	0.008	2.100	1.270
RC13	0.052	**0.142**	0.231	3.113	**0.179**	3.435	0.008	2.100	1.270
RC14	-0.251	0.143	0.537	0.709	0.166	0.907	0.008	2.100	1.270
RC15	-0.097	0.227	0.551	1.372	0.250	1.698	0.008	2.100	1.270
RC16	-0.169	0.024	0.217	0.245	0.021	0.217	0.008	2.100	1.270
RC17	-0.204	0.039	0.283	0.316	0.046	0.395	0.008	2.100	1.270
RC18	-0.204	0.039	0.283	0.316	0.045	0.394	0.008	2.100	1.270
RC19	0.041	**0.125**	0.208	2.925	**0.165**	3.341	0.008	2.100	1.270
RC20	0.055	**0.146**	0.236	3.159	**0.184**	3.470	0.008	2.100	1.270

Note: In this table, we examine the sensitivity of our estimated corn acreage effects to a series of additional control variables described in Table 12. We do so separating the consquences of data availability from the consequences of the control variable(s). In panel A, We show point estimates of the elasticity of nitrogen concentration with respect to corn acreage along with their 95% confidence intervals and the t statistics using the same observations as the ones for which the control variable is available in the absence of the control variable(s). In panel B, we show the point estimate and t statistic of the elasticities in the presence of the control variable(s). In panel C, we show the assumed increase in acres (Δ acres), the mean nitrogen concentration ($\bar{y}$), and the 75% percentile of precipitation (precip) used to evaluate the acreage effects. The bold-faced entries show elasticities that are significant at 5% level. The estimates pertain to the EAST-100 (U.S., east of the 100th meridian) and are based on USGS-NWIS data for nitrogen concentration. For additional details, see Section 8.2.

Table 15. Elasticity of nitrogen concentration with respect to acreage
panel FE regressions, additional controls, monitoring sites

	A. sample size				B. control(s)		C. additional info		
model	low	est	upp	t-stat	est	t-stat	Δ acres	$\bar{y}$	precip.
RC1	0.022	**0.077**	0.131	2.729	**0.078**	2.865	0.053	2.400	1.270
RC2	0.022	**0.077**	0.131	2.729	**0.079**	2.939	0.053	2.400	1.270
RC3	0.022	**0.077**	0.131	2.729	**0.106**	3.399	0.053	2.400	1.270
RC4	0.022	**0.077**	0.131	2.729	**0.078**	2.835	0.053	2.400	1.270
RC5	0.022	**0.077**	0.131	2.729	**0.079**	2.902	0.053	2.400	1.270
RC6	0.022	**0.077**	0.131	2.729	**0.105**	3.350	0.053	2.400	1.270
RC7	-0.059	0.084	0.228	1.152	0.082	1.128	0.053	2.400	1.270
RC8	-0.059	0.084	0.228	1.152	0.084	1.162	0.053	2.400	1.270
RC9	-0.059	0.084	0.228	1.152	0.124	1.849	0.053	2.400	1.270
RC10	-0.074	0.052	0.179	0.809	0.066	1.010	0.053	2.400	1.270
RC11	-0.074	0.052	0.179	0.809	0.067	1.028	0.053	2.400	1.270
RC12	-0.059	0.084	0.228	1.152	0.091	1.241	0.053	2.400	1.270
RC13	0.019	**0.079**	0.138	2.577	**0.106**	3.118	0.053	2.400	1.270
RC14	-0.263	-0.027	0.208	-0.228	0.032	0.285	0.053	2.400	1.270
RC15	-0.243	-0.033	0.177	-0.307	-0.011	-0.109	0.053	2.400	1.270
RC16	-0.217	-0.032	0.152	-0.341	-0.013	-0.148	0.053	2.400	1.270
RC17	-0.172	0.011	0.193	0.116	0.044	0.490	0.053	2.400	1.270
RC18	-0.172	0.011	0.193	0.116	0.044	0.486	0.053	2.400	1.270
RC19	0.021	**0.077**	0.132	2.711	**0.107**	3.405	0.053	2.400	1.270
RC20	0.021	**0.081**	0.140	2.665	**0.110**	3.248	0.053	2.400	1.270

Note: In this table, we examine the sensitivity of our estimated corn acreage effects to a series of additional control variables described in Table 12. We do so separating the consquences of data availability from the consequences of the control variable(s). In panel A, We show point estimates of the elasticity of nitrogen concentration with respect to corn acreage along with their 95% confidence intervals and the t statistics using the same observations as the ones for which the control variable is available in the absence of the control variable(s). In panel B, we show the point estimate and t statistic of the elasticities in the presence of the control variable(s). In panel C, we show the assumed increase in acres (Δ acres), the mean nitrogen concentration ($\bar{y}$), and the 75% percentile of precipitation (precip) used to evaluate the acreage effects. The bold-faced entries show elasticities that are significant at 5% level. The estimates pertain to the EAST-100 (U.S., east of the 100th meridian) and are based on USGS-NWIS data for nitrogen concentration. For additional details, see Section 8.2.

Table 16. Elasticity of nitrogen concentration with respect to corn acreage panel FE regressions, temporal variation

A. counties							
model	estim	s.e.	t-stat	p-value	Δ acres	$\bar{y}$	precip.
baseline	0.117	0.035	3.353	0.001	0.010	2.450	1.270
1970s	0.013	0.049	0.269	0.788	0.010	2.450	1.270
1980s	0.171	0.049	3.491	0.001	0.010	2.450	1.270
1990s	0.171	0.038	4.449	0.000	0.010	2.450	1.270
2000s	0.146	0.050	2.907	0.004	0.010	2.450	1.270
2010s	0.134	0.051	2.621	0.010	0.010	2.450	1.270
B. hydrologic units							
model	estim	s.e.	t-stat	p-value	Δ acres	$\bar{y}$	precip.
baseline	0.131	0.042	3.100	0.002	0.008	2.100	1.270
1970s	0.037	0.051	0.720	0.473	0.008	2.100	1.270
1980s	0.202	0.051	3.971	0.000	0.008	2.100	1.270
1990s	0.216	0.056	3.841	0.000	0.008	2.100	1.270
2000s	0.102	0.056	1.821	0.071	0.008	2.100	1.270
2010s	0.128	0.061	2.101	0.038	0.008	2.100	1.270
C. monitoring sites							
model	estim	s.e.	t-stat	p-value	Δ acres	$\bar{y}$	precip.
baseline	0.077	0.028	2.729	0.007	0.053	2.400	1.270
1970s	-0.011	0.034	-0.325	0.746	0.053	2.400	1.270
1980s	0.096	0.034	2.842	0.005	0.053	2.400	1.270
1990s	0.148	0.030	4.853	0.000	0.053	2.400	1.270
2000s	0.111	0.034	3.281	0.001	0.053	2.400	1.270
2010s	0.112	0.051	2.210	0.029	0.053	2.400	1.270

Note: The estimates refer to the elasticity of nitrogen concentration with respect to corn acreage. For clarity, we also show the assumed increase in acres (Δ acres), the mean nitrogen concentration ($\bar{y}$), and the 75% percentile of precipitation (precip) used to evaluate the acreage effects. The estimates pertain to the EAST-100 (U.S., east of the 100th meridian) and are based on USGS-NWIS data for nitrogen concentration. For additional details, see Section 8.2.

Table 17. Elasticity of nitrogen concentration with respect to corn acreage panel FE regressions, spatial variation

A. counties							
model	estim	s.e.	t-stat	p-value	Δ acres	$\bar{y}$	precip.
baseline	0.117	0.035	3.353	0.001	0.010	2.450	1.270
Top	0.153	0.043	3.545	0.001	0.010	2.450	1.270
Other	0.005	0.040	0.118	0.906	0.010	2.450	1.270
B. hydrologic units							
model	estim	s.e.	t-stat	p-value	Δ acres	$\bar{y}$	precip.
baseline	0.131	0.042	3.100	0.002	0.008	2.100	1.270
Top	0.169	0.053	3.186	0.002	0.008	2.100	1.270
Other	0.006	0.054	0.118	0.906	0.008	2.100	1.270
C. monitoring sites							
model	estim	s.e.	t-stat	p-value	Δ acres	$\bar{y}$	precip.
baseline	0.077	0.028	2.729	0.007	0.053	2.400	1.270
Top	0.100	0.032	3.136	0.002	0.053	2.400	1.270
Other	0.008	0.038	0.208	0.836	0.053	2.400	1.270

Note: The estimates refer to the elasticity of nitrogen concentration with respect to corn acreage. For clarity, we also show the assumed increase in acres (Δ acres), the mean nitrogen concentration ($\bar{y}$), and the 75% percentile of precipitation (precip) used to evaluate the acreage effects. The estimates pertain to the EAST-100 (U.S., east of the 100th meridian) and are based on USGS-NWIS data for nitrogen concentration. For additional details, see Section 8.2.

Table 18. Panel FE regressions robustness checks, streamflow

A. counties			**B. monitoring sites**		
	all	streamflow		all	streamflow
acres	-9.566**	-15.821***	acres	-1.359**	-6.070***
	(4.495)	(4.252)		(0.533)	(1.493)
acres × prec	13.517***	17.665***	acres × prec	1.566***	6.030***
	(3.805)	(3.229)		(0.477)	(1.335)
R-squared	0.56	0.69	R-squared	0.86	0.86
Observations	64,121	33,335	Observations	56,466	54,113
elast	0.1173	0.1021	elast	0.0765	0.1932
elast s.e.	0.0350	0.0386	elast s.e.	0.0280	0.0795
elast t-stat	3.3531	2.6424	elast t-stat	2.7295	2.4301
elast low	0.0487	0.0264	elast low	0.0216	0.0374
elast high	0.1859	0.1778	elast high	0.1315	0.3491

Note: The estimates are for the specifications in column C8 of Table 4 and Table 6 for counties and monitoring sites, respectively. The results in the Streamflow column of panel A (panel B) are based on monitoring sites (counties) downstream (upstream) of the counties (monitoring sites). The estimates pertain to the EAST-100 (U.S., east of the 100th meridian) and are based on USGS-NWIS data for nitrogen concentration. For additional details, see Section 8.2.

Table 19. Panel FE regressions robustness checks, runoff

A. counties			B. hydrologic units			C. monitoring sites		
	precip.	runoff		precip.	runoff		precip.	runoff
acres	-9.566**	-0.521	acres	-18.535***	-3.473	acres	-1.359**	-0.385
	(4.495)	(2.692)		(6.704)	(3.340)		(0.533)	(0.268)
acres × prec	13.517***		acres × prec	21.895***		acres × prec	1.566***	
	(3.805)			(6.168)			(0.477)	
acres × runoff		0.002***	acres × runoff		0.003***	acres × runoff		0.000***
		(0.001)			(0.001)			(0.000)
R-squared	0.56	0.56	R-squared	0.68	0.68	R-squared	0.86	0.86
Observations	64,121	62,420	Observations	17,943	17,387	Observations	56,466	54,387
elast	0.1173	0.1204	elast	0.1307	0.1233	elast	0.0765	0.0859
elast s.e.	0.0350	0.0324	elast s.e.	0.0422	0.0359	elast s.e.	0.0280	0.0221
elast t-stat	3.3531	3.7165	elast t-stat	3.0995	3.4353	elast t-stat	2.7295	3.8834
elast low	0.0487	0.0569	elast low	0.0481	0.0529	elast low	0.0216	0.0426
elast high	0.1859	0.1839	elast high	0.2134	0.1936	elast high	0.1315	0.1293

Note: The estimates are for the specifications in column C8 of Table 4, Table 5, and Table 6 for counties, hydrologic units, and monitoring sites, respectively. The estimates pertain to the EAST-100 (U.S., east of the 100th meridian) and are based on USGS-NWIS data for nitrogen concentration. For additional details, see Section 8.2.

Table 20. Panel FE regressions robustness checks, censoring

A. counties				B. hydrologic units			
	excl	cens	zero		excl	cens	zero
acres	-9.566**	-11.043***	-11.276***	acres	-18.535***	-18.849***	-20.641***
	(4.495)	(3.795)	(3.935)		(6.704)	(6.665)	(6.916)
acres × prec	13.517***	15.602***	15.128***	acres × prec	21.895***	23.659***	25.316***
	(3.805)	(3.356)	(3.530)		(6.168)	(6.254)	(6.432)
R-squared	0.56	0.57	0.59	R-squared	0.68	0.69	0.69
Observations	64,121	64,670	64,676	Observations	17,943	18,466	18,469
elast	0.1173	0.1354	0.1225	elast	0.1307	0.1579	0.1623
elast s.e.	0.0350	0.0315	0.0285	elast s.e.	0.0422	0.0453	0.0426
elast t-stat	3.3531	4.3008	4.2925	elast t-stat	3.0995	3.4874	3.8088
elast low	0.0487	0.0737	0.0666	elast low	0.0481	0.0691	0.0788
elast high	0.1859	0.1970	0.1784	elast high	0.2134	0.2466	0.2458

C. monitoring sites			
	excl	cens	zero
acres	-1.359**	-1.298**	-1.544***
	(0.533)	(0.528)	(0.528)
acres × prec	1.566***	1.744***	1.863***
	(0.477)	(0.474)	(0.480)
R-squared	0.86	0.86	0.85
Observations	56,466	62,170	62,181
elast	0.0765	0.1114	0.0999
elast s.e.	0.0280	0.0302	0.0309
elast t-stat	2.7295	3.6941	3.2343
elast low	0.0216	0.0523	0.0394
elast high	0.1315	0.1706	0.1605

Note: The estimates are for the specifications in column C8 of Table 4, Table 5, and Table 6 for counties, hydrologic units, monitoring sites, respectively. In column excl, we replicate the estimates from column C8 of Table 4, Table 5, and Table 6. In column cens, we set the value of nitrogen concentration equal to the censoring point (lower reporting limit). In column zero, we set the value of nitrogen concentration equal to zero. The estimates pertain to the EAST-100 (U.S., east of the 100th meridian) and are based on USGS-NWIS data for nitrogen concentration. For additional details, see Section 8.2.

Table 21. Elasticity of nitrogen concentration with respect to corn acreage panel FE regressions, alternative radii

A. counties							
miles	estim	s.e.	t-stat	p-value	Δ acres	$\bar{y}$	precip.
50	0.117	0.035	3.353	0.001	0.010	2.450	1.270
100	0.096	0.025	3.907	0.000	0.010	2.450	1.270
200	0.072	0.017	4.159	0.000	0.010	2.450	1.270
B. monitoring sites							
miles	estim	s.e.	t-stat	p-value	Δ acres	$\bar{y}$	precip.
50	0.077	0.028	2.729	0.007	0.053	2.400	1.270
100	0.021	0.010	2.125	0.036	0.053	2.400	1.270
200	0.005	0.004	1.330	0.186	0.053	2.400	1.270

Note: The estimates refer to elasticities of nitrogen concentration with respect to corn acres that are calculated for alternative radii of 50, 100, and 200 miles. The estimates for the 50-mile radius are the ones for the baseline results in column C8 in Table 4 and Table 6. For clarity, we also show the assumed increase in acres (Δ acres), the mean nitrogen concentration ($\bar{y}$), and the 75% percentile of precipitation (precip) used to evaluate the acreage effects. The estimates pertain to the EAST-100 (U.S., east of the 100th meridian) and are based on USGS-NWIS data for nitrogen concentration. For additional details, see Section 8.2.

Table 22. Elasticity of nitrogen concentration with respect to corn acreage panel FE regressions, data cleaning following Keiser and Shapiro (2018)

A. counties							
sample	estim	s.e.	t-stat	p-value	Δ acres	$\bar{y}$	precip.
baseline	0.117	0.035	3.353	0.001	0.010	2.450	1.270
KS	0.120	0.035	3.451	0.001	0.010	2.450	1.270
B. hydrologic units							
sample	estim	s.e.	t-stat	p-value	Δ acres	$\bar{y}$	precip.
baseline	0.131	0.042	3.100	0.002	0.008	2.100	1.270
KS	0.131	0.042	3.115	0.002	0.008	2.100	1.270
C. monitoring sites							
sample	estim	s.e.	t-stat	p-value	Δ acres	$\bar{y}$	precip.
baseline	0.077	0.028	2.729	0.007	0.053	2.400	1.270
KS	0.077	0.028	2.770	0.006	0.053	2.400	1.270

Note: The estimates refer to the elasticity of nitrogen concentration with respect to corn acres. For clarity, we also show the assumed increase in acres (Δ acres), the mean nitrogen concentration ($\bar{y}$), and the 75% percentile of precipitation (precip) used to evaluate the acreage effects. The filtering of the nitrogen concentration data following Keiser and Shapiro (2018) is discussed in Section 8. The estimates pertain to the EAST-100 (U.S., east of the 100th meridian) and are based on USGS-NWIS data for nitrogen concentration. For additional details, see Section 8.2.

Table 23. Elasticity of nitrogen concentration with respect to corn acreage panel FE regressions, seasonality

A. counties							
period	est.	s.e.	t-stat	p-value	Δ acres	$\bar{y}$	precip.
jan-dec	0.117	0.035	3.353	0.001	0.010	2.450	1.270
jan-jun	0.060	0.030	2.037	0.044	0.010	2.604	0.655
mar-aug	0.055	0.028	1.961	0.052	0.010	2.528	0.705
apr-sep	0.063	0.029	2.140	0.034	0.010	2.461	0.701
may-oct	0.080	0.035	2.270	0.025	0.010	2.435	0.688
B. hydrologic units							
period	estim	s.e.	t-stat	p-value	Δ acres	$\bar{y}$	precip.
jan-dec	0.131	0.042	3.100	0.002	0.008	2.100	1.270
jan-jun	0.070	0.035	2.008	0.047	0.008	2.214	0.651
mar-aug	0.070	0.032	2.234	0.027	0.008	2.164	0.697
apr-sep	0.076	0.040	1.902	0.059	0.008	2.123	0.700
may-oct	0.071	0.043	1.672	0.097	0.008	2.110	0.693
c. monitoring sites							
period	estim	s.e.	t-stat	p-value	Δ acres	$\bar{y}$	precip.
jan-dec	0.077	0.028	2.729	0.007	0.053	2.400	1.270
jan-jun	0.054	0.031	1.737	0.085	0.053	2.328	0.653
mar-aug	0.086	0.034	2.549	0.012	0.053	2.335	0.700
apr-sep	0.111	0.040	2.741	0.007	0.053	2.320	0.705
may-oct	0.086	0.044	1.973	0.051	0.053	2.335	0.700

Note: We show the sensitivity of the corn acreage effects on nitrogen concentration that are calculated using alternative time periods during the year to measure nitrogen concentration and precipitation. The estimates for the 12-month period January–December (jan-dec) are the ones for results in column C8 in Table 4 and Table 6. For clarity, we also show the assumed increase in acres (Δ acres), the mean nitrogen concentration ($\bar{y}$), and the 75% percentile of precipitation (precip) used to evaluate the acreage effects. For additional details, see Section 8.

Table 24. Elasticity of nitrogen concentration with respect to corn acreage panel FE regressions, inference

A. counties							
clustering	estim	s.e.	t-stat	p-value	Δ acres	$\bar{y}$	precip.
baseline	0.117	0.035	3.353	0.001	0.010	2.450	1.270
HUC2	0.117	0.035	3.307	0.007	0.010	2.450	1.270
YEAR	0.117	0.043	2.749	0.008	0.010	2.450	1.270
HUC2YEAR	0.117	0.042	2.805	0.005	0.010	2.450	1.270
HUC4YEAR	0.117	0.035	3.364	0.001	0.010	2.450	1.270
B. hydrologic units							
clustering	estim	s.e.	t-stat	p-value	Δ acres	$\bar{y}$	precip.
baseline	0.131	0.042	3.100	0.002	0.008	2.100	1.270
HUC2	0.131	0.048	2.749	0.018	0.008	2.100	1.270
YEAR	0.131	0.038	3.429	0.001	0.008	2.100	1.270
HUC2YEAR	0.131	0.040	3.269	0.001	0.008	2.100	1.270
HUC4YEAR	0.131	0.040	3.286	0.001	0.008	2.100	1.270
C. monitoring sites							
clustering	estim	s.e.	t-stat	p-value	Δ acres	$\bar{y}$	precip.
baseline	0.077	0.028	2.729	0.007	0.053	2.400	1.270
HUC2	0.077	0.034	2.238	0.045	0.053	2.400	1.270
YEAR	0.076	0.038	2.016	0.050	0.053	2.400	1.270
HUC2YEAR	0.077	0.038	2.010	0.045	0.053	2.400	1.270
HUC4YEAR	0.077	0.033	2.292	0.022	0.053	2.400	1.270

Note: The estimates refer to the elasticity of nitrogen concentration with respect to corn acreage for the models in column C8 of tables 4–6. For clarity, we also show the assumed increase in acres (Δ acres) that is equal to a 10% of the average acres, the mean nitrogen concentration ($\bar{y}$), and the 75% percentile of precipitation (precip) used to evaluate the acreage effects. The estimates pertain to the EAST-100 (U.S., east of the 100th meridian) and are based on USGS-NWIS data for nitrogen concentration. For additional details, see Section 8.2.

Table 25. Areal extent of the Gulf hypoxic zone and nitrogen flux

monitoring site	site name	drainage	time	obs	years	effect	delta	flux	hzone
USGS-05465500	IOWA RIVER AT WAPELLO, IA	12500	SPRING	28	1982–2010	3590	17690	29850	13142
USGS-05420500	MISSISSIPPI RIVER AT CLINTON, IA	85600	SPRING	25	1982–2010	2558	18416	43680	13683
USGS-07022000	MISSISSIPPI RIVER AT THEBES, IL	713200	SPRING	28	1982–2010	1148	76050	238068	13142
USGS-05587455	MISSISSIPPI RIVER BELOW GRAFTON, IL	171300	SPRING	27	1982–2010	3068	62352	164441	12955
USGS-07373420	MISSISSIPPI RIVER NEAR ST. FRANC., LA	1125300	SPRING	28	1982–2010	768	97129	361139	13142
USGS-06934500	MISSOURI RIVER AT HERMANN, MO	522500	SPRING	28	1982–2010	2163	18868	51886	13142
USGS-03612500	OHIO RIVER NEAR GRAND CHAIN, IL	203100	SPRING	28	1982–2010	564	35863	94925	13142

Note: The drainage area (drainage) is in square miles. The effect of nitrogen flux on the areal extent of the hypoxic zone (effect) is in square kilometers and is estimated using the quadratic regression equation in Whittaker et al. (2015) and annual data. The assumed increase in nitrogen flux (delta) is in metric tons. The average nitrogen flux (flux) is in metric tons. The average size of the hypoxic zone (hzone) is in square kilometers. The effect is calculated assuming an increase equal to 1 standard deviation from the average flux in metric tons. The 7 monitoring sites are the ones from Murphy et al. (2013). For additional details, see the discussion on page 42.

Table 26. CRP acres and nitrogen reduction within 100 miles from USGS-05587455 in the Mississippi River below Grafton, IL

year	CRPD	CRPA	CORN	CONC	FLOW	SHARE	BASE	CF	CHNG	COST-N	TVC	PS
1990	12.78	106	463	3.00	3030	23	287.000	293.586	6.586	1.94	6.95	5.84
1991	12.86	111	511	4.14	3810	22	498.000	508.786	10.786	1.19	7.28	5.58
1992	14.31	125	543	4.29	3350	23	453.000	463.424	10.424	1.37	8.67	5.63
1993	15.46	137	480	3.21	7100	29	718.000	738.548	20.548	0.75	9.14	6.33
1994	15.14	137	535	2.49	3640	26	286.000	293.349	7.349	2.06	8.95	6.19
1997	13.90	132	573	3.39	3410	23	365.000	373.445	8.445	1.65	8.70	5.20
1998	12.90	121	544	4.11	3920	22	508.000	519.334	11.334	1.14	9.42	3.48
1999	12.47	118	571	4.14	4020	21	525.000	535.880	10.880	1.15	8.06	4.41
2000	12.48	120	608	3.12	2420	20	238.000	242.717	4.717	2.65	8.29	4.19
2001	13.29	130	608	3.35	3890	21	411.000	419.820	8.820	1.51	8.67	4.62
2002	13.04	130	602	3.01	3590	22	341.000	348.340	7.340	1.78	8.51	4.52
2003	12.63	128	607	2.47	2320	21	181.000	184.807	3.807	3.32	9.02	3.61
2004	12.39	128	624	3.19	3070	21	309.000	315.354	6.354	1.95	8.81	3.57
2005	12.14	130	656	4.02	3040	20	385.000	392.607	7.607	1.60	8.68	3.46
2006	11.96	131	586	2.97	2200	22	206.000	210.619	4.619	2.59	8.77	3.19
2007	11.86	133	692	3.88	3220	19	394.000	401.579	7.579	1.56	8.11	3.75
2008	10.94	124	589	3.42	5340	21	576.000	588.110	12.110	0.90	7.66	3.28
2009	10.44	118	646	3.66	4180	18	482.000	490.810	8.810	1.19	7.49	2.96
2010	9.93	113	679	2.88	6140	17	558.000	567.303	9.303	1.07	7.77	2.16
2011	10.54	113	698	2.98	5010	16	471.000	478.637	7.637	1.38	10.28	0.26
2012	10.71	112	748	2.29	2120	15	153.000	155.286	2.286	4.69	9.72	1.00
2013	8.05	79	518	3.08	3950	15	384.000	389.835	5.835	1.38	3.94	4.11
2014	9.14	75	594	2.58	3830	13	312.000	315.918	3.918	2.33	3.89	5.25
2015	10.17	81	575	3.22	3710	14	377.000	382.303	5.303	1.92	5.20	4.97
2016	10.81	85	681	3.72	4700	12	552.000	558.898	6.898	1.57	8.13	2.68

Note: The monitoring site USGS-5587455 is located before the confluence of the Missouri River to the Mississippi River. It accounts for the confluence of the South Fork Iowa River, the Iowa River, the Des Moines River, and the Illinois River. **CRPD:** CRP dollars (millions); **CRPA:** CRP acres in thousands; **CORN:** corn planted acres in thousands; **CONC:** nitrogen concentration in mg/L; **FLOW:** flow in cubic meters per second; **SHARE:** CRP acres as a fraction of corn acres; **BASE:** baseline nitrogen flux in million metric tons per year); **CF**: counterfactual nitrogen flux in million metric tons per year assuming CRP acres turn into CORN acres; **CHNG**: change in flux (counterfactual-baseline) in million metric tons; **COST-N:** cost of nitrogen, in thousands of dollars per ton, caculated as the total CRP dollars divided by the change in nitrogen flux; **TVC:** total variable cost in millions of dollars; **PS:** producer surplus in millions of dollars. For additional details, see the discussion on page 44.

Table 27. Scenarios for NRCS practices #391, riparian forest buffer

scenario	state	unit	cost	unit size	cost/unit
15 - SEEDING	KS	AC	3223	10	322
01 - DIRECT SEEDING	OH	AC	5714	5	1143
01 - DIRECT SEEDING	MO	AC	5827	5	1165
01 - DIRECT SEEDING	IA	AC	5875	5	1175
01 - DIRECT SEEDING	IL	AC	5923	5	1185
01 - DIRECT SEEDING (FI)	KS	AC	3087	2.5	1235
01 - DIRECT SEEDING (FI)	NE	AC	3145	2.5	1258
02 - BARE-ROOT TREES AND SHRUBS	IN	AC	6423	5	1285
02 - BARE-ROOT TREES AND SHRUBS	IA	AC	6432	5	1286
02 - BARE-ROOT TREES AND SHRUBS	IL	AC	6467	5	1293
02 - BARE-ROOT, MACHINE PLANTED (FI)	KS	AC	4528	3	1509
02 - BARE-ROOT, MACHINE PLANTED (FI)	NE	AC	4581	3	1527
18 - BARE-ROOT, MACHINE PLANTED	KS	AC	5136	3	1712
03 - SMALL CONTAINER, MACHINE PLANTED (FI)	KS	AC	7228	3	2409
03 - SMALL CONTAINER, MACHINE PLANTED (FI)	NE	AC	7258	3	2419
04 - BARE-ROOT, MACHINE PLANTED	MN	AC	7616	3	2539
20 - SMALL CONTAINER, MACHINE PLANTED	KS	AC	7736	3	2579
17 - BARE-ROOT, HAND PLANTED	KS	AC	7994	3	2665
21 - LARGE CONTAINER, HAND PLANTED	KS	AC	8436	3	2812
19 - SMALL CONTAINER, HAND PLANTED	KS	AC	10593	3	3531
03 - BARE-ROOT, HAND PLANTED	MN	AC	10669	3	3556
02 - CUTTINGS	MN	AC	4651	1	4651
16 - CUTTINGS	KS	AC	4879	1	4879

Note: For additional details, see the discussion on page 45.

Table 28. scenarios for NRCS practices #656, constructed wetland

scenario	state	unit	cost	unit size	cost/unit
12 - CONSTRUCTED WETLAND, EARTHWORK ONLY	IA	AC	4940	1	4940
12 - CONSTRUCTED WETLAND, EARTHWORK ONLY	IL	AC	5230	1	5230
11 - MEDIUM, 0.1 TO 0.5 AC	MN	AC	1350	.3	5400
03 - LARGE, MORE THAN 1.0 AC.	NE	AC	9418	1.3	7534
03 - LARGE, MORE THAN 1.0 AC.	KS	AC	9457	1.3	7565
02 - CONSTRUCTED WETLAND, LIGHT PLANTING	IA	AC	8579	1	8579
02 - CONSTRUCTED WETLAND, LIGHT PLANTING	OH	AC	8590	1	8590
02 - CONSTRUCTED WETLAND, LIGHT PLANTING	IL	AC	9028	1	9028
02 - LARGE, 0.5 TO 1.0 AC.	NE	AC	9702	1	9702
02 - LARGE, 0.5 TO 1.0 AC.	KS	AC	9735	1	9735
01 - CONSTRUCTED WETLAND, DENSE PLANTING	IA	AC	11214	1	11214
01 - CONSTRUCTED WETLAND, DENSE PLANTING	OH	AC	11217	1	11217
01 - CONSTRUCTED WETLAND, DENSE PLANTING	IN	AC	11310	1	11310
01 - CONSTRUCTED WETLAND, DENSE PLANTING	IL	AC	11778	1	11778
01 - MEDIUM, 0.5 AC OR LESS	NE	AC	3478	.3	13912
01 - MEDIUM, 0.5 AC OR LESS	KS	AC	3497	.3	13988

Note: For additional details, see the discussion on page 46.

Table 29. Change in social welfare due to a decrease in corn acreage

period	state	bushels	price	%Δacres	ΔTR	ΔCS	ΔPS	ΔTS
2014-2016	ALL	14.32	3.56	-1	-0.73	-1.03	-0.60	-1.64
2014-2016	ALL	14.32	3.56	-5	-3.50	-5.11	-2.85	-7.96
2014-2016	ALL	14.32	3.56	-10	-6.69	-10.09	-5.26	-15.34
2014-2016	ALL	14.32	3.56	-15	-9.57	-14.94	-7.21	-22.15
2014-2016	ALL	14.32	3.56	-20	-12.14	-19.68	-8.68	-28.36

Note: We report average annual total quantity (bushels) and average price (price) for 2014–2016 using data from the USDA HTR. We also report the assumed percentage change in corn acreage (%Δacres). Finally, we report the change in total revenue (ΔTR), change in consumer surplus (ΔCS), change in producer surplus (ΔPS), and change in total surplus (ΔTS), in dollars. The bushels and dollars are in billions. The price is in dollars per bushel. Our calculations do not account for improved environmental outcomes due to reduction in nitrogen pollution. For additional details, see Section 9.

Table 30. Gains due to reduced nitrogen load in the Gulf of Mexico

period	%Δacres	elast.	conc.	flow	load	Δflux	gains
2014-2016	-1	0.100	3.057	22,800	2,198,358	−2,198	0.035
2014-2016	-5	0.100	3.057	22,800	2,198,358	−10,992	0.174
2014-2016	-10	0.100	3.057	22,800	2,198,358	−21,984	0.348
2014-2016	-15	0.100	3.057	22,800	2,198,358	−32,975	0.522
2014-2016	-20	0.100	3.057	22,800	2,198,358	−43,967	0.696

Note: We report the average flow (cubic meters/second) for years 2014–2016 from column F (Total Mississippi-Atchafalaya River) here and the annual nitrogen load (flow × concentration) in metric tons of the Mississippi River in the Gulf. We also report the reduction in nitrogen flux (Δflux) in metric tons due to the assumed percentage change in corn acreage (Δacres) and the elasticity of nitrogen concentration with respect to corn acres (elast). Finally, we report gains in billions of dollars due to reduced nitrogen load in the Gulf assuming $15.84 (2008$) per kilogram of nitrogen (declines in fisheries and estuarine/marine habitat, coastal zone, median) from Sobota et al. (2015). For additional details, see Section 9.

A Appendix

A.1 Studies related to damage costs

Taylor and Heal (2021) estimate the economic effects of U.S. algal blooms generated by nitrogen fertilizers excluding health effects, which, according to the authors, can be viewed as lower bounds for the external costs of the fertilizers. Based on their estimates, 1 ton of nitrogen entails an external (damage) cost of $583 (they also report the range $370–$1,400) to downstream coastal counties. Blottnitz et al. (2006) estimate damage costs of nitrogen fertilizer equal to €0.3 per kilogram (see their Table 2) that is about 60% of the market price of fertilizer (farmers' private cost) at the time. Damages pertain to global warming due to the production of fertilizer, damages due to air pollutants emitted during the production of fertilizer, global warming due to the application of fertilizer, eutrophication due to leaching of fertilizer, and damages due to to the release of volatile substances from fertilizer.

Sobota et al. (2015) compile damage costs associated with specific nitrogen inputs from Compton et al. (2011) and Van Grinsven et al. (2013b) per kilogram of nitrogen input (see their Table 1). They provide damage costs for air/climate, land, freshwater, drinking water, and coastal zones. The damages associated with coastal nitrogen loadings (2008$), which are relevant for some analysis in this paper, are due to recreational use ($6.38), and declines in fisheries and estuarine/marine habitat ($15.84). The damages from recreational use are for the Chesapeake Bay and are from Figure 2 in Birch et al. (2011). Van Grinsven et al. (2013a) provide a range of damage costs from nitrogen pollution that account for human health, ecosystems, and climate from nitrogen for E.U. 27 in 2008 (see their Table 2). The range of the total cost attributed to nitrogen loss to rivers and seas from agricultural sources is €25–100 billion per year. The cost of €25–100 billion per year implies a cost of €4.11–16.43 per pound of nitrogen using $0.6 \times 4.6 = 2.6$ million tons of nitrogen attributed to agricultural sources. At an exchange rate of about $1.5/€ in 2008, we have cost of 6.05–24.20 per pound of nitrogen in 2008$.

UCS (2020) found that, on average, 87,000 tons of excess nitrogen (per year) have washed off Midwest cropland into the Mississippi and Atchafalaya rivers, and ultimately into the Gulf of Mexico. This nitrogen has contributed between $552 million and $2.4 billion (2018$) of damages to ecosystem services generated by fisheries and marine habitat every year during 1980–2017. Ho et al. (2019) argue that freshwater algal blooms result in economic losses of more than $4 billion annually in the U.S. alone (citing Kudela et al. (2015)), primarily due to harm to aquatic food production, recreation and tourism, and drinking water supplies. Dodds et al. (2009) calculate potential annual value losses in recreational water usage, waterfront real estate, spending on re-

covery of threatened and endangered species, and drinking water, due to nutrient pollution and the resulting eutrophication in U.S. freshwaters. The combined costs are approximately $2.2 billion annually. In an early paper, Anderson et al. (2000) discuss annual economic impacts from harmful U.S. algal blooms. The estimates (2000$) are for 1987–1992 and pertain to public health, commercial fishery, recreation & tourism, and monitoring management. Their low, average, and high estimates of the 15-year capitalized impacts are: $309 million, $449 million, and $743 million, respectively (see also GOMNTF (2015)).

Abatement and averted damage costs. Xu et al. (2021) use an integrated assessment model to evaluate the effects of energy and nitrogen fertilizer prices on nitrogen runoff to the Gulf and to assess abatement costs. They find that changes in energy costs have a modest impact on land-use change and nitrogen runoff, while the price of nitrogen fertilizer has a more notable effect on acreage and nitrogen delivery to the Gulf. The cost of achieving the Hypoxia Task Force (HTF) goal for reducing the nitrogen runoff to the Gulf is $6 billion, which corresponds to the average cost of $29.3 per kilogram of nitrogen runoff abatement.

UCS (2020) show how improved agricultural practices in the Midwest can offer economic benefits to the Gulf fishing industry. Their findings are based on nitrogen-loss reduction scenarios achieved through changes in agricultural practices, derived from four previously published studies (NRCS (2017a), Kling et al. (2014), Rabotyagov et al. (2014a), and Tallis et al. (2019)). Their calculations show that 98 million to 2.8 billion (2018$) in damage costs to Gulf fisheries and marine habitat could have been averted every year from 1980–2017 through shifts in agricultural practices (see their Figure 5 and Appendix 3 for details). Moreover, reductions in the May Gulf nitrogen loading of the Mississippi and Atchafalaya rivers due to shifts in agricultural practices upstream ranged from just over 5% to 45%.

Tallis et al. (2019) analyze 5 financial mechanisms to increase adoption of beneficial practices in the Mississippi River Basin (MRB) aiming to reduce GHG emissions and nutrient runoff in Iowa, Illinois, Indiana, and Ohio. They estimate the nutrient runoff savings and the associated costs.[44] The 5 mechanisms could save up approximately 168,000 tons of nutrient runoff each year, which is equivalent to a 25% reduction (see their Table 1). This reduction exceeds the intermediate HTF target (20% reduction by 2025) and achieves more than half of the long-term HTF target (45% reduction) for the Gulf. The reductions could be achieved at a cost of about $15 per kilogram of nitrate reduced for a total cost of $2.6 billion.

[44]Examples of beneficial practices considered include cover crops, nutrient management, land retirement, conservation tillage, and sub-surface tile management. The five mechanisms are: crop insurance incentives, increased private technical services, expansion and redistribution of Farm Bill funds, creation of new state funds, redirection of federal disaster funds. In general, nutrient management costs include annualized installation and implementation costs, and foregone income associated with changes in crop yields net of savings from reduced commercial fertilizer purchases.

Marshall et al. (2018) model changes that would achieve the 45% reduction in nitrogen and phosphorous loads from cropland to the Gulf at least cost to consumers and producers using 2 implementation scenarios, the USDA REAP model, and data from the USDA CEAP.[45] In the Gulf Constraints (GC) scenario, the objective is to reduce overall nutrient loads regardless of where they originate. In the Regional Constraints (RC) scenario, they require a 45% reduction in nutrient loads in each of the 135 REAP regions in the MRB. The study aims to identify the combination of conservation practices, crop rotations, tillage, irrigation, and land-use change that meets nutrient-reduction goals at least cost.

Under the GC scenario, domestic consumer surplus, falls an estimated 2.5%, or $1.9 billion relative to the baseline case. Under the RC scenario, consumer surplus drops an estimated 4.4%, or $3.3 billion. These dollar amounts do not account for benefits to the consumers due to improvements in water quality. Under the GC scenario, meeting a 45% nutrient-reduction goal at the Gulf is estimated to increase producer net returns within the MRB by 1.3%, or $847 million. The RC scenario, on the other hand, decreases producer net returns by 0.4% or $264 million. Hence, depending on the scenario, the reduction of 3,305 square miles in the average size of the summer hypoxic zone is at a cost between $1.053 (GC) and $3.564 (RC) billion. The implied cost is $123,015 per square kilometer (GC) to $416,358 per square kilometer (RC), which is of the same order of magnitude of the cost in Rabotyagov et al. (2014a) discussed below.

McLellan et al. (2016) use SPARROW to explore the downstream water quality impacts for a set of agricultural conservation and landscape restoration practices in the Upper Mississippi Ohio River basins (UMORB). Their modeling aims to identify scenarios (types and levels of practice implementation at various locations throughout the UMORB) capable of achieving the HTF target of 45% reduction in nitrogen loads delivered to the UMORB outlet at Cairo, IL. The authors consider adaptive nitrogen management (ANM) on 25% of the land in the UMORB, and cover crops on 20% of the land in the UMORB excluding Minnesota and Wisconsin. They then vary the levels and locations of implementation of the buffer, wetland, and stream practices, as needed to achieve a 45% reduction in nitrogen loads at the UMORB outlet. The annualized costs of implementing the proposed restoration scenario is about $1.48 billion in their Table 5 with a detailed breakdown provided in their Table 4.

Whittaker et al. (2015) use SWAT to simulate the reduction in nitrogen loads in the Upper Mississippi River Basin (UMRB) that would result from enrolling all row crop acreage in the USDA CRP. Nitrogen loads at the outlet of the UMRB are used to predict the areal of the hypoxic zone, and net cash farm rent is used as the price for participation in the Conservation Reserve Program

[45] To give some context, this is the reduction required to limit the average size of the summer hypoxic zone in the Gulf from 5,236 square miles (13,561 square kilometers) to 1,931 (5,000 square kilometers, 5-year moving average).

(CRP).[46] Over the course of the 42-year (1960–2001) simulation, the direct CRP costs are more than $388 billion ($9.25 billion annually), and the assumed HTF goal (5-year moving average) of hypoxic area less than 5,000 square kilometers is met in only 2 years (see their graphical abstract).

In Rabotyagov et al. (2014a), a reduction of about 60% in the areal extent of the hypoxic zone in the Gulf is required to achieve the goal of 5,000 square kilometers at a cost of $2.7 billion per year using the HUMUS-CEAP model. Hence, the cost of reduction is equal to $(2.7 \times 10^9)/7{,}500 =$ $360,000 per square kilometer per year—a 60% reduction in 12,500 square kilometers implies 5,000 square kilometers. The reduction requires investment on approximately 178,000 square kilometers of cropland implying an average cost of $62 per acre of cropland.

Kling et al. (2014) use the LUMINATE IAM combining SWAT with a land-use economic model (see their Figure 2) to analyze the costs and benefits of cover crop scenarios in the UMRB and the Ohio-Tennessee River Basin (OTRB).[47] The cover crop scenario in the paper consists of planting rye within the typical 2-year rotations of corn and soybeans or continuous corn, in which the rye cover crop was planted in the fall after corn or soybean harvest and then harvested shortly before planting of the following row crop in the spring. Based on the assumed costs of cover crop adoption from $61.8–$86.6 per hectare ($25–$35 per acre), the cost of reducing a kilogram of nitrogen is $12.02–$17.10 for the UMRB and $7.74–$10.88 for the OTRB (see their Table 4).

Compton et al. (2011) provide the abatement costs for reducing nitrogen from various sources and from integrated projects (Table 3). The abatement cost for agriculture is $10 per kilogram of nitrogen. The abatement cost for agricultural drainage water is $2.71 per kilogram of nitrogen. Both of these abatement costs are from Birch et al. (2011). As a benchmark to the damage costs that captures external costs, the price of nitrogen fertilizer (private cost to the farmers), was 0.44 per kilogram of nitrogen from 1980—2000 and it was 1.21 per kilogram of nitrogen in 2008. Birch et al. (2011) report marginal abatement cost per ton of reactive nitrogen by source in 2000 in the Chesapeake Bay watershed. In the case of nitrate nitrogen from agriculture, the abatement cost per ton of reactive nitrogen is 10,000 according to their Table 2.

USEPA (2001) reports a range of TMDL implementation costs from under $1 billion per year to $4.3 billion per year depending on the efficiency of the TMDLs in Table ES-1. The table breaks down the costs by type of source (point and non-point). Table IV-1 shows leading causes of impairment—nutrients account for 11.5%—and leading sources of impairment (agriculture ac-

[46] Although the CRP average price at the county level is available, where a large part of land goes into the CRP, the authors argue that the average cash rent price (for non-irrigated cropland) is a better estimate.

[47] As the authors discuss, winter cover crops including rye, oats, winter wheat or other close grown crops, are used in the Corn belt region to maintain and improve the quality of soil resources, and mitigate export of sediment and nutrients from cropland landscapes.

counts for 24.6%) based on the States' 303(d) lists in 1998.

Ribaudo et al. (2001) analyze the cost effectiveness of intercepting nitrogen through wetland restoration of 0.4, 2.0, 4.0, and 7.0 million hectares (equivalently, 1, 5, 10, 18 million acres) targeted to maximize nitrogen reductions in the MRB using the USMP market equilibrium and the EPIC biophysical models. Restoring 1 million acres of wetlands was estimated to remove 97,000 tons of nitrogen from field runoff per year (see their Table 1). The welfare cost is $1,022 million and the net welfare cost is $468 million (equivalently, $(468 \times 10^6)/97{,}000 = \$4{,}824$ per ton of nitrogen removed). The cost per ton when restoring 5, 10, and 18 million acres is $3,651, $4,062, and $4,620, respectively. Expressed in dollars per pound of nitrogen removed, the cost is $1.7–$2.2 depending on the wetland acreage. Expressed in dollars per acre of wetland, the cost of nitrogen removed is $345–$468. Assuming that these costs are expressed in 2000$ (it is not clear from the paper, hence, based on the year of publication), when expressed in 2017$ they would be close to 40% higher taking into account only the inflation (GDP implicit price deflator).[48]

Finally, in one of the earliest studies we are aware of, Doering et al. (1999) analyze the costs of the following nitrogen loss reduction strategies in the MRB: (1) EoF nitrogen loss reductions of 20%–60% through economically optimum actions; (2) fertilizer reductions of 20% and 45%, (3) 500% increase in fertilizer tax; (4) wetland acreage of 1–18 million acres (assuming filtering capacity of 15 grams of nitrogen per square meter per year); (5) 27 million acres acres of riparian buffers assuming filtering of 4 grams of nitrogen per square meter per year (equivalently, $4{,}046.86 \times 4/1{,}000 \approx 16.2$ tons per acre per year). The analysis is based on the USDA ERS USMP economic model coupled with the EPIC biophysical model (see Section 4.1 of Topic 6) using the 1997 USDA Economic Baseline and the 1992 NRI and is summarized in their Table 6.1. Depending on the loss reduction strategy, Doering et al. report net social costs of $-$0.1 (hence, savings are possible) to $17.95 billion.

[48] According to the note in Table 2 of the paper, welfare costs include changes in consumer and producer surpluses plus wetland restoration costs. Government costs include restoration and easement costs. Net welfare costs include producer and consumer surplus, wetland restoration costs, erosion benefits, and wetland benefits. Government costs are shown for information only, and are already included under welfare costs. The cost of wetland restoration consists of permanent easement and restoration. Easement costs equal the full opportunity costs of removing productive cropland from production. Restoration costs are the one-time cost of converting cropland back into a functioning wetland. Landowners participating in wetland restoration sell a conservation easement to the government to restore and protect wetlands. The landowner and the NRCS develop a plan for the restoration and the maintenance of the wetland. The government pays for the easement and 100% of the costs of restoring the wetland.

A.2 Water Quality Portal Data

Table A5 shows that the split of surface- and ground-water monitoring sites is roughly 96% and 4%. According to Table A6, 94% of the activities are routine samples. Table A7 shows that approximately 14% of the nitrogen data are subject to censoring. In more detail, the reported value for nitrogen concentration is less than or equal to a historical lower reporting limit. The hydrologic event is equal to routine sample for about 88% of the data. Setting aside storms (5.6%), no other hydrologic event accounts for more than 3% of the data (Table A8). Finally, 98% of the result value measurements are actual with the remaining 2% being estimates (Table A9).

Table A10 shows a breakdown of the nitrogen data by decade keeping in mind that the 2010s stop in 2018. There is a steady decline in the number of monitoring sites, counties, and 8-digit hydrologic units. The decrease is more notable in 2010s and seems to be rather unlikely that the smaller number of years explain the decrease. For example, the number of monitors drops from about 12,700 in the 1970s to about 4,400. We also see a drop in the number of counties and 8-digit hydrologic units from 1,653 (1,334) to 871 (690). The drop in coverage across multiple dimensions documented here is consistent with the findings in Sprague et al. (2017).

Table A11 shows a breakdown of the nitrogen data by site type following the categories in Read et al. (2017). Stream (84%) and lake (8%) site types account for about 92% of all observations. No other site type accounts for more than 3.8%, which is the case of well sites.

Table A12 shows alternative calculations of nitrogen concentration based on parameter codes we identified in the technical information regarding the data and graphics on the U.S. Geological Survey National Water-Quality Assessment annual reporting Web site. These alternative calculations are based on sums of alternative parameter codes. As the table shows, our calculation of nitrogen concentration is essentially identical to those alternative ones.

A.3 Total Nitrogen Calculation using the USGS NWQN Methods

This section describes the approach we followed to construct the USGS-NWQN data as discussed in the main text. The calculation of total nitrogen follows the NWQN methodology described here.

The steps for collecting the data associated with the relevant parameter codes are as follows. First, we downloaded the data from WQP portal using web service calls based on parameter codes. Second, We limited the data to years 1970–2018 and to those for which the activity media name field is "water" and the activity media subdivision name field is "surface water" or "groundwater." Finally we excluded data with for which the organization identifier field is "usgs-ak," "usgs-hi,"

and “usgs-pr.”

We converted mg/L of nitrate or nitrite to mg/L of nitrogen following the NWQN methods. For the parameter codes 71850 and 71851, we multiplied the concentrations (result values) by 0.2259. For the parameter code 71856, we multiplied the concentrations by 0.3045. We calculate dissolved NO_3+NO_2 (nitrate plus nitrite) concentrations following the NWQN methods. Among the parameter codes used in these calculations, parameter code 00631 accounted for 51% of the observations for dissolved nitrate plus nitrite concentrations. Parameter code 00630 accounted for 29% of the observations for dissolved nitrate plus nitrite concentrations, and parameter code 00618 accounted for 13% of the observations. Parameter code 00620 accounted for 5% of the observations while the rest of the parameter codes accounting for the remaining 2% of the observations.

We calculate total organic nitrogen plus ammonia concentrations following NWQN methods. Parameter code 00625 accounted for 93% of the observations. Parameter codes 00605 and 00608 accounted for 5% of the observations, and parameter codes 00605 and 00610 for the remaining 2% of the observations.

We calculate total nitrogen concentrations using the following NWQN methods:

- Method 1: dissolved NO_3+NO_2 + total organic nitrogen plus ammonia (638,135 obs)
- Method 2: dissolved NO_3+NO_2 + 00623+45970 (19,818 obs)
- Method 3: 62854+45970 (16,542 obs)

Once we completed the steps described above, parameter code 00600 accounted for 91% of the observations for nitrogen concentrations. NWQN Method 1 accounted for the remaining 9% of the observations. In all, using imputed nitrogen concentrations following the NWQN methodology allowed us to have a sample of 681,313 obs while using parameter code 00600 allowed to have a sample of 620,816 observations, which is an increase of 9.7% in the number of observations. See also Table A13.

A.4 Alternative Calculations of Total Nitrogen Concentration

For the USGS-NWIS data discussed in the main text, we use the USGS parameter code 00600. We accessed the data from the WQP portal using web service calls based on this parameter code. Subsequently, we limited the data to those for the CONUS for which the activity media name is “water” and the activity media subdivision name is “surface” or “groundwater.” Finally, we excluded observations for which the nitrogen concentration was negative or exceeded 50 mg/L.

For the USGS+EPA data, we used the NWIS parameter codes 00600, 71887, and 62855 in the case of the USGS data. Subsequently, we limited the data to those for the CONUS for which the activity media name is "water" and the activity media subdivision name is "surface" or "groundwater." Finally, we excluded observations for which the nitrogen concentration was negative or exceeded 50 mg/L. In the case of EPA STORET data, we limited the data to those for CONUS for which the activity media name is "water". We also limited the data to those for which the result measure unit code is "mg/L" or "μ g/L." and the characteristic name is one of the following: (i) nitrogen, mixed forms (nh3), (nh4), (ii) organic, (no2) and (no3), (iii) nutrient-nitrogen, (iv) total nitrogen, mixed forms, and (v) total nitrogen, mixed forms (nh3), (nh4), organic, (no2) and (no3).

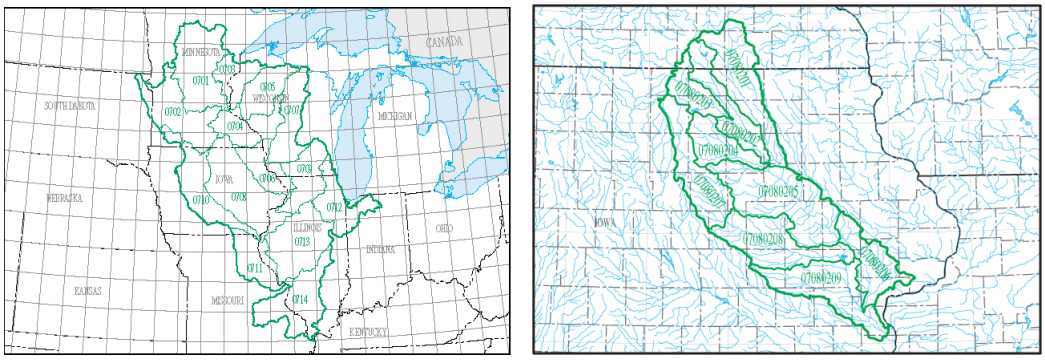
A Appendix Figures

Figure A1. Map of 2- and 4- digit hydrologic units



Note: The U.S. is divided into successively smaller hydrologic units classified into four levels: 21 regions, 221 subregions, 378 accounting units, and 2,264 cataloging units. The hydrologic units are arranged or nested within each other, from the largest geographic area (regions) to the smallest geographic area (cataloging units). Each hydrologic unit is identified by a unique hydrologic unit code consisting of 2 to 8 digits based on the four levels of classification in the hydrologic unit system. The figure reproduces the USGS Watershed Boundary Dataset Subregions Map for the CONUS available here. See also here. For additional details, see the discussion in Section 3.3.

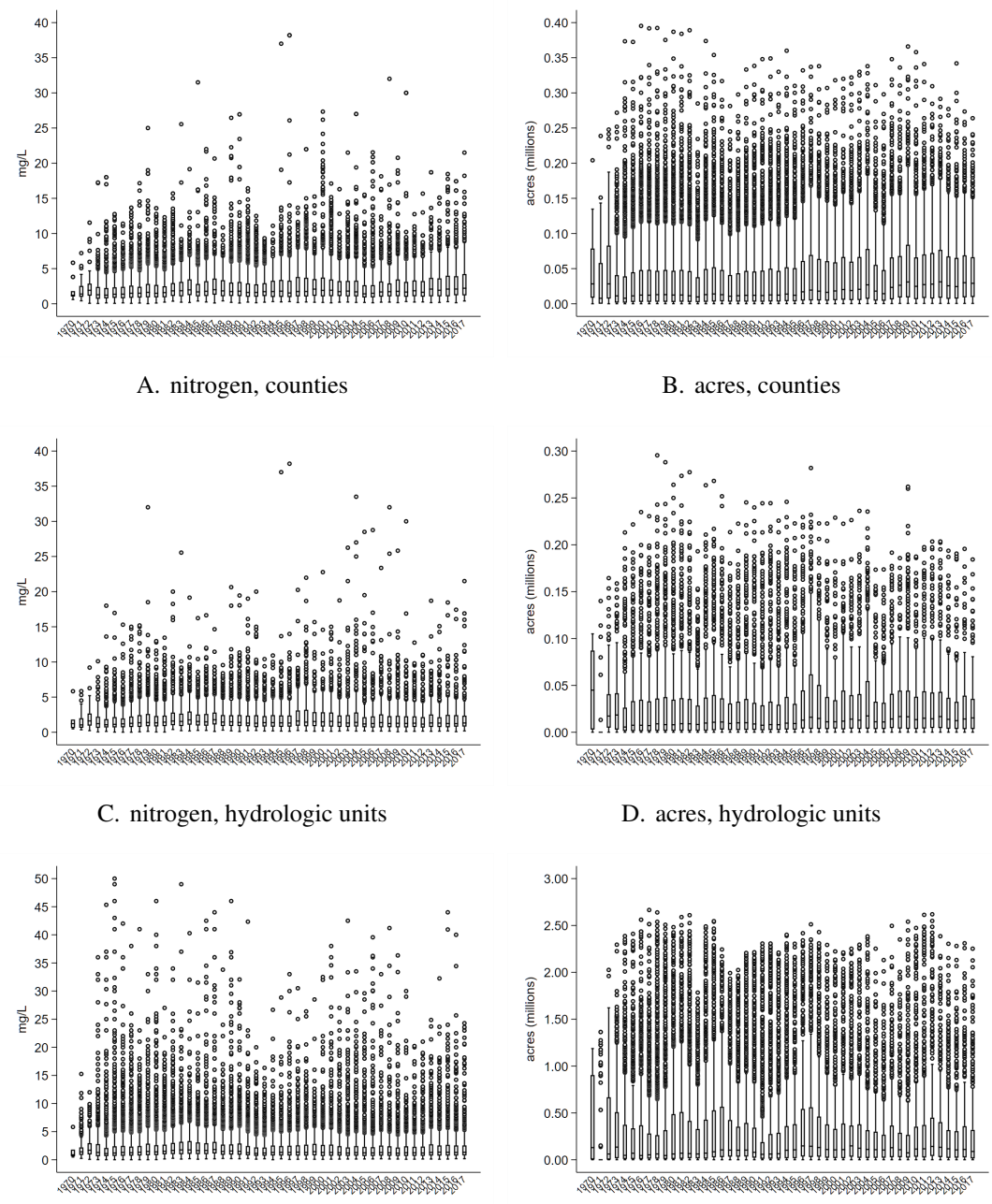
Figure A2. Examples of hydrologic units in the upper Mississippi River Basin



A. Subregions within region 07 B. Catalogic units within subregion 0708

Note: The regions correspond to 2-digit hydrologic units, the subregions correspond to 4-digit hydrologic units, and the cataloging units correspond to 8-digit hydrologic units. For additional details, see the discussion in Section 3.3.

Figure A3. Distribution of nitrogen pollution and corn acres planted



A. nitrogen, counties

B. acres, counties

C. nitrogen, hydrologic units

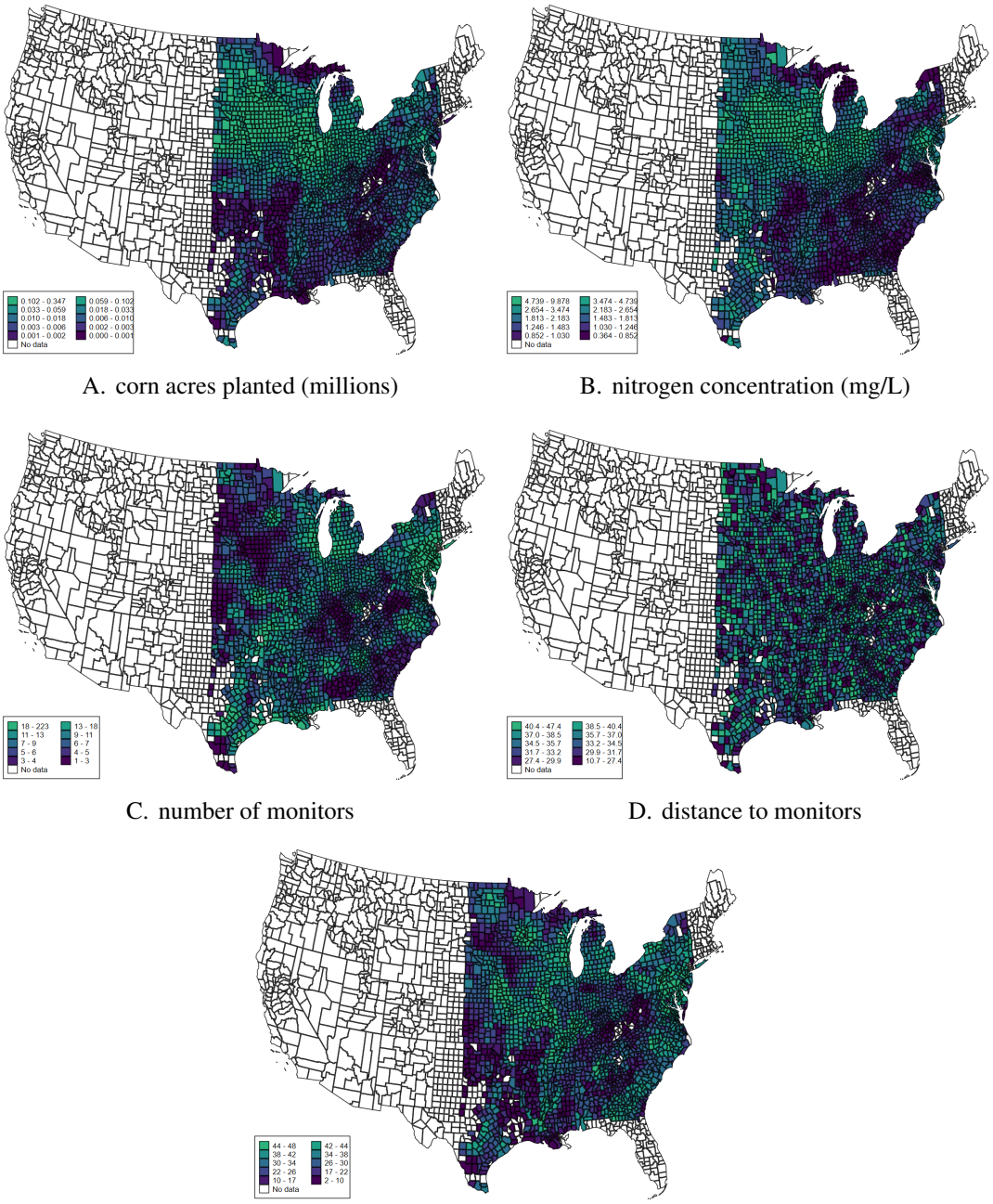
D. acres, hydrologic units

E. nitrogen, monitoring sites

F. acres, monitoring sites

Note: The data points are county-year, hydrologic unit-year, and monitoring site-year combinations. For each of the box-and-whisker plots, the boxes cover the interquartile range, from the lower quartile to the upper quartile, and contain a vertical white line indicating the median. The whiskers, denoted by horizontal lines, intend to cover most or all the range of the data. The bottom whisker extends to a value that is the lower quartile minus 1.5 times the interquartile range, or the minimum should this be smaller. The top whisker extends to a value that is the upper quartile plus 1.5 times the interquartile range, or at the maximum, if this is smaller. The estimates pertain to the EAST-100 (U.S., east of the 100th meridian) and are based on USGS-NWIS data for nitrogen concentration. For additional details, see the discussion in Section 5.

Figure A4. Choropleth maps for counties



A. corn acres planted (millions)

B. nitrogen concentration (mg/L)

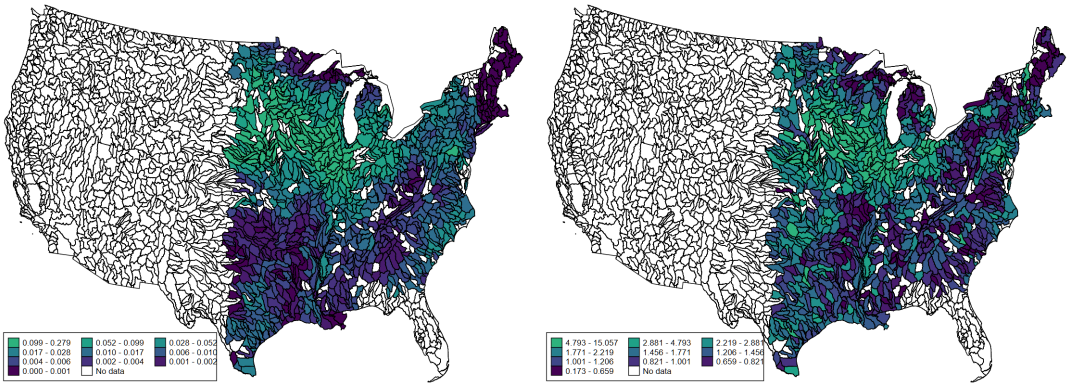
C. number of monitors

D. distance to monitors

E. years

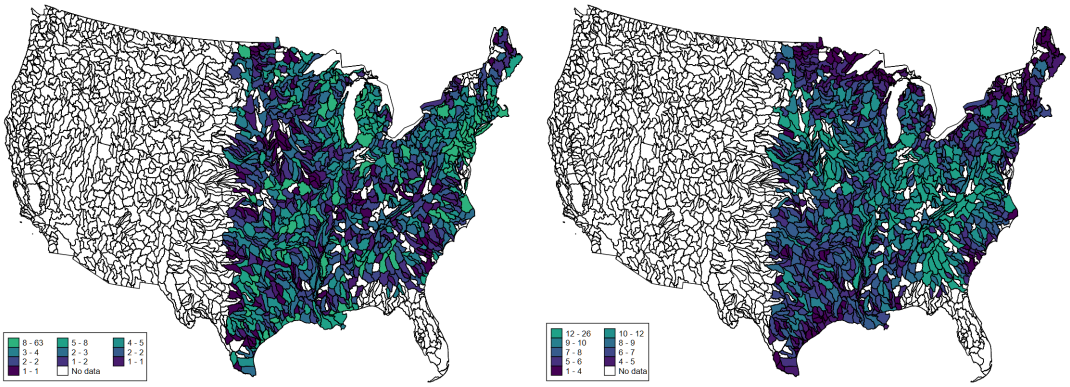
Note: We report average acres planted during 1970–2017. We also report average nitrogen concentration using monitors located within a 50-mile radius from the county centroids, the average number of monitors, the average distance between the county centroids and the monitors, and the number of years we track a county in the data. The shading of the choropleth maps is based on the deciles of the empirical distribution. We show counties east of the 100th meridian. For additional details, see the discussion in Section 5.

Figure A5. Choropleth maps for hydrologic units



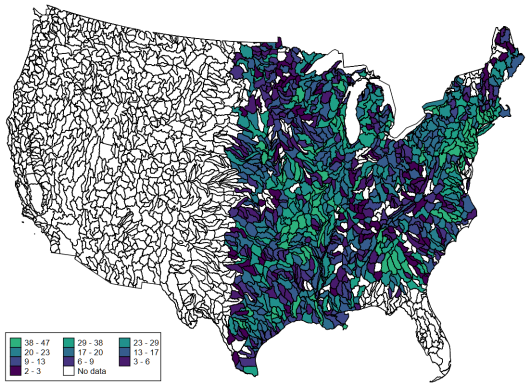
A. corn acres planted (millions)

B. nitrogen concentration (mg/L)



C. number of monitors

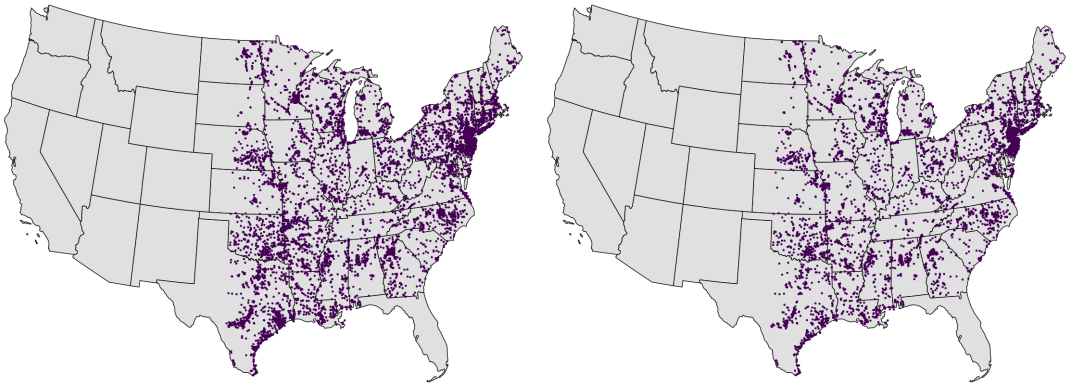
D. number of counties



E. years

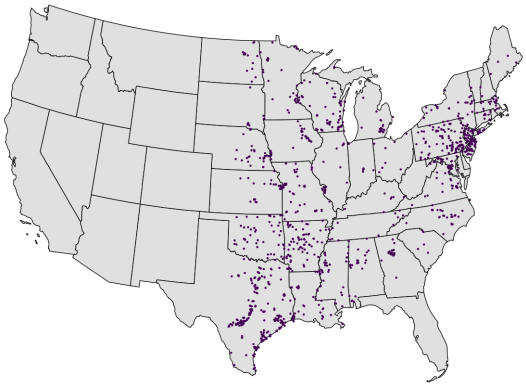
Note: We report average acres (in millions) planted during 1970–2017. We also report average nitrogen concentration (mg/L), the average number of monitors, the average number of counties, and the number of years we track a hydrologic unit in the data. The shading of the choropleth maps is based on the deciles of the empirical distribution. We show hydrologic units east of the 100th meridian. For additional details, see the discussion in Section 5.

Figure A6. Spatial distribution of nitrogen monitoring sites

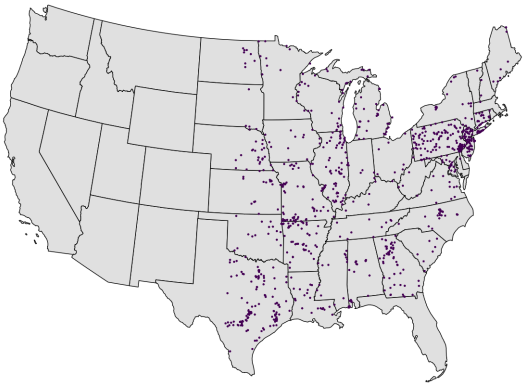


A. 1 year or more

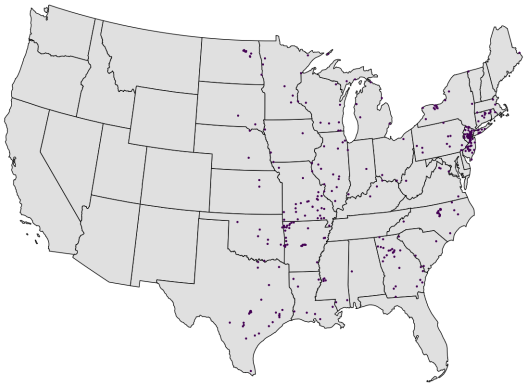
B. 1–5 years



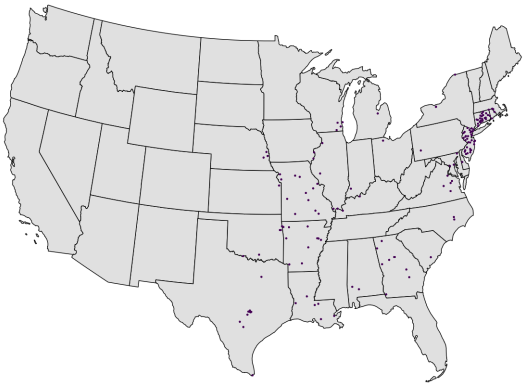
C. 6–10 years



D. 11–20 years



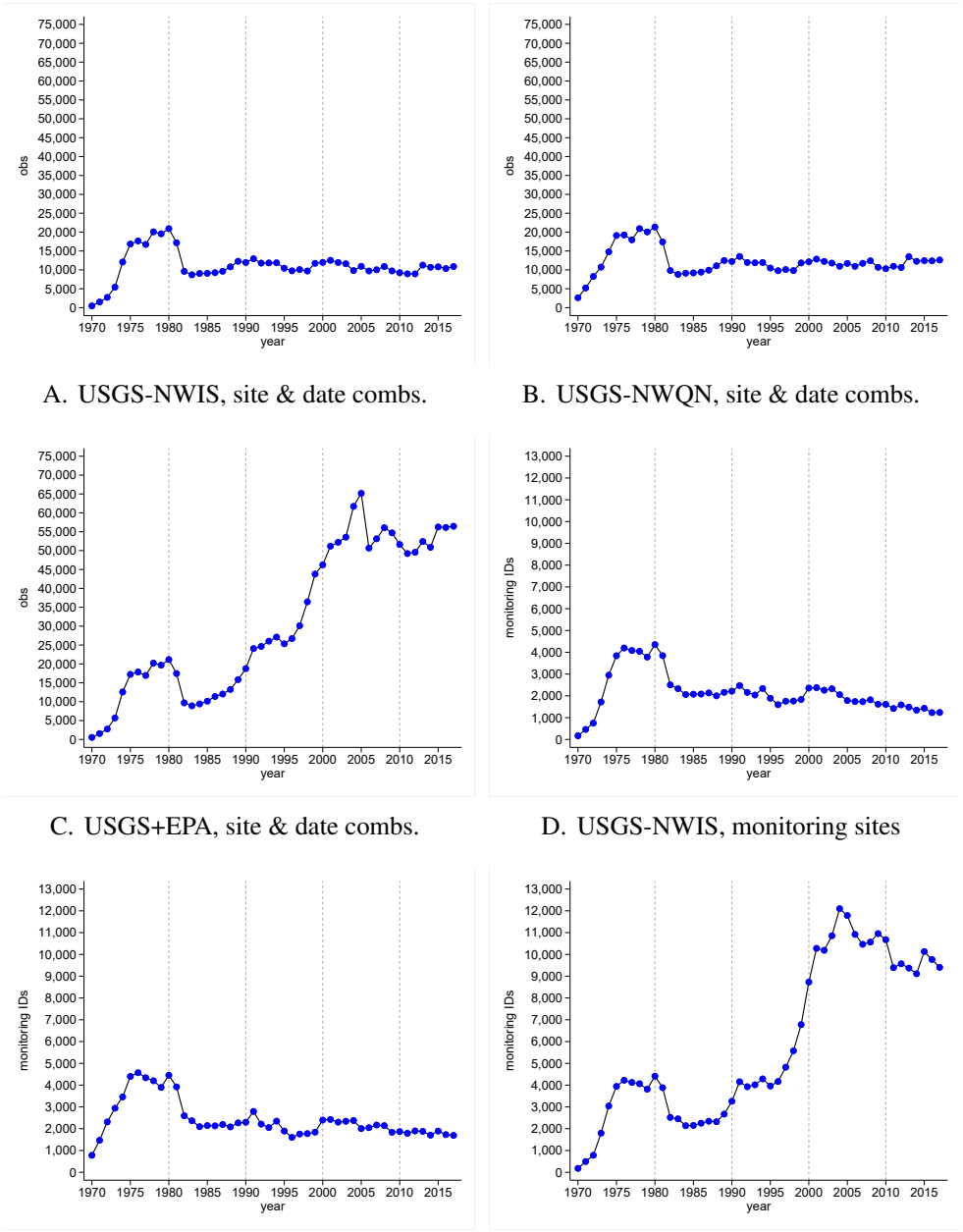
E. 21–30 years



F. 31 years or more

Note: The maps in the various panels show the spatial distribution of the USGS monitoring sites in our data. Each blue dot shows the location of a USGS monitoring site and the red vertical line marks the 100th meridian. Panel (a) shows the location of 9,596 USGS monitoring sites that appear at least once in our data, and panel (b) shows the location of 6,854 USGS monitoring sites with up to 5 years of data. Analogous reasoning holds for the remaining panels. For additional details, see the discussion in Section 5.

Figure A7. Alternative datasets used to track nitrogen concentration I



A. USGS-NWIS, site & date combs.

B. USGS-NWQN, site & date combs.

C. USGS+EPA, site & date combs.

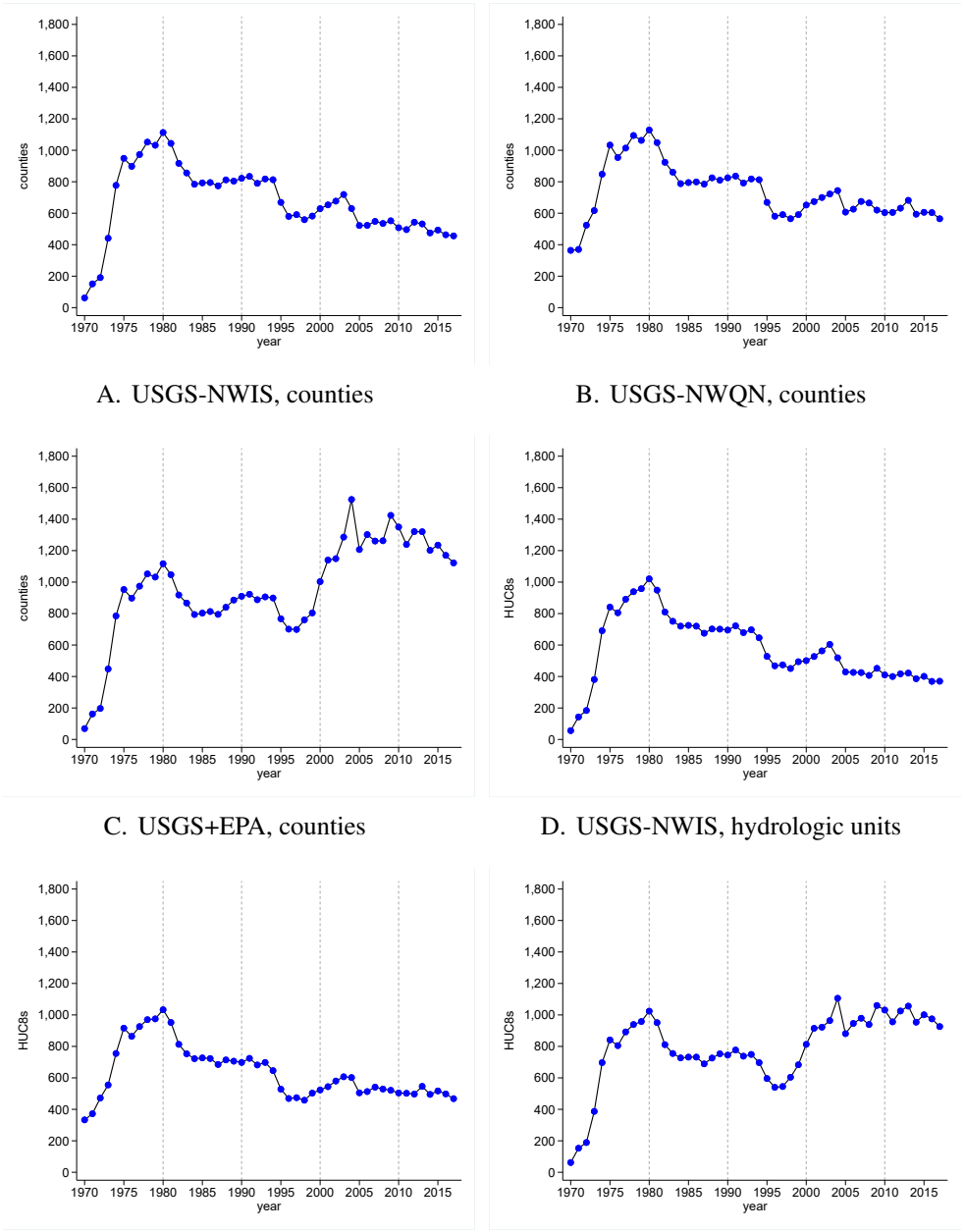
D. USGS-NWIS, monitoring sites

E. USGS-NWQN, monitoring sites

F. USGS+EPA, monitoring sites

Note: The figure shows the coverage implied by alternative datasets in terms of monitoring-site & date combinations in panels A–C and monitoring sites in panels D–F as discussed on page 33.

Figure A8. Alternative datasets used to track nitrogen concentration II



A. USGS-NWIS, counties

B. USGS-NWQN, counties

C. USGS+EPA, counties

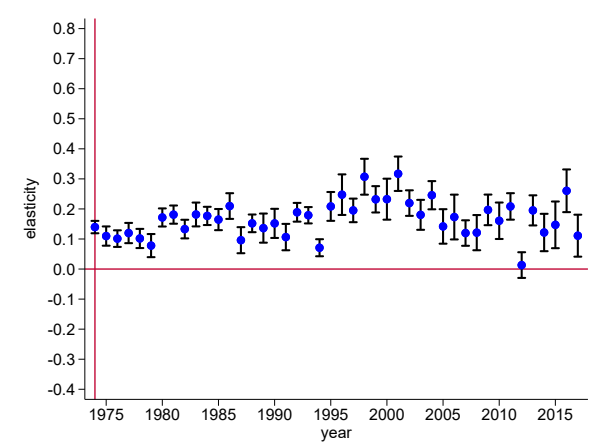
D. USGS-NWIS, hydrologic units

E. USGS-NWQN, hydrologic units

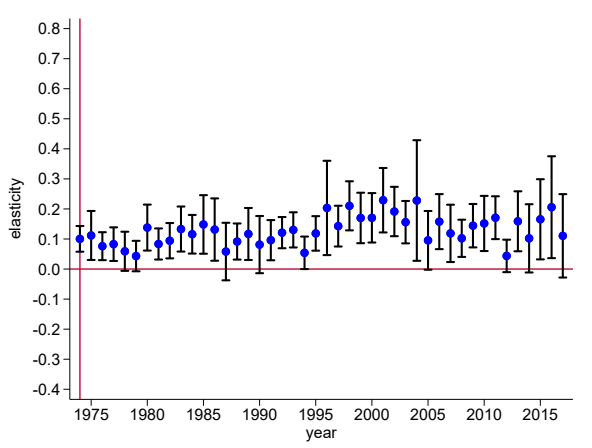
F. EPA+STORET, hydrologic units

Note: The figure shows the coverage implied by alternative datasets in terms of counties in panels A–C and hydrologic units in panels D–F as discussed on page 33.

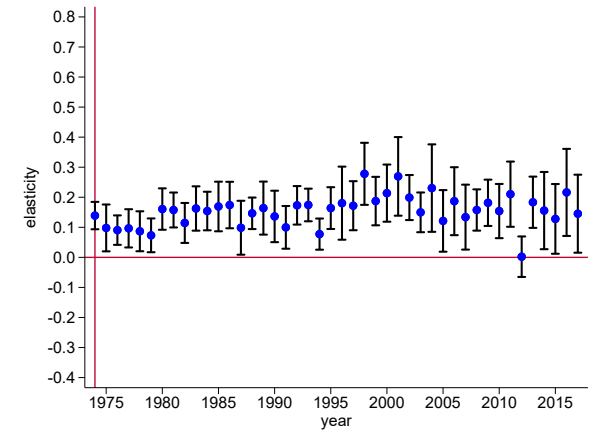
Figure A9. Cross-section regressions, counties
corn acres not interacted with precipitation



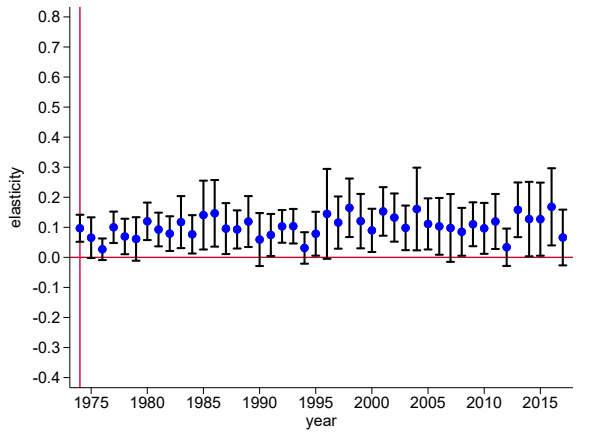
A. no fixed effects



B. state fixed effects



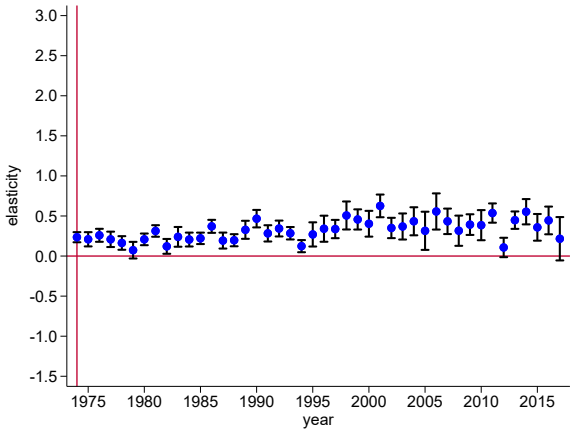
C. HUC2 fixed effects



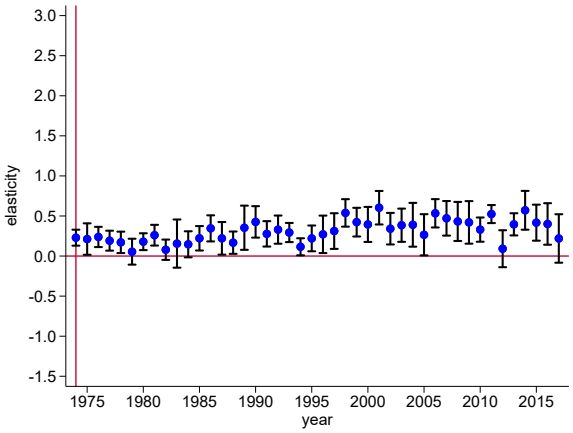
D. HUC4 fixed effects

Note: For additional details, see the discussion on page 39.

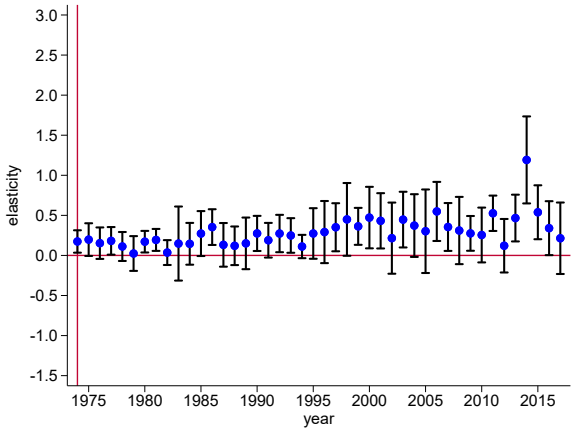
Figure A10. Cross-section regressions, hydrologic units
corn acres not interacted with precipitation



A. no fixed effects



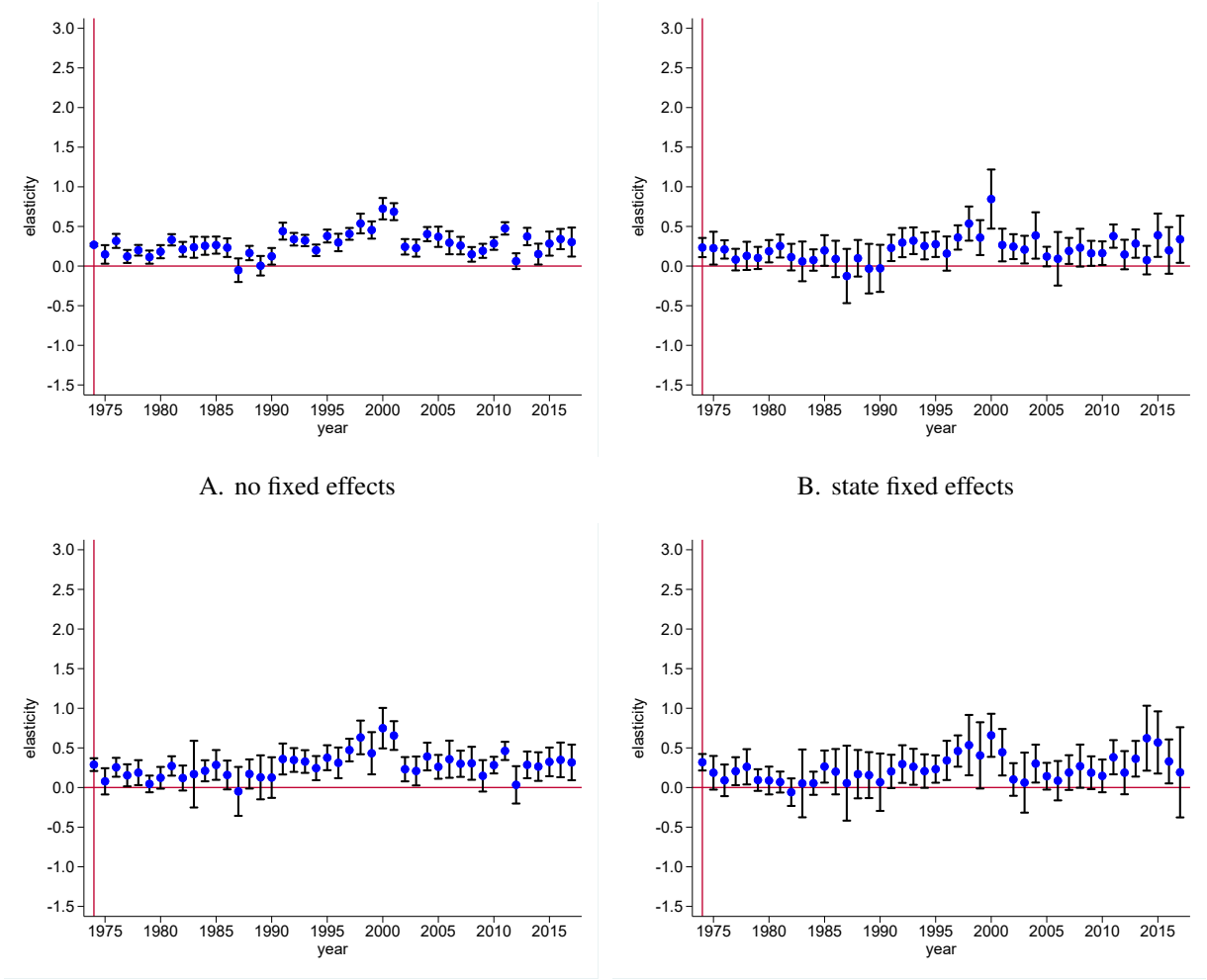
B. HUC2 fixed effects



C. HUC4 fixed effects

Note: For additional details, see the discussion on page 39.

Figure A11. Cross-section regressions, monitoring sites
corn acres not interacted with precipitation



A. no fixed effects

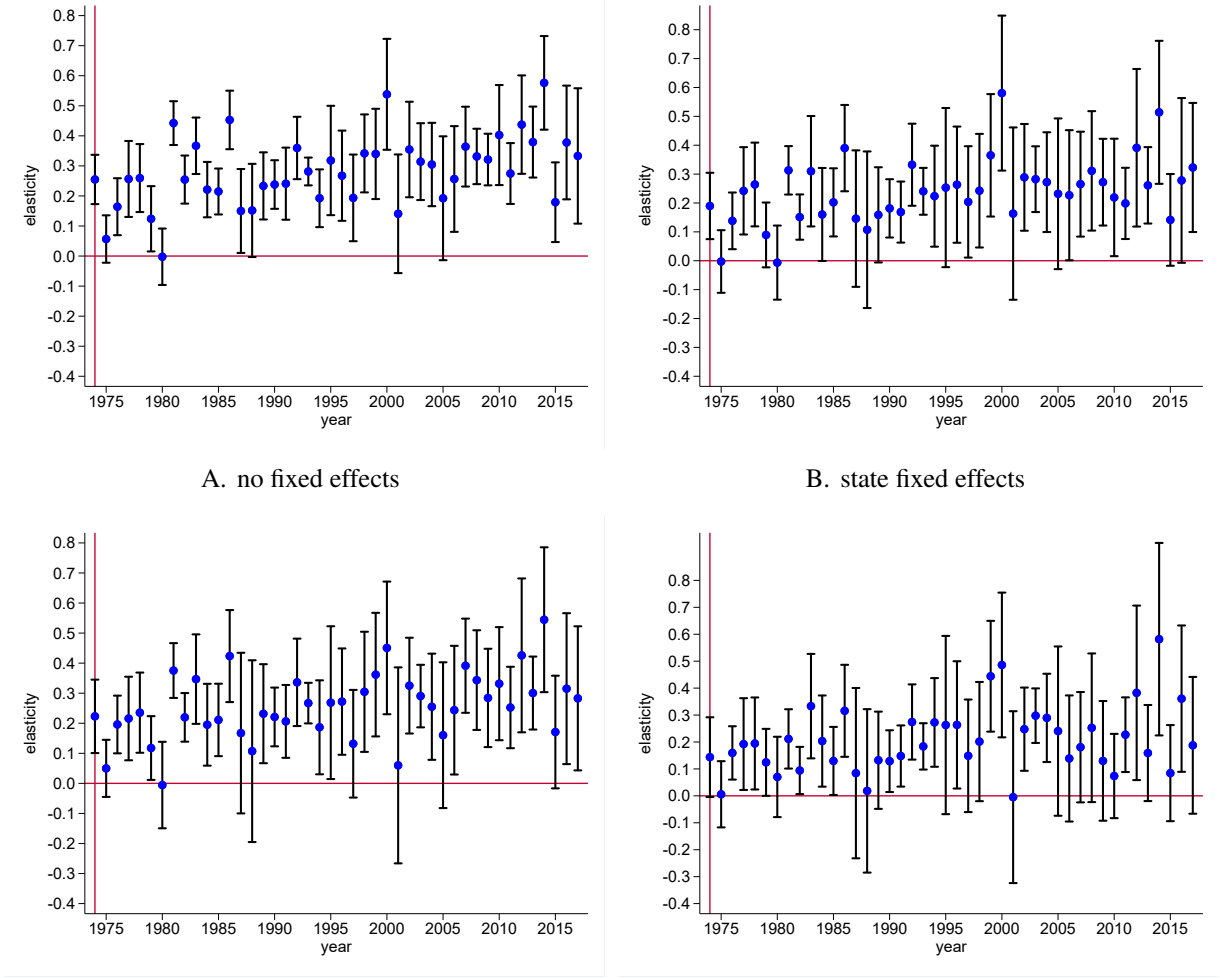
B. state fixed effects

C. HUC2 fixed effects

D. HUC4 fixed effects

Note: For additional details, see the discussion on page 39.

Figure A12. Cross-section regressions, counties
adjust for streamflow using downstream monitoring sites



A. no fixed effects

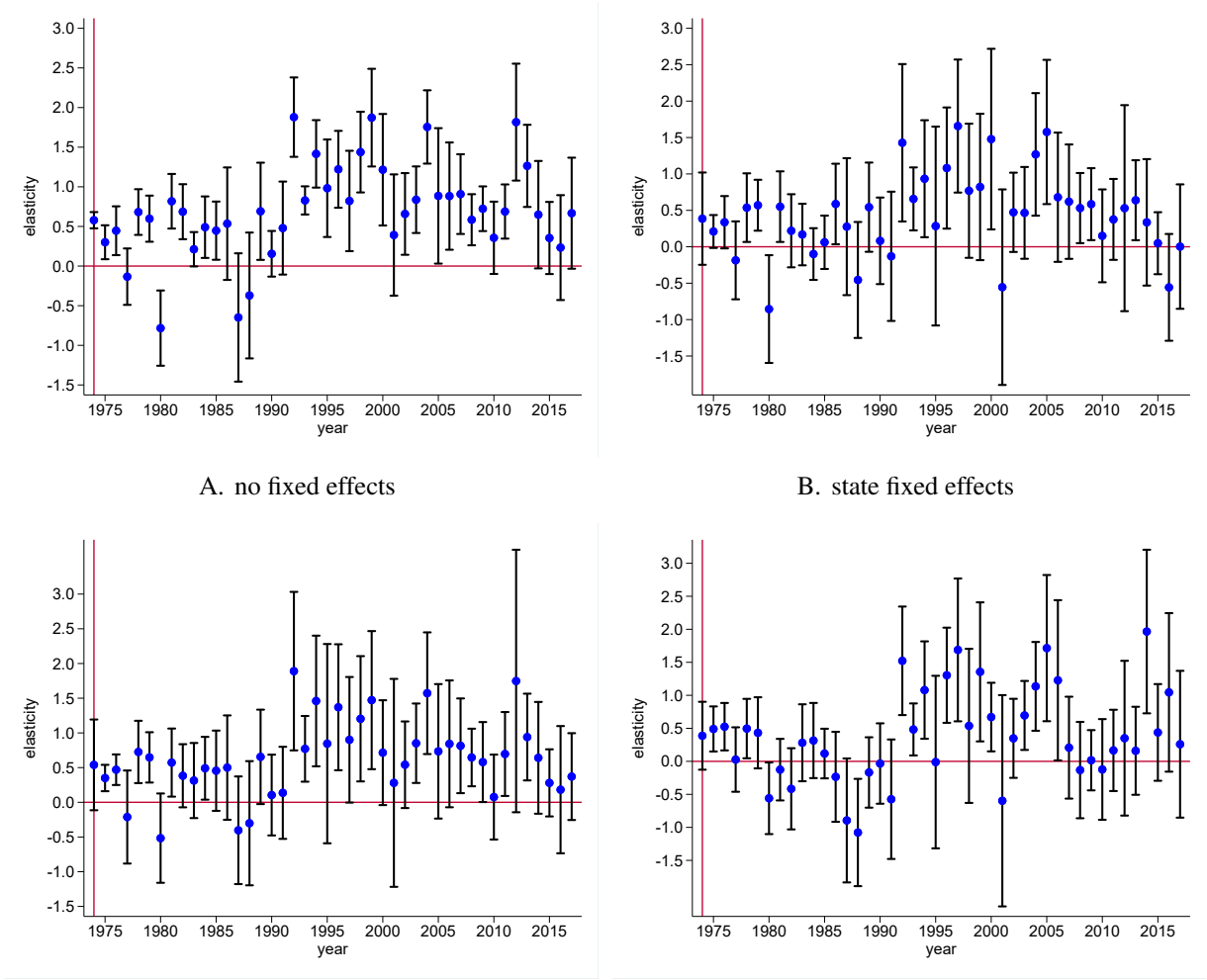
B. state fixed effects

C. HUC2 fixed effects

D. HUC4 fixed effects

Note: For additional details, see the discussion on page 40.

Figure A13. Cross-section regressions, monitoring sites
adjust for streamflow using upstream counties



A. no fixed effects

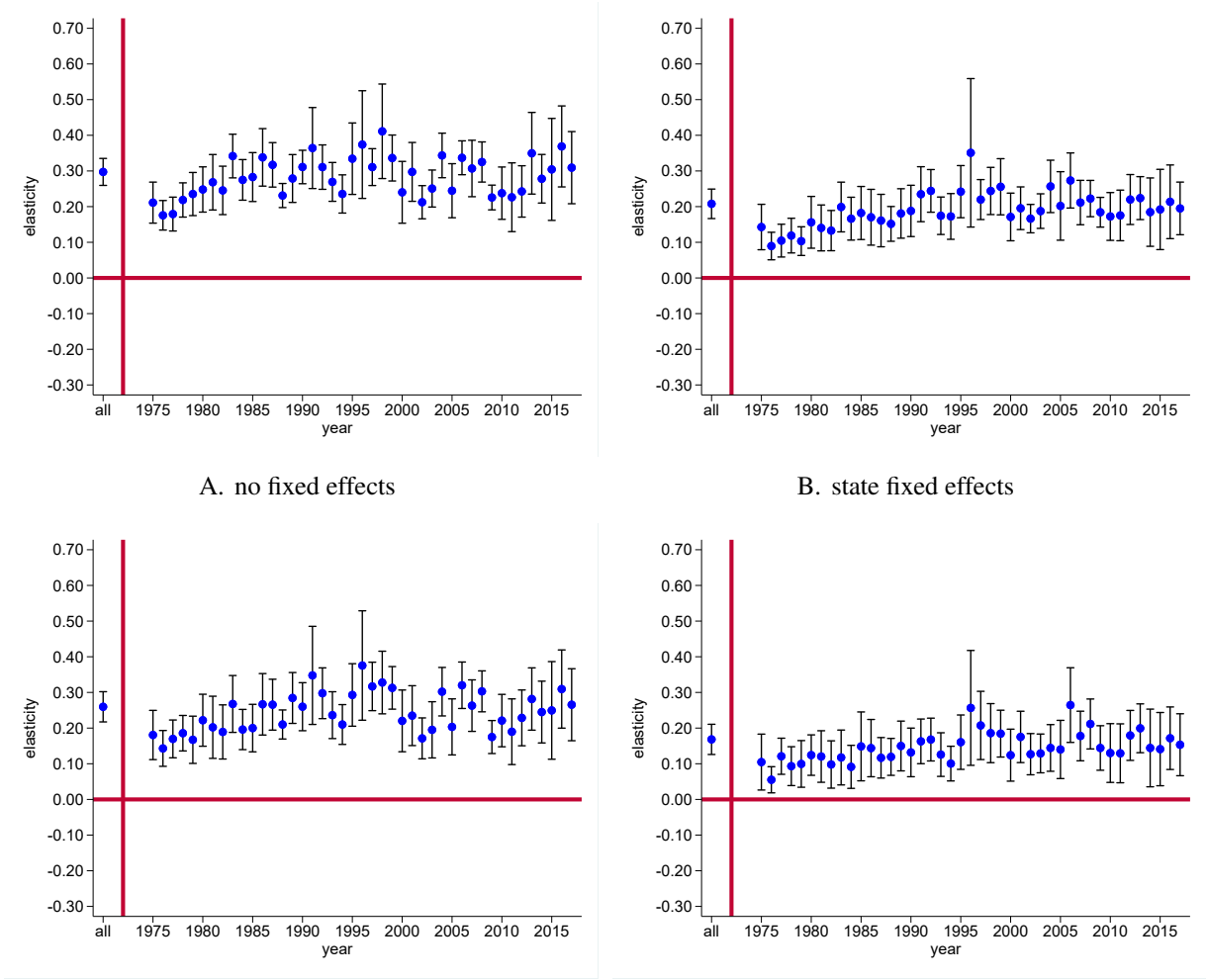
B. state fixed effects

C. HUC2 fixed effects

D. HUC4 fixed effects

Note: For additional details, see the discussion on page 40.

Figure A14. Cross-section regressions, counties, USGS+EPA data, CONUS
SPEC 1: corn acres not interacted with precipitation, no controls



A. no fixed effects

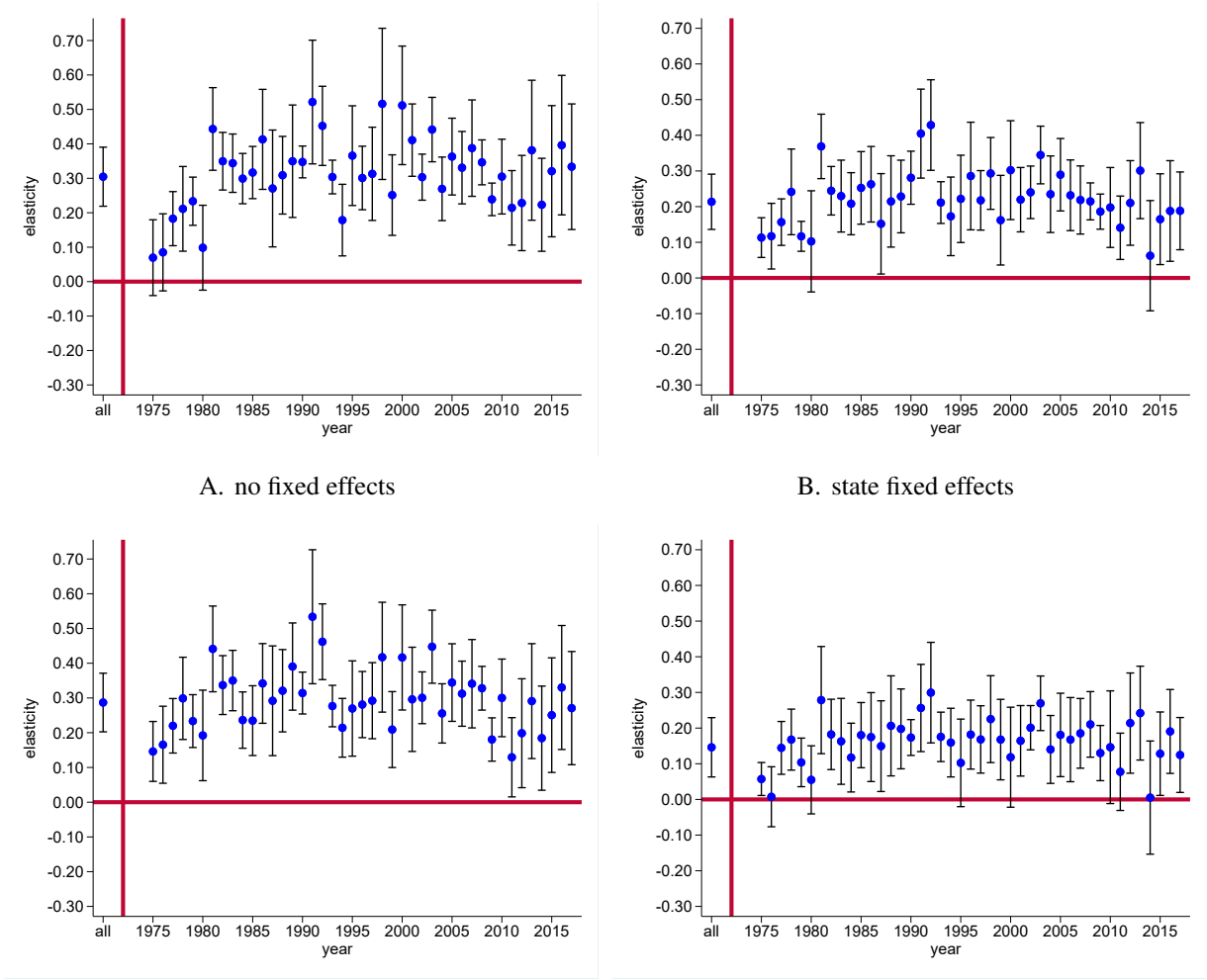
B. state fixed effects

C. HUC2 fixed effects

D. HUC4 fixed effects

Note: For a summary of these elasticities, see Table A20. For additional details, see the discussion on page 40.

Figure A15. Cross-section regressions, counties, USGS+EPA data, CONUS
SPEC 2: corn acres × prec, no other controls



A. no fixed effects

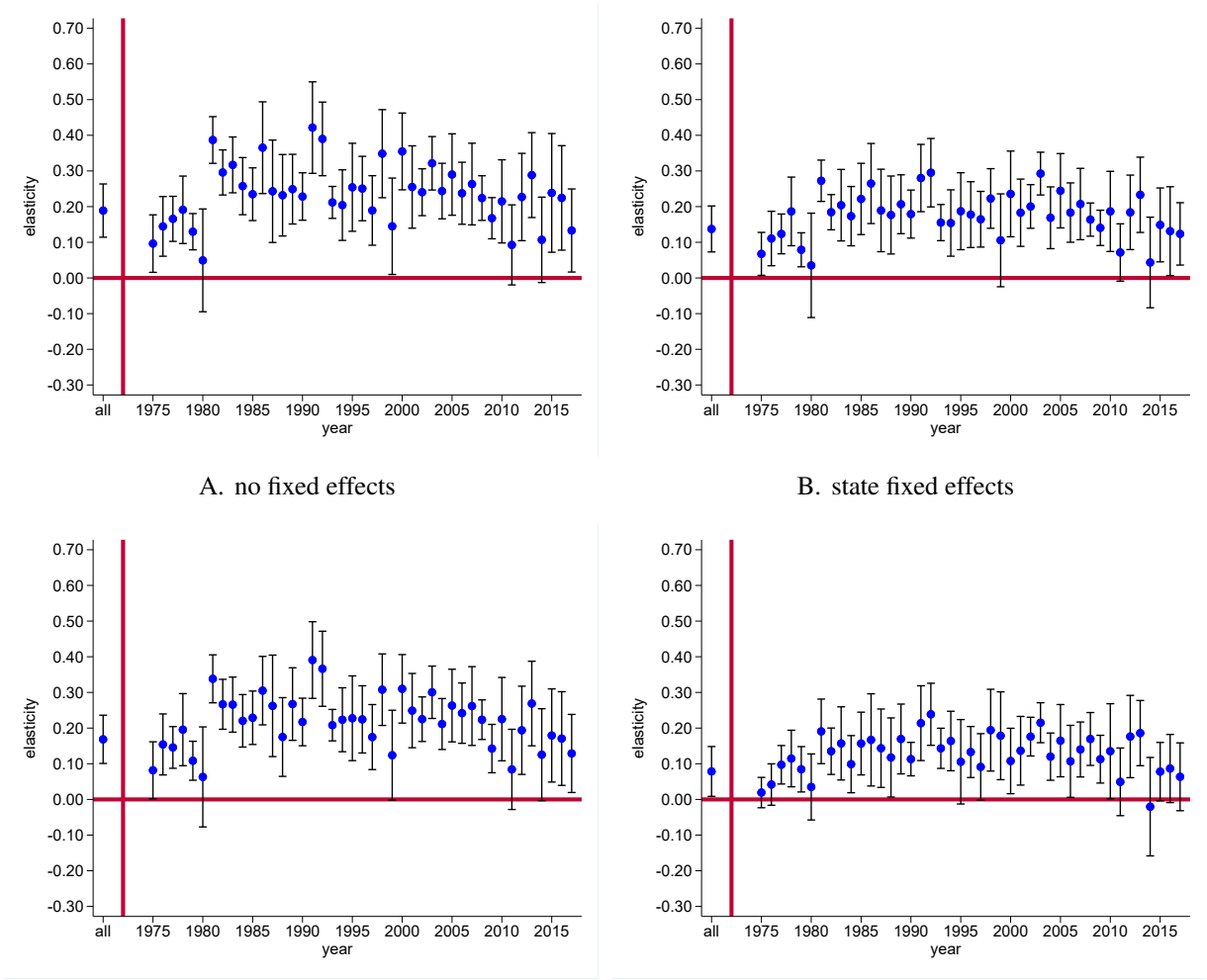
B. state fixed effects

C. HUC2 fixed effects

D. HUC4 fixed effects

Note: For a summary of these elasticities, see Table A20. For additional details, see the discussion on page 40.

Figure A16. Cross-section regressions, counties, USGS+EPA data, CONUS
SPEC 3: corn acres × prec, weather-related controls



A. no fixed effects

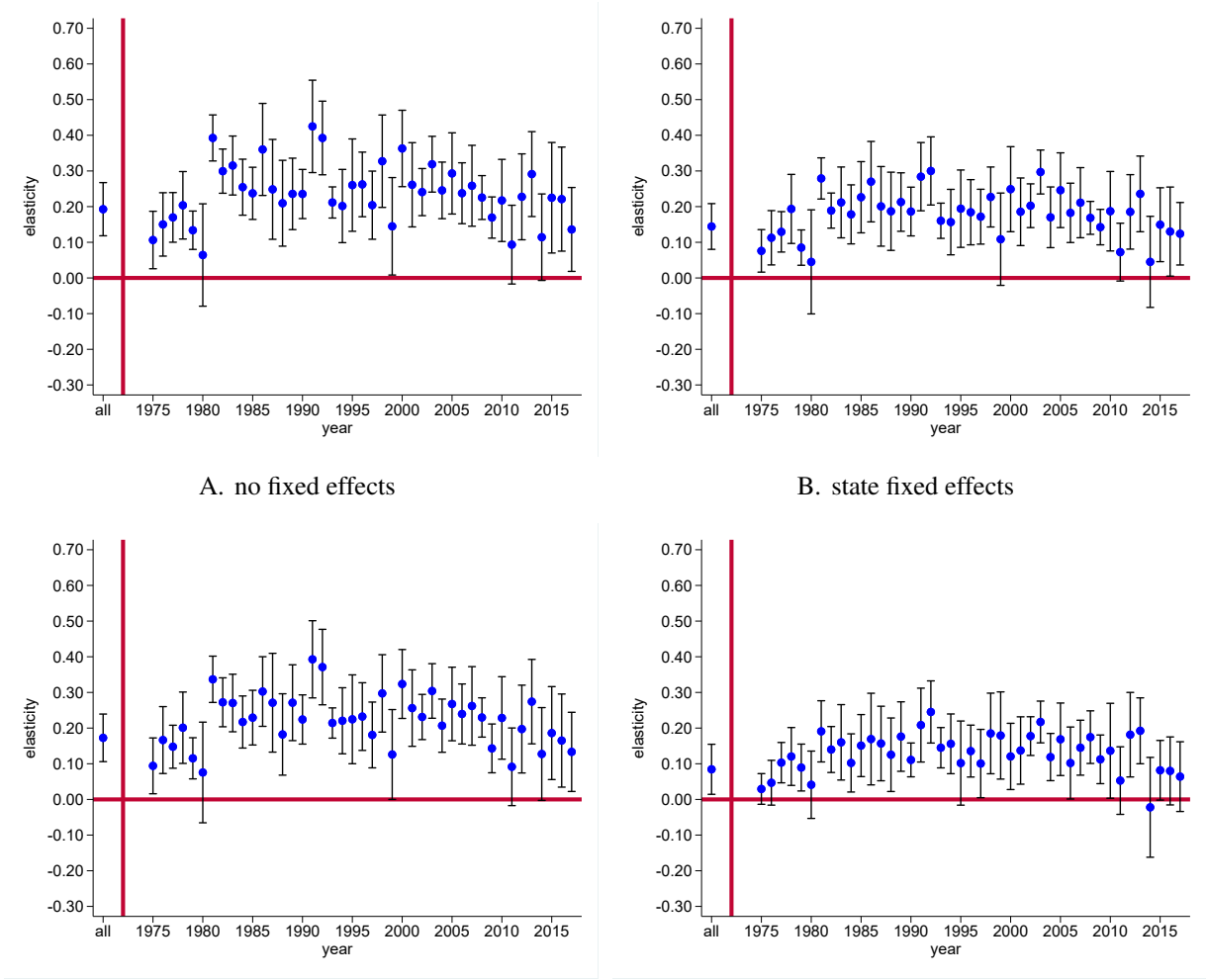
B. state fixed effects

C. HUC2 fixed effects

D. HUC4 fixed effects

Note: For a summary of these elasticities, see Table A20. For additional details, see the discussion on page 40.

Figure A17. Cross-section regressions, counties, USGS+EPA data, CONUS
SPEC 4: corn acres × prec, weather, population, GDP



A. no fixed effects

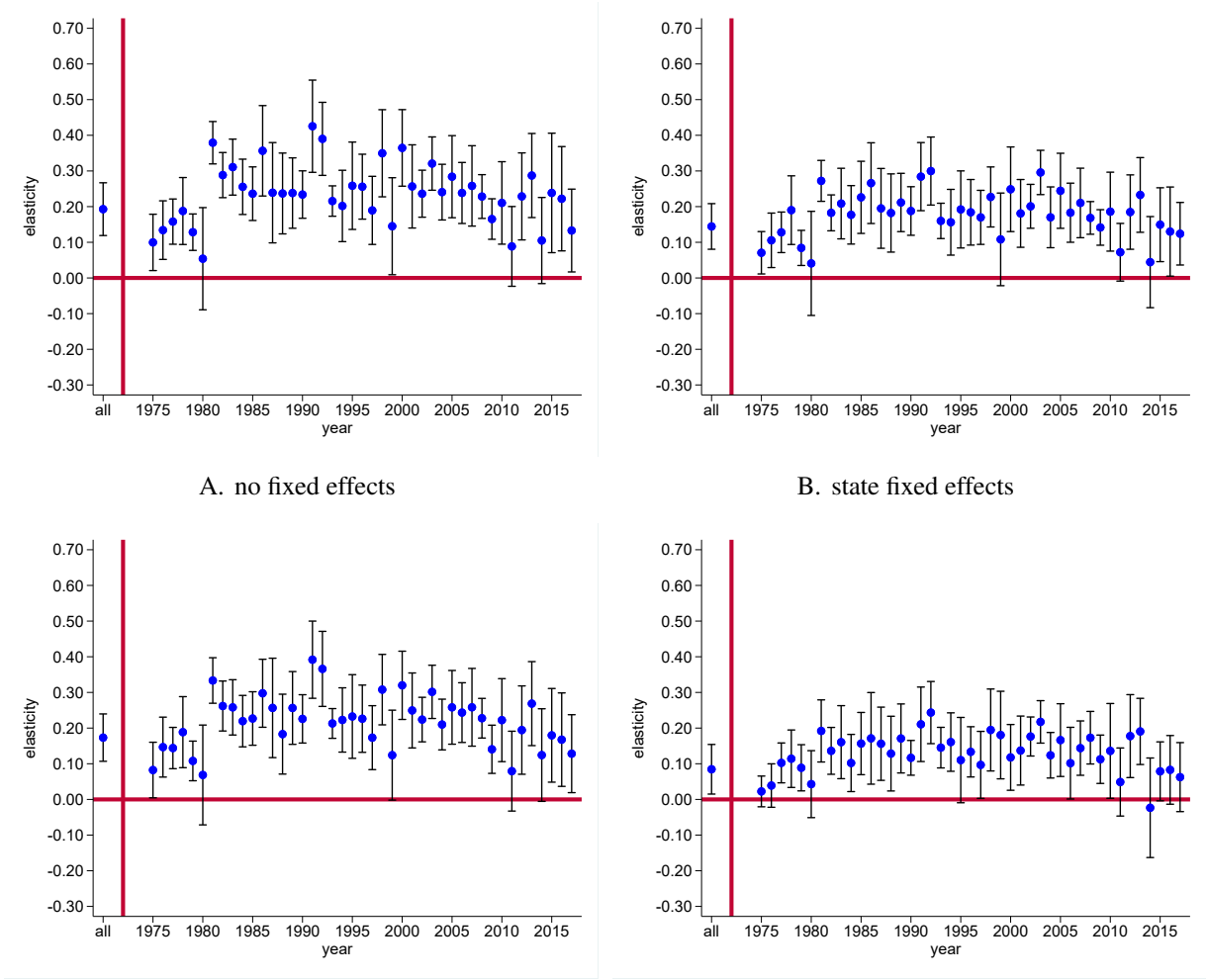
B. state fixed effects

C. HUC2 fixed effects

D. HUC4 fixed effects

Note: For a summary of these elasticities, see Table A20. For additional details, see the discussion on page 40.

Figure A18. Cross-section regressions, counties, USGS+EPA data, CONUS
SPEC 5: corn acres × prec, weather, population, per-capita income



A. no fixed effects

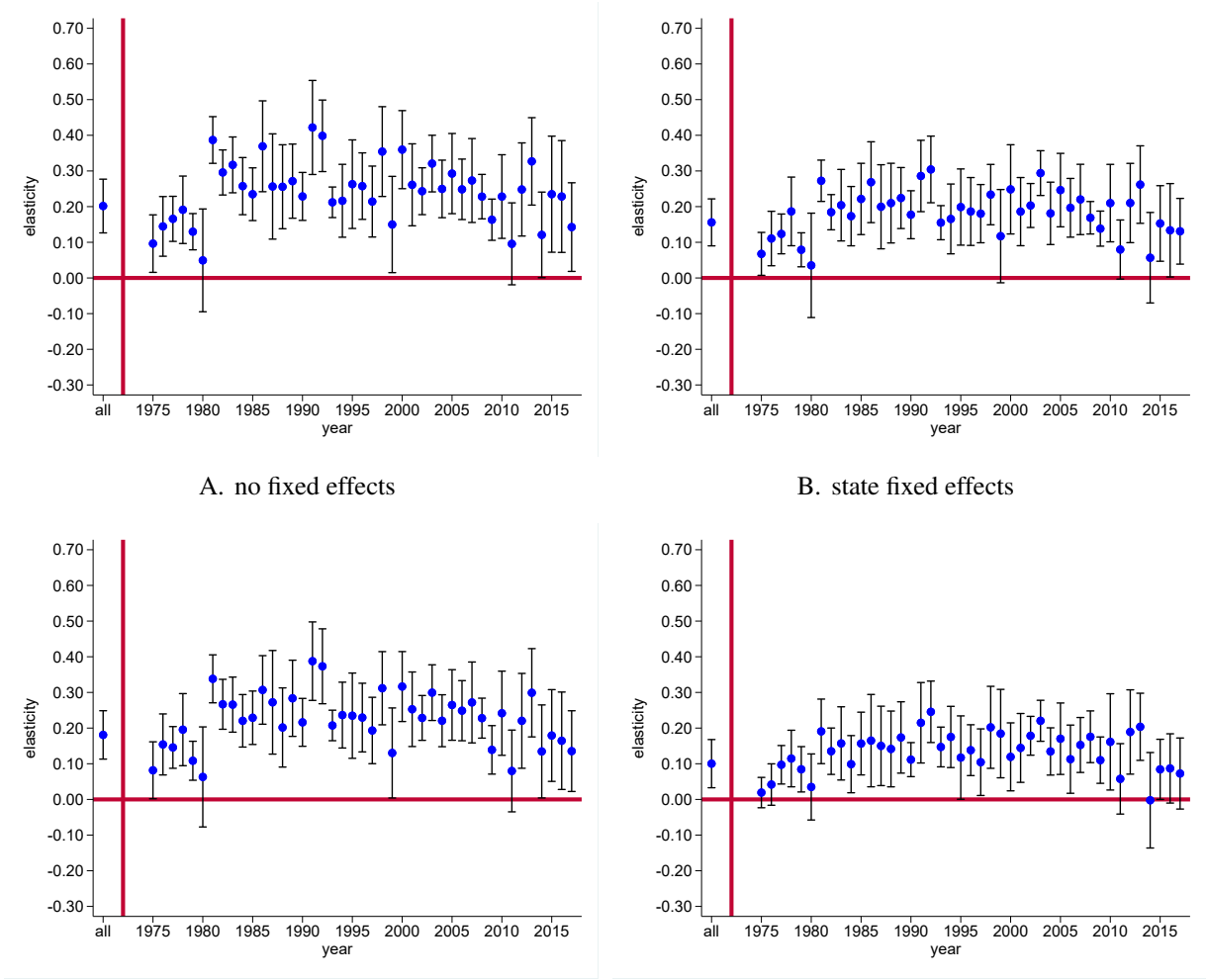
B. state fixed effects

C. HUC2 fixed effects

D. HUC4 fixed effects

Note: For a summary of these elasticities, see Table A20. For additional details, see the discussion on page 40.

Figure A19. Cross-section regressions, counties, USGS+EPA data, CONUS
SPEC 6: corn acres × prec, weather, CRP acres



A. no fixed effects

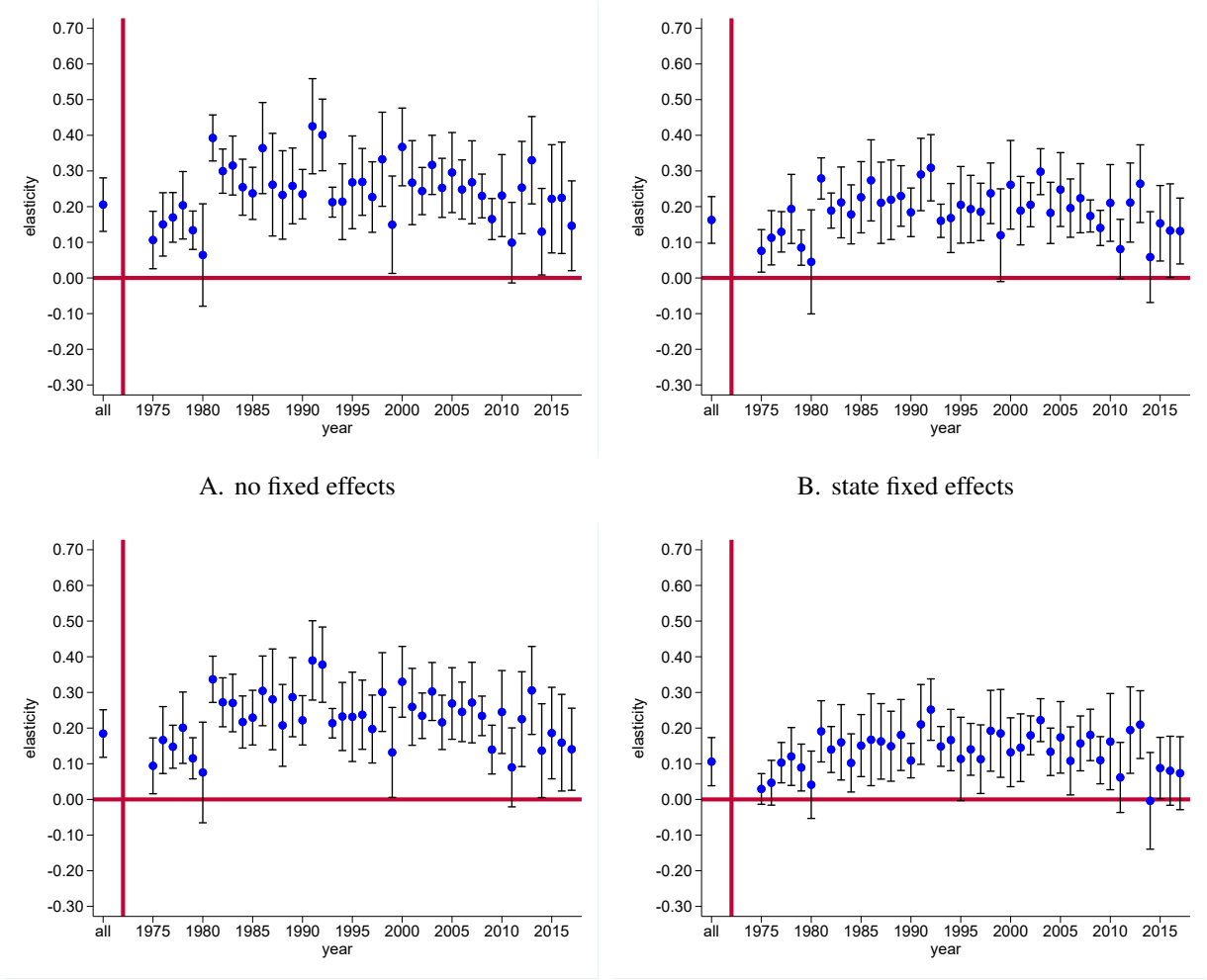
B. state fixed effects

C. HUC2 fixed effects

D. HUC4 fixed effects

Note: For a summary of these elasticities, see Table A20. For additional details, see the discussion on page 40.

Figure A20. Cross-section regressions, counties, USGS+EPA data, CONUS
SPEC 7: corn acres × prec, weather, CRP acres, population, GDP



A. no fixed effects

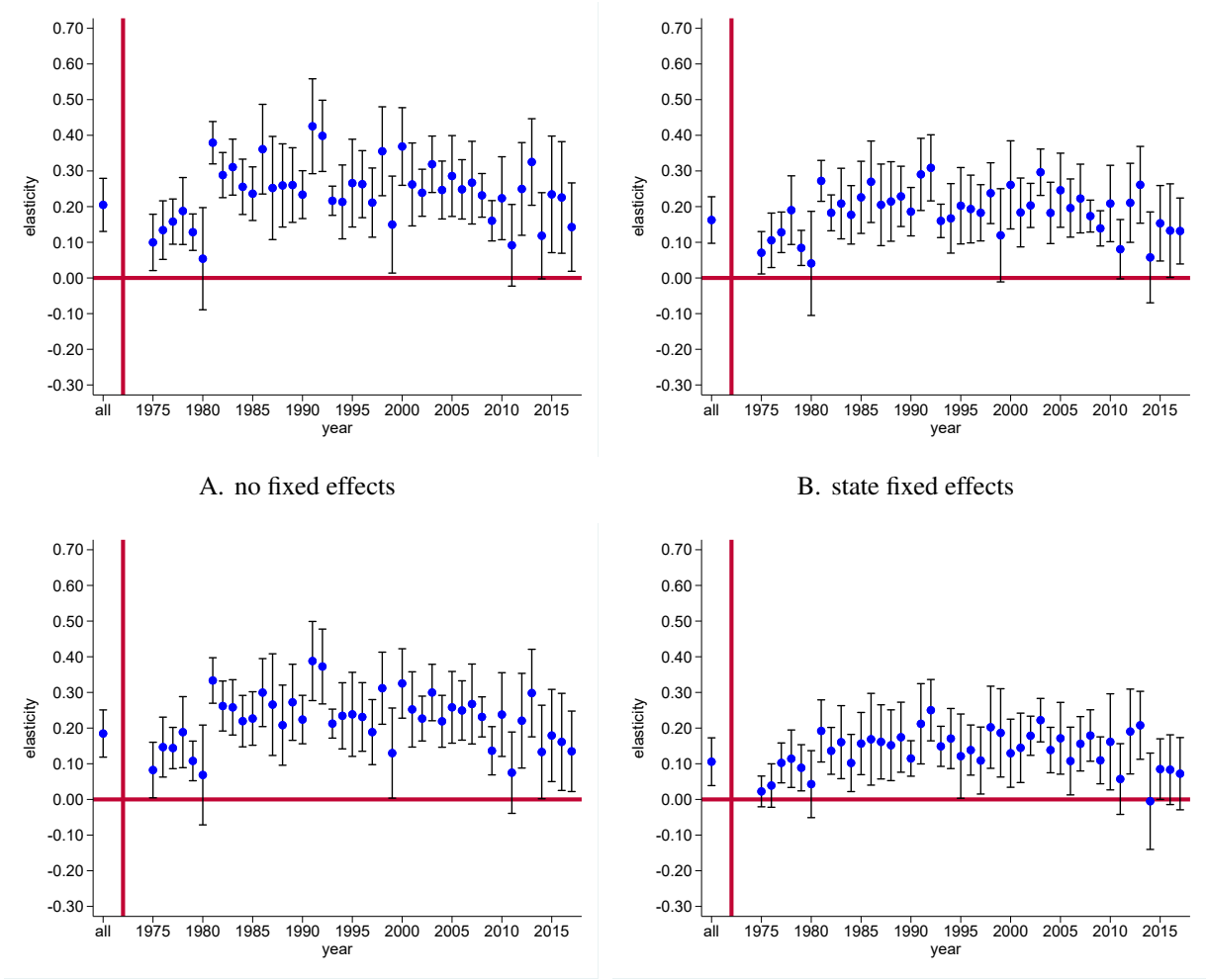
B. state fixed effects

C. HUC2 fixed effects

D. HUC4 fixed effects

Note: For a summary of these elasticities, see Table A20. For additional details, see the discussion on page 40.

Figure A21. Cross-section regressions, counties, USGS+EPA data, CONUS
SPEC 8: corn acres × prec, weather, CRP acres, population, per-capita income



A. no fixed effects

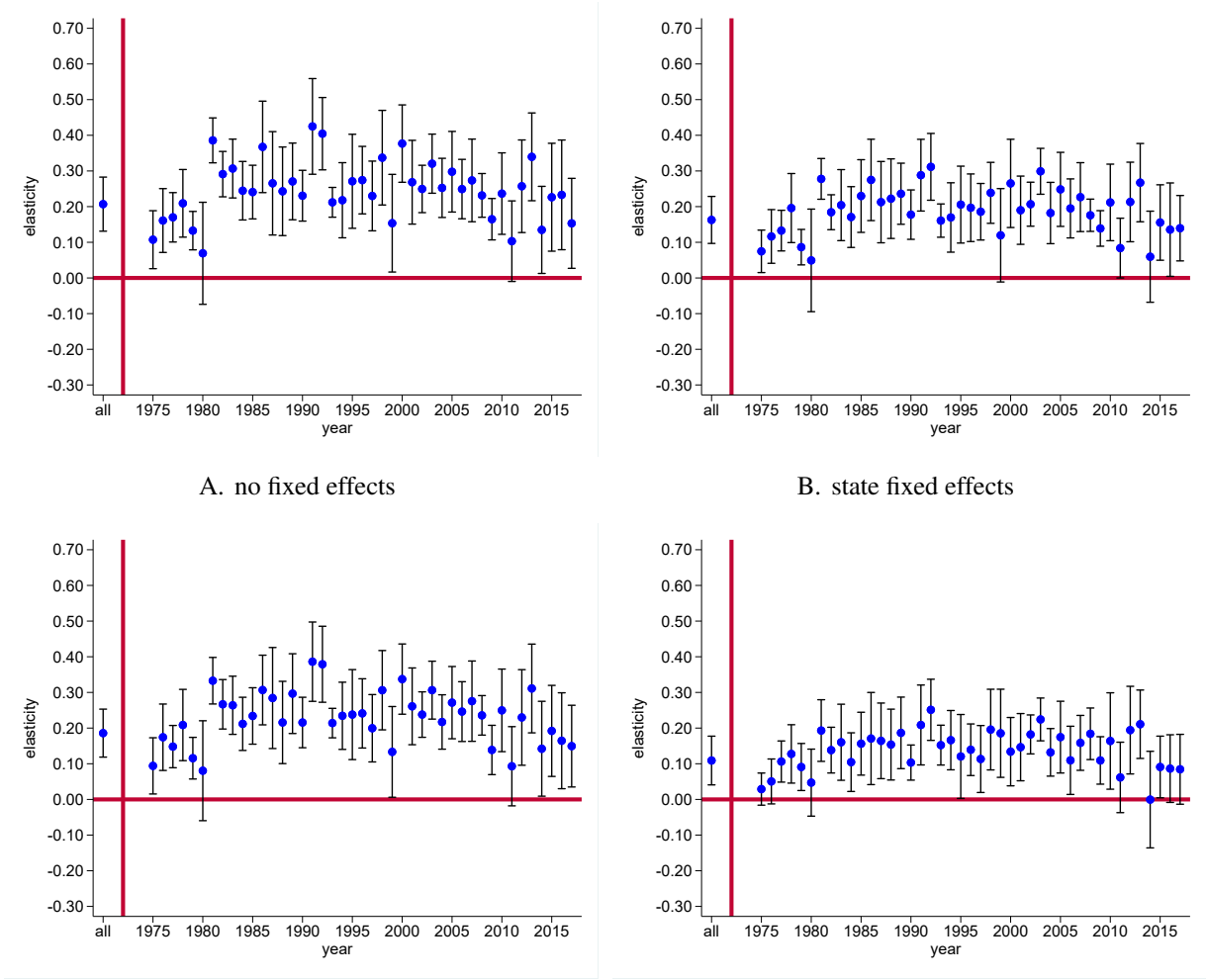
B. state fixed effects

C. HUC2 fixed effects

D. HUC4 fixed effects

Note: For a summary of these elasticities, see Table A20. For additional details, see the discussion on page 40.

Figure A22. Cross-section regressions, counties, USGS+EPA data, CONUS
SPEC 9: corn acres×precip, weather, CRP acres, population, GDP, land area



A. no fixed effects

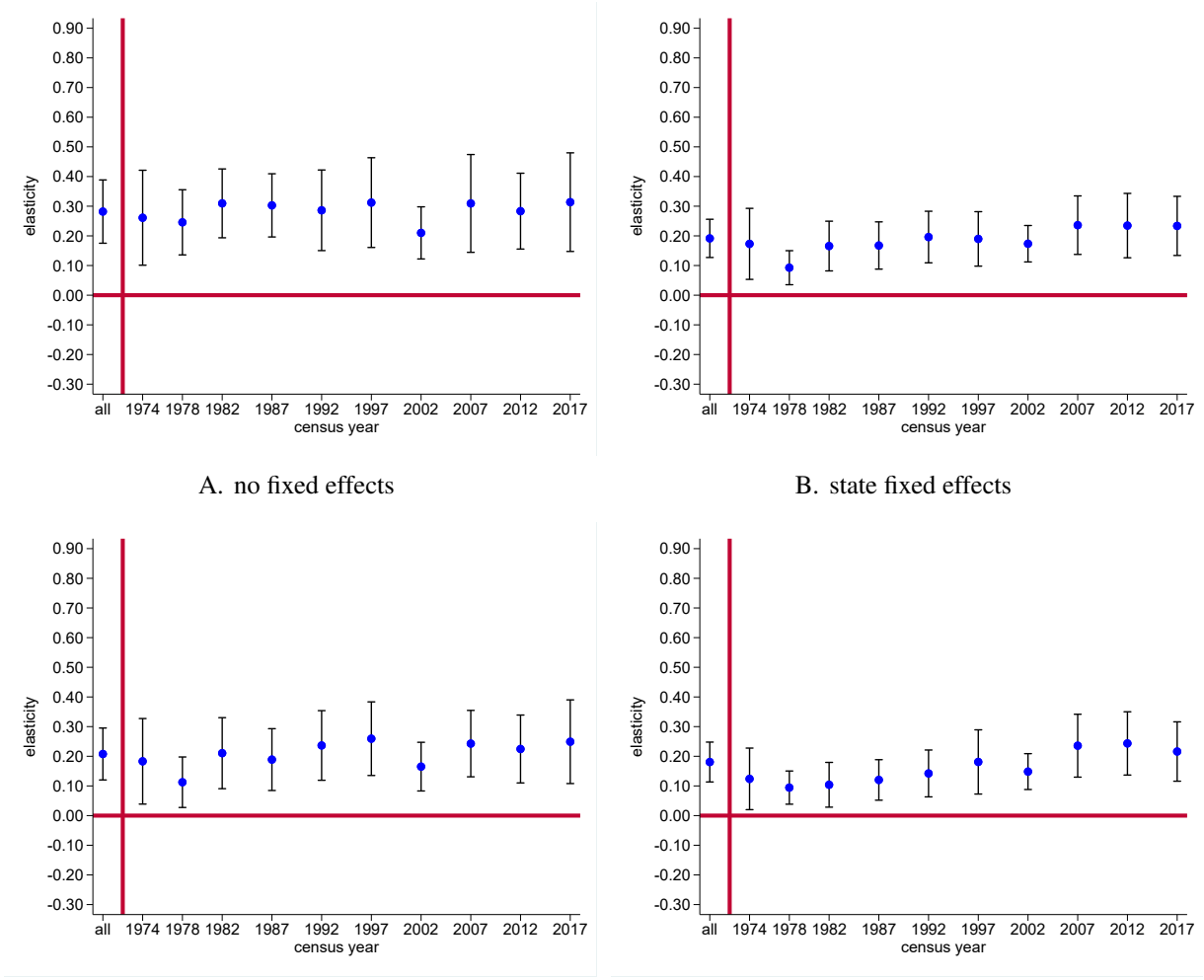
B. state fixed effects

C. HUC2 fixed effects

D. HUC4 fixed effects

Note: For a summary of these elasticities, see Table A20. For additional details, see the discussion on page 40.

Figure A23. Cross-section regressions, counties, CONUS, USGS+EPA data
SPEC 1: cropland acres, no controls



A. no fixed effects

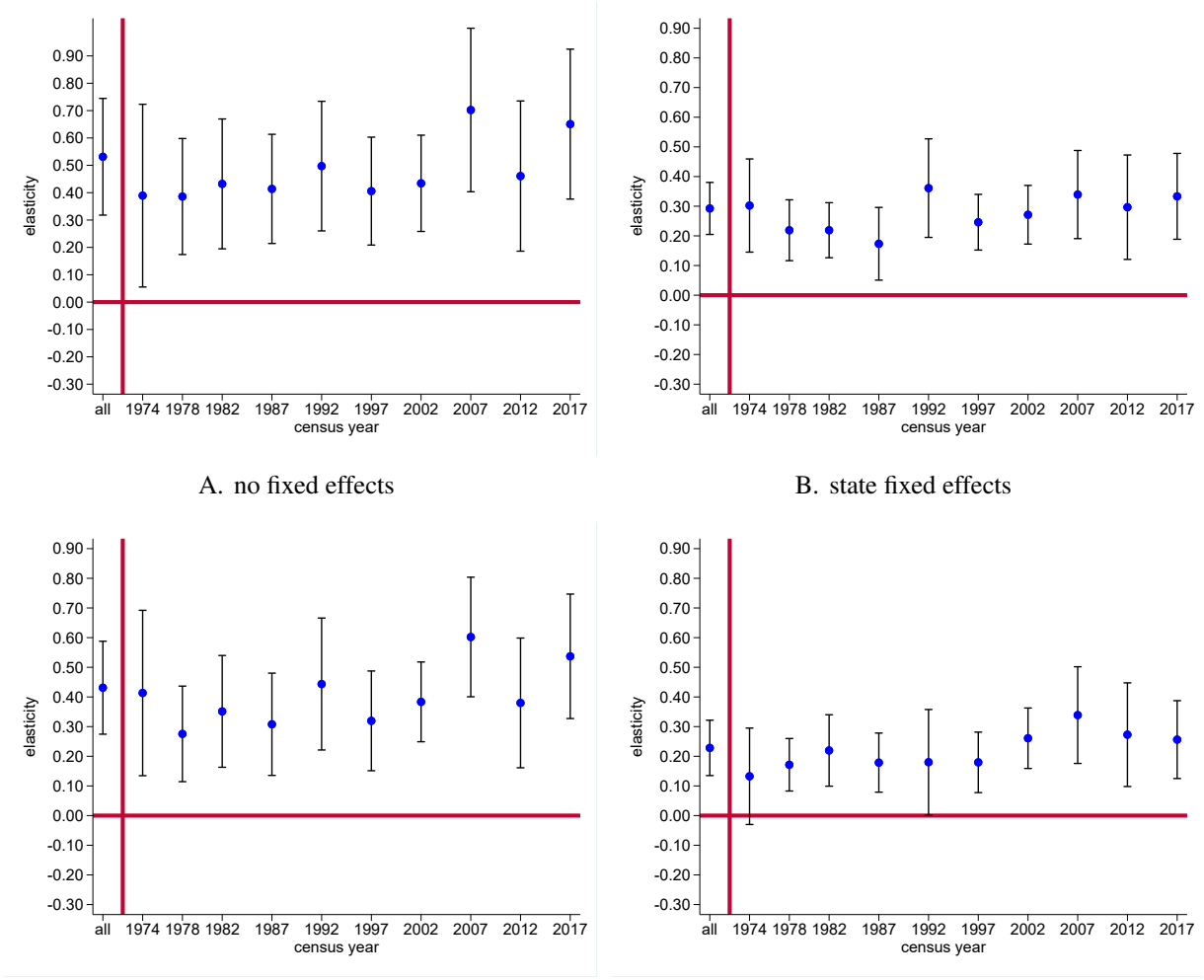
B. state fixed effects

C. HUC2 fixed effects

D. HUC4 fixed effects

Note: For a summary of these elasticities, see Table A22. For additional details, see the discussion on page 41.

Figure A24. Cross-section regressions, counties, CONUS, USGS+EPA data
SPEC 2: cropland acres×precip, no controls



A. no fixed effects

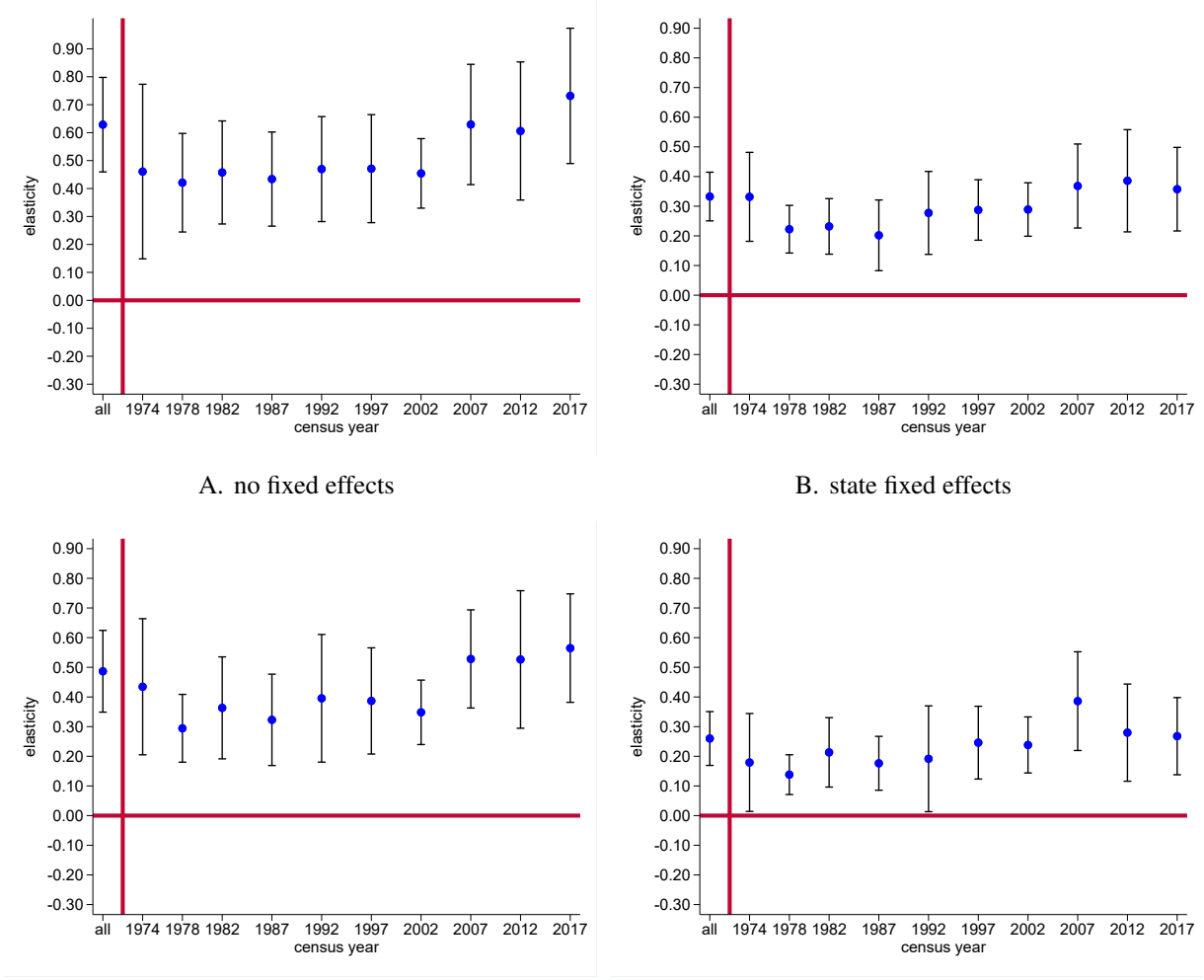
B. state fixed effects

C. HUC2 fixed effects

D. HUC4 fixed effects

Note: For a summary of these elasticities, see Table A22. For additional details, see the discussion on page 41.

Figure A25. Cross-section regressions, counties, CONUS, USGS+EPA data
SPEC 3: cropland acres×precip, weather



A. no fixed effects

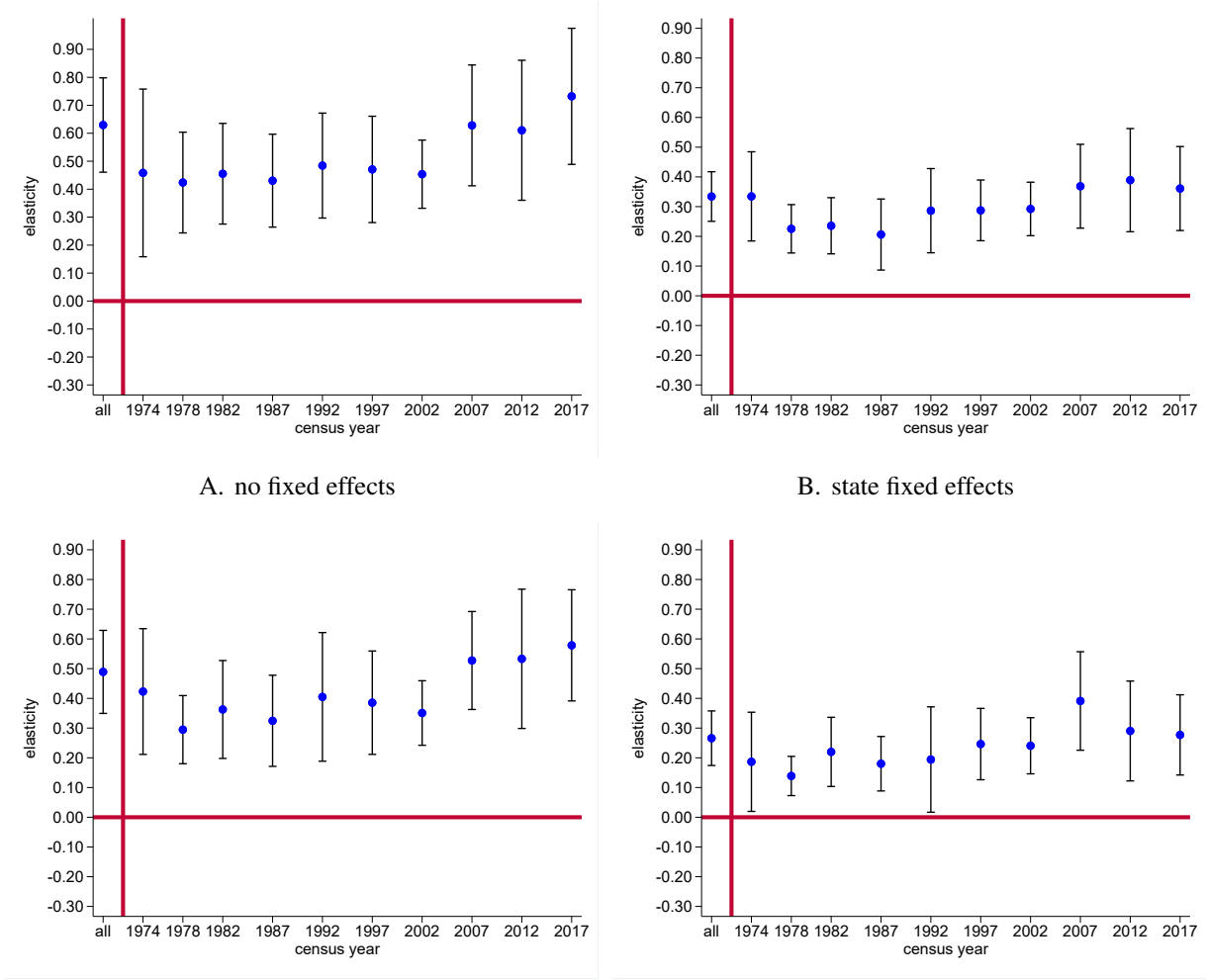
B. state fixed effects

C. HUC2 fixed effects

D. HUC4 fixed effects

Note: For a summary of these elasticities, see Table A22. For additional details, see the discussion on page 41.

Figure A26. Cross-section regressions, counties, CONUS, USGS+EPA data
SPEC 4: cropland acres×precip, weather, population, GDP



A. no fixed effects

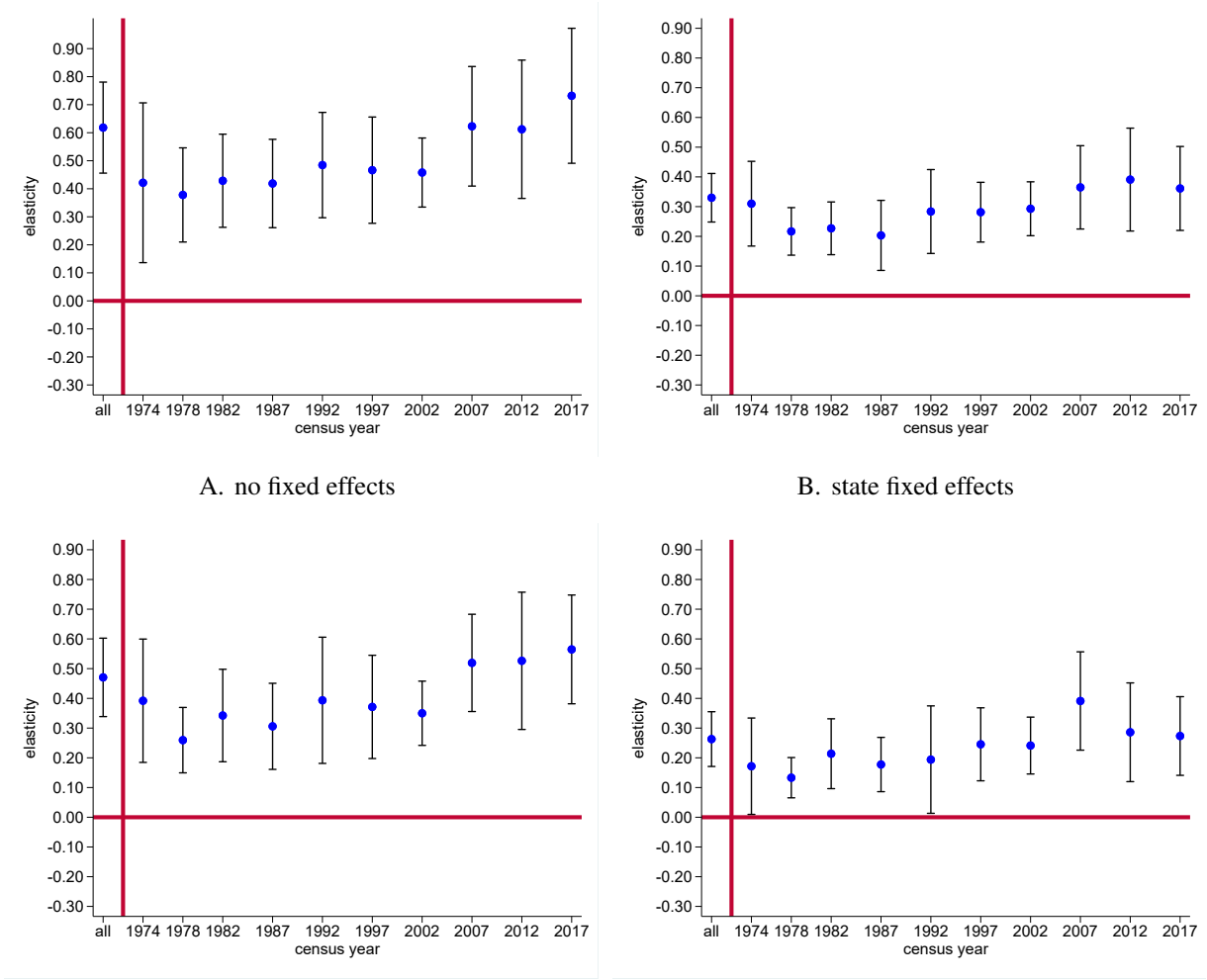
B. state fixed effects

C. HUC2 fixed effects

D. HUC4 fixed effects

Note: For a summary of these elasticities, see Table A22. For additional details, see the discussion on page 41.

Figure A27. Cross-section regressions, counties, CONUS, USGS+EPA data
SPEC 5: cropland acres×precip, weather, population, per-capita income



A. no fixed effects

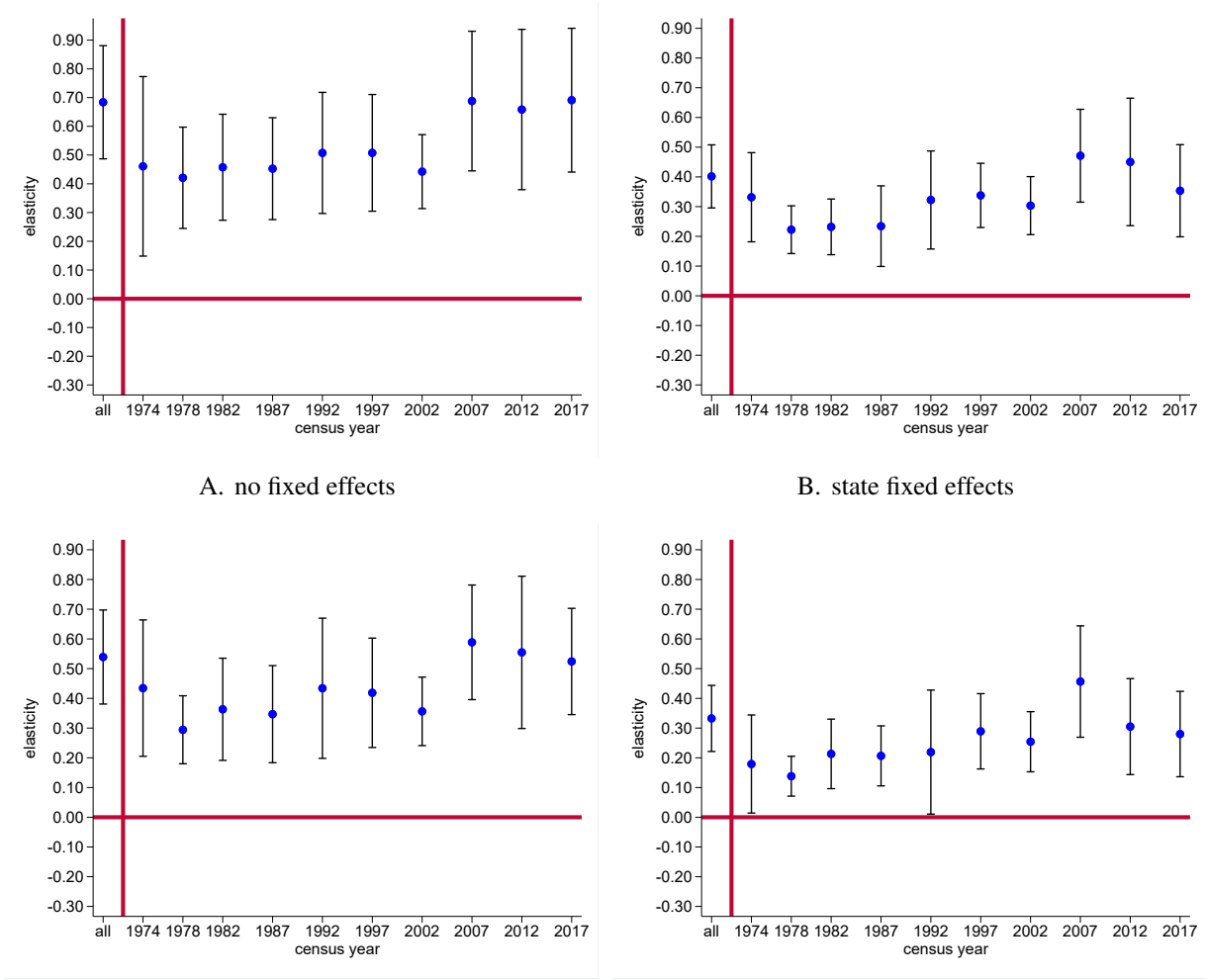
B. state fixed effects

C. HUC2 fixed effects

D. HUC4 fixed effects

Note: For a summary of these elasticities, see Table A22. For additional details, see the discussion on page 41.

Figure A28. Cross-section regressions, counties, CONUS, USGS+EPA data
SPEC 6: cropland acres×precip, weather, CRP acres



A. no fixed effects

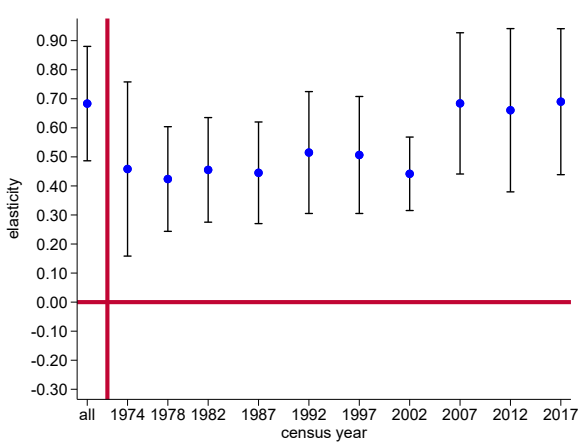
B. state fixed effects

C. HUC2 fixed effects

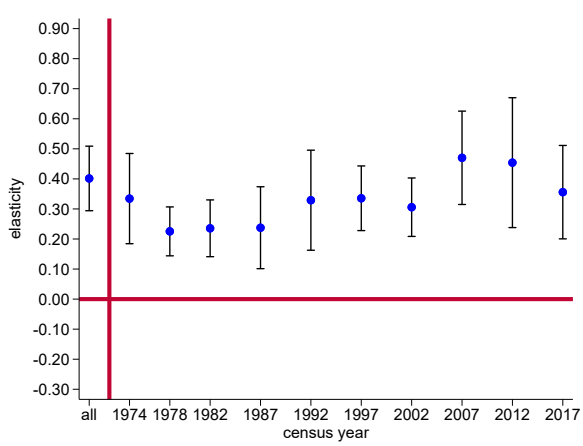
D. HUC4 fixed effects

Note: For a summary of these elasticities, see Table A22. For additional details, see the discussion on page 41.

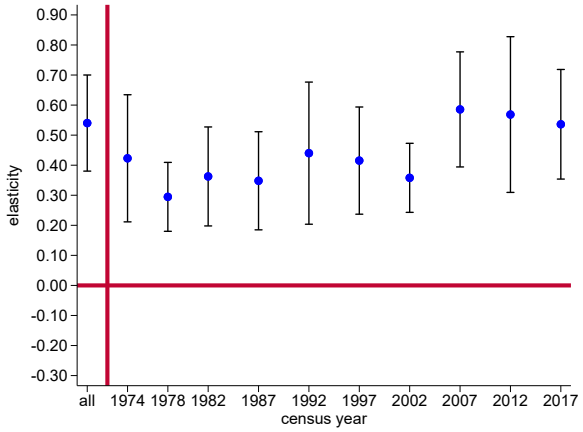
Figure A29. Cross-section regressions, counties, CONUS, USGS+EPA data
SPEC 7: cropland acres×precip, weather, CRP acres, population, GDP



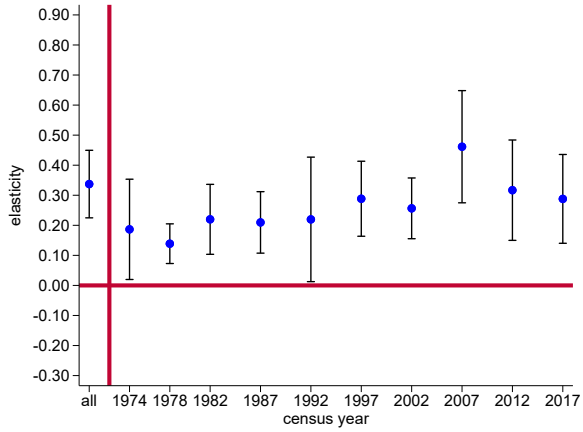
A. no fixed effects



B. state fixed effects



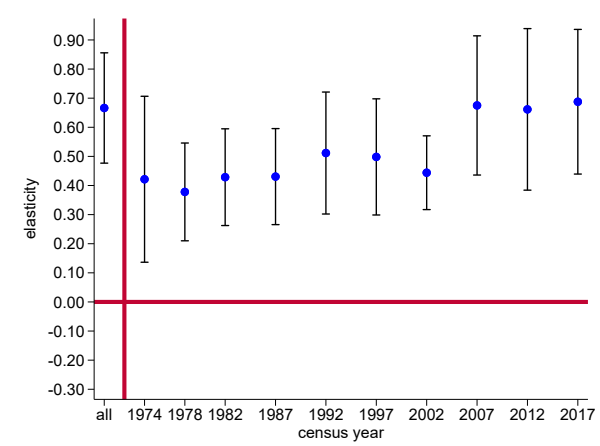
C. HUC2 fixed effects



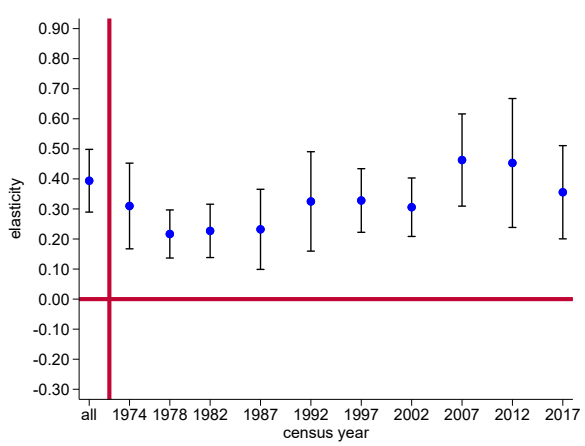
D. HUC4 fixed effects

Note: For a summary of these elasticities, see Table A22. For additional details, see the discussion on page 41.

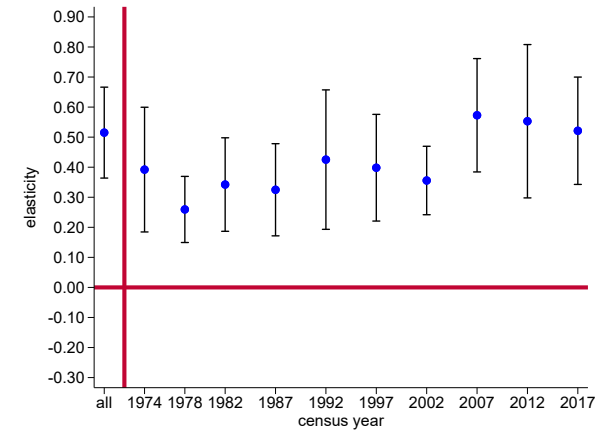
Figure A30. Cross-section regressions, counties, CONUS, USGS+EPA data
SPEC 8: cropland acres×precip, weather, CRP acres, population, per-capita income



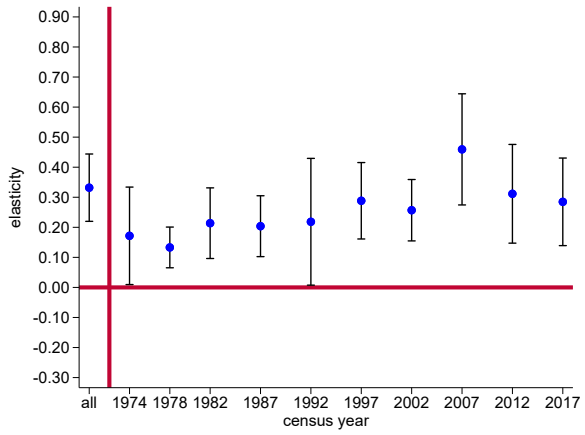
A. no fixed effects



B. state fixed effects



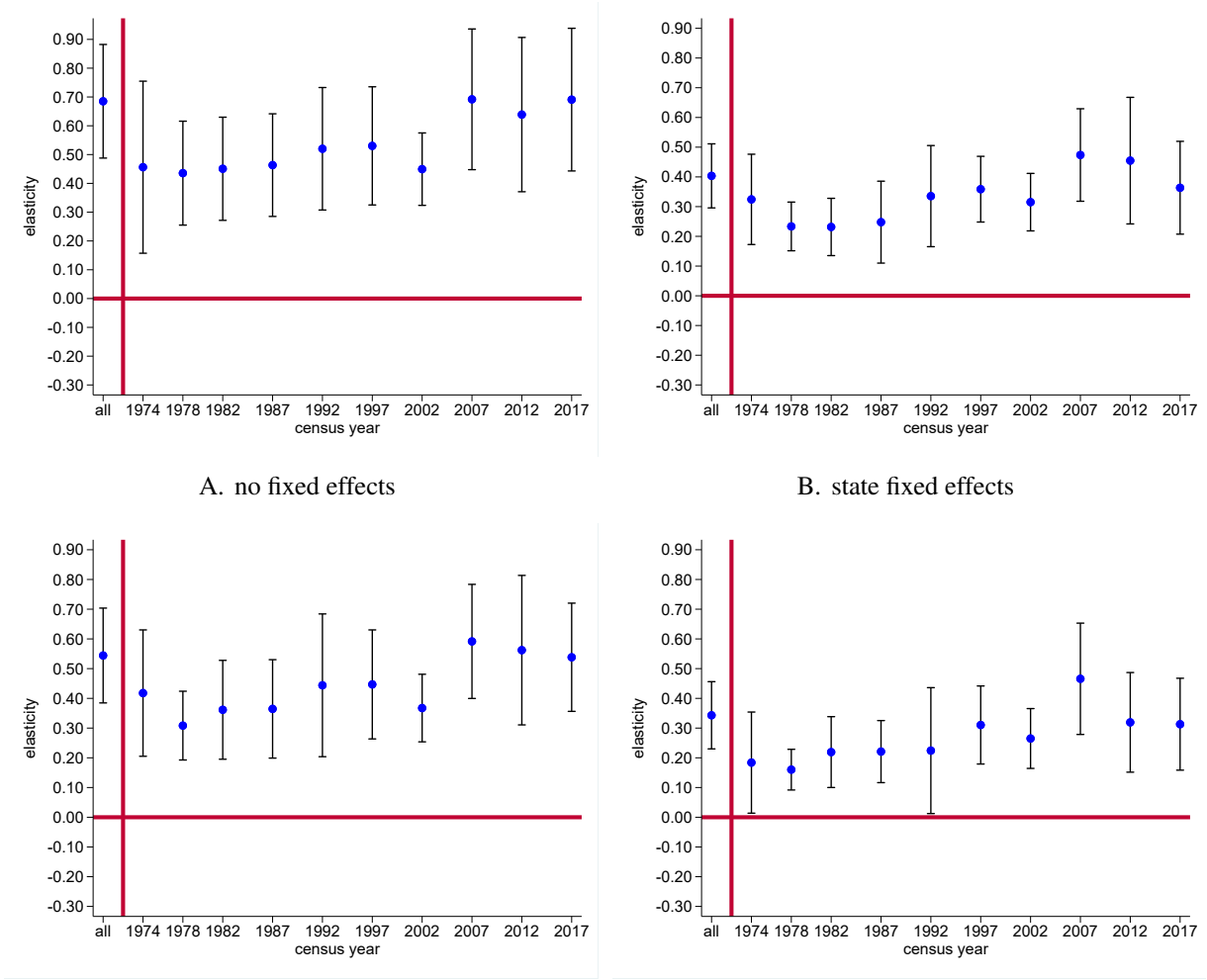
C. HUC2 fixed effects



D. HUC4 fixed effects

Note: For a summary of these elasticities, see Table A22. For additional details, see the discussion on page 41.

Figure A31. Cross-section regressions, counties, CONUS, USGS+EPA data
SPEC 9: cropland acres×precip, weather, CRP acres, population, GDP, land area



A. no fixed effects

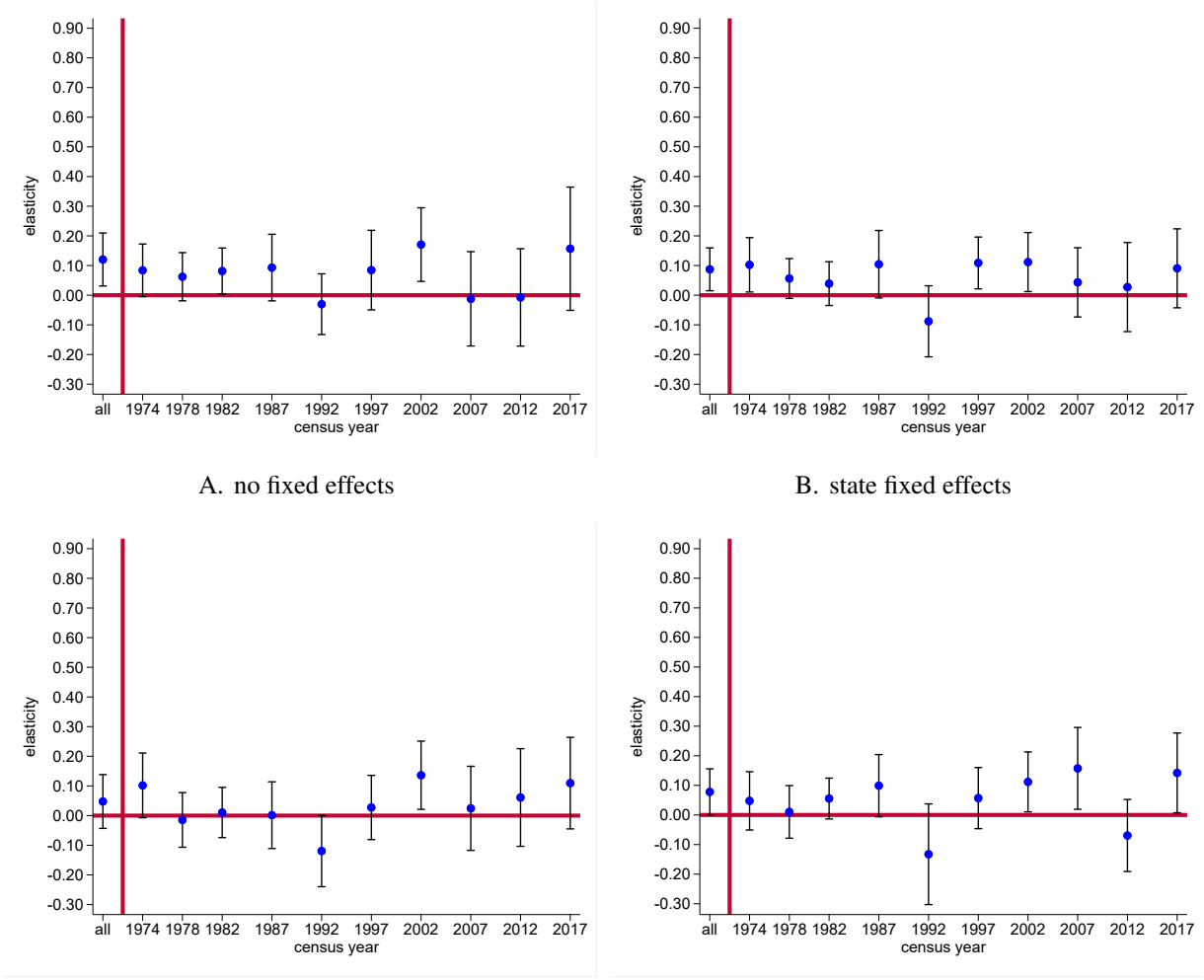
B. state fixed effects

C. HUC2 fixed effects

D. HUC4 fixed effects

Note: For a summary of these elasticities, see Table A22. For additional details, see the discussion on page 41.

Figure A32. Cross-section regressions, counties, CONUS, USGS+EPA data
spec 10: cropland acres×precip, weather, CRP acres, popul., GDP, land area, corn acres



A. no fixed effects

B. state fixed effects

C. HUC2 fixed effects

D. HUC4 fixed effects

Note: For a summary of these elasticities, see Table A22. For additional details, see the discussion on page 41.

A Appendix Tables

Table A1. Ranking of corn producing states, 1970–2018

	A. rank			B. production		C. plant		D. harvest	
state	prod.	plant	harvest	bushels	cum. %	acres	cum. %	acres	cum. %
IA	1	1	1	83.654	19.044	0.627	16.654	0.604	17.441
IL	2	2	2	73.772	35.839	0.524	30.563	0.533	32.855
NE	3	3	3	50.132	47.251	0.389	40.897	0.368	43.496
MN	4	4	4	41.537	56.707	0.334	49.773	0.313	52.546
IN	5	5	5	35.276	64.738	0.269	56.921	0.272	60.401
OH	6	8	6	20.657	69.441	0.169	71.235	0.164	65.138
WI	7	7	8	17.189	73.354	0.178	66.761	0.139	73.835
SD	8	6	7	16.605	77.134	0.193	62.048	0.162	69.805
KS	9	11	10	13.422	80.190	0.120	81.007	0.107	80.399
MO	10	9	9	13.268	83.210	0.128	74.629	0.120	77.295
MI	11	10	11	11.696	85.873	0.120	77.820	0.103	83.389
TX	12	12	12	8.284	87.759	0.080	83.138	0.071	85.455
KY	13	14	13	6.741	89.293	0.066	86.716	0.060	87.176
ND	14	15	16	5.518	90.550	0.062	88.350	0.048	91.518
CO	15	18	17	5.419	91.783	0.049	92.345	0.040	92.675
PA	16	13	15	5.263	92.981	0.069	84.963	0.050	90.126
NC	17	17	14	4.484	94.002	0.050	91.048	0.052	88.687
TN	18	20	19	3.162	94.722	0.036	94.339	0.030	94.543
NY	19	16	20	2.840	95.369	0.052	89.724	0.026	95.303
GA	20	19	18	2.542	95.948	0.040	93.396	0.034	93.664

Note: Bushels and acres are in billions. For additional detials regarding the data, see Section 4.

Table A2. Corn acres planted and weather variables by quartile of nitrogen, counties

	Q1	Q2	Q3	Q4
acres planted	0.0126	0.0200	0.0380	0.0806
precip. 1	0.0986	0.0845	0.0628	0.0455
precip. 2	0.0866	0.0783	0.0585	0.0449
precip. 3	0.1137	0.0996	0.0836	0.0716
precip. 4	0.0992	0.0959	0.0930	0.0910
precip. 5	0.1100	0.1118	0.1130	0.1110
precip. 6	0.1094	0.1091	0.1073	0.1096
precip. 7	0.1142	0.1064	0.1003	0.1011
precip. 8	0.1053	0.0998	0.0944	0.0978
precip. 9	0.1040	0.0981	0.0893	0.0847
precip. 10	0.0863	0.0866	0.0808	0.0742
precip. 11	0.0926	0.0892	0.0781	0.0687
precip. 12	0.0955	0.0890	0.0698	0.0560
mod. heat 1	0.0281	0.0226	0.0138	0.0074
mod. heat 2	0.0408	0.0338	0.0223	0.0125
mod. heat 3	0.0943	0.0823	0.0612	0.0421
mod. heat 4	0.1650	0.1547	0.1297	0.1039
mod. heat 5	0.2757	0.2686	0.2446	0.2226
mod. heat 6	0.3717	0.3704	0.3564	0.3438
mod. heat 7	0.4385	0.4379	0.4286	0.4158
mod. heat 8	0.4211	0.4184	0.4047	0.3873
mod. heat 9	0.3179	0.3095	0.2869	0.2652
mod. heat 10	0.1811	0.1723	0.1492	0.1261
mod. heat 11	0.0859	0.0756	0.0567	0.0387
mod. heat 12	0.0371	0.0319	0.0201	0.0109
ext. heat 1	0.0000	0.0000	0.0000	0.0000
ext. heat 2	0.0000	0.0001	0.0001	0.0001
ext. heat 3	0.0003	0.0003	0.0004	0.0003
ext. heat 4	0.0044	0.0039	0.0037	0.0025
ext. heat 5	0.0293	0.0255	0.0193	0.0142
ext. heat 6	0.1236	0.1185	0.1021	0.0784
ext. heat 7	0.2360	0.2350	0.2180	0.1734
ext. heat 8	0.1910	0.1971	0.1785	0.1298
ext. heat 9	0.0691	0.0692	0.0624	0.0422
ext. heat 10	0.0055	0.0070	0.0063	0.0041
ext. heat 11	0.0001	0.0001	0.0002	0.0002
ext. heat 12	0.0000	0.0000	0.0000	0.0000

Note: we report the mean of the conditional distribution of each variable for each of the 4 quartiles of nitrogen concentration. An observation is a county-year combination. We use 1–12 to denote January—December. Acres planted are measured in millions. The moderate heat (mod. heat) is measured in 1,000 degree days. The extreme heat (ext. heat) is measured in 100 degree days. The precipitation is measured in meters. For additional detials regarding the data, see the discussion in Section 4.

Table A3. Corn acres planted and weather variables by quartile of nitrogen, hydrologic units

	Q1	Q2	Q3	Q4
acres planted	0.0113	0.0146	0.0261	0.0666
precip. 1	0.0878	0.0851	0.0703	0.0518
precip. 2	0.0753	0.0771	0.0658	0.0494
precip. 3	0.1019	0.0974	0.0870	0.0750
precip. 4	0.1002	0.0972	0.0922	0.0900
precip. 5	0.1118	0.1156	0.1137	0.1130
precip. 6	0.1071	0.1107	0.1096	0.1081
precip. 7	0.1064	0.1038	0.0999	0.0968
precip. 8	0.1014	0.1012	0.0949	0.0953
precip. 9	0.1025	0.1022	0.0947	0.0869
precip. 10	0.0908	0.0924	0.0873	0.0786
precip. 11	0.0923	0.0916	0.0824	0.0717
precip. 12	0.0930	0.0902	0.0769	0.0607
mod. heat 1	0.0216	0.0287	0.0221	0.0123
mod. heat 2	0.0322	0.0421	0.0329	0.0193
mod. heat 3	0.0751	0.0926	0.0784	0.0534
mod. heat 4	0.1390	0.1630	0.1489	0.1183
mod. heat 5	0.2451	0.2742	0.2620	0.2342
mod. heat 6	0.3435	0.3712	0.3676	0.3511
mod. heat 7	0.4137	0.4390	0.4367	0.4237
mod. heat 8	0.3945	0.4202	0.4166	0.3982
mod. heat 9	0.2857	0.3147	0.3051	0.2794
mod. heat 10	0.1552	0.1839	0.1703	0.1412
mod. heat 11	0.0680	0.0846	0.0724	0.0496
mod. heat 12	0.0284	0.0390	0.0311	0.0174
ext. heat 1	0.0000	0.0000	0.0000	0.0000
ext. heat 2	0.0001	0.0002	0.0002	0.0001
ext. heat 3	0.0004	0.0008	0.0006	0.0005
ext. heat 4	0.0035	0.0051	0.0051	0.0039
ext. heat 5	0.0232	0.0311	0.0275	0.0190
ext. heat 6	0.1041	0.1347	0.1272	0.0984
ext. heat 7	0.2072	0.2628	0.2555	0.2123
ext. heat 8	0.1768	0.2329	0.2261	0.1736
ext. heat 9	0.0623	0.0884	0.0834	0.0616
ext. heat 10	0.0054	0.0116	0.0106	0.0073
ext. heat 11	0.0001	0.0004	0.0003	0.0003
ext. heat 12	0.0000	0.0000	0.0000	0.0000

Note: we report the mean of the conditional distribution of each variable for each of the 4 quartiles of nitrogen concentration. An observation is a hydrologic unit-year combination. We use 1–12 to denote January—December. Acres planted are measured in millions. The moderate heat (mod. heat) is measured in 1,000 degree days. The extreme heat (ext. heat) is measured in 100 degree days. The precipitation is measured in meters. For additional detials regarding the data, see the discussion in Section 4.

Table A4. Corn acres planted and weather variables by quartile of nitrogen, monitoring sites

	Q1	Q2	Q3	Q4
acres planted	0.1160	0.1651	0.2908	0.5956
precip. 1	0.0892	0.0854	0.0739	0.0645
precip. 2	0.0741	0.0731	0.0660	0.0562
precip. 3	0.1025	0.0962	0.0883	0.0813
precip. 4	0.1002	0.0970	0.0936	0.0936
precip. 5	0.1133	0.1150	0.1145	0.1129
precip. 6	0.1106	0.1131	0.1103	0.1091
precip. 7	0.1064	0.1052	0.1001	0.0986
precip. 8	0.1005	0.1007	0.0960	0.0974
precip. 9	0.1064	0.1044	0.0976	0.0929
precip. 10	0.0942	0.0945	0.0893	0.0850
precip. 11	0.0926	0.0905	0.0833	0.0776
precip. 12	0.0952	0.0898	0.0798	0.0707
mod. heat 1	0.0220	0.0273	0.0220	0.0129
mod. heat 2	0.0328	0.0392	0.0324	0.0199
mod. heat 3	0.0765	0.0883	0.0772	0.0544
mod. heat 4	0.1432	0.1593	0.1472	0.1191
mod. heat 5	0.2513	0.2708	0.2600	0.2348
mod. heat 6	0.3536	0.3715	0.3663	0.3494
mod. heat 7	0.4241	0.4400	0.4363	0.4234
mod. heat 8	0.4063	0.4219	0.4173	0.4002
mod. heat 9	0.2964	0.3146	0.3054	0.2812
mod. heat 10	0.1630	0.1814	0.1700	0.1436
mod. heat 11	0.0699	0.0819	0.0727	0.0527
mod. heat 12	0.0297	0.0374	0.0309	0.0186
ext. heat 1	0.0000	0.0000	0.0000	0.0000
ext. heat 2	0.0001	0.0002	0.0002	0.0001
ext. heat 3	0.0005	0.0007	0.0006	0.0004
ext. heat 4	0.0034	0.0052	0.0054	0.0040
ext. heat 5	0.0243	0.0303	0.0273	0.0193
ext. heat 6	0.1079	0.1315	0.1221	0.0937
ext. heat 7	0.2191	0.2572	0.2461	0.2019
ext. heat 8	0.1909	0.2291	0.2192	0.1667
ext. heat 9	0.0675	0.0865	0.0820	0.0584
ext. heat 10	0.0074	0.0117	0.0115	0.0071
ext. heat 11	0.0001	0.0003	0.0003	0.0002
ext. heat 12	0.0000	0.0000	0.0000	0.0000

Note: we report the mean of the conditional distribution of each variable for each of the 4 quartiles of nitrogen concentration. An observation is a monitoring site-year combination. We use 1–12 to denote January—December. Acres planted are measured in millions. The moderate heat (mod. heat) is measured in 1,000 degree days. The extreme heat (ext. heat) is measured in 100 degree days. The precipitation is measured in meters. For additional detials regarding the data, see the discussion in Section 4.

Table A5. USGS-NWIS WQP data diagnostics, Activity Media Subdivision Name

value	obs.	obs. %
surface water	693,671	95.978
groundwater	29,068	4.022

Note: For additional details, see the discussion in Section A.2.

Table A6. USGS-NWIS WQP data diagnostics, Activity Type Code

value	obs.	obs. %
sample-routine	680,274	94.124
not determined	18,174	2.515
sample-composite without parents	11,774	1.629
quality control sample-field replicate	11,670	1.615
quality control sample-field spike	446	0.062
quality control sample-field blank	202	0.028
quality control sample-reference sample	67	0.009
quality control sample-other	62	0.009
quality control sample-spike solution	39	0.005
quality control sample-reference material	13	0.002
quality control sample-blind	12	0.002
unknown	6	0.001

Note: For additional details, see the discussion in Section A.2.

Table A7. USGS-NWIS WQP data diagnostics, Detection Quantitation Limit Type Name

value	obs.	obs. %
	612,111	84.693
historical lower reporting limit	103,289	14.291
laboratory reporting level	5,003	0.692
lower reporting limit	1,496	0.207
method detection limit (mdl)	795	0.110
upper reporting limit	39	0.005
lower quantitation limit	3	0.000
elevated detection limit	3	0.000

Note: For additional details, see the discussion in Section A.2.

Table A8. USGS-NWIS WQP data diagnostics, Hydrologic Event

value	obs.	obs. %
routine sample	632,764	87.551
storm	40,579	5.615
not determined (historical)	19,404	2.685
regulated flow	8,238	1.140
snowmelt	6,469	0.895
flood	4,119	0.570
tidal action	3,475	0.481
not applicable	3,031	0.419
under ice cover	2,494	0.345
spring breakup	1,078	0.149
drought	644	0.089
hurricane	211	0.029
volcanic action	100	0.014
earthquake	79	0.011
spill	23	0.003
affected by fire	16	0.002
dambreak	9	0.001
backwater	6	0.001

Note: For additional details, see the discussion in Section A.2.

Table A9. USGS-NWIS WQP data diagnostics, Result Value Type Name

value	obs.	obs. %
actual	709,831	98.214
estimated	12,908	1.786

Note: For additional details, see the discussion in Section A.2.

Table A10. Breakdown of USGS-NWIS WQP nitrogen data

decade	monitors	dates	states	counties	HUC8s	obs R.	obs D.
1970	12,702	2,992	49	1,653	1,334	127,658	1,128
1980	11,700	3,393	49	1,626	1,332	139,579	29,308
1990	11,006	3,566	49	1,670	1,232	128,577	37,670
2000	10,349	3,252	49	1,387	1,029	117,701	18,963
2010	4,402	3,004	47	871	690	105,813	23,559
All	40,001	16,207	49	2,529	1,758	619,328	110,628

Note: The column "obs. R" indicates the number of observations for which the the Result Measure Value is available. The column "obs. D" indicates the number of observations for which the Detection Quantitation Limit Measure/Measure Value is available. For additional details, see the discussion in Section A.2.

Table A11. Breakdown of WQP nitrogen data

group 1	group 2	obs.	obs. %
stream	stream	604,604	83.655
lake	lake	58,675	8.118
groundwater	well	27,306	3.778
facility	facility	11,932	1.651
marine	estuary	10,575	1.463
spring	spring	4,233	0.586
other	land	1,427	0.197
groundwater	subsurface	1,225	0.169
		854	0.118
marine	ocean	761	0.105
other	wetland	739	0.102
other	atmosphere	402	0.056
other	surface	6	0.001

Note: For additional details, see the discussion in Section A.2.

Table A12. Alternative total nitrogen concentration calculations

calculation	obs.	R^2	intercept	slope
00625+00631	277,364	0.997	-0.001	0.998
49570+62854	15,723	0.998	0.007	0.996
00623+00631+49570	15,723	0.998	0.007	0.996

Note: An observation is identified as monitoring site-date combination. For each monitoring site, we collected the average daily Result Measure Value of the relevant parameter code and calculated the three sums indicated in the leftmost column of the table. The four rightmost columns report the results of a regression of the average daily Result Measure Value of parameter code 00600 used in the paper on the three alternative sums. There are 543,111 observations with non-missing values for patemeter code 00600. See also the National Water Quality Network (NWQN) sample collection and reporting methods link. For additional details, see the discussion in Section A.2.

Table A13. Alternative nitrogen concentration calculations

A. dissolved nitrate plus nitrite 00613				
calculation	obs.	intercept	slope	R^2
00630	63,860	-0.0459	1.0010	0.9762
00618	367,968	0.0191	1.0025	0.9952
00620	28,299	-0.0205	1.0073	0.9891
71851	366,995	0.0198	1.0025	0.9953
71850	487	0.1066	0.9667	0.9316
00620+00613	15,363	-0.0316	0.9922	0.9937
00620+71856	16,641	-0.0321	0.9922	0.9935
00620+00615	20,121	-0.0028	0.9711	0.9913
71851+00613	223,843	0.0055	1.0000	0.9941
71851+71856	233,714	0.0053	1.0000	0.9941
71851+00615	16,834	-0.0113	0.9998	0.9998
71850+00613	59	0.1474	0.9032	0.8090
71850+71856	99	0.0894	0.9747	0.9111
71850+00615	19	0.1841	0.5836	0.5362
B. total organic nitrogen plus ammonia 00625				
calculation	obs.	intercept	slope	R^2
00605+00608	271,805	0.0044	1.0000	1.0000
00605+00610	267,772	0.3535	0.7825	0.7961
C. total nitrogen 00600				
calculation	obs.	intercept	slope	R^2
method 1	577,683	0.0122	0.9980	0.9804
method 2	19,818	-0.0011	1.0001	0.9965
method 3	16,542	-0.0005	1.0001	0.9996

Note: An observation is identified as a monitoring site-and-date combination. For each monitoring site, we collected the average daily Result Measure Value for the relevant parameter code from the WQP. The four rightmost columns report the results of a regression of the average daily Result Measure Value for dissolved nitrate plus nitrite, total organic nitrogen plus ammonia, and total nitrogen, on the average daily Result Measure Value of the parameter codes indicated in the leftmost column. These parameter codes are based on the authors' review of USGS methodologies. For additional detials, see the discussion in Section A.3.

Table A14. Two-digit hydrologic units in the Mississippi River Basin

HUC2	name	states
04	Great Lakes Region	CN,IL,IN,ME,MI,MN,NH,NY,OH,PA,VT,WI
05	Ohio Region	IL,IN,KY,MD,NC,NY,OH,PA,TN,VA,WV
06	Tennessee Region	AL,GA,KY,MS,NC,SC,TN,VA,WV
07	Upper Mississippi Region	IA,IL,IN,KY,MI,MN,MO,ND,SD,WI
08	Lower Mississippi Region	AR,IL,KY,LA,MO,MS,TN
09	Souris-Red-Rainy Region	CN,MN,MT,ND,SD
10	Missouri Region	CN,CO,IA,ID,KS,MN,MO,MT,ND,NE,SD,WY
11	Arkansas-White-Red Region	AR,CO,KS,LA,MO,NM,OK,TX
12	Texas-Gulf Region	LA,NM,TX



Note: For additional details, see the discussion in Section 8.2.

Table A15. Elasticity of nitrogen concentration with respect to corn acres spatial variation by 2-digit hydrologic unit

A. counties							
model	estim	s.e.	t-stat	p-value	Δ acres	$\bar{y}$	precip.
baseline	0.117	0.035	3.353	0.001	0.010	2.450	1.270
HUC2: 04	-0.193	0.149	-1.295	0.198	0.010	2.450	1.270
HUC2: 05	-0.006	0.036	-0.172	0.864	0.010	2.450	1.270
HUC2: 06	-0.175	0.074	-2.377	0.019	0.010	2.450	1.270
HUC2: 07	0.128	0.073	1.762	0.081	0.010	2.450	1.270
HUC2: 08	0.018	0.039	0.460	0.647	0.010	2.450	1.270
HUC2: 10	0.195	0.058	3.346	0.001	0.010	2.450	1.270
HUC2: 11	0.215	0.119	1.802	0.074	0.010	2.450	1.270
B. hydrologic units							
model	estim	s.e.	t-stat	p-value	Δ acres	$\bar{y}$	precip.
baseline	0.131	0.042	3.100	0.002	0.008	2.100	1.270
HUC2: 04	0.046	0.125	0.367	0.714	0.008	2.100	1.270
HUC2: 05	-0.015	0.060	-0.249	0.804	0.008	2.100	1.270
HUC2: 06	1.882	1.207	1.558	0.122	0.008	2.100	1.270
HUC2: 07	0.136	0.087	1.570	0.119	0.008	2.100	1.270
HUC2: 08	0.048	0.040	1.210	0.229	0.008	2.100	1.270
HUC2: 10	0.097	0.081	1.196	0.234	0.008	2.100	1.270
HUC2: 11	-0.076	0.151	-0.499	0.619	0.008	2.100	1.270
C. monitoring sites							
model	estim	s.e.	t-stat	p-value	Δ acres	$\bar{y}$	precip.
baseline	0.077	0.028	2.729	0.007	0.053	2.400	1.270
HUC2: 04	-0.089	0.150	-0.592	0.555	0.053	2.400	1.270
HUC2: 05	0.025	0.038	0.653	0.515	0.053	2.400	1.270
HUC2: 06	0.021	0.070	0.303	0.763	0.053	2.400	1.270
HUC2: 07	0.100	0.045	2.236	0.027	0.053	2.400	1.270
HUC2: 08	0.045	0.020	2.204	0.029	0.053	2.400	1.270
HUC2: 10	0.039	0.075	0.519	0.605	0.053	2.400	1.270
HUC2: 11	0.062	0.322	0.193	0.848	0.053	2.400	1.270

Note: The estimates refer to the elasticity of nitrogen concentration with respect to corn acreage. For clarity, we also show the assumed increase in acres (Δ acres), the mean nitrogen concentration ($\bar{y}$), and the 75% percentile of precipitation (precip) used to evaluate the acreage effects.We report results for the following HUC2s: 02, 03, 04, 05, 06, 07, 08, 09, 10, 11, 12, 13. We have eliminated HUC2:01 due to the very small number of obserbations. For additional details, see the discussion on page 32.

Table A16. Elasticity of nitrogen concentration with respect to corn acres spatial variation by 2-digit hydrologic unit II

A. counties							
model	estim	s.e.	t-stat	p-value	Δ acres	$\bar{y}$	precip.
baseline	0.117	0.035	3.353	0.001	0.010	2.450	1.270
HUC2: 05	0.029	0.063	0.467	0.641	0.010	2.450	1.270
HUC2: 06	-0.143	0.242	-0.588	0.558	0.010	2.450	1.270
HUC2: 07	0.091	0.067	1.372	0.171	0.010	2.450	1.270
HUC2: 08	-0.033	0.031	-1.050	0.296	0.010	2.450	1.270
HUC2: 10	0.102	0.051	1.988	0.048	0.010	2.450	1.270
HUC2: 11	0.076	0.146	0.525	0.600	0.010	2.450	1.270
B. hydrologic units							
model	estim	s.e.	t-stat	p-value	Δ acres	$\bar{y}$	precip.
baseline	0.131	0.042	3.100	0.002	0.008	2.100	1.270
HUC2: 05	0.015	0.069	0.218	0.828	0.008	2.100	1.270
HUC2: 06	2.089	1.059	1.973	0.058	0.008	2.100	1.270
HUC2: 07	0.289	0.169	1.713	0.089	0.008	2.100	1.270
HUC2: 08	0.010	0.063	0.162	0.872	0.008	2.100	1.270
HUC2: 10	-0.006	0.104	-0.053	0.958	0.008	2.100	1.270
HUC2: 11	0.076	0.162	0.469	0.640	0.008	2.100	1.270
C. monitoring sites							
model	estim	s.e.	t-stat	p-value	Δ acres	$\bar{y}$	precip.
baseline	0.077	0.028	2.729	0.007	0.053	2.400	1.270
HUC2: 05	0.110	0.065	1.697	0.090	0.053	2.400	1.270
HUC2: 06	0.098	0.229	0.430	0.668	0.053	2.400	1.270
HUC2: 07	0.238	0.102	2.335	0.020	0.053	2.400	1.270
HUC2: 08	0.013	0.061	0.219	0.826	0.053	2.400	1.270
HUC2: 10	0.031	0.066	0.468	0.640	0.053	2.400	1.270
HUC2: 11	-0.100	0.419	-0.239	0.811	0.053	2.400	1.270

Note: The estimates refer to the elasticity of nitrogen concentration with respect to corn acreage. For clarity, we also show the assumed increase in acres (Δ acres), the mean nitrogen concentration ($\bar{y}$), and the 75% percentile of precipitation (precip) used to evaluate the acreage effects. The standard errors are clustered by county, hydrologic unit, and monitoring site, respectively. For additional details, see the discussion on page 32.

Table A17. Elasticity of nitrogen concentration with respect to corn acres cross-section, streamflow

A. counties							
model	estim	s.e.	t-stat	p-value	Δ acres	$\bar{y}$	precip.
none	0.255	0.042	6.089	0.000	0.010	2.450	1.270
state FE	0.190	0.059	3.237	0.002	0.010	2.450	1.270
HUC2 FE	0.223	0.062	3.578	0.000	0.010	2.450	1.270
HUC4 FE	0.144	0.075	1.905	0.059	0.010	2.450	1.270
C. monitoring sites							
model	estim	s.e.	t-stat	p-value	Δ acres	$\bar{y}$	precip.
none	0.579	0.052	11.062	0.000	0.053	2.400	1.270
state FE	0.386	0.323	1.194	0.235	0.053	2.400	1.270
HUC2 FE	0.539	0.334	1.617	0.108	0.053	2.400	1.270
HUC4 FE	0.388	0.262	1.477	0.142	0.053	2.400	1.270

Note: The estimates refer to the elasticity of nitrogen concentration with respect to corn acreage. For clarity, we also show the assumed increase in acres (Δ acres) that is equal to a 10% of the average acres, the mean nitrogen concentration ($\bar{y}$), and the 75% percentile of precipitation (precip) used to evaluate the acreage effects.There is a drop in the number of observations from 2255 to 2030 in the case of the m-centric regressions when we account for streamflow. For additional details, see the discussion on page 40.

Table A18. Elasticity of nitrogen concentration with respect to corn acreage cross-section, average acres

A. counties							
model	estim	s.e.	t-stat	p-value	Δ acres	$\bar{y}$	precip.
none	0.274	0.051	5.338	0.000	0.010	2.450	1.270
state FE	0.219	0.043	5.040	0.000	0.010	2.450	1.270
HUC2 FE	0.255	0.047	5.407	0.000	0.010	2.450	1.270
HUC4 FE	0.170	0.045	3.780	0.000	0.010	2.450	1.270
B. hydrologic units							
model	estim	s.e.	t-stat	p-value	Δ acres	$\bar{y}$	precip.
none	0.300	0.094	3.185	0.002	0.008	2.100	1.270
HUC2 FE	0.304	0.099	3.069	0.003	0.008	2.100	1.270
HUC4 FE	0.355	0.136	2.614	0.010	0.008	2.100	1.270
C. monitoring sites							
model	estim	s.e.	t-stat	p-value	Δ acres	$\bar{y}$	precip.
none	0.375	0.119	3.157	0.002	0.003	2.510	1.270
state FE	0.409	0.119	3.442	0.001	0.003	2.510	1.270
HUC2 FE	0.482	0.104	4.624	0.000	0.003	2.510	1.270
HUC4 FE	0.539	0.122	4.419	0.000	0.003	2.510	1.270

Note: The estimates refer to the elasticity of nitrogen concentration with respect to corn acreage. For clarity, we also show the assumed increase in acres (Δ acres) that is equal to a 10% of the average acres, the mean nitrogen concentration ($\bar{y}$), and the 75% percentile of precipitation (precip) used to evaluate the acreage effects. For additional details, see the discussion on page 40.

Table A19. Cross-section regressions, counties, corn acres, USGS+EPA data, CONUS, obs.

A. no fixed effects										
SPEC	POOL	1975	1980	1985	1990	1995	2000	2005	2010	2015
1	3101	2648	2795	2601	2682	2318	2373	2462	2679	2535
2	3029	2594	2739	2548	2622	2262	2321	2397	2610	2465
3	3029	2594	2739	2548	2622	2262	2321	2397	2610	2465
4	2984	2555	2699	2515	2582	2227	2289	2353	2565	2421
5	2984	2555	2699	2515	2582	2227	2289	2353	2565	2421
6	3029	2594	2739	2548	2622	2262	2321	2397	2610	2465
7	2984	2555	2699	2515	2582	2227	2289	2353	2565	2421
8	2984	2555	2699	2515	2582	2227	2289	2353	2565	2421
9	2984	2555	2699	2515	2582	2227	2289	2353	2565	2421
B. state fixed effects										
SPEC	POOL	1975	1980	1985	1990	1995	2000	2005	2010	2015
1	3101	2648	2795	2601	2682	2318	2373	2462	2679	2535
2	3029	2594	2739	2548	2622	2262	2321	2397	2610	2465
3	3029	2594	2739	2548	2622	2262	2321	2397	2610	2465
4	2984	2555	2699	2515	2582	2227	2289	2353	2565	2421
5	2984	2555	2699	2515	2582	2227	2289	2353	2565	2421
6	3029	2594	2739	2548	2622	2262	2321	2397	2610	2465
7	2984	2555	2699	2515	2582	2227	2289	2353	2565	2421
8	2984	2555	2699	2515	2582	2227	2289	2353	2565	2421
9	2984	2555	2699	2515	2582	2227	2289	2353	2565	2421
C. HUC2 fixed effects										
SPEC	POOL	1975	1980	1985	1990	1995	2000	2005	2010	2015
1	3101	2648	2795	2601	2682	2318	2373	2462	2679	2535
2	3029	2594	2739	2548	2622	2262	2321	2397	2610	2465
3	3029	2594	2739	2548	2622	2262	2321	2397	2610	2465
4	2984	2555	2699	2515	2582	2227	2289	2353	2565	2421
5	2984	2555	2699	2515	2582	2227	2289	2353	2565	2421
6	3029	2594	2739	2548	2622	2262	2321	2397	2610	2465
7	2984	2555	2699	2515	2582	2227	2289	2353	2565	2421
8	2984	2555	2699	2515	2582	2227	2289	2353	2565	2421
9	2984	2555	2699	2515	2582	2227	2289	2353	2565	2421
D. HUC4 fixed effects										
SPEC	ALL	1975	1980	1985	1990	1995	2000	2005	2010	2015
1	3101	2648	2795	2601	2682	2318	2373	2462	2679	2535
2	3029	2594	2739	2548	2622	2262	2321	2397	2610	2465
3	3029	2594	2739	2548	2622	2262	2321	2397	2610	2465
4	2984	2555	2699	2515	2582	2227	2289	2353	2565	2421
5	2984	2555	2699	2515	2582	2227	2289	2353	2565	2421
6	3029	2594	2739	2548	2622	2262	2321	2397	2610	2465
7	2984	2555	2699	2515	2582	2227	2289	2353	2565	2421
8	2984	2555	2699	2515	2582	2227	2289	2353	2565	2421
9	2984	2555	2699	2515	2582	2227	2289	2353	2565	2421

Note: For additional details, see the discussion on page 40.

Table A20. Cross-section regressions, counties, corn acres, USGS+EPA data, CONUS, elasticities

A. no fixed effects										
SPEC	POOL	1975	1980	1985	1990	1995	2000	2005	2010	2015
1	0.297	0.211	0.248	0.283	0.311	0.334	0.240	0.245	0.238	0.304
2	0.305	0.070	0.098	0.317	0.348	0.366	0.512	0.363	0.305	0.321
3	0.189	0.096	0.049	0.235	0.228	0.254	0.355	0.290	0.215	0.238
4	0.193	0.106	0.064	0.237	0.235	0.260	0.363	0.293	0.217	0.225
5	0.193	0.100	0.054	0.236	0.234	0.259	0.365	0.284	0.210	0.238
6	0.202	0.096	0.049	0.235	0.229	0.263	0.360	0.293	0.228	0.235
7	0.206	0.106	0.064	0.237	0.235	0.268	0.367	0.296	0.231	0.222
8	0.205	0.100	0.054	0.236	0.234	0.266	0.369	0.286	0.223	0.234
9	0.207	0.107	0.069	0.241	0.231	0.271	0.377	0.298	0.237	0.226
B. state fixed effects										
SPEC	POOL	1975	1980	1985	1990	1995	2000	2005	2010	2015
1	0.208	0.143	0.156	0.182	0.188	0.242	0.171	0.202	0.172	0.192
2	0.214	0.113	0.103	0.253	0.281	0.222	0.302	0.289	0.198	0.165
3	0.137	0.068	0.035	0.222	0.179	0.187	0.236	0.245	0.187	0.149
4	0.144	0.076	0.045	0.226	0.186	0.194	0.249	0.246	0.187	0.149
5	0.144	0.071	0.041	0.226	0.188	0.192	0.249	0.244	0.186	0.149
6	0.156	0.068	0.035	0.222	0.177	0.199	0.248	0.246	0.210	0.153
7	0.163	0.076	0.045	0.226	0.184	0.205	0.261	0.248	0.210	0.153
8	0.162	0.071	0.041	0.226	0.186	0.202	0.261	0.246	0.209	0.153
9	0.163	0.075	0.049	0.230	0.178	0.206	0.265	0.248	0.212	0.155
C. HUC2 fixed effects										
SPEC	POOL	1975	1980	1985	1990	1995	2000	2005	2010	2015
1	0.260	0.181	0.222	0.200	0.260	0.293	0.220	0.203	0.221	0.250
2	0.287	0.146	0.192	0.235	0.314	0.270	0.417	0.344	0.300	0.251
3	0.168	0.082	0.063	0.229	0.217	0.227	0.310	0.263	0.225	0.179
4	0.173	0.094	0.076	0.229	0.224	0.225	0.324	0.268	0.228	0.186
5	0.173	0.082	0.069	0.227	0.226	0.233	0.320	0.258	0.222	0.180
6	0.181	0.082	0.063	0.229	0.216	0.235	0.316	0.265	0.242	0.179
7	0.185	0.094	0.076	0.229	0.222	0.232	0.330	0.269	0.245	0.186
8	0.185	0.082	0.069	0.227	0.224	0.238	0.325	0.258	0.238	0.179
9	0.186	0.094	0.080	0.234	0.216	0.238	0.337	0.271	0.250	0.192
D. HUC4 fixed effects										
SPEC	ALL	1975	1980	1985	1990	1995	2000	2005	2010	2015
1	0.168	0.105	0.124	0.149	0.132	0.160	0.124	0.140	0.130	0.141
2	0.146	0.057	0.055	0.180	0.174	0.102	0.118	0.181	0.146	0.128
3	0.078	0.019	0.035	0.157	0.113	0.105	0.108	0.165	0.135	0.078
4	0.084	0.029	0.041	0.151	0.111	0.102	0.121	0.169	0.136	0.082
5	0.085	0.022	0.043	0.157	0.117	0.110	0.118	0.166	0.136	0.079
6	0.100	0.019	0.035	0.157	0.112	0.117	0.119	0.170	0.161	0.084
7	0.106	0.029	0.041	0.151	0.109	0.113	0.132	0.174	0.162	0.088
8	0.106	0.022	0.043	0.157	0.115	0.121	0.130	0.171	0.161	0.085
9	0.109	0.029	0.047	0.156	0.103	0.120	0.134	0.175	0.164	0.091

Note: Detailed elasticity estimates for the 9 specifications are available in Figure A14–Figure A22. For additional details, see the discussion on page 40.

Table A21. Cross-section regressions, counties, cropland acres, census years, obs.

A. no fixed effects											
SPEC	POOL	1974	1978	1982	1987	1992	1997	2002	2007	2012	2017
1	3056	2427	2650	2618	2514	2554	2067	2429	2521	2536	2468
2	3000	2402	2615	2579	2476	2514	2042	2400	2476	2491	2428
3	3000	2402	2615	2579	2476	2514	2042	2400	2476	2491	2428
4	2976	2382	2593	2559	2456	2496	2028	2386	2453	2468	2405
5	2976	2382	2593	2559	2456	2496	2028	2386	2453	2468	2405
6	3000	2402	2615	2579	2476	2514	2042	2400	2476	2491	2428
7	2976	2382	2593	2559	2456	2496	2028	2386	2453	2468	2405
8	2976	2382	2593	2559	2456	2496	2028	2386	2453	2468	2405
9	2976	2382	2593	2559	2456	2496	2028	2386	2453	2468	2405
10	2976	2382	2593	2559	2456	2496	2028	2386	2453	2468	2405
B. state fixed effects											
SPEC	POOL	1974	1978	1982	1987	1992	1997	2002	2007	2012	2017
1	3056	2427	2650	2618	2514	2554	2067	2429	2521	2536	2468
2	3000	2402	2615	2579	2476	2514	2042	2400	2476	2491	2428
3	3000	2402	2615	2579	2476	2514	2042	2400	2476	2491	2428
4	2976	2382	2593	2559	2456	2496	2028	2386	2453	2468	2405
5	2976	2382	2593	2559	2456	2496	2028	2386	2453	2468	2405
6	3000	2402	2615	2579	2476	2514	2042	2400	2476	2491	2428
7	2976	2382	2593	2559	2456	2496	2028	2386	2453	2468	2405
8	2976	2382	2593	2559	2456	2496	2028	2386	2453	2468	2405
9	2976	2382	2593	2559	2456	2496	2028	2386	2453	2468	2405
10	2976	2382	2593	2559	2456	2496	2028	2386	2453	2468	2405
C. HUC2 fixed effects											
SPEC	POOL	1974	1978	1982	1987	1992	1997	2002	2007	2012	2017
1	3056	2427	2650	2618	2514	2554	2067	2429	2521	2536	2468
2	3000	2402	2615	2579	2476	2514	2042	2400	2476	2491	2428
3	3000	2402	2615	2579	2476	2514	2042	2400	2476	2491	2428
4	2976	2382	2593	2559	2456	2496	2028	2386	2453	2468	2405
5	2976	2382	2593	2559	2456	2496	2028	2386	2453	2468	2405
6	3000	2402	2615	2579	2476	2514	2042	2400	2476	2491	2428
7	2976	2382	2593	2559	2456	2496	2028	2386	2453	2468	2405
8	2976	2382	2593	2559	2456	2496	2028	2386	2453	2468	2405
9	2976	2382	2593	2559	2456	2496	2028	2386	2453	2468	2405
10	2976	2382	2593	2559	2456	2496	2028	2386	2453	2468	2405
D. HUC4 fixed effects											
SPEC	ALL	1974	1978	1982	1987	1992	1997	2002	2007	2012	2017
1	3056	2427	2650	2618	2514	2554	2067	2429	2521	2536	2468
2	3000	2402	2615	2579	2476	2514	2042	2400	2476	2491	2428
3	3000	2402	2615	2579	2476	2514	2042	2400	2476	2491	2428
4	2976	2382	2593	2559	2456	2496	2028	2386	2453	2468	2405
5	2976	2382	2593	2559	2456	2496	2028	2386	2453	2468	2405
6	3000	2402	2615	2579	2476	2514	2042	2400	2476	2491	2428
7	2976	2382	2593	2559	2456	2496	2028	2386	2453	2468	2405
8	2976	2382	2593	2559	2456	2496	2028	2386	2453	2468	2405
9	2976	2382	2593	2559	2456	2496	2028	2386	2453	2468	2405
10	2976	2382	2593	2559	2456	2496	2028	2386	2453	2468	2405

Note: For additional details, see the discussion on page 41.

Table A22. Cross-section regressions, counties, cropland acres, census years, elasticties

SPEC	POOL	1974	1978	1982	1987	1992	1997	2002	2007	2012	2017
A. no fixed effects											
1	0.282	0.261	0.246	0.310	0.303	0.286	0.312	0.210	0.309	0.283	0.314
2	0.531	0.389	0.386	0.432	0.414	0.497	0.406	0.434	0.702	0.461	0.651
3	0.629	0.461	0.421	0.458	0.434	0.470	0.471	0.454	0.629	0.606	0.732
4	0.629	0.458	0.424	0.455	0.430	0.484	0.471	0.454	0.628	0.611	0.732
5	0.618	0.421	0.378	0.429	0.419	0.485	0.466	0.458	0.623	0.612	0.732
6	0.684	0.461	0.421	0.458	0.453	0.507	0.508	0.442	0.688	0.658	0.691
7	0.683	0.458	0.424	0.455	0.445	0.515	0.506	0.442	0.684	0.661	0.690
8	0.666	0.421	0.378	0.429	0.431	0.512	0.498	0.444	0.675	0.661	0.688
9	0.685	0.456	0.435	0.451	0.463	0.520	0.530	0.449	0.692	0.639	0.691
10	0.120	0.084	0.062	0.081	0.093	-0.030	0.085	0.171	-0.012	-0.008	0.157
B. state fixed effects											
SPEC	POOL	1974	1978	1982	1987	1992	1997	2002	2007	2012	2017
1	0.192	0.173	0.093	0.166	0.168	0.196	0.190	0.174	0.236	0.235	0.234
2	0.292	0.302	0.219	0.219	0.173	0.361	0.246	0.271	0.339	0.297	0.333
3	0.333	0.332	0.222	0.232	0.202	0.277	0.287	0.289	0.368	0.386	0.357
4	0.334	0.334	0.225	0.236	0.206	0.286	0.287	0.292	0.369	0.389	0.361
5	0.330	0.310	0.217	0.227	0.203	0.284	0.281	0.293	0.365	0.391	0.361
6	0.402	0.332	0.222	0.232	0.234	0.322	0.338	0.303	0.471	0.450	0.353
7	0.401	0.334	0.225	0.236	0.238	0.329	0.335	0.306	0.470	0.454	0.356
8	0.394	0.310	0.217	0.227	0.232	0.325	0.328	0.306	0.463	0.453	0.356
9	0.404	0.324	0.233	0.232	0.248	0.335	0.359	0.315	0.474	0.455	0.364
10	0.087	0.102	0.056	0.039	0.105	-0.088	0.109	0.112	0.043	0.027	0.091
C. HUC2 fixed effects											
SPEC	POOL	1974	1978	1982	1987	1992	1997	2002	2007	2012	2017
1	0.208	0.183	0.113	0.210	0.189	0.236	0.259	0.165	0.243	0.225	0.249
2	0.431	0.413	0.275	0.351	0.308	0.444	0.319	0.383	0.602	0.380	0.537
3	0.487	0.434	0.294	0.363	0.323	0.395	0.387	0.348	0.528	0.526	0.565
4	0.489	0.423	0.295	0.363	0.324	0.405	0.385	0.351	0.527	0.533	0.578
5	0.471	0.392	0.259	0.342	0.306	0.393	0.371	0.350	0.519	0.526	0.565
6	0.539	0.434	0.294	0.363	0.347	0.434	0.419	0.356	0.589	0.555	0.524
7	0.540	0.423	0.295	0.363	0.348	0.440	0.415	0.358	0.586	0.569	0.536
8	0.515	0.392	0.259	0.342	0.325	0.425	0.398	0.356	0.573	0.553	0.521
9	0.544	0.418	0.308	0.362	0.365	0.444	0.447	0.367	0.592	0.562	0.538
10	0.048	0.102	-0.015	0.010	0.001	-0.119	0.027	0.136	0.024	0.061	0.109
D. HUC4 fixed effects											
SPEC	POOL	1974	1978	1982	1987	1992	1997	2002	2007	2012	2017
1	0.181	0.124	0.094	0.104	0.120	0.142	0.181	0.148	0.236	0.243	0.216
2	0.228	0.133	0.171	0.220	0.179	0.180	0.180	0.261	0.339	0.273	0.256
3	0.260	0.179	0.138	0.213	0.176	0.192	0.246	0.238	0.386	0.280	0.268
4	0.266	0.187	0.139	0.220	0.180	0.194	0.246	0.241	0.391	0.290	0.277
5	0.263	0.172	0.133	0.214	0.177	0.194	0.245	0.241	0.391	0.286	0.273
6	0.333	0.179	0.138	0.213	0.207	0.219	0.289	0.254	0.457	0.305	0.280
7	0.337	0.187	0.139	0.220	0.210	0.220	0.288	0.256	0.461	0.317	0.288
8	0.332	0.172	0.133	0.214	0.204	0.218	0.288	0.257	0.459	0.312	0.285
9	0.343	0.184	0.160	0.219	0.221	0.224	0.310	0.265	0.466	0.319	0.313
10	0.078	0.048	0.010	0.056	0.099	-0.133	0.057	0.112	0.157	-0.069	0.142

Note: Detailed estimates are available in Figure A23–Figure A32. For additional details, see the discussion on page 41.

Table A23. Summary statistics, CONUS, USGS-NWIS data

A. counties							
variable	panel	obs	years	mean	s.d. B	s.d. W	median
nitrogen	2688	72751	27.1	2.4177	1.6564	1.7045	1.6533
acres planted	2688	72751	27.1	0.0348	0.0458	0.0103	0.0129
precipitation	2688	72751	27.1	1.0275	0.3492	0.1690	1.0375
B. hydrologic units							
variable	panel	obs	years	mean	s.d. B	s.d. W	median
nitrogen	1598	27228	17.0	2.0051	2.0811	1.6734	1.2333
acres planted	1598	27228	17.0	0.0221	0.0385	0.0074	0.0058
precipitation	1598	27228	17.0	0.9226	0.4125	0.1559	0.9633
C. monitoring sites							
variable	panel	obs	years	mean	s.d. B	s.d. W	median
nitrogen	14590	83540	5.7	2.2471	3.8088	1.3057	1.2385
acres planted	14590	83540	5.7	0.2048	0.3992	0.0444	0.0340
precipitation	14590	83540	5.7	1.0014	0.3879	0.1509	1.0600

Note: an observation is a county-year (panel A), hydrologic unit-year (panel B), and a monitoring site-year (panel C) combination. The panel column indicates the number of counties, units, and sites. The years column gives the average number of observations per county, hydrologic unit, and monitoring site. We also report the between-counties (s.d. B) and within-county (s.d. W) standard deviation. Analogous definitions hold in the case of the hydrologic units and the monitoring sites in panels B and C. The acres are measured in millions and the nitrogen concentration is measured in mg/L. The precipitaion is total annual (Januray–December) and is measured in meters. For additional details, see the discussion on page 33.

Table A24. Panel FE regressions, CONUS, USGS-NWIS data

A. counties								
	(A1)	(A2)	(A3)	(A4)	(A5)	(A6)	(A7)	(A8)
acres	0.788	-8.878**	-9.511**	-7.972**	-9.328**	-6.910**	-13.969***	-10.446**
	(2.904)	(3.775)	(3.758)	(3.529)	(3.619)	(3.390)	(4.670)	(4.386)
acres × prec	19.880***	15.726***	15.603***	15.110***	15.090***	14.556***	14.331***	13.608***
	(3.307)	(3.869)	(3.848)	(3.738)	(3.818)	(3.762)	(3.888)	(3.817)
$\overline{R}^2$	0.27	0.45	0.45	0.46	0.46	0.47	0.51	0.52
Obs.	72,751	72,751	72,751	72,751	72,751	72,751	72,751	72,751
Clusters	188	188	188	188	188	188	188	188
elast est.	0.375	0.160	0.148	0.161	0.142	0.167	0.061	0.098
elast s.e.	0.036	0.034	0.032	0.035	0.032	0.037	0.031	0.033
elast t-stat	10.300	4.706	4.566	4.628	4.424	4.448	1.992	2.955
B. hydrologic units								
	(B1)	(B2)	(B3)	(B4)	(B5)	(B6)	(B7)	(B8)
acres	8.908	-13.979***	-13.787**	-14.244***	-16.370***	-16.692***	-17.915***	-18.338***
	(6.905)	(5.338)	(5.346)	(5.289)	(5.859)	(5.782)	(5.771)	(5.754)
acres × prec	18.188**	19.228***	19.244***	19.333***	19.882***	19.690***	19.634***	19.516***
	(7.935)	(5.958)	(5.953)	(5.950)	(6.115)	(6.100)	(5.834)	(5.831)
$\overline{R}^2$	0.19	0.53	0.53	0.53	0.54	0.54	0.64	0.64
Obs.	27,228	27,228	27,228	27,228	27,228	27,228	27,228	27,228
Clusters	202	202	202	202	202	202	202	202
elast est.	0.353	0.115	0.117	0.114	0.098	0.092	0.077	0.071
elast s.e.	0.043	0.041	0.040	0.042	0.040	0.043	0.034	0.037
elast t-stat	8.135	2.807	2.923	2.680	2.425	2.108	2.262	1.921
C. monitoring sites								
	(C1)	(C2)	(C3)	(C4)	(C5)	(C6)	(C7)	(C8)
acres	1.046	-1.380**	-1.407**	-1.467**	-1.596***	-1.671***	-1.250**	-1.319**
	(0.771)	(0.626)	(0.625)	(0.616)	(0.604)	(0.593)	(0.546)	(0.536)
acres × prec	1.163	1.634***	1.603***	1.613***	1.602***	1.604***	1.481***	1.492***
	(0.880)	(0.498)	(0.499)	(0.497)	(0.505)	(0.503)	(0.473)	(0.472)
$\overline{R}^2$	0.09	0.81	0.81	0.81	0.81	0.81	0.81	0.81
Obs.	83,540	83,540	83,540	83,540	83,540	83,540	83,540	83,540
Clusters	202	202	202	202	202	202	202	202
elast est.	0.313	0.086	0.078	0.072	0.054	0.045	0.078	0.071
elast s.e.	0.054	0.024	0.021	0.023	0.023	0.025	0.025	0.027
elast t-stat	5.772	3.599	3.658	3.075	2.388	1.821	3.114	2.608
county FE		✓	✓	✓	✓	✓	✓	✓
trend			✓					
year FE				✓		✓		✓
state × trend					✓	✓		
county × trend							✓	✓

Note: For additional details, see the discussion on page 33.

Table A25. Panel FE regressions, counties
CONUS, alternative datasets

	A. USGS-NWQN data							
	(A1)	(A2)	(A3)	(A4)	(A5)	(A6)	(A7)	(A8)
acres	3.429	-8.224**	-8.348**	-7.905**	-8.606**	-7.970**	-11.537***	-10.862***
	(3.123)	(3.702)	(3.726)	(3.671)	(3.456)	(3.421)	(3.766)	(3.765)
acres × prec	18.805***	15.755***	15.715***	15.469***	15.086***	14.839***	14.310***	13.897***
	(3.578)	(3.944)	(3.921)	(3.835)	(3.677)	(3.624)	(3.878)	(3.852)
$\overline{R}^2$	0.28	0.46	0.46	0.47	0.48	0.48	0.52	0.52
Obs.	107,994	107,994	107,994	107,994	107,994	107,994	107,994	107,994
Clusters	205	205	205	205	205	205	205	205
elast est.	0.393	0.170	0.167	0.169	0.152	0.157	0.096	0.098
elast s.e.	0.040	0.035	0.033	0.033	0.028	0.028	0.027	0.027
elast t-stat	9.951	4.835	5.063	5.198	5.362	5.494	3.513	3.681
	B. USGS+EPA data							
	(B1)	(B2)	(B3)	(B4)	(B5)	(B6)	(B7)	(B8)
acres	4.663	-5.557	-5.142	-4.656	-4.547	-3.785	-8.406**	-7.528**
	(3.457)	(4.095)	(4.144)	(4.101)	(3.709)	(3.639)	(3.734)	(3.628)
acres × prec	16.662***	14.813***	14.807***	14.678***	14.434***	14.223***	14.614***	14.386***
	(4.094)	(4.332)	(4.345)	(4.215)	(4.036)	(3.910)	(3.932)	(3.782)
$\overline{R}^2$	0.26	0.44	0.44	0.45	0.46	0.46	0.51	0.51
Obs.	113,372	113,372	113,372	113,372	113,372	113,372	113,372	113,372
Clusters	205	205	205	205	205	205	205	205
elast est.	0.372	0.191	0.197	0.201	0.198	0.206	0.146	0.155
elast s.e.	0.035	0.047	0.046	0.044	0.043	0.041	0.037	0.033
elast t-stat	10.504	4.092	4.257	4.584	4.665	5.070	3.936	4.755
county FE		✓	✓	✓	✓	✓	✓	✓
trend			✓					
year FE				✓		✓		✓
state × trend					✓	✓		
county × trend							✓	✓

Note: For additional details, see the discussion on page 33.

Table A26. Panel FE regressions, counties
CONUS, USGS+EPA data, acres of other major crops and CRP acres

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
corn	21.391**	6.695	7.211	7.607	5.552	6.320	-6.060	-4.798
	(10.100)	(10.601)	(10.647)	(10.547)	(9.556)	(9.481)	(4.005)	(4.088)
corn × prec	4.236	6.775	6.281	6.439	7.400	7.458	12.749***	12.541***
	(8.420)	(8.415)	(8.487)	(8.409)	(7.579)	(7.520)	(4.088)	(4.164)
soy	-14.718	-11.202	-11.875	-11.865	-10.601	-10.833	-2.656	-3.127
	(9.400)	(9.550)	(9.560)	(9.435)	(8.659)	(8.567)	(2.978)	(3.115)
soy × prec	12.474*	7.921	8.366	8.070	7.423	7.307	1.953	2.060
	(7.173)	(7.429)	(7.465)	(7.410)	(6.664)	(6.631)	(2.500)	(2.687)
wheat	-2.940**	-0.492	-0.646	0.302	-1.301	-0.554	0.216	0.558
	(1.342)	(1.199)	(1.182)	(1.221)	(1.011)	(0.995)	(0.821)	(0.826)
wheat × prec	5.972***	0.798	0.187	-2.066	0.350	-1.820	-1.037	-3.456**
	(2.203)	(1.418)	(1.339)	(1.365)	(1.205)	(1.248)	(1.242)	(1.350)
other	0.748	4.823***	4.273***	4.023**	2.938*	2.502	2.121	1.204
	(2.350)	(1.610)	(1.606)	(1.653)	(1.499)	(1.537)	(1.503)	(1.443)
other × prec	-0.626	-0.002	-0.130	0.793	-0.164	0.757	0.422	1.637
	(2.420)	(1.404)	(1.389)	(1.462)	(1.241)	(1.309)	(1.335)	(1.374)
CRP	4.942	2.053	1.756	1.428	2.921	2.751	-0.287	-0.034
	(3.784)	(2.053)	(2.057)	(2.031)	(1.997)	(1.971)	(2.676)	(2.614)
CRP × prec	-7.527	-4.853	-2.262	0.937	-6.362	-3.474	-6.799	-3.737
	(5.561)	(4.759)	(4.798)	(4.755)	(4.186)	(4.113)	(4.575)	(4.280)
$\overline{R}^2$	0.25	0.44	0.44	0.45	0.46	0.46	0.51	0.51
Obs.	113,372	113,372	113,372	113,372	113,372	113,372	113,372	113,372
Clusters	205	205	205	205	205	205	205	205
elast est.	0.330	0.189	0.187	0.195	0.185	0.195	0.125	0.137
elast s.e.	0.038	0.045	0.046	0.046	0.041	0.040	0.032	0.030
elast t-stat	8.750	4.156	4.053	4.274	4.535	4.882	3.855	4.528
elast est. CRP	-0.013	-0.012	-0.003	0.008	-0.015	-0.005	-0.026	-0.014
elast s.e. CRP	0.012	0.013	0.013	0.013	0.011	0.011	0.012	0.011
elast t-stat CRP	-1.084	-0.928	-0.250	0.590	-1.351	-0.442	-2.172	-1.253
county FE		✓	✓	✓	✓	✓	✓	✓
trend			✓					
year FE				✓		✓		✓
state × trend					✓	✓		
county × trend							✓	✓

Note: For additional details, see the discussion on page 33.

Table A27. Panel FE regressions, counties
CONUS, USGS+EPA data, acres of other major crops, CRP acres, and fertilizer sales

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
corn	5.050	-6.159	-5.498	-5.130	-6.115	-5.208	-11.722***	-10.180**
	(6.517)	(5.944)	(5.912)	(5.813)	(5.677)	(5.546)	(4.500)	(4.342)
corn × prec	14.169***	14.496***	13.611***	14.261***	14.181***	14.533***	15.955***	16.291***
	(5.152)	(4.838)	(4.882)	(4.949)	(4.593)	(4.624)	(3.854)	(3.938)
soy	2.873	3.544	2.227	2.141	1.535	1.056	4.105	3.464
	(6.684)	(4.964)	(4.937)	(4.880)	(5.080)	(4.981)	(2.751)	(2.574)
soy × prec	-0.672	-2.500	-1.634	-1.892	-1.113	-1.090	-2.814	-2.701
	(4.853)	(3.879)	(3.945)	(3.962)	(3.858)	(3.844)	(1.885)	(1.908)
wheat	-2.558*	1.070	0.971	1.142	-0.060	-0.011	0.702	0.429
	(1.311)	(1.282)	(1.267)	(1.266)	(1.182)	(1.149)	(1.103)	(1.065)
wheat × prec	4.652**	-0.511	-1.523	-3.760**	-1.297	-3.516**	-2.154	-4.547***
	(2.036)	(1.663)	(1.633)	(1.637)	(1.509)	(1.518)	(1.615)	(1.628)
other	2.043	5.449***	4.411**	3.873**	2.647*	1.872	3.771*	2.340
	(2.537)	(1.820)	(1.795)	(1.826)	(1.559)	(1.548)	(1.915)	(1.722)
other × prec	-2.267	-0.922	-1.039	-0.069	-1.297	-0.299	-1.582	-0.155
	(2.687)	(1.803)	(1.838)	(1.873)	(1.713)	(1.698)	(1.829)	(1.758)
CRP	3.752	1.455	0.827	0.134	3.768*	3.152	1.965	0.952
	(3.127)	(2.086)	(2.127)	(2.060)	(2.039)	(1.958)	(3.818)	(3.842)
CRP × prec	-8.217	-4.664	0.603	1.664	-4.480	-3.731	-4.241	-3.210
	(5.013)	(4.849)	(4.928)	(4.909)	(4.092)	(3.990)	(5.309)	(4.948)
fert	-0.000	-0.000	0.000	0.000	0.000	0.000	0.000	0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
fert × prec	0.000	0.000	0.000	0.000	0.000	0.000	0.000*	0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
$\overline{R}^2$	0.25	0.43	0.43	0.44	0.44	0.45	0.48	0.49
Obs.	97,093	97,093	97,093	97,093	97,093	97,093	97,093	97,093
Clusters	205	205	205	205	205	205	205	205
elast est.	0.284	0.151	0.146	0.160	0.147	0.164	0.105	0.130
elast s.e.	0.030	0.042	0.043	0.043	0.038	0.037	0.038	0.035
elast t-stat	9.397	3.633	3.388	3.742	3.826	4.390	2.773	3.756
elast est. CRP	-0.019	-0.013	0.005	0.007	-0.006	-0.005	-0.010	-0.009
elast s.e. CRP	0.012	0.013	0.013	0.013	0.011	0.011	0.014	0.013
elast t-stat CRP	-1.688	-0.994	0.347	0.486	-0.512	-0.424	-0.709	-0.713
county FE		✓	✓	✓	✓	✓	✓	✓
trend			✓					
year FE				✓		✓		✓
state × trend					✓	✓		
county × trend							✓	✓

Note: For additional details, see the discussion on page 33.

Table A28. Panel FE regressions, counties and hydrologic units
CONUS, USGS+EPA data, corn acreage and nitrogen-fertilizer elasticities

A. counties							
model	estim	s.e.	t-stat	p-value	Δ acres	$\bar{y}$	precip.
corn	0.158	0.033	4.755	0.000	0.010	2.45	1.27
corn and fertilizer	0.158	0.038	4.165	0.000	0.010	2.45	1.27
model	estim	s.e.	t-stat	p-value	Δ fert	$\bar{y}$	precip.
corn and fertilizer	0.071	0.031	2.305	0.022	1089	2.45	1.27
fertilizer	0.148	0.045	3.328	0.001	1089	2.45	1.27
B. hydrologic units							
model	estim	s.e.	t-stat	p-value	Δ acres	$\bar{y}$	precip.
corn	0.203	0.057	3.543	0.000	0.008	2.1	1.27
corn and fertilizer	0.251	0.069	3.645	0.000	0.008	2.1	1.27
model	estim	s.e.	t-stat	p-value	Δ fert	$\bar{y}$	precip.
corn and fertilizer	-0.049	0.044	-1.110	0.268	828	2.1	1.27
fertilizer	0.061	0.063	0.975	0.331	828	2.1	1.27

Note: We control for weather (precipitation, squared precipitation, moderate heat, and extreme heat in both models. We also include county FE, year FE, and county specific trends. The standard errors are clustered by 4-digit hydrologic unit. We calculate the elasticities assuming an increase in corn acres or fertilizer use equal to 1 standard deviation within county or 8-digit hydrologic unit as indicated in columns Δ acres and Δ fert. We also assume precipitation equal to the 75th percentile of its empirical distribution. The percentage changes in nitrogen concentration and corn acres or fertilizer sales used in the elasticities are relative to their sample means. For additional details, see the discussion on page 34.

Table A29. Panel FE regressions, counties
CONUS, USGS+EPA data, corn acreage elasticities, lagged acres summary

Lags	SPEC	obs.	Cont.	+1 lag	+2 lags	+3 lags
1	8	75854	**0.096***	**0.208*****	.	.
2	8	73470	**0.070***	**0.100***	**0.266*****	.
3	8	71409	0.036	0.064	**0.195***	**0.261*****

Note: he elasticity estimates reported in the 4 rightmost columns of the table are based on the models in Tables A30–A32. We use "Cont" to denote elasticities based on contemporaneous values of corn acres alone in the three tables. We use "+1 lag" to denote elasticities based on both contemporaneous and lagged (1 year) values of corn acres. Analogous notation holds for "+2 lags" and "+3 lags" in which we also account for additional lags, namely 2 and 3 years. For additional details, see the discussion on page 35.

Table A30. Panel FE regressions, counties
CONUS, USGS+EPA data, lagged acres (1 lag)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
acres(t)	-11.477*	-6.764	-6.660	-5.328	-2.436	-0.646	-2.711	-0.331
	(6.843)	(7.166)	(7.194)	(6.806)	(6.850)	(6.482)	(6.464)	(5.977)
acres(t) × prec	22.179***	10.726	10.683	10.981*	7.312	7.573	4.903	5.069
	(6.216)	(6.921)	(6.959)	(6.231)	(6.639)	(5.961)	(6.048)	(5.412)
acres(t-1)	13.640*	2.024	2.117	1.299	-0.287	-0.990	-6.382	-6.352
	(6.952)	(7.673)	(7.670)	(7.257)	(7.400)	(7.035)	(6.733)	(6.463)
acres(t-1) × prec	-4.124	4.047	4.078	3.609	7.409	6.967	11.040**	10.666**
	(5.666)	(6.130)	(6.144)	(5.853)	(6.085)	(5.849)	(5.411)	(5.263)
$\overline{R}^2$	0.27	0.44	0.44	0.45	0.45	0.46	0.49	0.50
Obs.	75,854	75,854	75,854	75,854	75,854	75,854	75,854	75,854
Clusters	188	188	188	188	188	188	188	188
county FE		✓	✓	✓	✓	✓	✓	✓
trend			✓					
year FE				✓		✓		✓
state × trend					✓	✓		
county × trend							✓	✓

For additional details, see the discussion on page 35.

Table A31. Panel FE regressions, counties
CONUS, USGS+EPA data, lagged acres (2 lags)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
acres(t)	-13.954**	-6.462	-6.379	-5.038	-1.768	0.045	-0.922	1.574
	(6.920)	(7.415)	(7.438)	(6.867)	(6.979)	(6.477)	(6.573)	(5.936)
acres(t) × prec	22.394***	8.760	8.725	9.251	4.936	5.407	2.099	2.208
	(6.410)	(7.161)	(7.187)	(6.410)	(6.782)	(6.054)	(6.168)	(5.467)
acres(t-1)	4.708	1.372	1.441	1.532	0.246	0.437	-1.928	-1.272
	(8.697)	(7.931)	(7.940)	(8.084)	(8.049)	(8.218)	(7.863)	(7.999)
acres(t-1) × prec	-0.408	0.855	0.866	-0.383	2.719	1.544	3.511	2.561
	(7.411)	(6.663)	(6.675)	(6.854)	(6.822)	(7.052)	(6.201)	(6.473)
acres(t-2)	11.502*	1.121	1.153	0.083	-0.392	-1.371	-5.807	-6.383*
	(6.496)	(6.169)	(6.162)	(6.198)	(5.632)	(5.700)	(3.523)	(3.732)
acres(t-2) × prec	-3.929	5.474	5.496	5.955	7.528	7.964	11.255***	11.828***
	(6.645)	(5.730)	(5.715)	(5.966)	(4.967)	(5.303)	(3.668)	(4.079)
$\overline{R}^2$	0.27	0.44	0.44	0.45	0.45	0.46	0.50	0.50
Obs.	73,470	73,470	73,470	73,470	73,470	73,470	73,470	73,470
Clusters	187	187	187	187	187	187	187	187
county FE		✓	✓	✓	✓	✓	✓	✓
trend			✓					
year FE				✓		✓		✓
state × trend					✓	✓		
county × trend							✓	✓

For additional details, see the discussion on page 35.

Table A32. Panel FE regressions, counties
CONUS, USGS+EPA data, lagged acres (3 lags)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
acres(t)	-13.417	-3.493	-3.431	-1.534	0.593	2.946	2.762	5.571
	(8.329)	(8.562)	(8.595)	(7.984)	(8.085)	(7.536)	(7.043)	(6.379)
acres(t) × prec	19.453***	4.392	4.371	4.975	1.231	1.677	-2.790	-2.689
	(7.102)	(7.631)	(7.657)	(6.892)	(7.265)	(6.541)	(6.257)	(5.505)
acres(t-1)	3.655	0.567	0.623	0.231	-0.270	-0.437	-1.389	-0.924
	(9.174)	(8.486)	(8.492)	(8.674)	(8.522)	(8.703)	(8.269)	(8.427)
acres(t-1) × prec	-0.261	1.165	1.166	0.859	2.775	2.378	2.576	2.167
	(8.237)	(7.559)	(7.563)	(7.778)	(7.557)	(7.820)	(6.832)	(7.151)
acres(t-2)	3.196	1.228	1.204	2.021	0.203	0.906	-0.028	0.797
	(6.413)	(4.938)	(4.922)	(4.563)	(5.011)	(4.661)	(4.970)	(4.877)
acres(t-2) × prec	-0.331	3.182	3.209	3.817	4.627	5.294	3.627	4.448
	(5.957)	(4.388)	(4.358)	(4.143)	(4.293)	(4.121)	(4.273)	(4.308)
acres(t-3)	8.908	-1.852	-1.771	-3.938	-1.955	-3.997	-9.533**	-11.461**
	(7.544)	(7.711)	(7.682)	(7.998)	(7.002)	(7.294)	(4.764)	(4.739)
acres(t-3) × prec	-1.006	6.265	6.260	4.780	6.388	5.063	13.597***	12.507**
	(7.669)	(7.188)	(7.207)	(7.555)	(6.472)	(6.856)	(4.711)	(5.088)
$\overline{R}^2$	0.27	0.44	0.44	0.45	0.45	0.46	0.50	0.50
Obs.	71,409	71,409	71,409	71,409	71,409	71,409	71,409	71,409
Clusters	185	185	185	185	185	185	185	185
county FE		✓	✓	✓	✓	✓	✓	✓
trend			✓					
year FE				✓		✓		✓
state × trend					✓	✓		
county × trend							✓	✓

For additional details, see the discussion on page 35.

Table A33. Panel FE regressions, counties
CONUS, USGS+EPA data, average of acres at time t through $t-3$

				A. contemporaneous plus 1 lag				
	(A1)	(A2)	(A3)	(A4)	(A5)	(A6)	(A7)	(A8)
acres	2.074	-4.861	-4.669	-4.041	-2.803	-1.609	-9.156*	-6.668
	(3.464)	(4.811)	(4.806)	(4.762)	(4.397)	(4.267)	(4.852)	(4.676)
acres × prec	18.120***	14.900***	14.891***	14.593***	14.820***	14.507***	16.030***	15.694***
	(4.070)	(4.590)	(4.596)	(4.373)	(4.336)	(4.147)	(4.170)	(3.915)
$\overline{R}^2$	0.27	0.44	0.44	0.45	0.45	0.46	0.49	0.50
Obs.	75,854	75,854	75,854	75,854	75,854	75,854	75,854	75,854
Clusters	188	188	188	188	188	188	188	188
elast est.	0.390	0.217	0.220	0.224	0.248	0.261	0.172	0.204
elast s.e.	0.038	0.055	0.053	0.049	0.053	0.050	0.051	0.044
elast t-stat	10.341	3.940	4.175	4.556	4.694	5.218	3.373	4.688
				B. contemporaneous plus 2 lags				
	(B1)	(B2)	(B3)	(B4)	(B5)	(B6)	(B7)	(B8)
acres	2.081	-4.032	-3.848	-3.418	-1.895	-0.824	-8.537*	-6.021
	(3.494)	(4.961)	(4.939)	(4.859)	(4.578)	(4.429)	(5.036)	(4.841)
acres × prec	18.199***	15.115***	15.113***	14.730***	15.132***	14.752***	16.758***	16.396***
	(4.091)	(4.620)	(4.622)	(4.381)	(4.352)	(4.162)	(4.146)	(3.887)
$\overline{R}^2$	0.27	0.44	0.44	0.45	0.45	0.46	0.50	0.50
Obs.	73,470	73,470	73,470	73,470	73,470	73,470	73,470	73,470
Clusters	187	187	187	187	187	187	187	187
elast est.	0.392	0.235	0.237	0.237	0.269	0.278	0.196	0.228
elast s.e.	0.038	0.059	0.057	0.053	0.057	0.054	0.057	0.050
elast t-stat	10.305	3.949	4.185	4.461	4.686	5.110	3.424	4.544
				C. contemporaneous plus 3 lags				
	(C1)	(C2)	(C3)	(C4)	(C5)	(C6)	(C7)	(C8)
acres	2.153	-3.466	-3.290	-3.119	-1.298	-0.468	-7.710	-5.753
	(3.511)	(5.100)	(5.074)	(5.019)	(4.699)	(4.545)	(5.024)	(4.810)
acres × prec	18.009***	14.949***	14.950***	14.385***	14.935***	14.352***	16.776***	16.271***
	(4.104)	(4.619)	(4.620)	(4.343)	(4.316)	(4.089)	(4.108)	(3.813)
$\overline{R}^2$	0.27	0.44	0.44	0.45	0.45	0.46	0.50	0.50
Obs.	71,409	71,409	71,409	71,409	71,409	71,409	71,409	71,409
Clusters	185	185	185	185	185	185	185	185
elast est.	0.389	0.240	0.243	0.235	0.274	0.276	0.209	0.230
elast s.e.	0.039	0.063	0.060	0.055	0.062	0.058	0.065	0.056
elast t-stat	10.002	3.844	4.063	4.271	4.426	4.783	3.222	4.142

Note: For additional details, see the discussion on page 35.

Table A34. Panel FE regressions, counties
CONUS, USGS+EPA data, corn share

A. controlling for total acres								
	(A1)	(A2)	(A3)	(A4)	(A5)	(A6)	(A7)	(A8)
share	0.041***	-0.003	-0.002	-0.003	-0.001	-0.002	-0.005	-0.006*
	(0.005)	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)	(0.003)	(0.003)
share × prec	-0.026***	0.003	0.002	0.004	0.002	0.004	0.005*	0.006**
	(0.004)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)
$\overline{R}^2$	0.22	0.44	0.44	0.45	0.45	0.46	0.50	0.51
Obs.	101,234	101,234	101,234	101,234	101,234	101,234	101,234	101,234
Clusters	204	204	204	204	204	204	204	204
effect est.	4.261	0.545	0.306	0.530	1.194	1.528	0.746	1.189
effect s.e.	1.190	0.528	0.640	0.627	0.520	0.525	0.491	0.495
effect t-stat	3.580	1.032	0.478	0.844	2.294	2.912	1.520	2.402
B. controlling for total acres and acres of major crops								
	(B1)	(B2)	(B3)	(B4)	(B5)	(B6)	(B7)	(B8)
share	0.029***	-0.000	-0.001	-0.002	0.002	0.000	-0.000	-0.002
	(0.005)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)
share × prec	-0.022***	-0.000	-0.001	0.000	-0.001	0.000	0.000	0.002
	(0.004)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
$\overline{R}^2$	0.24	0.44	0.44	0.45	0.45	0.46	0.50	0.51
Obs.	101,234	101,234	101,234	101,234	101,234	101,234	101,234	101,234
Clusters	204	204	204	204	204	204	204	204
effect est.	0.404	-0.192	-0.809	-0.857	0.106	0.181	0.132	0.294
effect s.e.	0.789	0.469	0.547	0.500	0.457	0.419	0.473	0.432
effect t-stat	0.512	-0.409	-1.479	-1.713	0.232	0.433	0.279	0.681
C. controlling for total acres and CRP acres								
	(C1)	(C2)	(C3)	(C4)	(C5)	(C6)	(C7)	(C8)
share	0.040***	-0.002	-0.002	-0.003	-0.000	-0.001	-0.005	-0.006*
	(0.005)	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)	(0.003)	(0.003)
share × prec	-0.026***	0.002	0.002	0.003	0.002	0.003	0.004*	0.006**
	(0.004)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)
$\overline{R}^2$	0.22	0.44	0.44	0.45	0.45	0.46	0.50	0.51
Obs.	101,234	101,234	101,234	101,234	101,234	101,234	101,234	101,234
Clusters	204	204	204	204	204	204	204	204
effect est.	3.873	0.394	0.245	0.496	1.092	1.483	0.458	1.028
effect s.e.	1.239	0.552	0.646	0.626	0.516	0.523	0.460	0.479
effect t-stat	3.126	0.713	0.380	0.792	2.115	2.838	0.995	2.149

Note: We show the percentage change in nitrogen concentration due to an increase in the corn share of total acres equal to 1 within-county SD. Total acres is the sum of corn acres, acres of major crops (barley, cotton, rice, sorghum, soybeans, wheat), and CRP acres. We assume CRP acres are zero before 1986 and we set CRP acres to zero if missing. For additional details, see the discussion on page 35.