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Nutrient Pollution and US Agriculture
Causal Effects, Integrated Assessment, and Implications of Climate Change

Konstantinos Metaxoglou and Aaron Smith

9.1 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 percent of the contiguous US (CONUS) into the Gulf of Mexico (GoM), nutrients from row crops, large farms, and concentrated animal feeding operations account for most of the nutrient pollution. Fertilizer runoff from agricultural crops has been estimated to

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contribute somewhere between 50 percent (CENR 2000) and 76 percent (David, Drinkwater, and McIsaac 2010) of the annual and spring nitrogen riverine export from the MRB to the GoM fueling a hypoxic ("dead") zone, with oxygen levels that are too low for fish and other marine life to survive. The GoM hypoxic zone is the second largest in the world behind the dead zone in the Arabian Sea with a peak areal extent equal to that of New Jersey (8,776 square miles) recorded in the summer of 2017.

According to the EPA (2016), 46 percent (about 546,000 miles) of US streams and rivers are in poor condition in terms of their phosphorous levels, and 41 percent (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 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.[1] Reducing the areal extent of the hypoxic zone to a five-year running average of 5,000 square kilometers, a target set in the Action Plan of the GoM Hypoxia Task Force, comes at an estimated price tag of $2.7 billion per year (Rabotyagov et al. 2014b).

In this chapter, we focus on water pollution and its relationship to US agriculture. We use regression analysis to establish a causal link between farmers' decisions about crop acreage and nutrient pollution that is detrimental to surface water quality. In particular, we estimate the causal effects of corn acreage on nitrogen concentration in water bodies using panel fixed-effect (FE) regressions and what we call "(c)ounty-centric" analysis. We make few and transparent assumptions that allow us to the assess the robustness of our findings to various factors. In contrast, most prior estimates of effects similar to the ones estimated in this chapter are based on agronomic and hydrologic models.

To perform our c-centric analysis, we combine annual county-level data on acres planted and nitrogen pollution. Data on acres planted are readily available from the US Department of Agriculture (USDA). We compile data on nitrogen pollution using US Geological Survey (USGS) monitoring sites within a 50-mile radius from the county centroids. Based on our preferred estimate of the elasticity of nitrogen concentration (mg/L) with respect to corn acreage of about 0.1, an increase in corn acres planted equal to 1 within-county standard deviation implies a 3.3 percent increase in the level of nitrogen concentration. At the average nitrogen concentration of about 2.5 mg/L and the average streamflow of the Mississippi River in the GoM in our sample, this effect entails close to 50,800 additional metric tons of nitrogen in the GoM. Using the median potential damages of nitrogen

1. See CENR (2000), EPA (2007), and, more recently, Olmstead (2010), GOMNTF (2013) and Rabotyagov et al. (2014a). Several papers assess the cost of nitrogen pollution employing a variety of methodologies; see Dodds et al. (2009), Compton et al. (2011), Birch et al. (2011), Rabotyagov et al. (2014b), and Sobota et al. (2015), among others.

due to declines in fisheries and estuarine/marine life of \$15.84 per kilogram (\$2008) from Sobota et al. (2015), the implied annual external cost is about \$800 million. The magnitude of the estimated effects depends on the amount of annual precipitation but not on extreme heat despite its well-documented negative impact on crop growth and, hence, nutrient uptake.

We also explore the implications of climate change for nitrogen pollution using the NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP-CMIP6) data set to obtain out-of-sample projections for precipitation and temperature, which we translate into projections of corn acreage marginal effects on nitrogen pollution. The NEX-GDDP-CMIP6 data set is comprised of global downscaled climate scenarios derived from the General Circulation Model runs conducted under the Coupled Model Intercomparison Project Phase 6 and across two of the four "Tier 1" greenhouse gas emissions scenarios known as shared socioeconomic pathways (SSPs), namely, SSP2–4.5 and SSP5–8.5. Abstracting from the impact that climate change may have an acreage, yields, nitrogen fertilizer use, legacy nitrogen, runoff, and streamflow, all of which may contribute to nitrogen pollution, the out-of-sample precipitation and temperature projections imply similar effects of corn acreage on nitrogen concentration as in our estimation sample. This finding arises because the climate models project relatively small changes in precipitation and because our estimated effects of corn acreage on nitrogen concentration do not vary a lot with temperature.

The focus of this chapter is different from the chapter by Elbakidze et al. (2022) in this volume. Elbakidze et al. study the effects of changes in nitrogen fertilizer use by US farmers on surface water quality due to climate change. Investigating the effect of climate-driven productivity changes on water quality in the GoM using an integrated hydro-economic agricultural land use model (IHEAL), they find that land and nitrogen use adaptation in agricultural production to climate change increases nitrogen loads to the GoM by 0.4–1.58 percent. As we discuss later in the chapter, our findings are consistent with new research in environmental science arguing that there is a large amount of nitrogen stored in subsurface soil and groundwater contributing to the so-called legacy nitrogen, which may increase loadings in rivers and streams with a long delay. The work by Elbakidze et al. does not address legacy nitrogen. Elbakidze et al. account for farmers' adaptation to climate change in their analysis while our reduced-form econometric analysis does not.

The remainder of the paper is organized as follows. Section 9.2 provides a background on nutrient pollution emphasizing the role of agriculture and shedding light on the impacts of climate change. Section 9.3 is a simple theoretical backdrop for section 9.4, where we describe the empirical approach for estimating the causal effects of interest. Subsequently, having discussed the data and provided some descriptive analysis in section 9.5, we present the results from our regressions in section 9.6. We next explore the implications of climate change for nitrogen pollution in section 9.7. We finally conclude.

9.2 Background on Nutrient Pollution

Preamble. 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, which drains most US 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.

Aside from oscillations in 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 GoM (Goolsby et al. 1999). Between 1980 and 2016, close to 1.5 million metric tons of nitrogen (about 63 percent in the form of nitrate) per year were discharged, on average, to the GoM. From 1968 to 2016, the average annual Mississippi streamflow was close to 21,500 cubic meters per second.[2] During this time, there was a strong positive relationship between the streamflow of the Mississippi and nitrogen flux in the GoM.

Dairy, beef, 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. The major point sources of direct discharges of nutrients, particularly nitrogen-nitrogen, appear to be domestic wastewater treatment plants. Fossil-fuel combustion in car engines and electric generating plants 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).

2. 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 in this link: http://toxics.usgs.gov/hypoxia/mississippi/flux_ests/delivery/index.html.

Table 9.1 Nitrogen pollution damages and abatement costs

Source	Damages	Details
	A. Damages	
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. (2013)	$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
Source	Abatement costs	Geographic scope
	B. Abatement costs	
Xu et al. (2021)	$6 billion	Mississippi River Basin
Tallis et al. (2019)	$2.6 billion	Mississippi River Basin
Marshall et al. (2018)	$1.9–$3.3 billion	Mississippi River Basin
McLellan et al. (2016)	$1.48 billion	Mississippi River Basin
Whittaker et al. (2015)	$9.25 billion	Mississippi River Basin
Rabotyagov et al. (2014a)	$2.6 billion	Mississippi River Basin
USEPA (2001)	<$1–$4.3 billion	US, national
Ribaudo et al. (2001)	$0.1–$7.91 billion	Mississippi River Basin
Doering et al. (1999)	−$0.1–$17.95 billion	Mississippi River Basin

Note: 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. We report the cost per ton of nitrogen. In the case of USEPA (2001), the costs are per year for the development of TMDLs. 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. We use "CB" to refer to the Chesapeake Bay, "GoM" to refer to the Gulf of Mexico. For additional details, see section 9.2 in the main text and section A.1 of the online appendix (http://www.nber.org/data-appendix/c14692/appendix.pdf).

This nitrogen then enters streams and rivers and/or is retained in terrestrial systems in the same pathways as nitrate-nitrogen fertilizer.

Damages and abatement costs of nitrogen pollution. In table 9.1, we summarize studies related to damages and abatement costs associated with nitrogen pollution noting that the estimation of the economic value of the damages associated with nutrient pollution can be particularly challenging.[3] The social cost of pollution in the context of water quality has

3. EPA (2015) provides estimates of external costs associated with nutrient pollution impacts on tourism and recreation, commercial fishing, property values, human health, as well as drinking water treatment costs, mitigation costs, and restoration costs.

received less attention than the social cost of carbon in the context of climate change. 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 (Gourevitch, Keeler, and Ricketts 2018). 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).

Nitrogen pollution and agriculture. 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 in terms of nitrogen application 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.

The prevention of nutrient pollution, particularly in the form of nitrate-nitrogen, is possible 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.[4] 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.

Policy responses to nutrient pollution. 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 nutri-

4. 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.

ent 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.[5] 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.

In one of the most comprehensive assessments of conservation practices by US farmers, the USDA Conservation Effects Assessment Project (CEAP) national nitrogen loss report (NRCS 2017b) found that 29 percent 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 lb per cultivated cropland acre per year. The amount varied considerably, however, among cultivated cropland acres. Total nitrogen losses were highest for acres receiving manure (56 lb 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 lb per acre per year, on average, representing a 30 percent reduction.

9.3 A Simple Theoretical Framework

We estimate the *reduced-form* effect of an increase in corn acreage on nitrogen pollution via OLS regressions. We focus on this relationship in part because corn acreage is the driving force behind the amount of nitrogen fertilizer used. In addition, acreage is much better measured than fertilizer use. We observe nitrogen fertilizer sales by county, but we do not know in which county or year that fertilizer was applied to a field. In contrast, we observe annual acreage by county.[6]

5. We refer to this link, https://www.fsa.usda.gov/programs-and-services/conservation-programs/index, and Capel et al. (2018) for a succinct and very informative discussion of the various USDA conservation programs.

6. Paudel and Crago (2020) use the nitrogen fertilizer sales data to estimate the effect of fertilizer on nitrogen pollution. They obtain an elasticity of nitrogen pollution with respect to nitrogen fertilizer of about 0.15 for the US. We find an elasticity of nitrogen pollution with respect to corn acres of a very similar magnitude. Adding the assumption of no substitution between nitrogen fertilizer and other inputs to the assumption of a fixed amount of nitrogen fertilizer per corn acre allows us to link the price elasticity of the demand for fertilizer (η_{fert}) to the price elasticity demand for corn (η_{corn}) via $\eta_{fert} = (p_{fert} / p_{corn})\eta_{corn}$. In terms of notation, p_{fert} and p_{corn} are the prices of nitrogen fertilizer and corn, respectively. As we discuss later in the paper, fertilizer costs account for about 20 percent of the value of corn production during the period we study, which coupled with a reasonable value of η_{corn} of about −0.3, also supported empirically in subsequent section, imply $\eta_{fert} = -0.3 \times 0.2 = -0.06$. Hence, the demand for nitrogen fertilizer is highly inelastic.

Our empirical analysis, which focuses on the relationship between corn acreage and nitrogen pollution, is motivated by the following. Farmers decide how to allocate acreage to various crops including corn, which is the most fertilizer intensive and is the crop we focus on. Soybeans, the other commonly planted crop in the US Corn Belt, require little nitrogen fertilizer. Farmers apply about 150 lb of nitrogen fertilizer per planted acre of corn and 5 lb per planted acre of soybeans. About 70 percent of soybean acres receive no nitrogen fertilizer.[7] Crop production requires various inputs such as labor, capital, fuel, seeds, fertilizers, and chemicals. Farmers' planting decisions are based on the expected post-harvest crop price and expected costs. Weather conditions, especially precipitation and temperature, during the growing season determine plant growth and eventually yields. Preplanting weather conditions may also affect planting decisions.

As farmers plant more corn acres, they use more nitrogen fertilizer, generally following agronomic recommendations. The shape of the crop production function implies that fertilizer application in excess of agronomic recommendations does not reduce yields, which provides an insurance motivation to use extra fertilizer, as we discussed earlier. A combination of factors in and out of the farmers' control, including weather, determine the crop nitrogen uptake, and, hence, the amount of surplus (excess) nitrogen that will not be used by the plants and will remain in the soil. This surplus nitrogen will eventually find its way to lakes, rivers, and streams, contributing to nutrient pollution. The amount of surplus nitrogen that enters waterways is determined in part by the weather. Wetter conditions affect acreage, nutrient runoff, and streamflow, all of which can contribute to nutrient pollution. All else equal, more rainfall means more nutrients carried through the soil and along the surface into waterways. Thus, we expect increases in corn acreage to increase nitrogen concentration, especially in wet years. Similarly, extreme heat, which has a well-documented negative impact on crop growth (e.g., Jägermeyr et al. 2021, among others) may limit nutrient uptake and contribute to runoff. On the one hand, it is plausible that farmers may compensate for the loss in yields by fertilizing more. On the other hand, as discussed in the chapter by Elbakidze et al. (2022), lower yields may reduce the profitability of crop production and may result in decreased crop acreage, which could reduce nitrogen runoff.

In general, more rainfall due to a warmer and wetter atmosphere is increasing nitrogen pollution exacerbating algae growth and expanding dead zones in coastal areas.[8] Evidence suggests that several projected outcomes of global climate change will act to increase the prevalence and negative

7. Based on the USDA ERS Fertilizer Use and Price data for 2018 (US average).

8. In the US Gulf Coast, the frequency and severity of hurricanes, which have been linked to climate change, can also play an important role in the areal extent the hypoxic zone formed every summer.

impacts of dead zones.[9] Warmer waters hold less oxygen than cooler water, thus making it easier for dead zones to form. Warmer waters also increase metabolism of marine creatures, thereby increasing their need for oxygen. Additionally, warmer temperatures and increased runoff of fresh water will increase stratification of the water column, thus further promoting the formation of dead zones. Increased runoff will also increase nutrient inputs into coastal water bodies. On the other hand, projections of more intense tropical storms and lower runoff would act to decrease stratification and thus make dead zones less likely to form or less pronounced if they do form.[10]

Diaz and Rosenberg (2008) assembled a database of over 400 dead zones worldwide showing that their number is increasing exponentially over time. To characterize the severity of climate change that these ecosystems are likely to experience over the coming century, Diaz and Rosenberg also explored the future annual temperature anomalies predicted to occur for each of these systems. The majority of dead zones are in regions predicted to experience over 2°C warming by the end of this century. Sinha, Michalak, and Balaji (2017) show that precipitation changes due to climate changes alone will increase by 19 percent the riverine total nitrogen loading within the CONUS by the end of the century for their business-as-usual scenario. The impacts are particularly large in the Northeast (28 percent), the upper MRB (24 percent), and the Great Lakes Basin (21 percent). According to the authors, precipitation changes alone will lead to an 18 percent increase in nitrogen loads in the MRB, which would require a 30 percent reduction in nitrogen inputs. The target of a 20 percent load reduction set by the GoM Hypoxia Task Force in 2015 would require a 62 percent reduction in nitrogen inputs taking into account the confounding effect of precipitation.[11]

9.4 Empirical Approach

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

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

9. Our discussion borrows heavily from the discussion on "Dead Zones and Climate Change" available in the VIMS website here: https://www.vims.edu/research/topics/dead_zones/climate_change/index.php.

10. According to Diaz and Rosenberg (2008), tropical storms and hurricanes influence the duration, distribution, and size of the GoM dead zone in a complex way. In 2005, four hurricanes (Cindy, Dennis, Katrina, and Rita) disrupted stratification and aerated bottom waters. After the first two storms, stratification was reestablished and hypoxia reoccurred, but the total area was a fourth less than predicted from spring nitrogen flux. The other two hurricanes occurred later in the season and dissipated hypoxia for the year.

11. In February 2015, the states and federal agencies that comprise the Mississippi River/GoM Watershed Nutrient Task Force (Hypoxia Task Force, or HTF) announced that the HTF would retain its goal of reducing the areal extent of the GoM hypoxic zone to less than 5,000 km^2, but that it will take until 2035 to do so. The HTF agreed on an interim target of a 20 percent nutrient load reduction in the Gulf of Mexico by the year 2025 as a milestone toward achieving the final goal in 2035.

where i denotes the cross-sectional unit (county) and t denotes the time (year) in what we call the (c)ounty-centric (henceforth, *c-centric*) analysis. The dependent variable y_{it} is nitrogen concentration in milligrams per liter (mg/L), a_{it} denotes corn acres planted, p_{it} denotes precipitation, and $\mathbf{z}_{it}$ is a vector of weather-related control variables. The weather-related controls include precipitation, squared precipitation, moderate-heat, and extreme-heat degree days. We use $g_i(t)$ to denote alternative functions of time (e.g., time trend, year FE, etc.). Finally, ε_{it} is the error term.

For our c-centric analysis, y_{it} is the average nitrogen concentration recorded at USGS monitoring sites within a 50 mile-radius from the county centroids, and a_{it} are corn acres planted in county i at time t. As part of a series of robustness checks to our results, we estimate (1) using average nitrogen concentration recorded at sites within larger (100- and 200-mile) radii, as well as accounting for streamflow using only sites downstream of the county centroids.

Our specifications aim to capture the most salient factors that are both in the control and out of the control of US farmers and that influence the nitrogen concentration of waters draining cropland, some of which we have already discussed. Aside from weather, factors outside farmers' control include hydrologic conditions, 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 programs aiming to combat nutrient pollution by the US Environmental Protection Agency (EPA), and conservation programs administered by the USDA, among others.

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). Miao, Khanna, and Huang (2015) include monthly precipitation in March to May to control for the effect of pre-planting weather conditions on corn acreage in the US. They argue that a wet spring can make it difficult for corn to be planted on time, and, hence, corn acreage may be switched to soybean acreage. During the growing season, which is somewhere between March and September for most of the US, 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 that are not absorbed by the plants can be carried over to streams, rivers, and lakes, depending on soil characteristics and precipitation.

Nitrogen concentrations in a basin like the MRB, which 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. 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 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, as well as 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 the robustness checks discussed later in the chapter, we consider a long list of additional controls to capture factors that may be correlated with both corn acres planted and nitrogen concentration as discussed above to alleviate concerns for potentially biased estimates. We also explore alternative ways to measure nitrogen concentration including distance, streamflow, and time of the year, as well as spatial and temporal variation in the effects of corn acreage on nitrogen concentration.

9.5 Data

9.5.1 Data Sources

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 with more than more than 297 million water quality records.

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. At the time we accessed the WQP data, there were close to 754,000 observations in the sample results data and 41,800 observations in the site data.[12]

The site data contain information regarding the site's location such as longitude and latitude, county, and the eight-digit hydrologic unit (HUC8). 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 straightforward using the site location identifier field, which is present in both data sets.

We measure nitrogen pollution using concentration in milligrams per liter (mg/L). We limit the data to those for sites in the CONUS and for which we track "surface water" and "groundwater" concentration in the sample results data. For the interested reader, some additional information regarding the WQP data used in the paper is available in sections A.2–A.4 of the online appendix.

Crops. Annual county-level data on corn acres planted are available from the National Agricultural Statistics Service (NASS) of the USDA.[13] 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 rainfed 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 percent of the corn produced during the time relevant for our analysis; as part of our robustness checks, we expand the geographic scope of our analysis to the CONUS.

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 US agriculture and are discussed in great detail elsewhere (Roberts, Schlenker, and Eyer 2012).

12. The WQP data can be accessed in this link, https://www.waterqualitydata.us/ using web service calls. A parameter code is a five-digit number used in the National Water Information System (NWIS) to uniquely identify a water quality characteristic.

13. Table A1 in the online appendix (http://www.nber.org/data-appendix/c14692/appendix.pdf) shows corn production by state for 1970–2017.

Following this stream of the literature, we use precipitation, the square of precipitation, cumulative degree days (DDs) between 10°C and 29°C (moderate heat), and cumulative degree days above 29°C (extreme heat). In what follows, the precipitation is measured in meters, the moderate heat is measured in 1,000 DDs, and the extreme heat is measured in 100 DDs.

Hydrologic Units. We use the USDA Natural Resources Conservation Service (NRCS) watershed boundary data set (WBD) to identify hydrologic units of different size.[14] We use two-digit hydrologic unit codes (HUC2s) to explore spatial variation in our estimated acreage effects in the panel FE regressions and to construct spatial FEs in robustness checks that pertain to cross-section regressions. We use four-digit hydrologic unit codes (HUC4s) to cluster the standard errors in our regressions. We use HUC8s in an analysis based on an alternative data aggregation scheme, as part of our robustness checks.

National hydrography data set plus V21. As in Keiser and Shapiro (2018), we use the NHD Plus flowline network to follow water pollution upstream and downstream. In particular, we use the National Seamless Geodatabase built on NHD Plus to identify monitoring sites downstream of counties of interest.

9.5.2 Data Overview and Descriptive Statistics

For our baseline estimates, we use data for counties east of the 100th meridian (EAST-100) excluding Florida for 1970–2017. We use the latitude and longitude of the county centroids to identify the relevant EAST-100 counties which we obtain from the CENSUS TIGER shape files. As we discussed earlier, we calculate nitrogen concentration using USGS monitoring sites within a 50-mile radius from the county centroids.

Table 9.2 shows basic summary statistics for nitrogen concentration, our measure of pollution, and corn acres planted. These are the dependent and main explanatory variables of interest in our regression models. The table also shows summary statistics for precipitation (total annual and total by month), as well as for moderate and extreme heat by month. Precipitation

14. The GBD files for hydrologic units of different size are available in the following link: https://nrcs.app.box.com/v/gateway/folder/18546994164. The US is divided into successively smaller hydrologic units which are classified into four levels: regions, subregions, accounting units, and cataloging units. 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 two to eight digits based on the four levels of classification in the hydrologic unit system. 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*.

Table 9.2 **Summary statistics**

Variable	Panel	obs	Years	Mean	s.d. B	s.d. W	Median
nitrogen	2,232	64,121	28.7	2.451	1.645	1.663	1.683
acres planted	2,232	64,121	28.7	0.038	0.048	0.011	0.015
precipitation annual	2,232	64,121	28.7	1.088	0.259	0.174	1.070
precipitation jan	2,232	64,121	28.7	0.073	0.041	0.039	0.060
precipitation feb	2,232	64,121	28.7	0.067	0.036	0.036	0.055
precipitation mar	2,232	64,121	28.7	0.092	0.038	0.046	0.081
precipitation apr	2,232	64,121	28.7	0.095	0.024	0.048	0.086
precipitation may	2,232	64,121	28.7	0.111	0.022	0.050	0.104
precipitation jun	2,232	64,121	28.7	0.109	0.017	0.050	0.101
precipitation jul	2,232	64,121	28.7	0.106	0.023	0.049	0.098
precipitation aug	2,232	64,121	28.7	0.099	0.021	0.047	0.091
precipitation sep	2,232	64,121	28.7	0.094	0.021	0.056	0.082
precipitation oct	2,232	64,121	28.7	0.082	0.019	0.049	0.072
precipitation nov	2,232	64,121	28.7	0.082	0.031	0.044	0.073
precipitation dec	2,232	64,121	28.7	0.078	0.038	0.043	0.067
moderate heat jan	2,232	64,121	28.7	0.018	0.027	0.017	0.004
moderate heat feb	2,232	64,121	28.7	0.027	0.035	0.017	0.011
moderate heat mar	2,232	64,121	28.7	0.070	0.062	0.027	0.051
moderate heat apr	2,232	64,121	28.7	0.138	0.076	0.030	0.125
moderate heat may	2,232	64,121	28.7	0.253	0.082	0.040	0.245
moderate heat jun	2,232	64,121	28.7	0.361	0.071	0.029	0.365
moderate heat jul	2,232	64,121	28.7	0.430	0.061	0.027	0.439
moderate heat aug	2,232	64,121	28.7	0.408	0.068	0.031	0.415
moderate heat sep	2,232	64,121	28.7	0.295	0.082	0.033	0.291
moderate heat oct	2,232	64,121	28.7	0.157	0.079	0.031	0.144
moderate heat nov	2,232	64,121	28.7	0.064	0.055	0.024	0.047
moderate heat dec	2,232	64,121	28.7	0.025	0.033	0.017	0.008
extreme heat jan	2,232	64,121	28.7	0.000	0.000	0.000	0.000
extreme heat feb	2,232	64,121	28.7	0.000	0.001	0.001	0.000
extreme heat mar	2,232	64,121	28.7	0.000	0.003	0.002	0.000
extreme heat apr	2,232	64,121	28.7	0.004	0.010	0.009	0.000
extreme heat may	2,232	64,121	28.7	0.022	0.034	0.026	0.006
extreme heat jun	2,232	64,121	28.7	0.106	0.100	0.071	0.066
extreme heat jul	2,232	64,121	28.7	0.216	0.172	0.119	0.167
extreme heat aug	2,232	64,121	28.7	0.174	0.165	0.108	0.108
extreme heat sep	2,232	64,121	28.7	0.061	0.074	0.054	0.024
extreme heat oct	2,232	64,121	28.7	0.006	0.016	0.011	0.000
extreme heat nov	2,232	64,121	28.7	0.000	0.001	0.001	0.000
extreme heat dec	2,232	64,121	28.7	0.000	0.000	0.000	0.000

Note: An observation is a county-year combination. The panel column indicates the number of counties. The years column gives the average number of observations per county. We also report the between-counties (s.d. B) and within-county (s.d. W) standard deviation. The acres are measured in millions and the nitrogen concentration is measured in mg/L. The precipitation is measured in meters. The moderate heat is measured in 1,000 degree days between 10°C and 29°C. The extreme heat is measured in 100 degree days above 29°C. For additional details, see section 9.5.2.

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.

We have about 64,000 observations and 2,200 counties. 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 are around 1.65 mg/L. Hence, pollution exhibits similar variation across counties and within a county over time. On average, 38,000 acres of corn are planted per year in a county. Contrary to nitrogen pollution, the variation in acres is much larger across counties (48,000 acres) than within a county over time (11,000 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. On average, February and May are the months with the smallest (0.067 meters) and largest (0.111 meters) total precipitation, respectively. July is the month with the largest number of moderate-heat (430) and extreme-heat (21.6) DDs. While monthly precipitation varies more within a county over time than across counties with the exception of January, extreme and moderate heat DDs vary more across counties than within a county over time for most months.

9.5.3 Nitrogen Concentration Across Space and Over Time

The choropleth maps in figure 9.1 offer visualizations of the spatial variation for the variables used in our analyses and provide some descriptive evidence on the spatial correlation between nitrogen concentration and corn acreage. In general, we see higher concentration in watersheds in southern Minnesota, Iowa, Illinois, Indiana, and Ohio that drain large areas of agricultural land. We explore this spatial correlation in more depth using cross-section regressions.

In panel A of figure 9.2, based on monitoring-site level data on average daily nitrogen concentrations (mg/L), we show trends in nitrogen concentration. We also show flow-normalized annual nitrogen concentration in the GoM using data from the USGS National Water Quality Network in panel B. Panels C and D provide information related to fertilizer use and acreage, which are important in understanding the relationship between agriculture and nitrogen concentration.

The use of nitrogen fertilizer increased from about 2.5 million metric tons (mmts) in 1964 to 11.8 mmts in 2015; it reached its peak of about 12 mmts in 2013. Most of the almost fivefold increase took place before the early 1980s (panel C). By 1981, nitrogen use had steadily increased to 10.8 mmts.[15]

15. See table 9 (percent of corn acreage receiving nitrogen fertilizer) in this link: https://www.ers.usda.gov/webdocs/DataFiles/50341/fertilizeruse.xls?v=5014.

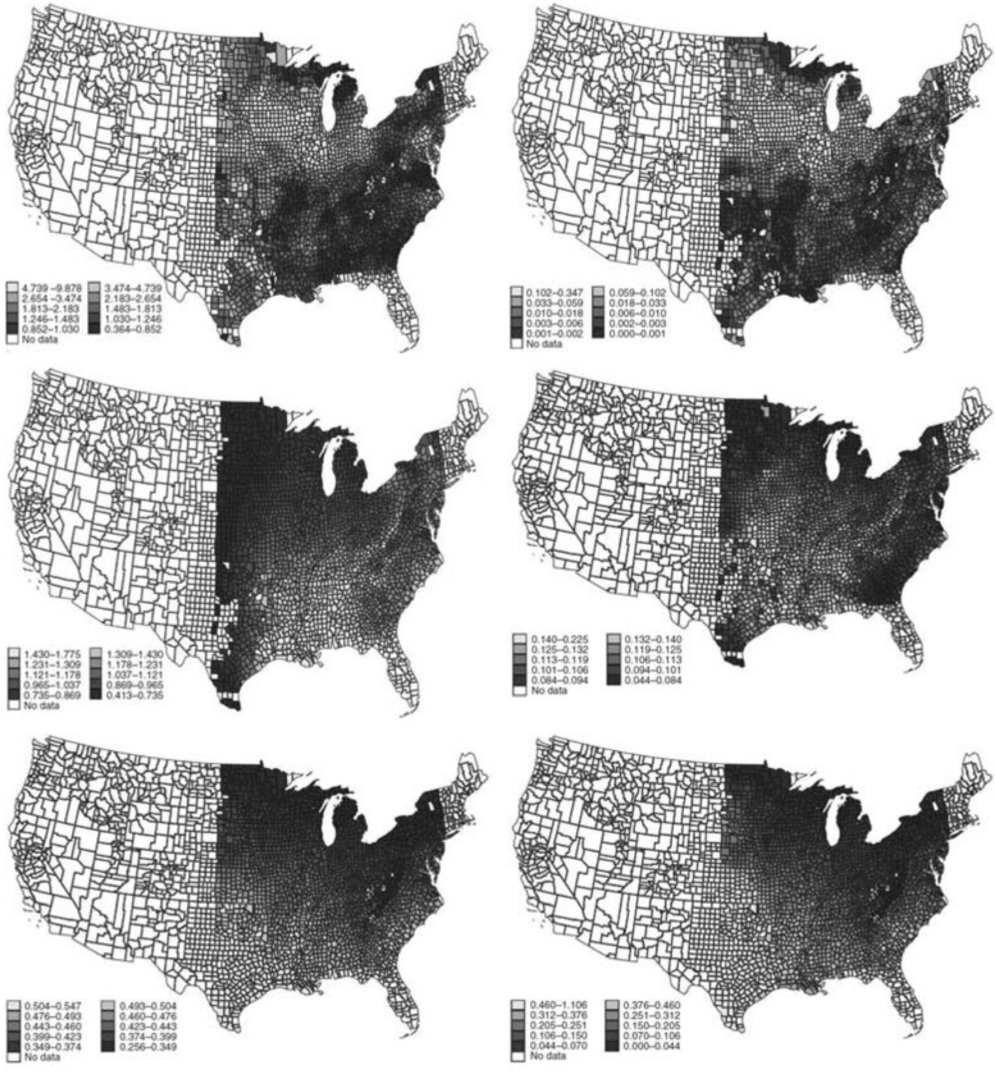


Fig. 9.1A–F Nitrogen concentration, corn acreage, and weather-related variables

Note: Panels A–F are read from left to right. In all panels, we show averages for 1970–2017. The shading of the choropleth maps is based on the deciles of the empirical distribution. In panels D, E, and F, we show the months with the highest average values. The acres are in millions and the nitrogen concentration is in mg/L. The precipitation is in meters. The moderate heat is in 1,000 degree days between 10°C and 29°C. The extreme heat is in 100 degree days above 29°C. For additional details, see section 9.5.2.

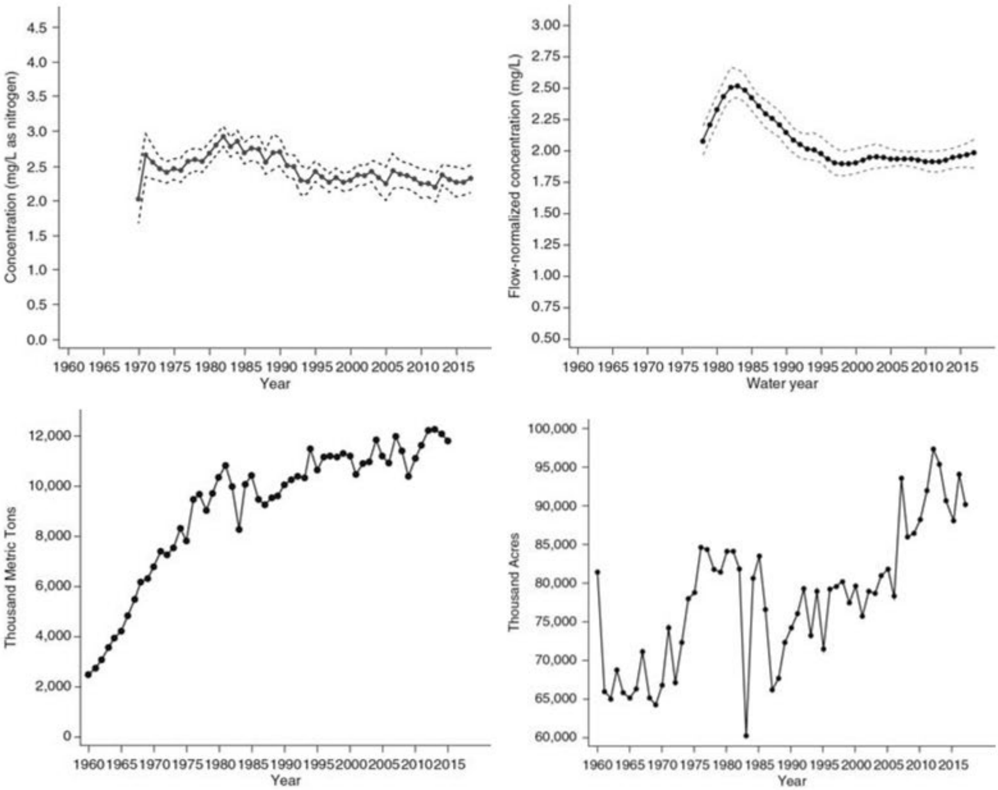


Fig. 9.2A–D Nitrogen pollution and related factors

Note: Panels A–D are read from top left to bottom right. In panel A, we regress the average daily nitrogen concentration at the USGS monitoring-site level for the CONUS on site fixed effects (FEs), year FEs, day, day squared, day cubed, month, month squared, month cubed, and report the estimated year FEs. 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: https://nrtwq.usgs.gov/nwqn/\#/GULF. In panel C, we show US consumption of nitrogen fertilizer from table 9.1 in the USDA ERS report on fertilizer use and price. In panel D, we show corn acres planted from the USDA Historical Track Records. For additional details, see section 9.5.3.

The expansion of nitrogen use during this time was due to expanded acreage (panel D), increase in application rates, and a higher share of acres receiving fertilizer (from 85 percent to 97 percent); the percent of US corn acreage receiving nitrogen fertilizer has been 95 percent, on average, in the last 50 years or so. 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, Vilorio, and Ribaudo 2019). The application rates in the major corn producing states follow similar trends with a notable increase between the mid-1960s and early 1980s. The fertilizer costs have oscillated between 14 percent and 27 percent of the corn gross value of production averaging close to 20 percent.

Overall, there is an increase in nitrogen concentration between the early 1970s and early 1980s from about 2 mg/L to a peak of about 3 mg/L. This pattern is consistent with the increase in corn acreage and nitrogen fertilizer use. Following a downward trend between the mid-1980s and the mid-1990s, nitrogen concentration has plateaued at about 2.3 mg/L in the last 20 years or so. These are roughly the concentration levels in the early 1970s. The flow-normalized annual nitrogen concentration in the GoM exhibits a very similar behavior over time.[16]

9.6 Econometric Estimates

Preamble. Table 9.3 shows detailed results of the panel FE regressions for our (c)ounty-centric analysis. 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 DDs, and extreme-heat DDs, 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 standard errors are clustered at the HUC4 level (124 clusters) accommodating arbitrary correlation of the unobservables across time and space.[17] To explore the implications of climate change for our estimated effects, we also interact corn acreage with moderate- and extreme-heat DDs in a subsequent section.

Baseline estimates. For the models without weather-related controls, the adjusted R-squared ($\bar{R}^2$) is 0.26–0.53 depending on the specification with most of the fit improvement attributed to the county FEs. Apart from the

16. Sprague, Hirsch, and Aulenbach (2011) estimate changes in nitrate concentration and flux during 1980–2008 at eight 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, Hirsch, and Sprague (2013), who extended the analysis in Sprague, Hirsch, and Aulenbach (2011), show that trends in FN nitrate concentration and flux were increasing or near-level at all sites for 1980–2018. They note, however, that trends at some sites began to exhibit decreases or greater increases during 2000–2008.

17. In Section A.5 of the online appendix (http://www.nber.org/data-appendix/c14692/appendix.pdf), we discuss results from cross-section regressions. In section A.6, we discuss results from *(h)ydrologic unit-centric* and *(m)onitoring site-centric* analyses. For the h-centric analysis, i denotes an eight-digit hydrologic unit (HUC8), y_{it} is the average nitrogen concentration using sites located in the same HUC8, and a_{it} are acres planted planted in counties that lie in the same HUC8 weighted by their area. For the m-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. 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 HUC8 polygons.

specifications with county-specific linear trends in columns A7 and A8, the acres coefficient is statistically significant at 5 percent level with values between 3.862 (column A5) and 23.581 (column A1). According to these estimates, the implied elasticities are 0.060–0.364 and they are significant at 5 percent level. For the specifications with county-specific linear trends, the elasticities are not significant at conventional levels.[18]

In the presence of weather-related controls, there is a notable change in the acres coefficient from 23.581 (column A1) to 18.458 (column B1) for the specification without county FEs. The model fit improvements, however, are relatively minor. As it was the case for the models without weather-related controls, the acres coefficients fail to be statistically significant at conventional levels for the specifications with county-specific trends (columns B7 and B8). Apart from the specification without county FEs (column B1), the elasticity of nitrogen concentration with respect to corn acreage is between 0.061 (column B5) and 0.093 (column B6).

The interaction of acres with precipitation implies effects that are significant at 5 percent level even in the presence of county-specific trends. Indeed, all but 2 of the 24 elasticities are significant at 5 percent level. Once again, apart from the specification without county FEs that implies elasticities of 0.278 (first precipitation quartile) to 0.395 (third quartile), we see elasticities of up to 0.086, 0.130, and 0.178, depending on the precipitation quartile, all of which are significant at 1 percent level. For the richest specification (column C8) that includes county FEs, county-specific trends, and year FEs, the elasticities are significant at 1 percent level and equal to 0.076 and 0.118 for the second and third precipitation quartiles, respectively; their counterpart for the first quartile is not significant at conventional levels.

Figure 9.3 shows point estimates along with 95 percent CIs for the 48 weather-related controls. Among the 48 coefficients, only the ones associated with January precipitation and its square are statistically significant. Based on multiple-hypotheses testing performed separately for each of the three sets of weather-related controls, the 24 precipitation controls, as well as the 12 extreme-heat controls, are jointly significant at 5 percent. The 12 moderate-heat controls are not jointly significant at conventional levels.[19]

Statistical significance. In all, we see positive and statistically significant effects of corn acreage on nitrogen pollution. The specifications that control for weather and contain an interaction of corn acreage with precipitation

18. Throughout the paper, we refer to statistical significance at ≤ 10 percent as significance at conventional levels.

19. We discuss additional estimates for the panel FE regressions summarized in tables 9.4–6 and figure 4 in section A.6 of the online appendix (http://www.nber.org/data-appendix/c14692/appendix.pdf). A detailed discussion of the motivation behind our additional estimates and any related data sources for the panel FE regressions is available in section A.6.1 and section A.6.2. A similar discussion for the cross-section regressions is available in section A.6.3.

Table 9.3 Panel fixed effect regressions and corn acreage elasticities

	(A1)	(A2)	(A3)	(A4)	(A5)	(A6)	(A7)	(A8)
				A. Acres only				
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)
$\bar{R}^2$	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 pval	0.000	0.003	0.013	0.003	0.017	0.002	0.793	0.163
	(B1)	(B2)	(B3)	(B4)	(B5)	(B6)	(B7)	(B8)
				B. Acres plus weather				
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)
$\bar{R}^2$	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 pval	0.000	0.002	0.010	0.004	0.011	0.003	0.727	0.205
	(C1)	(C2)	(C3)	(C4)	(C5)	(C6)	(C7)	(C8)
				C. Acres plus weather and interaction with precipitation				
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)

$\bar{R}^2$	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 25 est.	0.278***	0.072**	0.059**	0.079***	0.052**	0.086***	−0.015	0.037
elast 25 s.e.	(0.029)	(0.029)	(0.027)	(0.028)	(0.025)	(0.030)	(0.035)	(0.034)
elast 25 pval	0.000	0.013	0.031	0.006	0.042	0.005	0.666	0.275
elast 50 est.	0.333***	0.119***	0.105***	0.123***	0.097***	0.130***	0.026**	0.076***
elast 50 s.e.	(0.032)	(0.030)	(0.029)	(0.031)	(0.027)	(0.033)	(0.032)	(0.032)
elast 50 pval	0.000	0.000	0.000	0.000	0.000	0.000	0.032	0.001
elast 75 est.	0.395***	0.170*	0.155***	0.171***	0.147***	0.178***	0.071**	0.118***
elast 75 s.e.	(0.037)	(0.036)	(0.035)	(0.037)	(0.034)	(0.040)	(0.033)	(0.035)
elast 75 pval	0.000	0.000	0.000	0.000	0.000	0.000	0.032	0.001
precip 25	0.885	0.885	0.885	0.885	0.885	0.885	0.885	0.885
precip 50	1.070	1.070	1.070	1.070	1.070	1.070	1.070	1.070
precip 75	1.274	1.274	1.274	1.274	1.274	1.274	1.274	1.274
mean acres	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038
mean N	2.451	2.451	2.451	2.451	2.451	2.451	2.451	2.451
county FE		✓	✓	✓	✓	✓	✓	✓
trend			✓					
year FE				✓		✓		✓
state × trend					✓	✓		
county × trend							✓	✓

Note: We control for weather (precipitation, squared precipitation, moderate-heat degree days, and extreme-heat degree days) in all eight models of panels B and C. The standard errors reported in parentheses are clustered by HUC4. The elasticities in the bottom of each panel are calculated using the means of corn acreage (mean acres) and nitrogen concentration (mean N), and three precipitation quartiles (precip25, precip50, precip75) in panel C. The acreage is in millions, the concentration is in mg/L, and the precipitation is total annual (January–December) in meters. The asterisks denote statistical significance as follows: 1% (***), 5% (**), 10% (*). For additional details, see section 9.6.

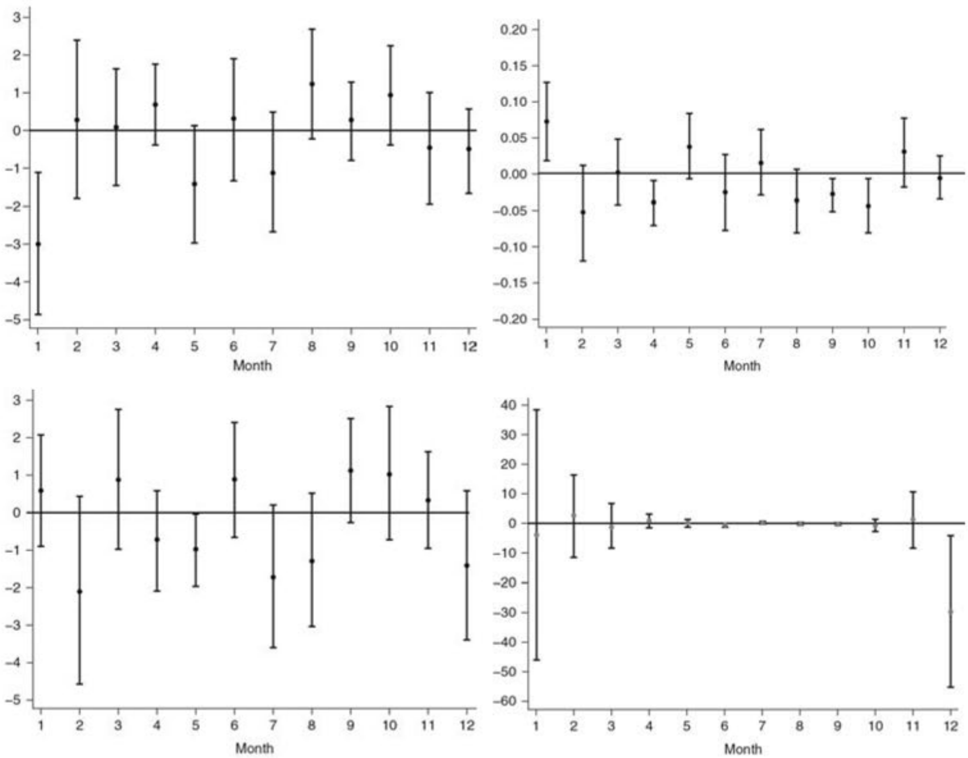


Fig. 9.3A–D Panel FE regressions, weather related controls

Note: Panels A–D are read from top left to bottom right. The figure shows point estimates and 95% confidence intervals (CIs) for the 48 weather related controls in specification C8 of the panel FE regressions in table 9.3. The CIs are constructed using standard errors clustered by HUC4. The F statistics and the *p*-values in squared brackets for the joint significance of the coefficients shown in the four panels are as follows: 2.06 [0.024] for panel A, 2.94 [0.001] for panel B, 1.39 [0.178] for panel C, and 2.02 [0.027] for panel D. For additional details, see section 9.6.

generally imply larger effects than their counterparts that do not contain such interactions. Spatial FEs matter more than time-related controls for the magnitude of the effects. According to our preferred specification (column C8), the elasticity of nitrogen concentration with respect to corn acreage is 0.076 for the second precipitation quartile and increases to 0.118 for the third quartile. In both instances, the elasticity is significant at 1 percent level.

Economic significance. The statistically significant effects reported above are also economically meaningful according to a back-of-the-envelope calculation that utilizes the (median) potential damage costs of nitrogen due to declines in fisheries and estuarine/marine life of $15.84 per kg ($2008) from table 1 in Sobota et al. (2015). At the third precipitation quartile, a 1 within-county standard deviation increase in corn acres planted implies a 3.3 percent increase in the level of nitrogen concentration. At the average nitrogen concentration of about 2.5 mg/L and the average streamflow of the Mississippi River in the GoM in our sample ($\approx$ 21,500 cubic meters per second), this effect entails close to 50,800 additional metric tons of nitrogen in the GoM. Hence, our estimated increase in nitrogen concentration of 3 percent implies an external cost of \$805.5 million per year in \$2008, or approximately \$805.5 × 1.14 = \$918.3 in \$2017 (the last year in our sample) using the GDP deflator (FRED GDPDEF series).[20]

Reconciling our baseline estimates. Table 4 in Hendricks, Smith, and Sumner (2014) gives the average nitrogen loss from the edge-of-field (EoF) as predicted by the SWAT model—coupled with an econometric model—for different land uses in Iowa, Illinois, and Indiana for 2000–2010. Nitrogen losses are the sum of nitrate and organic nitrogen loss. Corn after corn generates the largest nitrogen losses (34.7 lb per acre per year [lb/a/y], on average) 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 lb/a/y reported by the authors is similar to the average estimate of total nitrogen loss of 34 lb/a/y in the USDA CEAP national nitrogen loss report (NRCS 2017b) we discussed earlier.

Assuming the mean annual EoF loss of about 35 lb/a/y from Hendricks, Smith, and Sumner and 79,384,857 corn acres per year (average of national corn acres planted during the same period according to USDA data), we have 1,260,294 metric tons of total nitrogen per year. This calculation assumes that the EoF losses translate to an equivalent nitrogen loading in the GoM—admittedly a strong assumption, because some nitrogen that leaves the field does not reach the GoM. Note that the average annual total nitrogen flux of the Mississippi and the Atchafalaya Rivers to the GoM between is 1,460,419 metric tons for 1968–2016.[21]

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 GoM (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 lb/a/y using the average annual corn acreage for 1968–2016. However, a comparison of 46.8 lb/a/y with 35 lb/a/y from Hendricks, Smith, and Sumner 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 imperfect comparison, is to assume that 70 percent of the 1,685,245 metric tons are attributed to agriculture (David, Drinkwater, and McIsaac 2010), in which case we have 32.8 lb/a/y (see Wu and Tanaka 2005 for a similar approach). This loss of 32.8 lb/a/y cal-

20. We use the average flow for years 1970–2016 from column F (Total Mississippi-Atchafalaya River) available in the following link: https://toxics.usgs.gov/hypoxia/mississippi/flux_ests/delivery/Gulf-Annual-2016.xlsx.

21. See the USGS link here: https://toxics.usgs.gov/hypoxia/mississippi/flux_ests/delivery/index.html.

culated using our estimates is similar to the average loss of 34.7 lb/a/y in Hendricks, Smith, and Sumner.

According to our baseline panel FE estimates in column C8 of table 9.3, a 28 percent increase in corn acres planted—assuming an increase equal 1 within-county standard deviation (11,000 acres) and using the mean acreage (38,000 acres) from table 9.2 to calculate the percent increase—implies a a 3.3 percent increase in nitrogen concentration when evaluated at the mean concentration of 2.5 mg/L. A 3.3 percent 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 percent increase in concentration is associated with a 28 percent increase in 79,384,857 corn acres, the implied increase is 5.52 lb/a/y.

The effect of additional corn acres on measured nitrogen in waterways is an order of magnitude smaller than agronomic estimates of excess nitrogen applied to those acres assuming EoF losses translate to an equivalent nitrogen loading to streams and rivers. However, we do not interpret our results as evidence that the amount of surplus nitrogen used on crops is much smaller than previously believed. Instead, our findings are consistent with new research in environmental science arguing that there is a large amount of nitrogen stored in subsurface soil and groundwater (e.g., Van Meter, Basu, and Cappellen 2017; Van Meter, Van Cappellen, and Basu 2018; Ilampooranan, Van Meter, and Basu 2019) and contributes to the so-called legacy nitrogen, which may increase loadings in rivers and streams with a long delay.[22] The presence of large quantities of legacy nitrogen has substantive policy implications because it increases the relative efficacy of downstream policies such as fluvial wetlands (i.e., those connected to waterways) and it is a topic we explore in more detail in Metaxoglou and Smith (2022).

Using the elasticity estimate of 0.076 from column C8 of Table 9.3, an additional corn acre generates an average of 3.5 lb/a/y of nitrogen in small (level 4) streams within a 50-mile radius from the country centroids for median precipitation and average streamflow of 362 cubic feet per second (cfs).[23] This estimate is close to 10 percent of the USDA CEAP estimate of 34 lb/a/y of EoF losses. If we instead use 5.52 lb/a/y, per our discussion in the previous paragraph, and a streamflow of 1,997 cfs, which is the average across all streams, an additional corn acre generates an average of 30 lb/a/y in streams and rivers, which is almost 80 percent of the NRCS estimate of surplus nitrogen.

Additional estimates. Panel A of figure 9.4 shows that a more flexible specification for the interaction of corn acreage with precipitation does not have a material effect on our estimated corn acreage elasticities. Similar flexible

22. Van Meter et al. (2016) study soil data from cropland in the Mississippi River basin and find nitrogen accumulation of 25–70 kg per hectare per year (22–62 lb per acre per year).

23. This is the average streamflow based on the Enhanced Unit Runoff Method (EROM) Flow Estimation in the USGS NHD Plus data for years 1971–2000 and is readily available by river segment (COMID).

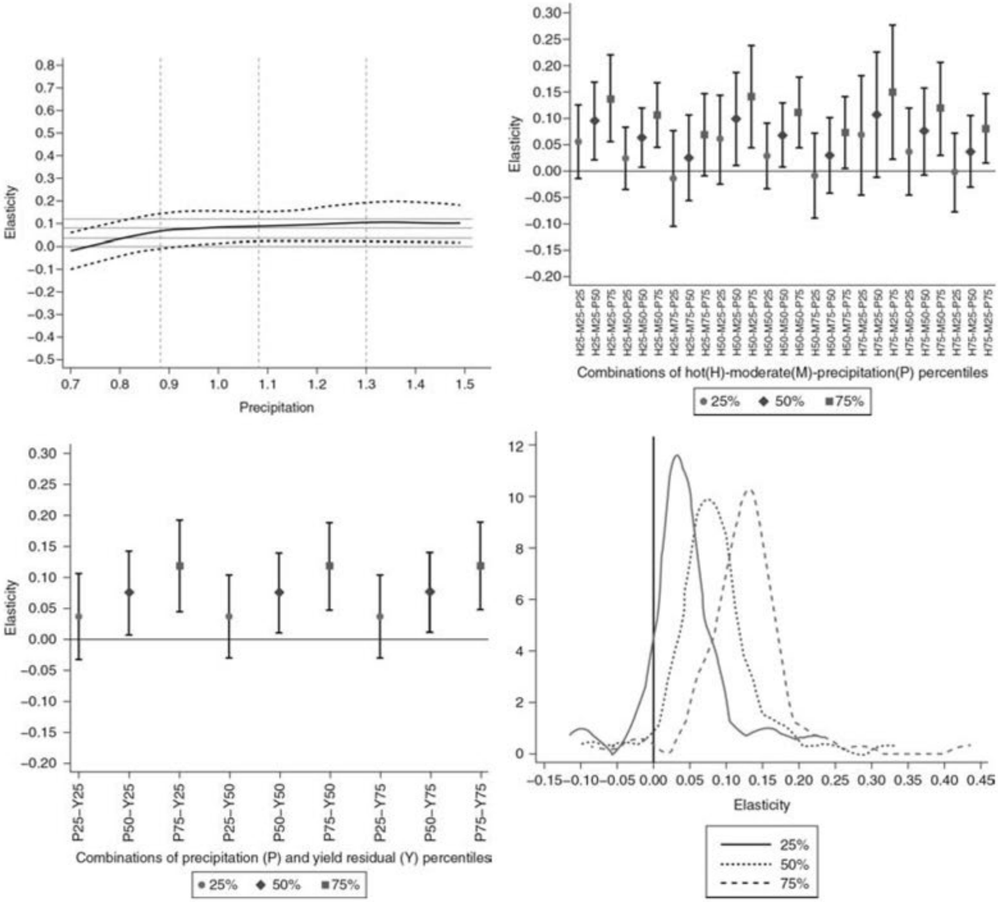


Fig. 9.4A–D Additional elasticity estimates based on panel fixed-effect regressions

Note: Panels A–D are read from top left to bottom right. In panels A–C, we report elasticity estimates along with 95% confidence intervals using standard errors clustered by HUC4. In panels B and C, the legend pertains to the quartiles of total annual precipitation. We use the same set of weather-related controls, county fixed effects (FEs), year FEs, and county-specific trends as in column C8 in table 9.3. In panel A, we use a flexible specification (cubic spline) to model the interaction of corn acreage and precipitation. We use the vertical dashed lines to indicate the precipitation quartiles and the horizontal gray lines to indicate the elasticities from specification C8 in table 9.3. In panel B, we interact corn acreage with total annual precipitation, annual moderate-, and extreme-heat degree days. In panel C, we interact corn acreage with total annual precipitation and corn yield residuals. We obtain the yield residuals by regressing yields on county-specific trends. In panel D, we summarize the elasticity estimates in tables 9.4– 9.6 by precipitation quartile using kernel density plots. For additional details, see section A.6 in the online appendix, http://www.nber.org/data-appendix/c14692/appendix .pdf.

Table 9.4 **Additional estimates of corn acreage elasticities based on panel fixed-effect regressions**

			sample					coefficients				precipitation			elasticities		
no.	model	obs	starts	ends	counties	years	Clusters	β_1	β_2	Mean nitrogen	Mean acres	25%	50%	75%	25%	50%	75%
M1	BEA SAEMP25	64,121	1970	2017	2,232	48	124	−9.561**	13.527**	2.451	0.038	0.885	1.070	1.274	0.037	0.076**	0.118***
M2	BEA SAGDP2	64,121	1970	2017	2,232	48	124	−9.598**	13.502**	2.451	0.038	0.885	1.070	1.274	0.036	0.075**	0.117***
M3	BEA REA CAINC	63,477	1970	2017	2,209	48	124	−7.123	13.477**	2.462	0.038	0.884	1.070	1.274	0.074*	0.113***	0.156***
M4	M1 plus EIA−SEDS	64,121	1970	2017	2,232	48	124	−9.518**	13.619**	2.451	0.038	0.885	1.070	1.274	0.039	0.078**	0.121***
M5	M2 plus EIA−SEDS	64,121	1970	2017	2,232	48	124	−9.547**	13.589**	2.451	0.038	0.885	1.070	1.274	0.038	0.077**	0.120***
M6	M3 plus EIA−SEDS	63,477	1970	2017	2,209	48	124	−7.325	13.564**	2.462	0.038	0.884	1.070	1.274	0.072*	0.111***	0.154***
M7	M4 plus EPA	23,735	1996	2017	1,749	22	117	−12.560*	16.716**	2.710	0.044	0.886	1.063	1.254	0.037	0.085	0.137
M8	M5 plus EPA	23,735	1996	2017	1,749	22	117	−12.428*	16.634**	2.710	0.044	0.886	1.063	1.254	0.038	0.086	0.137
M9	M6 plus EPA	23,488	1996	2017	1,731	22	117	−7.555	16.884**	2.725	0.045	0.884	1.062	1.254	0.121	0.170	0.223**
M10	BLS LAUS	33,496	1990	2017	1,983	28	121	−8.207	10.625**	2.637	0.042	0.894	1.076	1.272	0.020	0.051	0.084
M11	M10 plus EIA−SEDS	33,496	1990	2017	1,983	28	121	−8.112	10.675**	2.637	0.042	0.894	1.076	1.272	0.023	0.053	0.086
M12	M11 plus EPA	23,735	1996	2017	1,749	22	117	−12.664*	16.407**	2.710	0.044	0.886	1.063	1.254	0.030	0.078	0.129
M13	M6 plus WWTPs	11,475	1978	2012	559	35	46	5.738	6.035	2.845	0.042	0.718	0.912	1.124	0.147*	0.164**	0.183***
M14	M6 plus TREND livestock	63,406	1970	2017	2,207	48	124	−7.306*	13.568**	2.459	0.038	0.884	1.070	1.275	0.073*	0.112***	0.155***
M15	M6 plus TREND human	63,406	1970	2017	2,207	48	124	−7.335*	13.581**	2.459	0.038	0.884	1.070	1.275	0.072*	0.111***	0.154***
M16	M6 plus TREND ATMDEP	63,406	1970	2017	2,207	48	124	−7.321*	13.481**	2.459	0.038	0.884	1.070	1.275	0.071*	0.110***	0.153***
M17	M6 plus TREND fertilizer	63,406	1970	2017	2,207	48	124	−7.444*	13.431**	2.459	0.038	0.884	1.070	1.275	0.069*	0.107***	0.150***
M18	M6 plus TREND fixing	63,406	1970	2017	2,207	48	124	−7.561*	13.512**	2.459	0.038	0.884	1.070	1.275	0.068*	0.107**	0.149***
M19	M6 plus TREND uptake	63,406	1970	2017	2,207	48	124	−7.320*	13.649**	2.459	0.038	0.884	1.070	1.275	0.073*	0.113***	0.156***

Note: The coefficients β_1 and β_2 are the ones for corn acres and their interaction with precipitation in equation (1). All regressions are estimated using the 48 weather-related controls, the fixed effects, and the time-related controls, in specification C8 in table 9.3. The corn acres (acres) are in millions and the nitrogen concentration (nitrogen) is in mg/L. The precipitation (measured in meters) and runoff (measured in millimeters) are both total annual. The elasticities in the three rightmost columns are calculated using the precipitation (or runoff, when appropriate) quartiles and the mean acreage and nitrogen concentration reported in the table. The standards errors are clustered by HUC4 except for the robustness checks in which we explore alternative clustering schemes. The asterisks denote statistical significance as follows: 1% (***), 5% (**), 10% (*). For additional details, see section A.6 at http://www.nber.org/data-appendix/c14692/appendix.pdf.

Table 9.5 **Additional estimates of corn acreage elasticities based on panel fixed-effect regressions (continued)**

	sample						coefficients				precipitation/runoff			elasticities		
model	obs	starts	ends	counties	years	Clusters	β_1	β_2	mean nitrogen	mean acres	25%	50%	75%	25%	50%	75%
A. Baseline																
Baseline	64,121	1970	2017	2,232	48	124	−9.566**	13.517**	2.451	0.038	0.885	1.070	1.274	0.037	0.076**	0.118***
B. Control for conservation programs, acres of other major crops, and fertilizer sales																
Other acres	64,121	1970	2017	2,232	48	124	−10.440**	14.320**	2.451	0.038	0.885	1.070	1.274	0.034	0.075*	0.120***
CRP acres	64,121	1970	2017	2,232	48	124	−10.135**	13.655**	2.451	0.038	0.885	1.070	1.274	0.030	0.069**	0.112***
Fertilizer sales	58,047	1970	2012	2,230	42	124	−7.842	11.932**	2.408	0.037	0.877	1.071	1.279	0.041	0.076**	0.115***
Other and CRP acres	64,121	1970	2017	2,232	48	124	−11.018**	14.517**	2.451	0.038	0.885	1.070	1.274	0.028	0.070	0.115**
Other and Fertilizer	58,047	1970	2012	2,230	42	124	−7.542	12.540**	2.408	0.037	0.877	1.071	1.279	0.054	0.091**	0.132***
Other, CRP, Fertilizer	58,047	1970	2012	2,230	42	124	−8.049	12.743**	2.408	0.037	0.877	1.071	1.279	0.048	0.087**	0.128***
C. Temporal variation in corn acreage effects																
1970s	12,765	1970	1979	2,079	10	122	−9.481	3.085	2.020	0.034	0.873	1.109	1.341	−0.115	−0.103	−0.091
1980s	17,657	1980	1989	2,058	10	123	−5.666	14.718**	2.416	0.033	0.875	1.040	1.230	0.100*	0.133**	0.172**
1990s	14,878	1990	1999	1,920	10	121	2.534	12.690*	2.568	0.038	0.905	1.095	1.307	0.205	0.241	0.280
2000s	11,204	2000	2009	1,561	10	117	0.568	10.340*	2.630	0.043	0.875	1.064	1.252	0.159*	0.191**	0.223***
2010s	7,095	2010	2017	1,225	8	110	−9.319	15.012	2.785	0.047	0.906	1.056	1.232	0.072	0.109	0.154
D. Spatial variation in corn acreage effects																
MRB	40,906	1970	2017	1,534	48	87	−10.456**	15.178**	2.866	0.048	0.789	1.008	1.230	0.026	0.082*	0.138***
North	26,799	1970	2017	826	48	58	−14.556**	18.324**	3.302	0.065	0.801	0.940	1.087	0.003	0.053	0.106
Middle	15,974	1970	2017	546	48	38	17.912**	−5.230	2.345	0.031	0.881	1.055	1.222	0.174***	0.162***	0.151***
South	21,348	1970	2017	860	48	51	−8.309	4.253	1.462	0.009	1.111	1.279	1.475	−0.022	−0.018	−0.012
E. Alternative time windows for measuring nitrogen concentration, precipitation, and degree days																
January-June	60,177	1970	2017	2,227	48	124	−3.271	11.310**	2.604	0.037	0.417	0.526	0.655	0.021	0.038	0.059**
March-August	61,308	1970	2017	2,227	48	124	−3.487	10.127**	2.528	0.038	0.503	0.600	0.705	0.024	0.038	0.054*
April-September	61,654	1970	2017	2,228	48	124	−5.550*	13.773**	2.461	0.038	0.509	0.599	0.701	0.022	0.042	0.063**
May-October	61,890	1970	2017	2,230	48	124	−9.066**	20.689**	2.435	0.038	0.501	0.588	0.688	0.020	0.048	0.080**
F. Interacting corn acres with runoff instead of precipitation																
Runoff	62,420	1970	2015	2,232	46	124	−0.521	0.002**	2.435	0.038	1752.310	2824.000	4112.086	0.048	0.083**	0.124***
G. Nitrogen concentration accounting for streamflow																
Downstream main	33,335	1970	2017	1,913	48	123	−15.821**	17.665**	2.305	0.038	0.878	1.059	1.261	−0.005	0.047	0.105***
Downstream all	40,145	1970	2017	2,037	48	124	−15.974**	17.006**	2.322	0.038	0.878	1.058	1.262	−0.017	0.033	0.090***

Note: The coefficients β_1 and β_2 are the ones for corn acres and their interaction with precipitation in equation (1). All regressions are estimated using the 48 weather-related controls, the fixed effects, and the time-related controls, in specification C8 in table 9.3. The corn acres (acres) are in millions and the nitrogen concentration (nitrogen) is in mg/L. The precipitation measured in meters is total annual unless it is indicated otherwise (panel E). The runoff (measured in millimeters) is total annual. The models with fertilizer sales in panel B exclude 1986 due to data availability. The elasticities in the three rightmost columns are calculated using the quartiles of precipitation or runoff and the mean acreage and nitrogen concentration reported in the table. The standards errors are clustered by HUC4 except for the robustness checks in which we explore alternative clustering schemes. The asterisks denote statistical significance as follows: 1% (***), 5% (**), 10% (*). For additional details, see section A.6 at http://www.nber.org/data-appendix/c14692/appendix.pdf.

Table 9.6 Additional estimates of corn acreage elasticities based on panel fixed-effect regressions (continued)

	sample						coefficients				precipitation/runoff			elasticities		
model	obs	starts	ends	counties	years	Clusters	β_1	β_2	mean nitrogen	mean acres	25%	50%	75%	25%	50%	75%
A. Baseline																
Baseline	64,121	1970	2017	2,232	48	124	–9.566**	13.517**	2.451	0.038	0.885	1.070	1.274	0.037	0.076**	0.118***
B. Nitrogen concentration accounting for streamflow and stream levels																
Downstream all L1	13,922	1971	2017	753	47	86	–16.085**	10.893**	1.803	0.026	0.916	1.091	1.290	–0.088	–0.060	–0.029
Downstream all L2	16,581	1970	2017	1,155	48	107	–10.587**	10.669**	1.873	0.038	0.920	1.084	1.277	–0.016	0.020	0.061
Downstream all L3	15,789	1971	2017	1,289	47	117	–26.341**	25.282**	1.813	0.043	0.882	1.061	1.257	–0.096	0.011	0.129**
Downstream all L4	8,667	1970	2017	977	48	112	–8.760	20.881**	1.755	0.045	0.838	1.033	1.231	0.226***	0.331***	0.438***
C. Include lagged acres																
1 lag	58,258	1970	2017	2,232	48	124	–8.307	13.331**	2.451	0.040	0.885	1.070	1.274	0.057**	0.097**	0.142**
2 lags	58,258	1970	2017	2,232	48	124	–6.713	13.516**	2.451	0.040	0.885	1.070	1.274	0.086*	0.126**	0.171**
3 lags	58,258	1970	2017	2,232	48	124	–6.451	13.774**	2.451	0.040	0.885	1.070	1.274	0.093*	0.135*	0.181*
D. Reporting limits in nitrogen concentration																
Reporting limit	64,670	1970	2017	2,232	48	128	–11.043**	15.602**	2.346	0.035	0.884	1.070	1.274	0.041	0.085***	0.133***
Zero	64,676	1970	2017	2,232	48	128	–11.276**	15.128**	2.157	0.035	0.884	1.070	1.274	0.034	0.081***	0.131***
E. Nitrogen concentration using alternative radii																
100 miles	80,612	1970	2017	2,242	48	124	–6.409**	9.943**	2.615	0.040	0.869	1.061	1.271	0.034	0.063***	0.094***
200 miles	85,359	1970	2017	2,243	48	124	–3.426**	6.379**	2.642	0.040	0.863	1.059	1.272	0.031*	0.050***	0.070***
F. Data filtering																
KS filter	64,096	1970	2017	2,232	48	124	–9.533**	13.651**	2.442	0.038	0.885	1.070	1.274	0.039	0.079**	0.122***
G. Alternative datasets and geographic scope (CONUS)																
USGS-NWIS	72,751	1970	2017	2,688	48	188	–10.446**	13.608**	2.418	0.035	0.814	1.038	1.256	0.009	0.053*	0.096***
USGS-NWQN	107,994	1970	2017	2,998	48	205	–10.862**	13.897**	2.200	0.026	0.798	1.049	1.278	0.003	0.043***	0.080***
USGS+EPA	113,372	1970	2017	3,027	48	205	–7.528**	14.386**	2.044	0.025	0.767	1.037	1.270	0.043**	0.091***	0.133***
H. Alternative data aggregation																
Hydrologic unit	17,943	1970	2017	986	48	128	–18.535**	21.895**	2.100	0.030	0.888	1.077	1.280	0.013	0.071*	0.134***
Monitoring site	56,466	1970	2017	9,596	48	129	–1.359**	1.566**	2.356	0.292	0.939	1.108	1.286	0.014	0.046*	0.081***
I. Statistical inference with alternative clustering schemes																
HUC2 × year	64,121	1970	2017	2,232	48	528	–9.566**	13.517**	2.451	0.038	0.885	1.070	1.274	0.037	0.076**	0.118***
HUC4 × year	64,121	1970	2017	2,232	48	5,132	–9.566**	13.517**	2.451	0.038	0.885	1.070	1.274	0.037	0.076**	0.118***
year	64,121	1970	2017	2,232	48	48	–9.566**	13.517**	2.451	0.038	0.885	1.070	1.274	0.037	0.076*	0.118***

Note: The coefficients β_1 and β_2 are the ones for corn acres and their interaction with precipitation in equation (1). All regressions are estimated using the 48 weather-related controls, the fixed effects, and the time-related controls, in specification C8 in table 9.3. The corn acres (acres) are in millions and the nitrogen concentration (nitrogen) is in mg/L. The precipitation (measured in meters) is total annual. The elasticities in the three rightmost columns are calculated using the quartiles of precipitation or runoff and the mean acreage and nitrogen concentration reported in the table. The standards errors are clustered by HUC4 except for the robustness checks in which we explore alternative clustering schemes. The asterisks denote statistical significance as follows: 1% (***), 5% (**), 10% (*). For additional details, see section A.6 at http://www.nber.org/data-appendix/c14692/appendix.pdf.

specifications based on total precipitation for different time windows during the year (March–August and April-September) produced very similar elasticities to the ones shown here. In panels B and C of figure 9.4, we explore the role of crop nutrient uptake. Holding extreme-heat DDs and precipitation constant, additional moderate-heat DDs imply lower elasticities. Holding moderate-heat DDs and precipitation constant, an increase in extreme-heat DDs has no material impact on the magnitude of the acreage elasticities despite the well-documented negative effect of extreme heat on yields. Holding moderate- and extreme-heat DDs constant, an increase in precipitation implies larger elasticities. In all, the elasticity estimates when we interact corn acreage with moderate- and extreme-heat DDs in addition to precipitation are very similar to their baseline counterparts obtained by interacting the corn acreage with precipitation alone. The pattern in the magnitude of the elasticities just described also holds for panel FE regressions estimated using counties in the MRB, and counties in the most northern (coldest) states east of the 100th meridian from Schlenker and Roberts (2009). The elasticity estimates for the most southern (warmest) states from Schlenker and Roberts are generally noisy and indistinguishable from zero at conventional levels. Their counterparts for the middle states exhibit very little variation across the quartiles of precipitation and heat we considered. Yield shocks, calculated as deviations from county-specific yield trends, do not matter for the magnitude of the acreage elasticities either.

The implied corn acreage elasticities for a number of models we estimated performing a series of robustness checks, discussed in detail in section A.6 in the online appendix,[24] are summarized by precipitation quartile using the kernel density plots in panel D of figure 9.4. Similar to the baseline results, the coefficient of the interaction of corn acreage and precipitation (coefficient β_2 in equation [1]) is positive and highly significant in the vast majority of the models we explored. Hence, the amount of precipitation matters for the magnitude of the estimated acreage elasticities. With very few exceptions, the corn acreage elasticities based on the second and third precipitation quartiles are highly significant. Their counterparts based on the first precipitation quartile are not. For the second precipitation quartile, the elasticities that are significant at conventional levels are 0.043–0.331. Their counterparts for the third precipitation quartile are 0.059–0.438. As a reminder, for our preferred baseline specification in column C8 of table 9.3, the acreage elasticities are 0.076 and 0.118 for the second and third precipitation quartiles.

9.7 Climate Change and Nitrogen Pollution

According to our econometric analysis, corn acreage drives nitrogen concentration and the magnitude of the acreage effect depends on precipitation

24. See http://www.nber.org/data-appendix/c14692/appendix.pdf.

with more precipitation implying larger effects for our baseline estimates that pertain to the part of the country east of the 100th meridian. An additional specification in which we also interact corn acreage with moderate and extreme-heat DDs shows that, all else equal, an increase in moderate-heat DDs implies smaller effects, while an increase in extreme-heat DDs has no material impact on the magnitude of the effects.

We now explore the implications of climate change for our findings regarding the relationship between corn acreage and nitrogen concentration. In particular, we use the NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP-CMIP6) data set to obtain projections for precipitation, moderate-, and extreme-heat DDs, and, in turn, projections of the marginal effects (MEs) of corn acreage on nitrogen concentration. The NEX-GDDP-CMIP6 data set is comprised of global downscaled climate scenarios derived from the General Circulation Model runs conducted under the Coupled Model Intercomparison Project Phase 6 (Eyring et al. 2016) and across two of the four "Tier 1" greenhouse gas emissions scenarios known as shared socioeconomic pathways (SSPs), namely, SSP2–4.5 and SSP5–8.5.[25]

We use out-of-sample projections from three climate models (CanESM5, UKESM1-0-LL, and GFDL-ESM4) and SSP2-4.5 and SSP5-8.5 for three weather-related variables available at a latitude/longitude resolution of 0.25°, namely, the mean of the daily precipitation rate (pr), the daily minimum near surface air temperature (tasmin), and the daily maximum near surface air temperature (tasmax). Projections of these variables from the climate models based on alternative SSPs allow us to obtain projections of total annual precipitation, moderate-heat, and extreme-heat DDs, which in their turn translate to projections of corn acreage ME on nitrogen concentration. These MEs do not take into account the impacts of climate change on other factors affecting nitrogen concentration and loads (e.g., streamflow, change in farmers' behavior as in Elbakidze et al. 2022, etc.).

Although projections for the three weather-related variables are available until 2100, we obtain ME projections for 2018–2050, as we are skeptical about the use of a model that has been estimated using data for 1970–2017 to project MEs more than 20 to 30 years out of sample. We opt for projections of MEs as opposed to elasticities because the former do not require an assumption about future values of nitrogen concentration and corn acreage while the later do. To the best of our knowledge, projections of both acreage and nitrogen concentration with the spatial and temporal coverage required to obtain projections of elasticities are not available. The MEs discussed are estimated assuming an increase in corn acreage equal to the historical (in-sample) within-county standard deviation and estimating different regressions for five sets of counties. The specification of these regression

25. The data are available here: https://www.nccs.nasa.gov/services/data-collections/land-based-products/nex-gddp-cmip6. Additional information including variable descriptions is available here: https://www.nccs.nasa.gov/sites/default/files/NEX-GDDP-CMIP6-Tech_Note.pdf.

equations is identical to specification C8 of table 9.3. The sets of counties for which we obtained projections of MEs are as follows: counties east of the 100th meridian excluding Florida (baseline), counties in the MRB, as well as all counties in the northern, middle, and southern states east of the 100th meridian as in Schlenker and Roberts (2009).

The precipitation projections are generally smaller than their historical counterparts across all climate models, SSPs, and quartiles of the precipitation distribution. A notable exception is the median precipitation for the middle counties for which the projections exceed their historical counterpart for all climate models and SSPs. The projected quartiles for moderate-heat DDs are larger than their historical counterparts for all climate models and SSPs for all sets of counties and all three quartiles of precipitation considered. The projected quartiles for extreme-heat DDs, on the other hand, are generally smaller than their historical counterparts, especially for the lower quartiles of the extreme-heat distribution. It is also the case that the differences between projected and historical quartiles are generally larger for the moderate- and extreme-heat DDs than for precipitation.

For the discussion that follows, it important to keep in mind that for the panel FE regressions in which we interact acreage only with precipitation, the coefficient on the interaction is significant at conventional levels for the MRB and northern counties, in addition to the baseline counties. For the regressions in which we interact corn acreage with precipitation and DDs, in addition to the baseline counties, the coefficient on the interaction of corn acreage with precipitation is significant at conventional levels in the MRB and northern counties. The coefficients on the interaction of the corn acreage with moderate-heat DDs, as well as those on the interaction of the corn acreage with extreme-heat DDs, are indistinguishable from zero at conventional levels.

For the baseline counties—depending on the climate model and SSP—the projected median precipitation is 1.047–1.078 meters (panel A, table 9.7). Its third-quartile counterpart is 1.242–1.289 meters. The implied MEs based on the projected median precipitation are 0.048–0.053 mg/L, which are similar in magnitude to the ME of 0.051 mg/L based on the historical median precipitation. For the MRB counties, an area of particular interest for policies aiming to address the GoM HZ areal extent, the median precipitation projections are 0.945–0.980 meters implying MEs of 0.045–0.051 mg/L, the lower end of which is slightly smaller than their historical counterpart of 0.056 mg/L but similar to their baseline counterparts. For the northern counties, the median precipitation projections are 0.875–0.937 meters implying MEs of 0.017–0.031 mg/L, respectively. Their historical ME counterpart is 0.032 mg/L. For the middle counties, the median precipitation projections are 1.057–1.079 meters implying MEs of 0.133–0.134 mg/L, which are essentially identical to their historical counterpart, noting that the coefficient of the interaction of corn acreage with precipitation is statistically indistinguishable from zero. Finally, for the southern coun-

Table 9.7 **Projections of precipitation, moderate, and extreme heat degree days**

		precipitation			moderate heat			extreme heat		
source	year	25%	50%	75%	25%	50%	75%	25%	50%	75%
A. Baseline										
Historical	1970–2017	0.885	1.070	1.274	1.700	2.149	2.695	0.150	0.415	0.854
CANESM5 SSP245	2018–2050	0.848	1.070	1.269	2.309	2.877	3.496	0.061	0.244	0.739
CANESM5 SSP585	2018–2050	0.852	1.078	1.289	2.395	2.960	3.593	0.071	0.301	0.812
GFDL-ESM4 SSP245	2018–2050	0.870	1.073	1.275	1.985	2.557	3.232	0.048	0.198	0.559
GFDL-ESM4 SSP585	2018–2050	0.866	1.062	1.251	2.016	2.590	3.265	0.052	0.213	0.615
UKESM1-0-LL SSP245	2018–2050	0.834	1.073	1.282	2.360	2.923	3.568	0.070	0.362	0.968
UKESM1-0-LL SSP585	2018–2050	0.838	1.047	1.242	2.411	2.989	3.633	0.116	0.488	1.342
B. Mississippi River Basin										
Historical	1970–2017	0.789	1.008	1.230	1.699	2.043	2.402	0.177	0.401	0.756
CANESM5 SSP245	2018–2050	0.695	0.963	1.203	2.278	2.705	3.151	0.055	0.234	0.716
CANESM5 SSP585	2018–2050	0.691	0.967	1.218	2.356	2.798	3.263	0.072	0.292	0.834
GFDL-ESM4 SSP245	2018–2050	0.720	0.980	1.208	1.928	2.369	2.818	0.033	0.146	0.452
GFDL-ESM4 SSP585	2018–2050	0.726	0.975	1.191	1.965	2.408	2.880	0.034	0.160	0.523
UKESM1-0-LL SSP245	2018–2050	0.673	0.960	1.199	2.308	2.725	3.170	0.058	0.296	0.813
UKESM1-0-LL SSP585	2018–2050	0.686	0.945	1.163	2.343	2.789	3.258	0.098	0.395	1.092
C. Northern states east of the 100th meridian										
Historical	1970–2017	0.801	0.940	1.087	1.421	1.642	1.887	0.061	0.142	0.286
CANESM5 SSP245	2018–2050	0.761	0.905	1.068	1.936	2.206	2.478	0.015	0.070	0.207
CANESM5 SSP585	2018–2050	0.767	0.907	1.074	1.979	2.281	2.590	0.018	0.084	0.243

GFDL-ESM4 SSP245	2018–2050	0.797	0.937	1.089	1.621	1.876	2.139	0.008	0.048	0.140
GFDL-ESM4 SSP585	2018–2050	0.793	0.927	1.069	1.649	1.911	2.176	0.008	0.050	0.137
UKESM1-0-LL SSP245	2018–2050	0.725	0.875	1.031	1.967	2.256	2.535	0.008	0.068	0.218
UKESM1-0-LL SSP585	2018–2050	0.731	0.883	1.019	1.992	2.305	2.612	0.021	0.109	0.296
D. Middle states east of the 100th meridian										
Historical	1970–2017	0.881	1.055	1.222	2.005	2.196	2.379	0.302	0.494	0.730
CANESM5 SSP245	2018–2050	0.848	1.066	1.215	2.622	2.856	3.058	0.106	0.307	0.711
CANESM5 SSP585	2018–2050	0.845	1.072	1.225	2.681	2.935	3.187	0.150	0.401	0.830
GFDL-ESM4 SSP245	2018–2050	0.868	1.076	1.244	2.305	2.542	2.752	0.089	0.249	0.536
GFDL-ESM4 SSP585	2018–2050	0.878	1.064	1.204	2.329	2.572	2.786	0.105	0.283	0.565
UKESM1-0-LL SSP245	2018–2050	0.866	1.079	1.216	2.650	2.894	3.107	0.156	0.445	0.817
UKESM1-0-LL SSP585	2018–2050	0.857	1.057	1.189	2.682	2.960	3.197	0.249	0.617	1.160
E. Southern states east of the 100th meridian										
Historical	1970–2017	1.111	1.279	1.475	2.673	3.000	3.368	0.636	0.991	1.414
CANESM5 SSP245	2018–2050	1.072	1.253	1.438	3.354	3.693	4.058	0.232	0.628	1.377
CANESM5 SSP585	2018–2050	1.082	1.275	1.468	3.427	3.788	4.177	0.270	0.676	1.372
GFDL-ESM4 SSP245	2018–2050	1.047	1.243	1.433	3.090	3.435	3.813	0.235	0.535	1.139
GFDL-ESM4 SSP585	2018–2050	1.047	1.233	1.401	3.110	3.471	3.853	0.256	0.604	1.370
UKESM1-0-LL SSP245	2018–2050	1.123	1.298	1.460	3.435	3.758	4.120	0.503	1.024	1.675
UKESM1-0-LL SSP585	2018–2050	1.074	1.253	1.436	3.480	3.808	4.184	0.601	1.382	2.227

Note: We report quartiles of total annual precipitation, moderate-heat, and extreme-heat degree days based on projections from three climate models (UKESM1-0-LL, CANESM5, and GFDL-ESM4) and two shared socioeconomic pathways (SSPs), namely 245, 585, for 2018–2050. We also report quartiles based on historical data for 1970–2017. The precipitation is total annual and it is measured in meters. The moderate heat is measured in 1,000 degree days between 10°C and 29°C. The extreme heat is measured in 100 degree days above 29°C. We use baseline to refer to counties east of the 100th meridian excluding Florida. We classify states as northern, middle, and southern following Schlenker and Roberts (2009). For additional details, see section 9.7.

Table 9.8 **Marginal effects of corn acreage on nitrogen concentration alternative climate models & SSPs**

Model & SSP	Year	P25%	P50%	P75%	ME25%	ME50%	ME75%
			A. Baseline				
Historical	1970–2017	0.885	1.070	1.274	0.025	0.051	0.080
CANESM5 SSP245	2018–2050	0.848	1.070	1.269	0.020	0.051	0.080
CANESM5 SSP585	2018–2050	0.852	1.078	1.289	0.020	0.053	0.083
GFDL-ESM4 SSP245	2018–2050	0.870	1.073	1.275	0.023	0.052	0.081
GFDL-ESM4 SSP585	2018–2050	0.866	1.062	1.251	0.023	0.050	0.077
UKESM1-0-LL SSP245	2018–2050	0.834	1.073	1.282	0.018	0.052	0.082
UKESM1-0-LL SSP585	2018–2050	0.838	1.047	1.242	0.018	0.048	0.076
			B. Mississippi River Basin				
Historical	1970–2017	0.789	1.008	1.230	0.018	0.056	0.095
CANESM5 SSP245	2018–2050	0.695	0.963	1.203	0.001	0.048	0.090
CANESM5 SSP585	2018–2050	0.691	0.967	1.218	0.000	0.048	0.092
GFDL-ESM4 SSP245	2018–2050	0.720	0.980	1.208	0.005	0.051	0.091
GFDL-ESM4 SSP585	2018–2050	0.726	0.975	1.191	0.006	0.050	0.088
UKESM1-0-LL SSP245	2018–2050	0.673	0.960	1.199	−0.003	0.047	0.089
UKESM1-0-LL SSP585	2018–2050	0.686	0.945	1.163	−0.001	0.045	0.083
			C. Northern states east of the 100th meridian				
Historical	1970–2017	0.801	0.940	1.087	0.002	0.032	0.063
CANESM5 SSP245	2018–2050	0.761	0.905	1.068	−0.007	0.024	0.059
CANESM5 SSP585	2018–2050	0.767	0.907	1.074	−0.006	0.024	0.060
GFDL-ESM4 SSP245	2018–2050	0.797	0.937	1.089	0.001	0.031	0.064
GFDL-ESM4 SSP585	2018–2050	0.793	0.927	1.069	−0.000	0.029	0.059
UKESM1-0-LL SSP245	2018–2050	0.725	0.875	1.031	−0.015	0.017	0.051
UKESM1-0-LL SSP585	2018–2050	0.731	0.883	1.019	−0.014	0.019	0.049
			D. Middle states east of the 100th meridian				
Historical	1970–2017	0.881	1.055	1.222	0.144	0.134	0.125
CANESM5 SSP245	2018–2050	0.848	1.066	1.215	0.146	0.133	0.125
CANESM5 SSP585	2018–2050	0.845	1.072	1.225	0.146	0.133	0.124
GFDL-ESM4 SSP245	2018–2050	0.868	1.076	1.244	0.145	0.133	0.123
GFDL-ESM4 SSP585	2018–2050	0.878	1.064	1.204	0.144	0.133	0.126
UKESM1-0-LL SSP245	2018–2050	0.866	1.079	1.216	0.145	0.133	0.125
UKESM1-0-LL SSP585	2018–2050	0.857	1.057	1.189	0.145	0.134	0.126
			E. Southern states east of the 100th meridian				
Historical	1970–2017	1.111	1.279	1.475	−0.030	−0.024	−0.017
CANESM5 SSP245	2018–2050	1.072	1.253	1.438	−0.031	−0.025	−0.018
CANESM5 SSP585	2018–2050	1.082	1.275	1.468	−0.031	−0.024	−0.017
GFDL-ESM4 SSP245	2018–2050	1.047	1.243	1.433	−0.032	−0.025	−0.018
GFDL-ESM4 SSP585	2018–2050	1.047	1.233	1.401	−0.032	−0.025	−0.020
UKESM1-0-LL SSP245	2018–2050	1.123	1.298	1.460	−0.029	−0.023	−0.017
UKESM1-0-LL SSP585	2018–2050	1.074	1.253	1.436	−0.031	−0.025	−0.018

Note: For each climate model and SSP combination, we report precipitation (P) quartiles and marginal effects (MEs) calculated assuming an increase in corn acreage equal to 1 within-county standard deviation using the appropriate set of counties in each panel. For comparison, we show MEs calculated using data for 1970–2017. The precipitation is total annual and it is measured in meters. In panel A, the MEs are in mg/L and they are calculated using specification C8 of the panel fixed-effect (FE) regressions in table 9.3. In panels B–E, the MEs are also in mg/L and they are calculated for the same specification of the panel FE regressions estimated using counties in the Mississippi River Basin, and the northern, middle, and southern states following the classification in Schlenker and Roberts (2009). For additional details, see section 9.7.

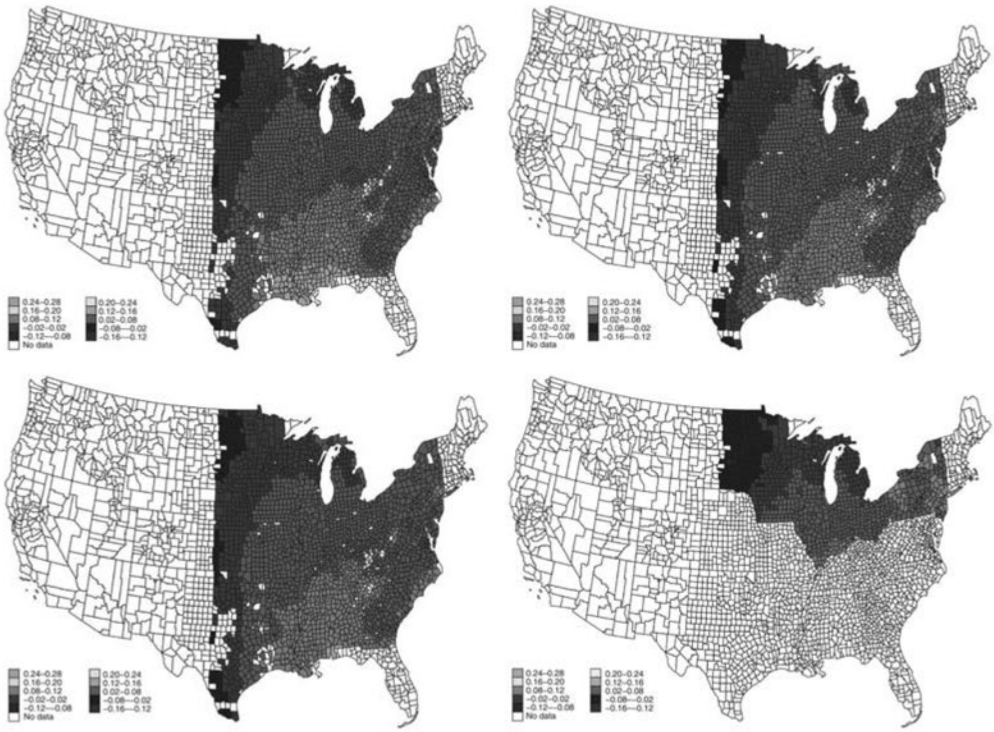
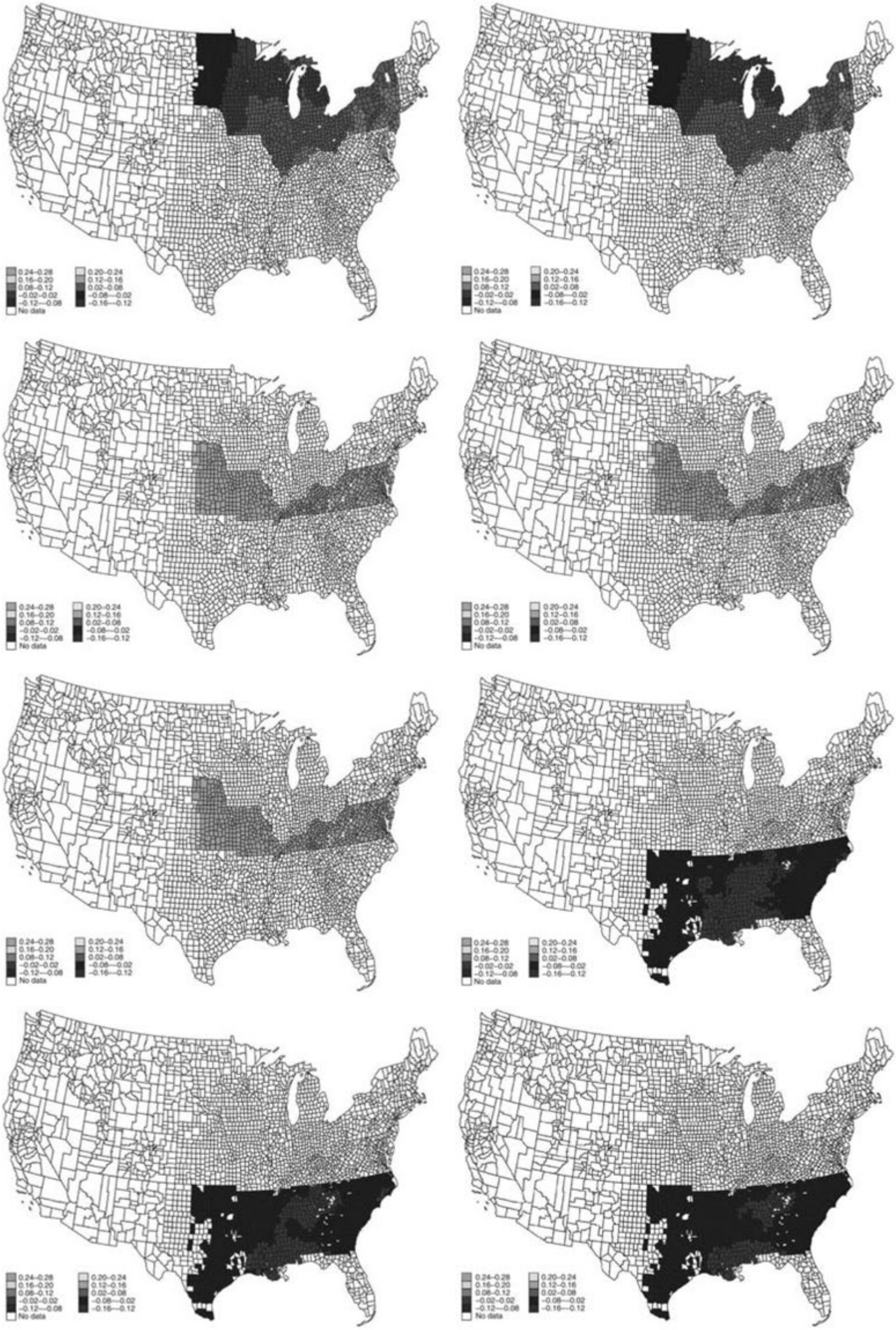


Fig. 9.5A–L Corn acreage marginal effects with GFDL-ESM4 precipitation projections

Note: Panels A–L are read from top left to bottom right. We show corn acreage marginal effects (MEs) in mg/L for specification C8 of the panel fixed-effect (FE) regressions in table 9.3. We use baseline to refer to counties east of the 100th meridian excluding Florida. We define the northern, middle, and southern states following Schlenker and Roberts (2009). For the MEs based on the historical data, we use precipitation averages for 1970–2017. For the MEs based on the projections from two SSPs of the GFDL-ESM4 climate model, we use precipitation averages for 2018–2050. The shading of the choropleth maps is based on deciles of the ME empirical distribution. For additional details, see section 9.7.

ties, the median precipitation projections are 1.233–1.298 meters implying MEs of −0.025 to −0.023 mg/L, which are also essentially identical to their historical counterpart. Similar to the middle counties, the coefficient of the interaction of corn acreage with precipitation is statistically indistinguishable from zero for the southern counties.

Figure 9.5 shows the spatial variation of the MEs when we interact corn acres with precipitation projections for the two SSPs of the GFDL-ESM4 climate model. For comparison, we also show MEs based on historical precipitation. For each county, we calculate MEs using the average precipitation for either 1970–2017 (historical) or 2018–2050 (projected) and the appropriate coefficients of the estimated panel FE regression. For the baseline counties, we see some of the largest MEs in counties in the South



0.24–0.28
0.16–0.20
0.08–0.12
−0.02–0.02
−0.12–−0.08
No data
0.20–0.24
0.12–0.16
0.02–0.08
−0.08–−0.02
−0.16–−0.12

Fig. 9.5 (cont.)

Fig. 9.6A–L Corn acreage marginal effects with GFDL-ESM4 precipitation and heat projections

Note: Panels A–L are read from left to right. We show corn acreage marginal effects (MEs) in mg/L for the panel fixed-effect (FE) regressions in which we interact corn acreage with precipitation, moderate-heat DDs, and extreme-heat DDs. In the regressions, we use the same set of weather-related controls, county fixed effects (FEs), year FEs, and county-specific trends as in column C8 in table 9.3. We use baseline to refer to counties east of the 100th meridian excluding Florida. We define the northern, middle, and southern states following Schlenker and Roberts (2009). For the MEs based on the historical data, we use precipitation, moderate-, and extreme-heat DD averages for 1970–2017. For the MEs based on the projections from two SSPs of the GFDL-ESM4 climate model, we use averages for 2018–2050. The shading of the choropleth maps is based on deciles of the ME empirical distribution. For additional details, see section 9.7.

(e.g., Louisiana, Mississippi, Alabama, Arkansas) and some of the smallest effects in the Plains (e.g., northern Texas, Oklahoma) and in the upper Midwest (e.g., Michigan, Wisconsin). We see a very similar spatial pattern in the MEs for the MRB counties. The lack of variation across the middle and southern counties is because of the coefficients on the interaction of corn acreage with precipitation being indistinguishable from zero. For the northern counties, we see negative MEs in North and South Dakota, and some of the larger positive MEs in Pennsylvania and New Jersey. The negative MEs are due to a combination of a large negative coefficient on corn acreage and very low precipitation.

Figure 9.6 shows the spatial variation of MEs when we interact corn

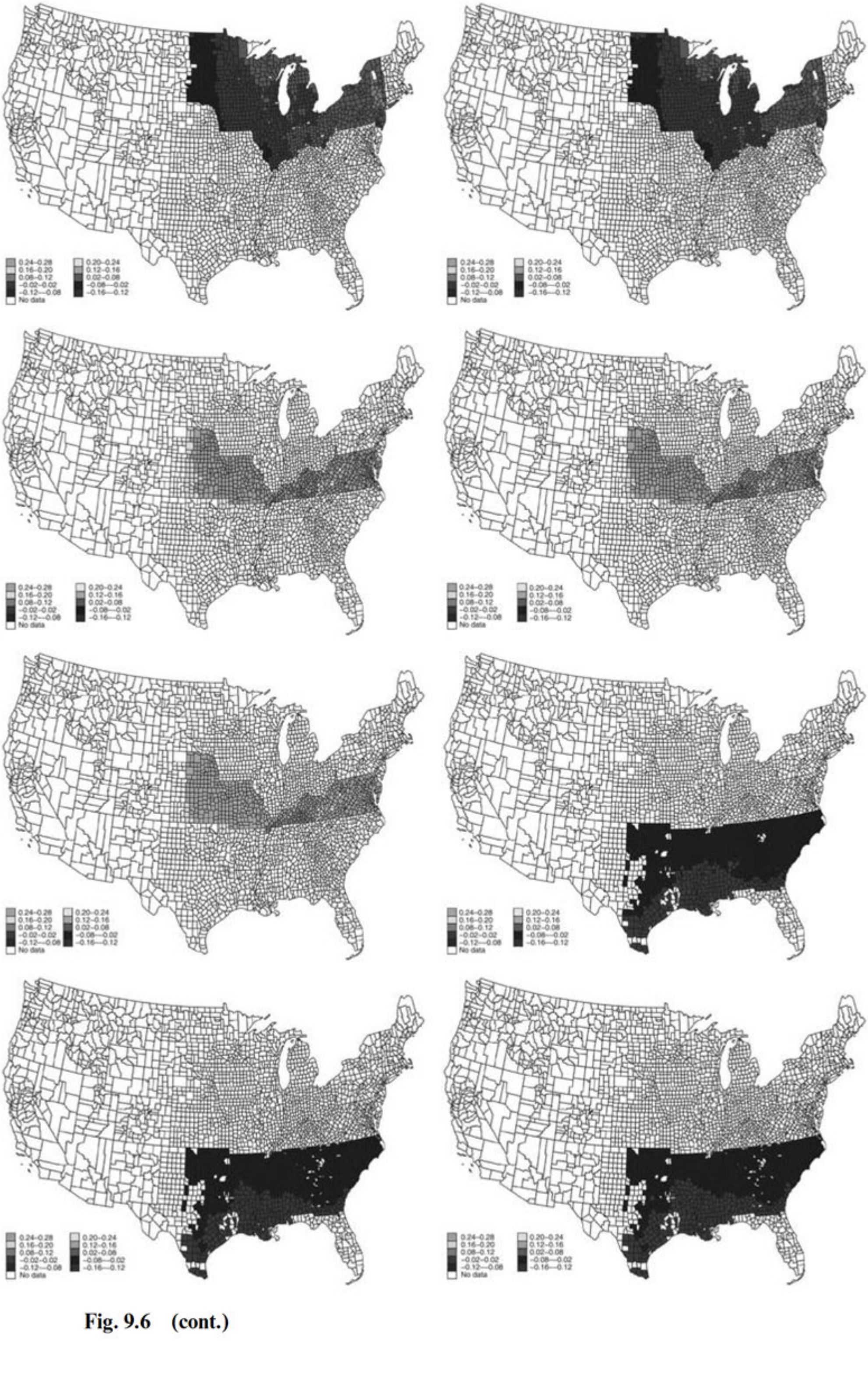

0.24–0.28
0.16–0.20
0.08–0.12
−0.02–0.02
−0.12—0.08
No data
0.20–0.24
0.12–0.16
0.02–0.08
−0.08—0.02
−0.16—0.12

Fig. 9.6 (cont.)

acres with precipitation, moderate-heat DDs, and extreme-heat DDs for the two SSPs of the GFDL-ESM4 climate model. For each county, we calculate MEs using the average precipitation, extreme-heat, and moderate heat DDs for either 1970–2017 (historical) or 2018–2050 (projected) and different panel FE regressions for each of the five sets of counties. Across the baseline set of counties, the median ME based on the historical data is 0.049. Its projections-based counterparts are 0.030 for SSP 245 and 0.027 SSP 585. All three median MEs are smaller than their counterparts based on the panel FE regression in which we interact corn acreage with precipitation only. This is especially true for the projected MEs. In terms of the spatial pattern of the MEs, we see some of the largest effects in Tennessee, and in the northern parts of Alabama and Mississippi. Some of the smallest MEs are those for counties along the 100th meridian, as well as in Georgia and South Carolina. Across the MRB counties, we also see smaller median MEs when we interact corn acres with precipitation and the DDs and more so when we use the 2018–2050 projections. The same is true for the middle and northern counties. For the southern counties, the median historical and projected MEs are negative and larger in magnitude than their counterparts based on the interaction of corn acreage with precipitation alone.

9.8 Conclusion and Policy Implications in an Era of Climate Change

We study the relationship between water nutrient pollution and US agriculture using data from 1970–2017 documenting a causal positive effect of corn acreage on nitrogen concentration in the country's water bodies east of the 100th meridian using alternative empirical approaches. According to our baseline estimates, a 10 percent increase in corn acreage increases nitrogen concentration in water by up to 1 percent. Annual precipitation plays an important role in the magnitude of the estimated effects with higher precipitation exacerbating the acreage effect on nitrogen concentration. Temperature also matters for the magnitude of the acreage effect. An increase in moderate-heat degree leads to smaller effects due to its beneficial effect on the crop nutrient uptake. Extreme-heat degree days do not seem to matter for the magnitude of the effect. The 1 percent 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 damages of about $16 per ton of nitrogen implies an annual external cost of $800 million.

Our estimated effect of additional corn acres on measured nitrogen in waterways is an order of magnitude smaller than agronomic estimates of excess nitrogen applied to those acres assuming edge-of-field losses translate to an equivalent nitrogen loading to streams and rivers. Our findings regarding the magnitude of the effect are consistent with a new line of research showing that large amounts of nitrogen stored in subsurface soil and groundwater give rise to the so-called legacy nitrogen, which may contribute to loadings in rivers and streams with a long delay, a topic we explore in more detail in Metaxoglou and Smith (2022).

Given the role of precipitation and temperature on the magnitude of the estimated effect of corn acreage on nitrogen concentration, we explore the implications of climate change for our findings. We use the NASA Earth Exchange Global Daily Downscaled Projections data set to obtain precipitation and temperature projections for 2018–2050, which we translate to projections of marginal effects of corn acreage on nitrogen concentration. The marginal effects based on precipitation projections from the NASA GFDL-ESM4 climate model and two shared socioeconomic pathways are very similar in magnitude to their counterparts calculated using historical data. The marginal effects based on temperature projections are slightly smaller than those using historical data. These estimated effects do not account for the impacts of climate change on acreage, nitrogen fertilizer use, legacy nitrogen, runoff, and streamflow, all of which contribute to nutrient pollution.

Based on recent work identifying wetlands as a powerful weapon in the war against nutrient pollution, especially due to their efficacy in also removing legacy nitrogen, we ought to emphasize their vulnerability to changes in landscapes and weather patterns impacted by climate change. Increased flooding, drought spells, extreme heat, and frequency of severe storms due to climate change all can negatively affect wetlands (Salimi, Almuktar, and Scholz 2021). Taking into consideration other ecosystem services that wetlands also provide, such as absorbing floodwaters, providing habitat for wildlife, and acting as net carbon sinks, adds to the case for policy discussion of these issues, especially in the light of recent developments in redefining the *Waters of the United States* that are protected by the Clean Water Act.

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