Agriculture's Nitrogen Legacy

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Nutrient pollution is costly and challenging

- 41% of US streams and rivers are in **poor condition** due to high nitrogen levels

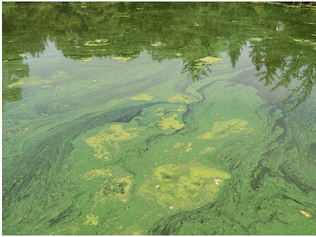
- **Excess fertilizer** from agriculture a major cause

  - plants use a fraction of applied nitrogen; excess leaches into waterways

  - other causes include animal manure and municipal sewage effluent

- What is the effect of cropland agriculture on nitrogen pollution?
  - most previous studies use hydrological models

  - we use panel data econometric methods



The story of this paper

1. Contemporaneous effect of US corn acreage on nitrogen pollution in waterways an order of magnitude smaller than implied by standard models

2. Models may be right about magnitude, but are wrong about timing
   - Over decades, large quantities of surplus nitrogen have accumulated in subsurface soil and groundwater and will enter waterways eventually

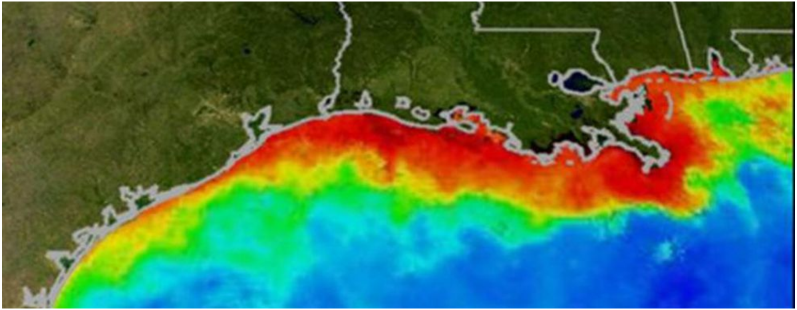
3. Presence of legacy nitrogen increases the efficacy of downstream policies relative to on-farm policies
   - Fluvial wetlands will do more than land retirement or buffer strips

Why is nutrient pollution a problem?

- High nutrient levels cause rapid algae growth
  - algae produce toxins that cause stomach aches, rashes, etc
  - algal blooms reduce recreation value e.g., fishing, boating
  - bacteria that decompose dead algae consume oxygen that fish and other aquatic organisms need to survive

- Excess nitrogen in drinking water is dangerous to infants

- The Gulf "dead zone" has averaged the size of Connecticut in the past 5 years ($\approx 5{,}400$ sq.mi.)



Why do we focus on corn?

- More acres are planted to corn than any other crop
- Farmers use much more nitrogen per acre on corn than other major crops
- Soybeans are the number two crop, but most soybean fields were corn last year and will be corn next year
- We find that, conditional on corn acres, other crops do not affect nitrogen concentration

Commodity	Acres (million)	Acres Receiving Nitrogen (percent)	Ave. Application Rate (lb per fertilized acre)
Corn	93	98	149
Cotton	11	78	94
Soybeans	87	29	17
Wheat	47	88	78

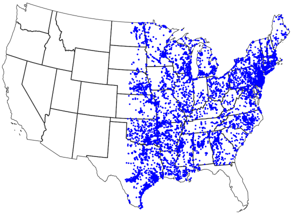
Model Estimates of Surplus Nitrogen

- USDA NRCS (2017) estimate average nitrogen losses 34 lb/acre/year
  - Use daily weather data, plus data on cropping patterns, farming activities, and conservation practices from NRI-CEAP Cropland Survey for 2003-06.
  - About 30% of nitrogen in fertilizer lost
- van Meter et al (2017) estimates average nitrogen losses in Mississippi River Basin of 57 lb/acre/year for 1990-2014.
- Hendricks et al. (2014) estimate 25 lb/acre/year edge of field nitrogen loss for corn grown after soybeans were grown the previous year
  - Use SWAT model for IA, IL, and IN in 2009
  - 35 lb/acre/year nitrogen loss for corn grown after corn

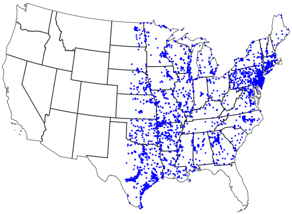
Data

- **Nitrogen concentration (mg/L)**
  - Annual average at the monitoring-site level
  - Source: USGS Water Quality Portal (40K monitoring sites, 720K obs.)
- **Corn acres planted (millions)**
  - Annual, county level
  - Source: USDA
- **Weather (Jan-Dec)**
  - Precipitation total (meters)
  - Moderate heat (ddays 10-29°C)
  - Extreme heat (ddays exceeding 29°C)
  - Source: PRISM (Wolfram Schlenker)
- **Time: 1970–2017**
- Focus on eastern US (east of 100th meridian, excl. FL)

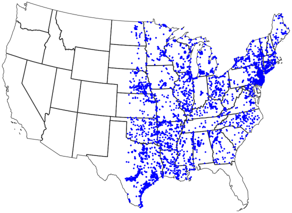
Locations of USGS Monitoring Sites



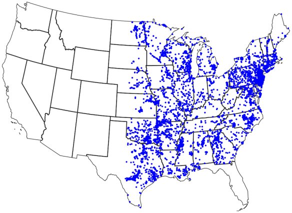
A. ≥ 1 YR (9,174)



B. ≥ 5 YRS (3,080)

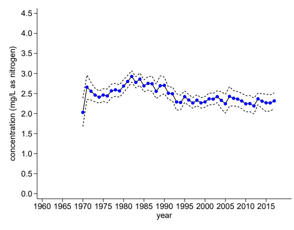


C. ≥ 1 YR, 1970–1989 (5,226)

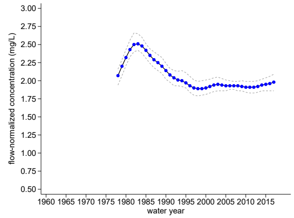


D. ≥ 1 YR, 1990–2017 (5,763)

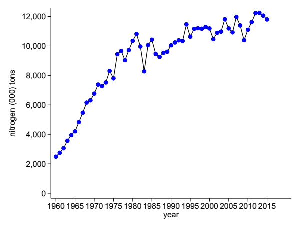
Nitrogen pollution flat since 1990



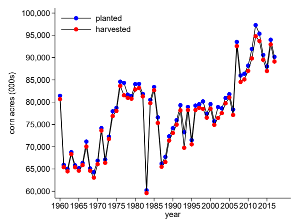
A. nitrogen concentration



B. flow-normalized conc.

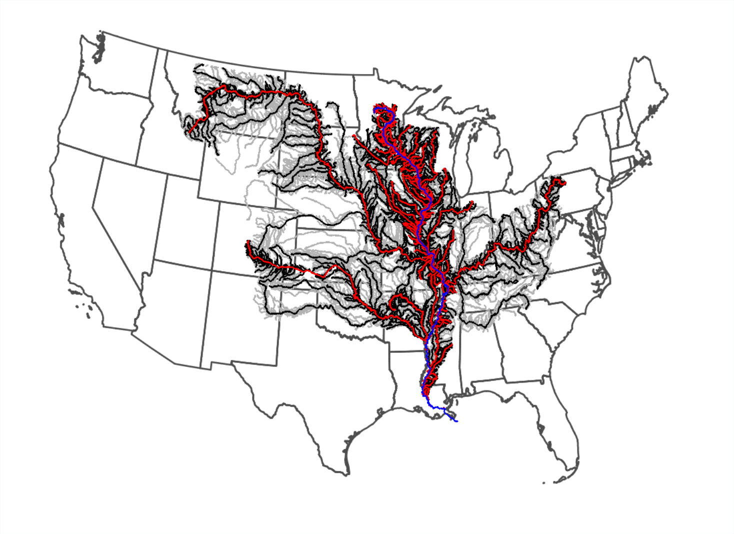


C. nitrogen fertilizer use



D. corn acres

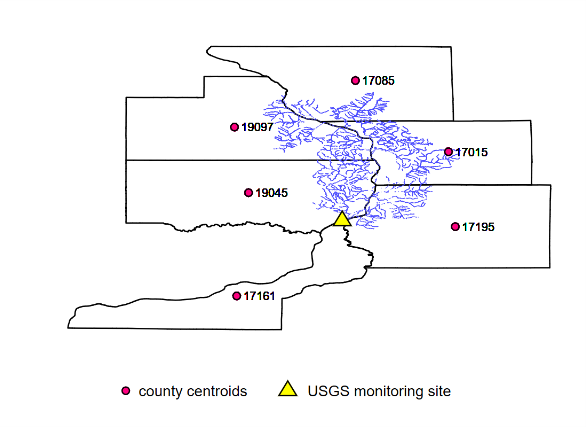
Stream flow in the Mississippi River Basin



- Focus on Stream Level 4 (gray)
- Four Levels: gray → black → red → blue

Monitor as unit of observation in regressions

- For each monitor, compute planted corn acres and precipitation in counties that have at least some area within 50 miles upstream of monitor
- Compute distance as the stream flows
- Also try other distance increments



Empirical Approach: Panel FE regressions

- Panel FE regressions estimated using OLS

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

- Interact acreage with precipitation

- Notation
  - i denotes the monitor and t denotes the year
  - a_{it} = acres planted in counties less than 50 miles upstream of monitor i
  - p_{it} = precipitation
  - y_{it} = nitrogen concentration
  - $\mathbf{z}_{it}$ = precipitation, sq. precipitation, moderate heat, and extreme heat
  - $g_i(t)$ = alternative functions of time

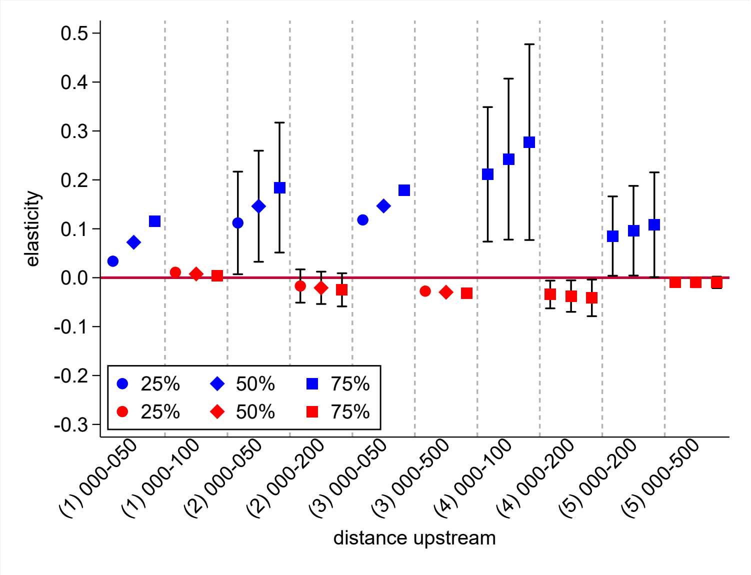
Regression Results

	(C1)	(C2)	(C3)	(C4)	(C5)	(C6)	(C7)	(C8)
acres	-1.794	-5.421*	-5.234*	-4.423	-3.936*	-3.256	-2.295	-1.588
	(6.079)	(2.937)	(2.907)	(2.747)	(2.289)	(2.263)	(2.144)	(2.044)
acres × prec	7.987	6.351**	6.357**	6.281**	6.063**	5.886**	5.439**	5.363**
	(6.141)	(2.589)	(2.590)	(2.592)	(2.555)	(2.524)	(2.623)	(2.649)
$\overline{R}^2$	0.13	0.80	0.80	0.80	0.80	0.80	0.82	0.82
Obs.	9,042	9,042	9,042	9,042	9,042	9,042	9,042	9,042
Clusters	114	114	114	114	114	114	114	114
elast 25 est.	0.131***	0.005	0.010	0.029	0.036	0.049*	0.063**	0.079**
elast 50 est.	0.167***	0.034*	0.039*	0.057**	0.063**	0.075**	0.087***	0.103***
elast 75 est.	0.208***	0.066*	0.071*	0.089**	0.094**	0.105**	0.115***	0.130***
monitor FE		✓	✓	✓	✓	✓	✓	✓
trend			✓					
year FE				✓		✓		✓
state × trend					✓	✓		
county × trend							✓	✓

- Elasticities evaluated at mean of acres and concentration, and 25^{th}, 50^{th}, and 75^{th} percentiles of precipitation.

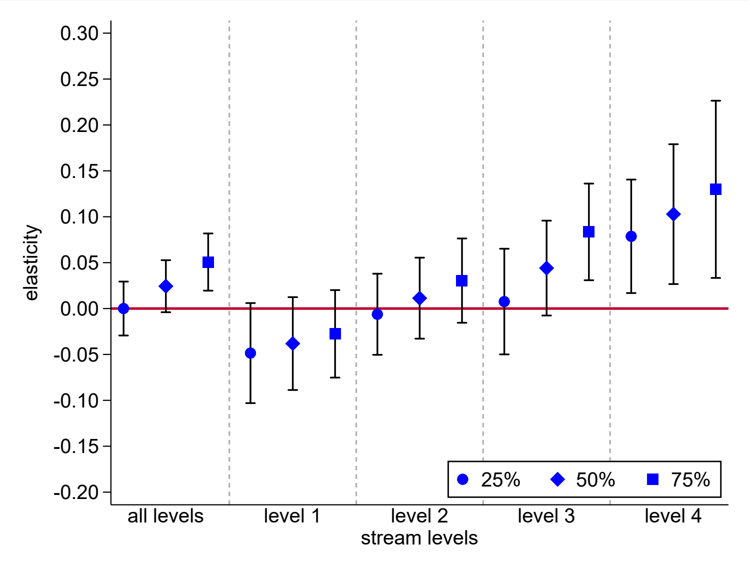
$$y_{it} = \delta_i + \beta_1 a_{it} + \beta_2 a_{it} p_{it} + \mathbf{z'}_{it}\gamma + g_i(t) + \varepsilon_{it}$$

Corn acres insignificant beyond 50-mile counties



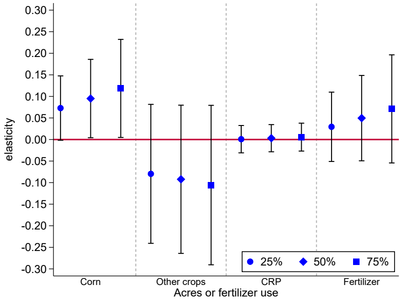
- 5 separate regressions, each with a blue and a red acreage variable

Elasticities largest for small streams

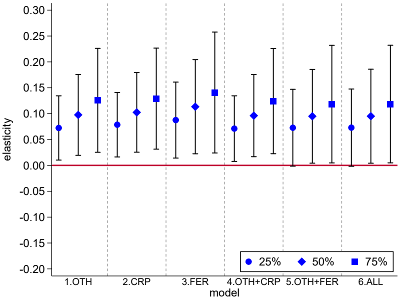


- 5 separate regressions, one for each level

Other land use and fertilizer sales insignificant



A. Various Elasticities: Single Regression



B. Corn Elasticity: Various Controls

- CRP is conservation reserve program
- Fertilizer data is annual sales by county (Source: USGS)

Estimates are robust to ...

- **Nitrogen take-up**: yield, moderate and extreme heat
- **Geographic scope**: entire US; USGS+EPA monitors
- **Controls for alternate nitrogen sources**: fossil-fuel combustion, animal manure, atmospheric deposition, point sources, economic activity
- **Controls for agricultural practices**: conservation, tillage, drainage
- **Specification**: flexible precipitation interaction (spline rather than linear), censoring outliers, alternate data filters, clustering
- **Season** (effects somewhat larger in summer)

Summary of Empirical Findings

- Our estimates imply 1.88, 2.45, and 3.09 lb/acre/year of additional nitrogen in small streams (level 4) from corn grown less than 50 miles upstream at the 25^{th}, 25^{th}, and 25^{th} percentiles of the rainfall distribution.

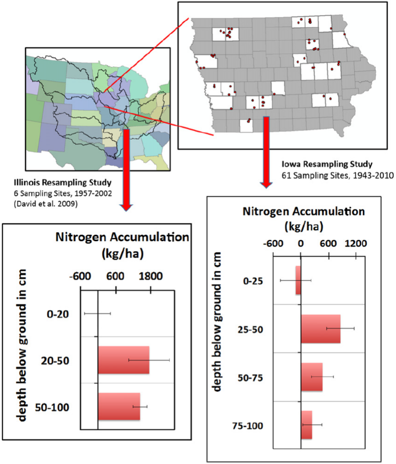
- Much smaller than estimated 34 lb/acre/year of surplus

- Corn within 50 miles of monitor matters most
  - conditional on corn acres, CRP, fertilizer sales, or other crops have no effect on nitrogen concentration
  - suggests farmers tend to over-apply nitrogen to corn more than other crops

- Elasticities about four times larger in small streams (level 4) than on average across all monitors
  - negligible effects in major rivers (levels 1 and 2), even when we look 500 miles upstream — perhaps not enough variation to identify well

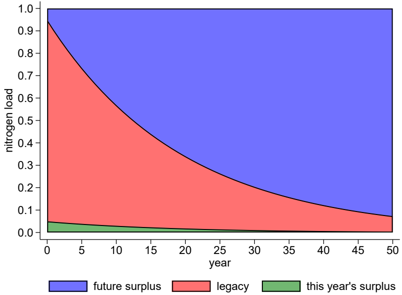
Legacy

- 22-62 lb/acre/year accumulation over ≈ 50 years
- **biogeochemical legacy:** organic nitrogen in root zone
    - *delayed mineralization*
- **hydrologic legacy:** dissolved nitrates in unsaturated soils or groundwater
    - *travel time delay*
- van Meter et al (Science, 2018) estimate 30 years to reach new steady state nitrogen load in rivers under zero surplus

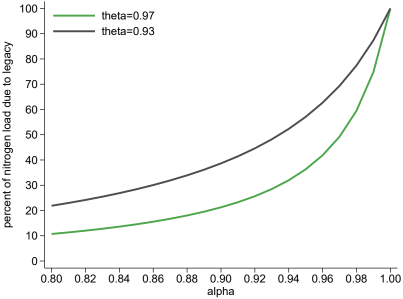


Source: van Meter et al (ERL, 2017)

Stylized model of legacy nitrogen



A. Sources of annual nitrogen load



B. Percent of damages due to legacy

- Van Meter et al. (2017) model implies exponential decay in the effect of an increase in soil nitrogen on future nitrogen load in a river downstream
  - Let α be that parameter
- Panel A sets $\alpha = 0.95$
- Panel B evaluates present value of future N load using discount rate of θ

Policy Implications

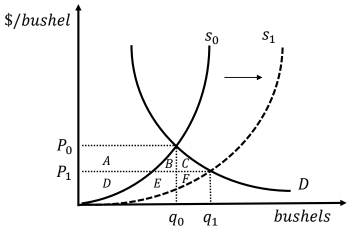
- Nitrogen pollution from agriculture largely exempt from Clean Water Act
  - Billions have been spent on state and federal voluntary programs

- On-farm mitigation
  - **Land retirement**
    - *Hard to retire just corn land*
    - *Lost production value far exceeds damage estimates*
    - *No mitigation of legacy nitrogen*
  - **Fertilizer tax**
    - *Ideally assess tax only on surplus nitrogen*
    - *Damage estimates imply tax that would triple cost of fertilizing corn*
    - *No mitigation of legacy nitrogen*
  - **Riparian buffers**
    - *See land retirement*

- Downstream mitigation
  - **Fluvial wetlands**
    - *Mitigates legacy nitrogen—a "fast-track solution"*
    - *Cheng et al. (Nature, 2020) and Hansen et al. (PNAS, 2021) estimate that targeted fluvial wetlands are most cost effective mitigation*

Land Retirement

- At 2014-16 prices, removing 1% of corn land implies revenue loss of $\$609$ per acre
  - but this would raise prices
- Small demand ($\eta_d = -0.30$) and supply ($\eta_s = 0.20$) elasticities imply an increase in producer surplus and decrease in consumer surplus
  - welfare loss of $\$509$ per retired acre
- Regressions imply nitrogen pollution reduction of 2.45 lb/acre, or $\$19.28$ per acre using Sobota et al. (2015) damage estimates.
  - long-term benefit may be 10-15 times larger because of delayed leaching



Conclusion

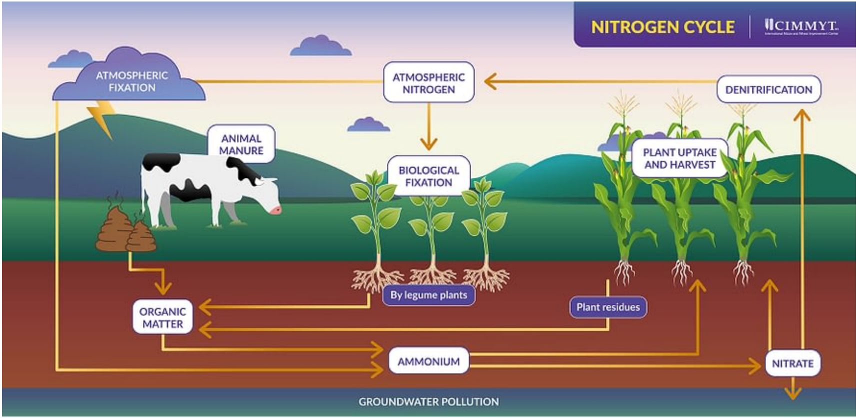
- Growing corn has a much smaller contemporaneous effect on nitrogen concentration than predicted by previous models.
- Consistent with massive accumulation of legacy nitrogen
- Results increase relative efficacy of downstream policies
- Is it possible the N_2O emissions are larger than thought?
    - would imply less legacy and more GHG
- Technologies to improve efficiency of nitrogen delivery important in future

Damage Estimates

Source	Damages	Additional information
Taylor and Heal (2021)	\$583	U.S., per ton of nitrogen applied
Sobota et al. (2015)	\$15,840	U.S., per ton of nitrogen in water
Van Grinsven et al. (2013a)	\$13,338–\$53,351	E.U., per ton of nitrogen in water
Compton et al. (2011)	\$56,000	GoM fisheries decline, per ton of N in water
Compton et al. (2011)	\$6,380	CB recreational use, per ton of N in water
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

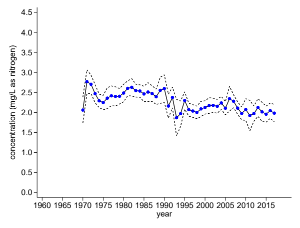
"CB" is Chesapeake Bay and "GoM" is Gulf of Mexico.

The Nitrogen Cycle

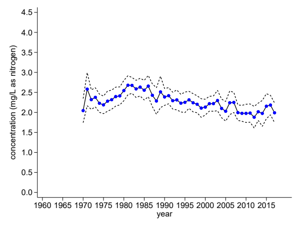


- Source: Nancy Valtierra/CIMMYT

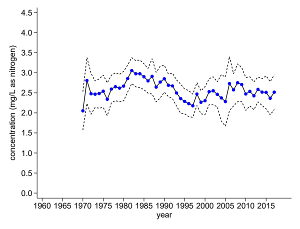
Nitrogen trends, by stream level



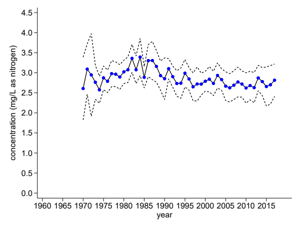
A. stream level 1



B. stream level 2

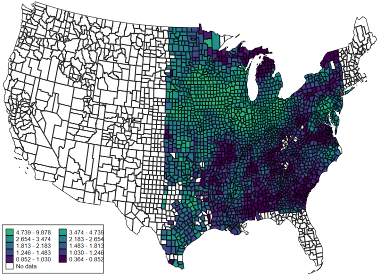


C. stream level 3

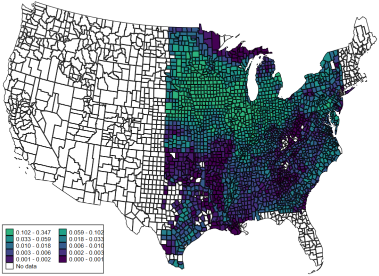


D. stream level 4

Nitrogen Concentration is Highest in the Cornbelt



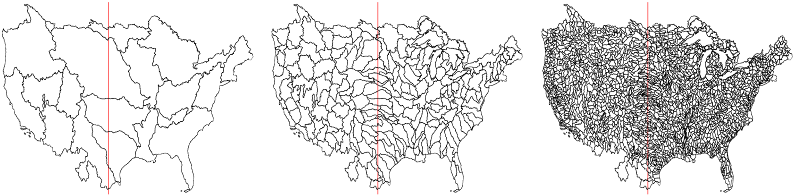
A. nitrogen concentration (mg/L)



B. corn acres planted (millions)

- Maps show county averages over 1970-2017

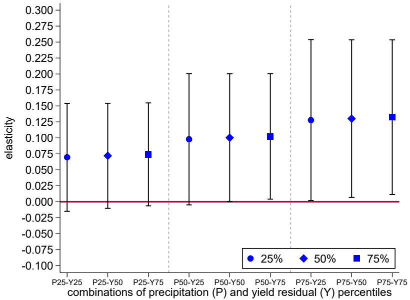
Hydrologic Regions



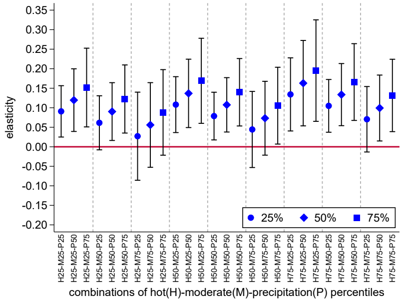
A. HUC2 (region) B. HUC4 (subregion) C. HUC8 (subbasin)

- We cluster standard errors by HUC4
- Average HUC4 is $15{,}831$ sq. mi.
- Average county east of 100th meridian is 611 sq. mi.

Interacting acres with proxy for nitrogen takeup



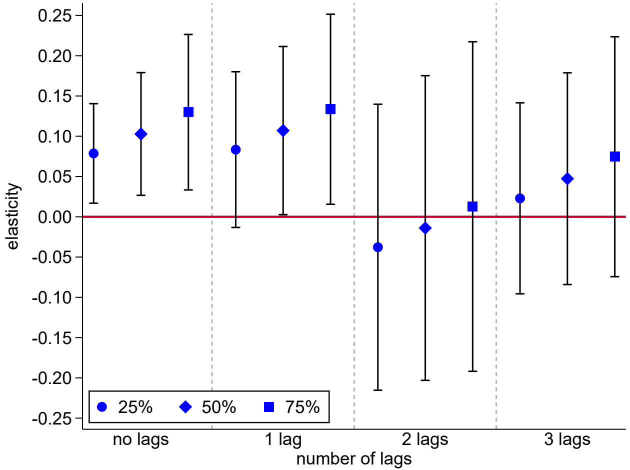
A. Yield shocks



B. Moderate and Extreme Heat

- A: interact corn acres with precipitation and within-county yield deviations from trend
- B: interact corn acres with precipitation, moderate heat ($10 - 29$ dday), and extreme heat (> 29dday)

Nothing statistically significant beyond one-year lag



- Different regression for each lag length.
- Use average acres, e.g., for 2 lags, we use the average of years t, $t-1$, and $t-2$.