Integrated Assessment of Nitrogen Runoff to the Gulf of Mexico: An Application of Spatially Explicit Partial Equilibrium and HAWQS Models

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April 22, 2021

Outline

1. Introduction
2. Methodology and data
3. Results
4. Discussion
5. Conclusion

Motivation

- Mississippi River Basin (MRB)
  - 70% of US cropland
  - Nitrogen (N) and phosphorus (P) fertilizer use in agricultural production
    - Large amounts of nutrient runoff to the Gulf of Mexico
    - The main factor of the Hypoxia (low oxygen)

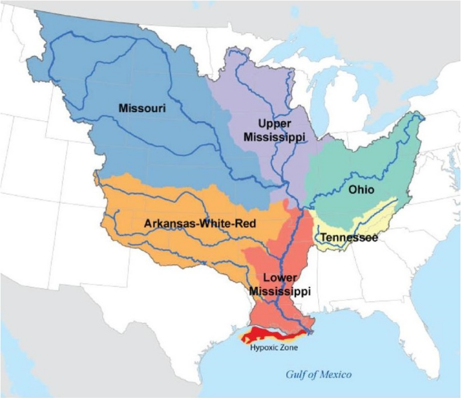

Figure: the MRB (Source: USDA ERS)

Motivation- Continued

- Hypoxia in the Gulf of Mexico
  - Lead to eutrophication and harmful to aquatic ecosystems
  - US EPA initially set up the Hypoxia Task Force in 2001 and updated it in 2008, which aims to reduce the size to 5,000 km^2 by 2035
    - corresponds to a 45% N reduction set in 2008 Action Plan
  - The size of the “dead zone” reached 18,005 km^2 in 2019

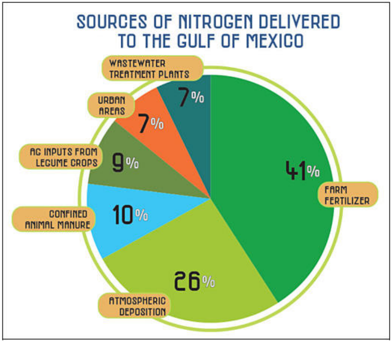

Figure: Sources of N delivered to the Gulf of Mexico (Source: USGS, 2017)

Motivation- Continued

Related Literature

- Previous studies identified that the Upper MRB and Ohio-Tennessee River Basin are critical area.
    - Investigated the nexus of the size of Hypoxia and the magnitude of N export to the Gulf
        - (Alexander et al., 2008; Robertson and Saad, 2014; White et al., 2014)
    - Provided cost-effective strategies to reduce nutrient losses from cropland in the MRB
        - (Ribaudo et al., 2001; Kling et al., 2014; Rabotyagov et al., 2014; Marshall et al., 2018)

Motivation- Continued

- Recent reduction in energy and N fertilizer prices
  - Influence farmer's crop planting decision at both intensive and extensive margins (Pfeiffer and Lin, 2014)
  - Affect the cost-efficiency of existing strategies

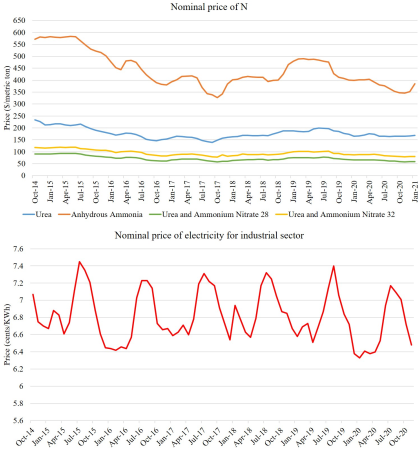

Figure: N and energy prices

Research questions

- It is important to understand how variations in prices of energy and N fertilizers affect
  - Farmers' crop acreage and N application decisions
  - Water quality in the Gulf of Mexico
- Research questions:
  - How is N runoff in the Gulf of Mexico affected by lower energy and N fertilizer prices?
  - Given low energy and N fertilizer prices, what is the opportunity cost to achieve the goal of Hypoxia Task Force.

Contribution

- An integrated hydro-economic model
  - Spatially explicit at the county level
    - Provide more detailed information for policy analysis
  - Endogenous fertilizer application rates and water use
    - Enable the model to estimate economic and environmental outcomes under various policy and price scenarios

An integrated hydro-economic model

- The economic model:
  - A price endogenous partial equilibrium (PE) model for the contiguous United States
- The hydrological model:
  - Hydrologic and Water Quality System (HAWQS) for the MRB
    - a calibrated web-based platform that uses Soil and Water Assessment Tool (SWAT) to assess water quantity and quality

The PE model

- The objective function maximizes the sum of consumer and producer surplus:

$$max_{X,L,\tau,\gamma} \sum \int_{0}^{X_c^d} P_c^d \left(X_c^d, \omega_c\right) dX_c^d - \sum_{c,i,n,w} tc_{ci} * L_{cinw} - \sum_{c,i,n,w} ec_{ci} * L_{cinw} - \sum_{c,i} FC_{ci} - \sum_{c,i} WC_{ci}. \quad (1)$$

- $P_c^d\left(X_c^d, \omega_c\right)$: inverse demand function
- X_c^d: the aggregate demand of crop c
- L_{cinw}: the acreage for crop c in county i, with n kg/ha N fertilizer and w water use
- tc_{ci}: per ha total production cost, excluding energy, fertilizer and water costs for crop c in county i
- ec_{ci}: per ha energy cost for crop c in county i
- FC_{ci}: total N fertilizer costs for crop c in county i
- WC_{ci}: total water costs for crop c in county i

The PE model- Continued

- Subject to:
- Balance equation:

$$X_c^d + exports \leq X_{ci}^s + imports \; \forall c \quad (2)$$

- Supply constraint:

$$\sum_{n,w} y_{cinw} * L_{cinw} \geq X_{ci}^s \; \forall c, i \quad (3)$$

- Crop mix constraint (Chen and Onal, 2012):

$$L_{ci} = \sum_{n,w} L_{cinw} = \sum_{m} \tau_{mi} * H_{cim} + \sum_{n} \gamma_{vi} * S_{civ} \; \forall c, i \quad (4)$$

- Convexity constraint:

$$\sum_{m} \tau_{mi} + \sum_{n} \gamma_{vi} = 1 \; \forall i \quad (5)$$

- y_{cinw}: per ha yield with n kg N fertilizer and w water use for crop c in county i
- H_{cim}: m-th county-specific historical crop acreages
- S_{civ}: v-th county-specific synthetic crop acreages
- τ_{mi} and γ_{vi}: weights determined endogenously

The PE model- Continued

- Fertilizer costs:

$$FC_{ci} = \sum_{n,w} \theta_{cin} * L_{cinw} \ \forall c, i \tag{6}$$

- Irrigation costs:

$$WC_{ci} = \sum_{n,w} \mu_{ciw} * L_{cinw} \ \forall c, i \tag{7}$$

- Total N delivered to the Gulf of Mexico:

$$TN = \sum_{i}^{I} (dr_i * \sum_{c,n,w} nrf_{cinw} * L_{cinw}) \tag{8}$$

- θ_{cin}: the per ha cost of N fertilizer corresponding to each fertilizer application level n for crop c in county i
- μ_{ciw}: the per ha water cost for crop c in county i
- dr_i: county specific N delivery ratio to the Gulf of Mexico
- nrf_{cinw} : per ha N runoff level for crop c in county i with n kg N fertilizer and w water use

Data for the PE model

- The baseline year is 2018
- Corn, soybean, wheat and sorghum
- Demand
  - Crop demand elasticities from literature and observed prices and quantities in 2018 from USDA NASS
- Supply
  - county-specific historical crop mixes from 2005 to 2019 obtained from USDA NASS
  - county-specific cost data in 2018 obtained from USDA ERS

HAWQS

- Hydrologic and Water Quality System (HAWQS)
  - A calibrated web-based SWAT
  - Estimate crop yields and N loading given various N fertilizer level and optimal irrigation for crops
  - Spatial unit: an eight-digit watershed (HUC8)
  - from 2000 to 2018
- Data: feed HUC8-level outputs to the county-specific PE model
  - HUC8-level outputs from HAWQS are converted into county-level by the weighted averages based on the % of each HUC8's area within the county

Model validation and baseline results- crop markets

	Validation results (historical mixes only)	Observed in 2018	Baseline results (historical and synthetic mixes)
	Land uses (million hectares for the contiguous United States)		
Corn	38.4	36.0	38.2
Soybean	37.8	36.1	37.2
Wheat	18.1	19.3	16.5
Sorghum	2.3	2.3	2.4
	Price ($/ metric ton)		
Corn	142.8	142	143.5
Soybean	312.2	314	320.0
Wheat	187.3	190	198.7
Sorghum	118.5	117	110.8

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Model validation and baseline results- N runoff and water use

	Validation results (historical mixes only)	Values from literature	Baseline results (historical and synthetic mixes)
N applied within the MRB (1,000 metric ton)	9,300 (MRB)	12,610 (national)	8,988 (MRB)
Total irrigation water use (million acre-feet)	21.9 (MRB)	83.4 (national)	21.4 (MRB)
N delivered to the Gulf from legume crops and N fertilizer application (metric ton)	461,010 (MRB)	796,000 (agriculture in the MRB)[ab]	455,570 (MRB)

[a]Source: White et al., 2014

[b]N fertilizer use from agriculture accounts for 68% of N delivered to the Gulf of Mexico from agriculture. The rest of N exported to the Gulf from agriculture comes from confined animal manure and agricultural inputs from legume crops (USGS, 2017).

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Changes in direct energy prices

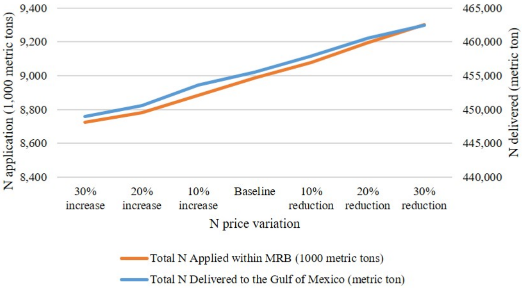
- Direct energy input costs in this analysis include “fuel, lubrication and electricity” related costs as defined by the USDA ERS.

Direct energy cost ($/ha)	15% increase	10%	5%	Baseline	5% reduction	10%	15%
Corn (million ha)	38.0	38.1	38.1	38.2	38.2	38.3	38.3
Soybean (million ha)	37.1	37.2	37.2	37.2	37.3	37.3	37.3
Wheat (million ha)	16.4	16.4	16.4	16.5	16.5	16.5	16.5
Sorghum (million ha)	2.4	2.4	2.4	2.4	2.5	2.5	2.5
N applied within MRB (1000 metric tons)	8,979	8,979	8,979	8,988	8,997	8,996	8,998
N Delivered to the Gulf of Mexico (metric ton)	455,410	455,460	455,480	455,570	455,660	455,690	455,730

- Direct energy costs represent a small portion of total operating costs, which accounts for 10.33%, 6.83%, 7.49% and 9.82% of total operating costs of corn, soybean, wheat and sorghum respectively.

Changes in N fertilizer prices

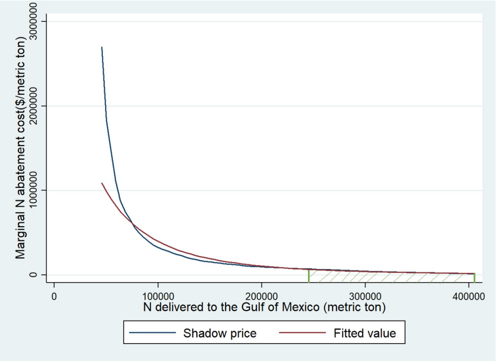
Figure: Total N applied within the MRB and total N delivered to the Gulf of Mexico given various levels of N fertilizer costs



Performance-based N reduction costs

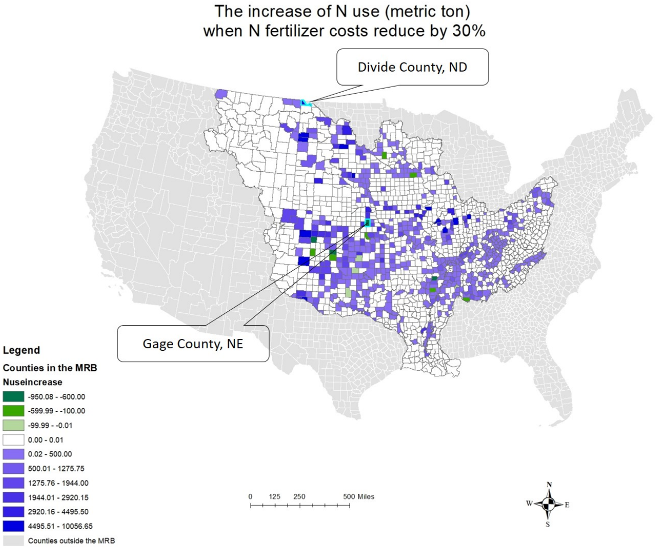
- Constrain aggregate N runoff in the Gulf of Mexico to estimate the marginal abatement cost of N loading in the Gulf iteratively
- A 45% reduction in the N load corresponds to the Hypoxia target according to the revised task force action plan in 2008
  - the abatement costs through N fertilizer use reduction and crop acreage changes is $6 billion; the average cost for N reduction is $29.3 per kg

Figure: N demand curve

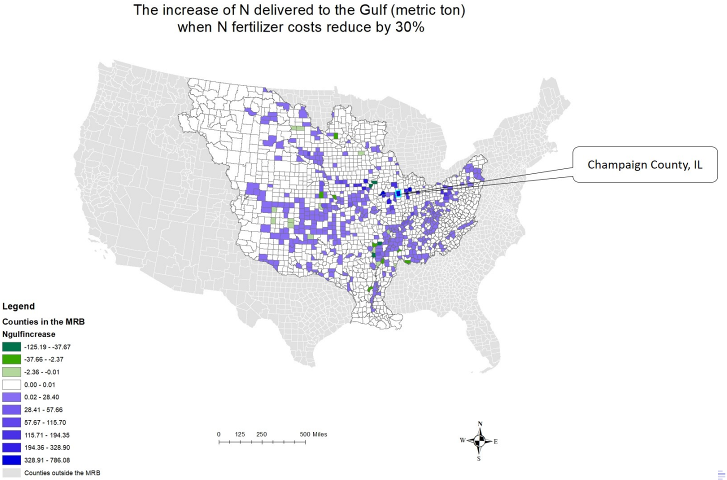


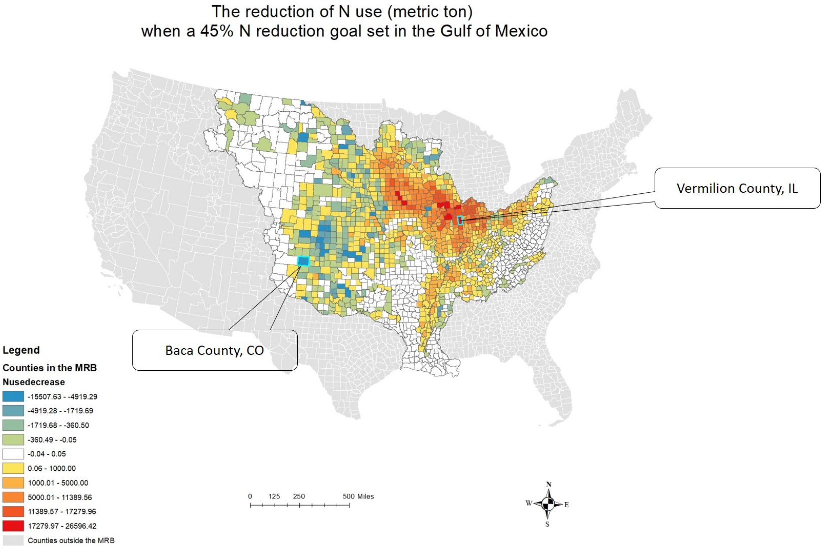
Spatial distribution of N use and runoff

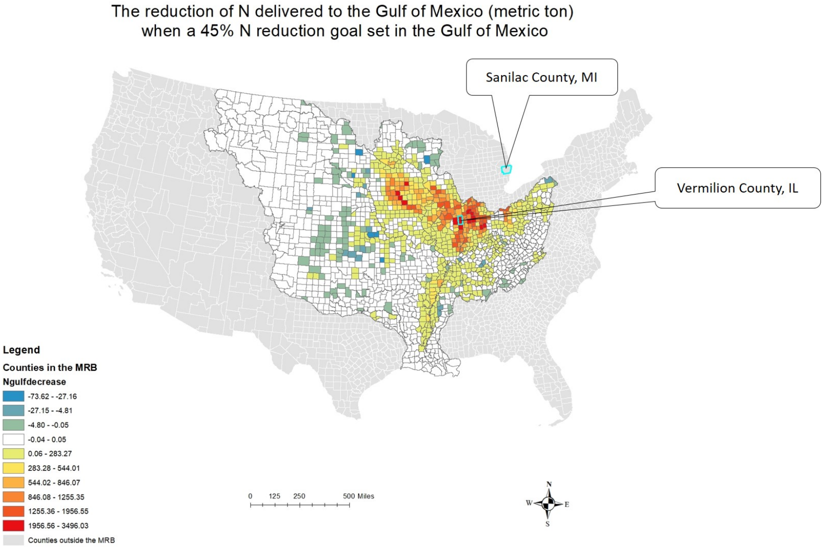
- Two scenarios
  - N fertilizer cost reduces by 30%
  - A 45% N runoff reduction goal set in the Gulf of Mexico given low energy and N fertilizer prices in 2018
- Two indicators are considered for both scenarios
  - county-specific N use
  - county-specific N delivered to the Gulf


The increase of N use (metric ton)
when N fertilizer costs reduce by 30%
Divide County, ND
Gage County, NE
Legend
Counties in the MRB
Nuseincrease
-950.08 - -600.00
-599.99 - -100.00
-99.99 - -0.01
0.00 - 0.01
0.02 - 500.00
500.01 - 1275.75
1275.76 - 1944.00
1944.01 - 2920.15
2920.16 - 4495.50
4495.51 - 10056.65
Counties outside the MRB
0 125 250 500 Miles
N
W
E
S

- Counties located in Illinois, Indiana and Iowa contribute 74% of total increased N runoff to the Gulf
  - Total increased N delivered: 6,922 metric ton; increased N delivered from IL, IN and IA: 5,090 metric ton.




The reduction of N use (metric ton)
when a 45% N reduction goal set in the Gulf of Mexico
Vermilion County, IL
Baca County, CO
Legend
Counties in the MRB
Nusedecrease
-15507.63 - -4919.29
-4919.28 - -1719.69
-1719.68 - -360.50
-360.49 - -0.05
-0.04 - 0.05
0.06 - 1000.00
1000.01 - 5000.00
5000.01 - 11389.56
11389.57 - 17279.96
17279.97 - 26596.42
Counties outside the MRB
0 125 250 500 Miles
N
W
E
S


The reduction of N delivered to the Gulf of Mexico (metric ton) when a 45% N reduction goal set in the Gulf of Mexico
Sanilac County, MI
Vermilion County, IL
Legend
Counties in the MRB
Ngulfdecrease
-73.62 - -27.16
-27.15 - -4.81
-4.80 - -0.05
-0.04 - 0.05
0.06 - 283.27
283.28 - 544.01
544.02 - 846.07
846.08 - 1255.35
1255.36 - 1956.55
1956.56 - 3496.03
Counties outside the MRB
0 125 250 500 Miles
N
W
E
S

Policy implications

- County-specific N use sensitivities to prices are heterogeneous across the MRB.
  - Counties located in Illinois, Iowa, Indiana, Kansas, North and South Dakota, show larger increase in N use
  - Counties located in the Upper Mississippi River Basin contribute most of increased N runoff to the Gulf.
- Spatial targeting based on both hydrological and economic factors are necessary to meet the goal of Hypoxia Task Force cost-effectively.
  - Upper Mississippi River Basin and Ohio-Tennessee River Basin are relatively higher in N runoff potential and export the majority of N to the Gulf.
  - N-intensive crop production shifts to Missouri River, Arkansas Red-White River Basin and counties outside the MRB.
    - Pay attention to local water quality of these regions

Limitations

- A social planner with perfect information
  - Crop production and N use are obtained based on the maximization of aggregate social welfare in the four commodity markets.
- Best Management Practices (BMPs) are not included in the model
  - Overestimate the costs of N reduction
  - BMPs investment or land use change or N use adjustment

Thank you!

Comments or Questions?