Relocation of Nutrient Runoff from Agricultural Production

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Outline

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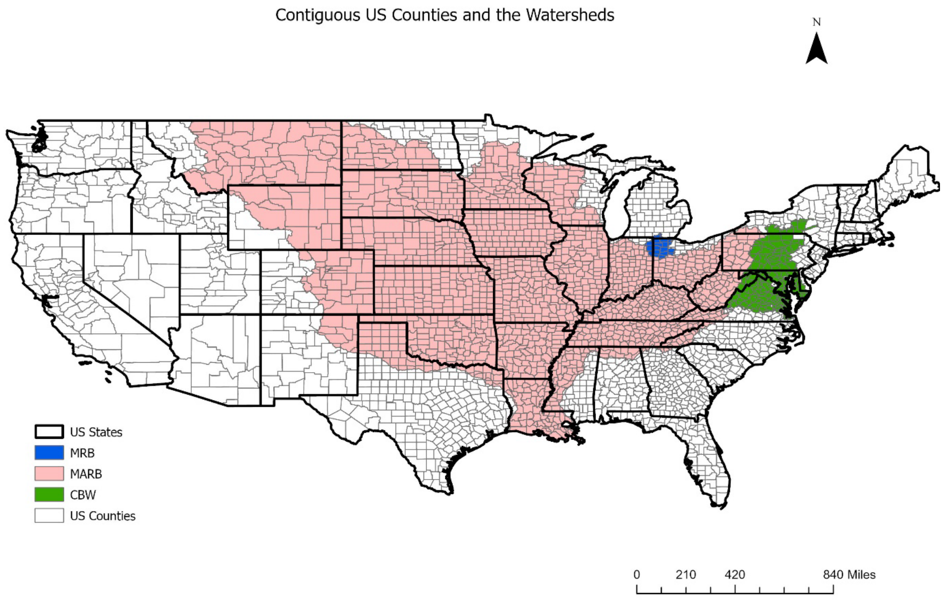
- Materials and Method
- Results
- Conclusion

Introduction

- Nitrogen (N) fertilizers for crop production contribute to eutrophication.
- Eutrophication leads to hypoxia (low oxygen) in aquatic ecosystems (Chang et al., 2021; Diaz & Rosenberg, 2008; Du et al., 2018)
  - damages marine habitats
  - disrupts the food web
  - decreases fishery catch, alters nutrient cycling, and
  - increases the acidity of the water column
- Gulf of Mexico
  - MARB covers 70% of US cropland and delivers large amounts of nutrient runoff to the Gulf of Mexico
  - a 45% N reduction set in the 2008 Action Plan by US EPA
    - to reduce the hypoxic zone to about 5,000 km^2 by 2035
    - Yet, the hypoxic zone grew to 22792km^2 in 2017 (Khanna et al. 2019)
- Chesapeake Bay
  - Total Maximum Daily Load (TMDL)
    - to reduce N, P, and sediment for each tributary draining into it
- Lake Erie
  - Major concern is the large amounts of P from agriculture runoff

Introduction Continued

- Mississippi Atchafalaya River Basin (MARB), Chesapeake Bay Watershed (CBW), and Maumee River Basin (MRB)
- Agricultural Production in the watersheds
  - a significant source of nutrient loadings in rivers, lakes, estuaries, and coastal waters
  - nonpoint source (NPS) water pollution is a public concern. The main issue is Hypoxia.

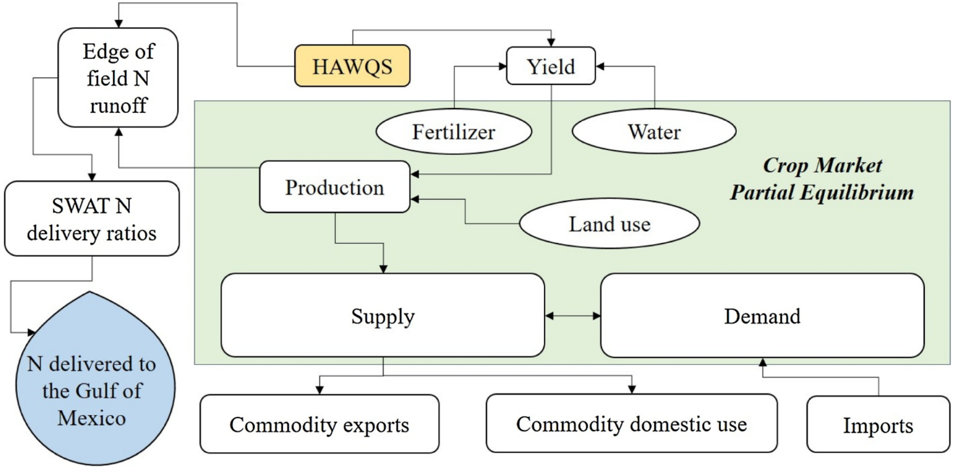


Motivation

- Nutrient runoff from agricultural production in the three watersheds has been extensively studied in isolation.
  - Cost-effective strategies to reduce nutrient losses from cropland in the MARB (Ribaudo et al., 2001; Kling et al., 2014; Rabotyagov et al., 2014; Marshall et al., 2018)
  - Reduction of controllable sources of N and P in CBW (Boesch et al., 2001; Ator et al., 2020, Bosch et al., 2018)
  - Nutrient loads from MRB, best management practices, and nutrient reduction in western Lake Erie (Kast et al., 2021; Liu et al., 2020).
- Xu et al. (2022) document a need for investigating the potential increase in N runoff to Lake Erie and other watersheds from restrictions on N runoff from MARB to the Gulf of Mexico.
  - An increase in the acreage of N-intensive crops outside of MARB when N runoff restrictions are imposed in the Gulf of Mexico.
  - Potential for runoff relocation from more to less stringently regulated watersheds
  - Take a global rather than local view of policies' impacts using a price endogenous model (Ribaudo et al., 2001).

An Integrated Hydro-Economic Land Use Model(IHEAL)

- Following Xu et al. (2022)
  - Economic model: a price endogenous partial equilibrium (PE) model for the contiguous United States
  - Hydrological Model: Hydrologic and Water Quality System (HAWQS) for the MARB, CBW, and MRB
    - Soil and Water Assessment Tool (SWAT) assesses water quality.



The IHEAL model schematic (Xu et al., 2022)

The PE model

- The objective function maximizes the sum of producer and consumer surplus in four commodity markets (Corn, soybean, wheat, and sorghum).
- Subject to constraints.
  - Supply-demand balance
  - Supply – production balance
  - Crop acreage convexity constraints
  - Fertilizer costs
  - Irrigation costs
  - N delivered to the Gulf of Mexico, Lake Erie, and the Chesapeake Bay

Research Questions

- Examine the interdependence of nutrient runoff from MARB, CBW, and MRB.
  - What are the potential impacts of reducing agricultural N runoff in the Gulf of Mexico (45%) on N runoff to
    - the Chesapeake Bay and
    - Lake Erie.
  - What is the opportunity cost of achieving the nutrient runoff reduction targets with
    - Unconstrained runoff to other watersheds (without Baseline Runoff Constraint Scenario (BRCS))
    - Constrained runoff to other watersheds i.e., with BRCS
  - What impacts do reducing N runoff from CBW or MRB have on MARB?

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Data

- Corn, soybean, wheat, and sorghum
    - N intensive crops with most acreage
- County scale production
    - MARB – 1590 counties
    - CBW – 157 counties
    - MRB – 24 counties
    - Outside Watersheds -1017 counties
- Demand
    - Commodity demand elasticities from literature and observed prices and quantities in 2018 from USDA NASS
- Supply
    - county-specific historical crop mixes from 2005 to 2019 (USDA NASS)
    - county-specific cost data in 2018 (USDA ERS)
    - Production functions obtained from SWAT/HAWQS

Model Validation and Baseline Results with Observed Values in 2018

	Validation results (historical acreage mix only)	Observed in 2018	Baseline results (historical and synthetic acreage mix)
Land use (million hectares) for the contiguous U.S.			
Corn	39.313	36	38.818
Soybean	38.511	36.1	37.608
Winter Wheat	13.747	13.27	11.162
Sorghum	2.187	2.3	2.099
Prices ($/metric ton)			
Corn	136.818	142	137.638
Soybean Price	316.326	314	321.288
Wheat Price	172.618	187	202.677
Sorghum Price	110.073	117	107.698
Land use (million hectares) in MARB			
Corn	31.977	30.247	30.796
Soybean	29.042	30.145	27.697
Wheat	10.640	11.116	6.940
Sorghum	1.667	1.903	1.357
Land use (million hectares) in CBW			
Corn	0.974	0.962	0.984
Soybean	0.825	0.703	0.829
Wheat	0.335	0.163	0.355
Land use (million hectares) in MRB			
Corn	0.705	0.689	0.707
Soybean	0.989	0.988	0.986
Wheat	0.142	0.118	0.144
Land use (million hectares) Outside the watersheds			
Corn	5.647	9.634	6.332
Soybean	7.655	9.104	8.095
Wheat	2.631	3.359	3.722
Sorghum	0.520	1.900	0.742

Results for Prices and Land use

	Baseline results (historical and synthetic acreage mix)	% change from 45% N Reduction to the Gulf	% change from 45% N Reduction to the Gulf and BRCS
Land use (million hectares) for the contiguous U.S.			
Corn	38.818	***1.04***	***1.04***
Soybean	37.608	***-4.41***	***-4.39***
Wheat	11.162	***2.65***	***2.66***
Sorghum	2.099	***7.72***	***7.72***
Prices ($/metric ton)			
Corn	137.638	***25.16***	***25.52***
Soybean	321.288	***21.04***	***21.08***
Wheat	202.677	***4.74***	***4.74***
Sorghum	107.698	***-13.41***	***-13.62***
Land use (million hectares) in MARB			
Corn	30.796	***-9.23***	***-9.13***
Soybean	27.697	***-15.36***	***-15.43***
Wheat	6.940	***2.56***	***2.64***
Sorghum	1.357	***-6.85***	***-6.78***
Land use (million hectares) in CBW			
Corn	0.984	***12.70***	***8.23***
Soybean	0.829	***-1.21***	***1.45***
Wheat	0.355	***-3.94***	***-3.69***
Land use (million hectares) in MRB			
Corn	0.707	***0.57***	***0.57***
Soybean	0.986	***-0.20***	***-0.20***
Wheat	0.144	***-0.69***	***-0.69***
Land use (million hectares) Outside the watersheds			
Corn	6.332	***49.19***	***49.45***
Soybean	8.095	***32.23***	***32.28***
Wheat	3.722	***3.60***	***3.47***
Sorghum	0.742	***34.37***	***34.37***

Results for N Use, Runoff, and Production

	Baseline results (historical and synthetic acreage mix)	% change from 45% N Reduction to the Gulf	% change from 45% N Reduction to the Gulf and BRCS
N runoff MARB			
N applied	6352.70	***-20.88***	***-20.81***
N delivered (Gulf of Mexico)	357680.00	***-45.00***	***-45.00***
N runoff CBW			
N applied	286.40	***13.66***	***0.00***
N delivered(Bay)	21109.00	***9.20***	***-0.00***
N runoff MRB			
N applied	175.82	***14.00***	***0.00***
N delivered(Lake Erie)	3349.20	***7.18***	***-0.00***
Production (million metric tons) for the contiguous U.S. Corn			
Corn	383.55	***-6.77***	***-6.87***
Soybean	119.64	***-6.29***	***-6.30***
Wheat	31.26	***-1.79***	***-1.79***
Sorghum	9.49	***3.58***	***3.69***
Production (million metric tons) for MARB			
Corn	329.48	***-13.38***	***-13.29***
Soybean	90.05	***-15.45***	***-15.54***
Wheat	16.10	***-4.41***	***-4.35***
Sorghum	5.99	***-15.36***	***-15.19***
Production (million metric tons) for CBW			
Corn	8.01	***12.48***	***5.37***
Soybean	2.18	***-1.83***	***0.92***
Wheat	1.33	***-3.76***	***-3.76***
Production (million metric tons) for MRB			
Corn	7.25	***2.76***	***0.41***
Soybean	3.57	***-0.28***	***-0.28***
Wheat	0.64	***-1.56***	***-1.56***
Production (million metric tons) Outside the water sheds			
Corn	38.82	***43.53***	***43.69***
Soybean	23.84	***26.97***	***27.01***
Wheat	13.19	***1.59***	***1.52***
Sorghum	3.51	***35.61***	***35.61***

Results

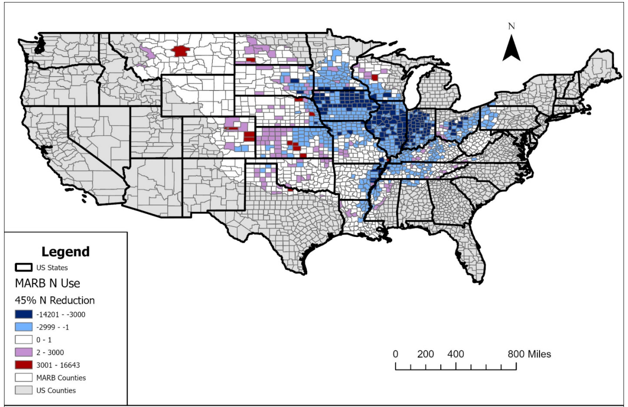
- Scenarios
  - A 45% N runoff reduction goal set in the Gulf of Mexico without BRCS
  - A 45% N runoff reduction goal set in the Gulf of Mexico with BRCS
- Indicators from the scenarios
  - County-Specific N Use
  - County-Specific N Runoff
  - Opportunity Cost of Enforcement
- CBW:
  - N Runoff Increase: 9.2%
- MRB
  - N Runoff Increase: 7.2%

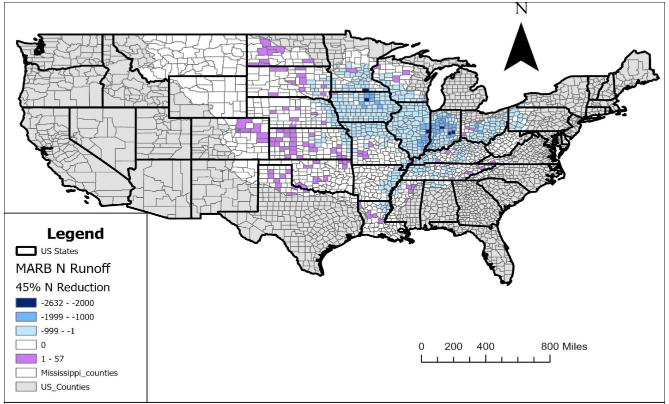
Gulf N Reduction(MARB)

N Use

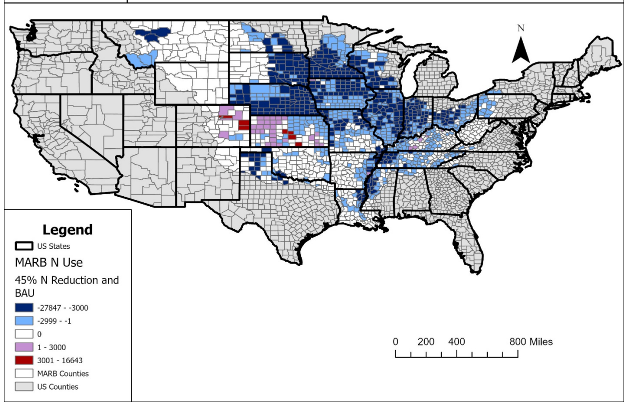
N Runoff

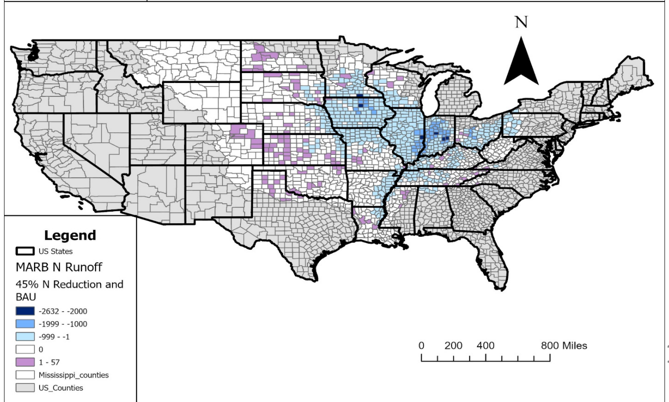
Without BRCS





With BRCS

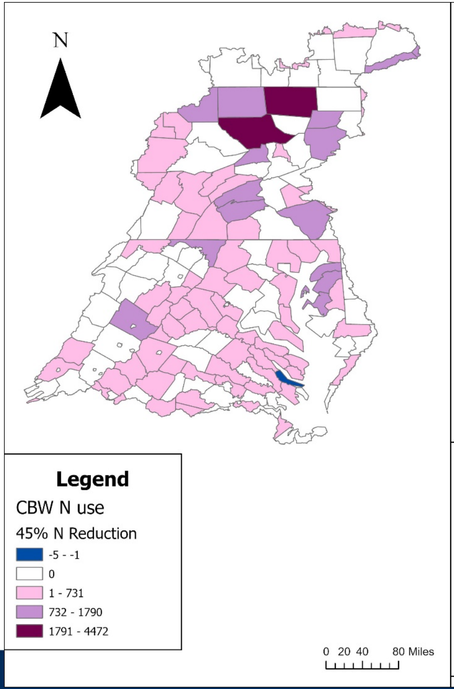




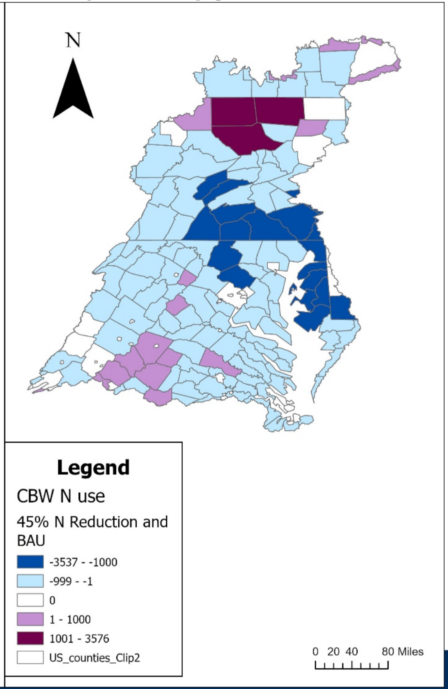
Gulf N Reduction(CBW)

N Use

Without BRCS

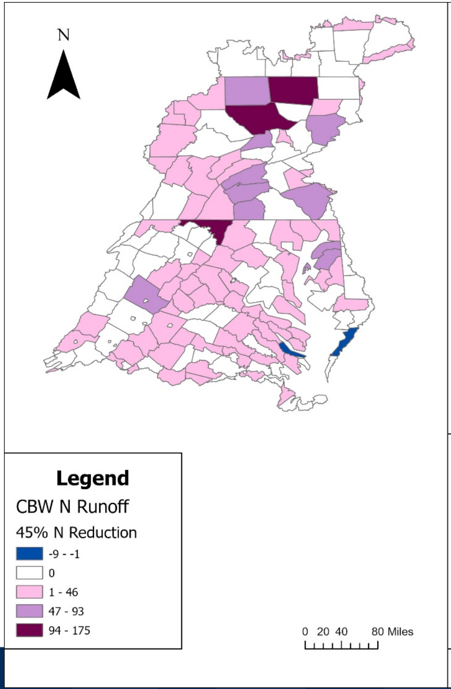


With BRCS

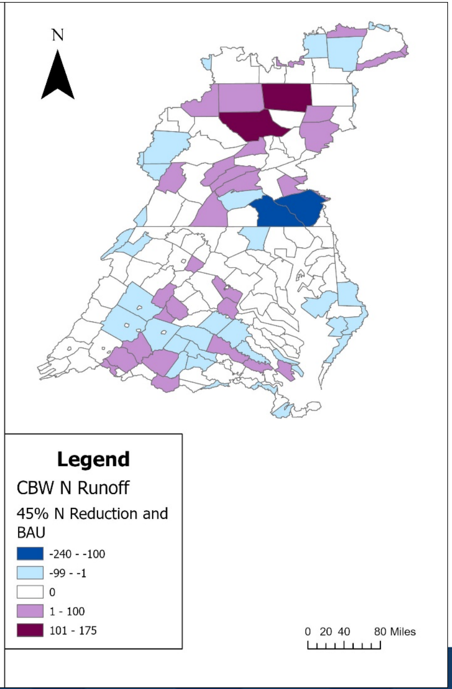


N Runoff

Without BRCS



With BRCS



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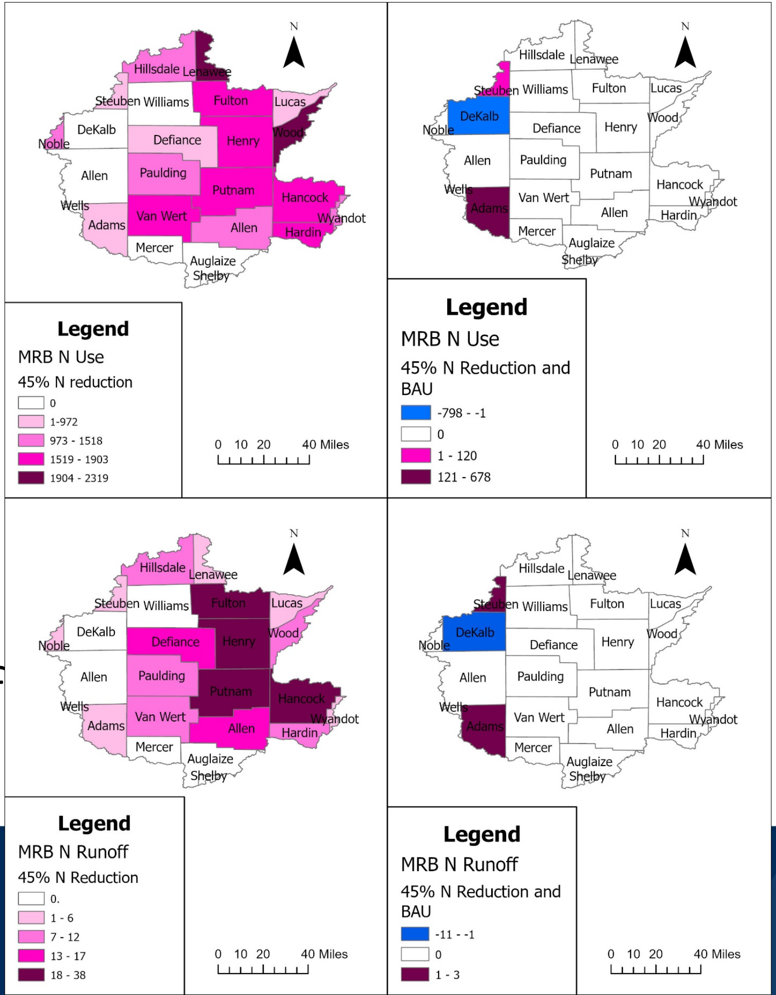
Gulf N Reduction (MRB)

Without BRCS | With BRCS

N Use

N Runoff



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Conclusion

- The opportunity cost of achieving the Hypoxia Task Force goal without BRCS:
  - **$6.7 billion annually** in consumer and producer surplus losses.

- With BRCS in CBW and MRB
  - An increase of about **18 $million**.

- Additional policy scenarios of 25% and 40% N reduction in CBW and MRB
  - Opportunity cost increases by **$0.2 billion**.

- The policy impacts are heterogeneous amongst counties.
  - Take account of the hydrological and agronomic factors of the counties for cost-effective policies.
    - Design spatially explicit recommendations based on in-field variability in N needs (Khanna et al., 2019).

Appendix

The PE model

- The objective function (equation 1) maximizes the sum of producer and consumer surplus.
- $\max_{X,L} \sum_c \int_0^{x_c^d} p_c^d\,(X_c^d, \omega_c) d\, X_c^d - \sum_{c,i,n} tc_{ci} * L_{cin} - \sum_{c,i} FC_{ci}$ (1)
- $P_c^d(X_c^d, \omega_c)$ is the inverse demand function
- X_c^d is the crop c aggregate demand
- ω_c is the corresponding demand shifter
- tc_{ci} represents production cost per ha excluding N fertilizer use for crop c in county i
- L_{cin} denotes the acreage of crop c in county i with n kg N fertilizer application
- FC_{ci} stands for the total N fertilizer costs for crop c in county i

The PE model- Continued

- The maximization problem is subject to the below constraints:
- Balance equation: $X_c^d + exports \leq X_{ci}^s + imports \; \forall \; c,$ (2)
- Supply constraint: $\sum_{n,w} y_{cin} * L_{cin} \geq X_{ci}^s \forall \; c, i,$ (3)
- Fertilizer costs: $FC_{ci} \; = \sum_{n,w} \theta_{cin} * L_{cin} \forall \; c, i,$ (4)
- Water costs: $WC_{ci} \; = \sum_{n,w} \boldsymbol{\mu}_{cin} * L_{cin} \forall \; c, i,$ (5)
- Total N delivered to the Gulf of Mexico: $\sum_n L_{cin} = \sum_m \tau_{mi} * h_{cim} + \sum_n \gamma_{vi} * s_{civ} \forall \; c, i,$ (6)
- Convexity constraint: $\sum_m \tau_{mi} + \sum_n \gamma_{vi} = 1 \forall \; i,$ (7)
- y_{cin}:yield of crop c per ha in county i as a function of the respective N fertilizer use, $n$kg
- h_{cim} and s_{civ} are $m - th$ and $v - th$ county-specific historical and synthetic crop acreages, respectively;
- τ_{mi} and γ_{vi} are weights determined endogenously

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HAWQS

- Hydrologic and Water Quality System (HAWQS)
  - SWAT: Calibrated and Web-based
  - Under various N fertilizer use and optimal irrigation level, it estimates crop yields and N loading.
  - Spatial unit is HUC8 (an eight-digit watershed)
  - Years: 2000 to 2018

- Data:
  - The HUC8 outputs are converted to county-level
    - using the weighted averages accounting for the % of each HUC8's area in the county.

	Baseline results (historical and synthetic acreage mix)	45% N Reduction to the Gulf	% change from 45% N Reduction to the Gulf	45% N Reduction to the Gulf and BAU	% change from 45% N Reduction to the Gulf and BAU
Land use (million hectares) for the contiguous U.S.					
Corn	38.818	39.220	1.04	39.222	1.04
Soybean	37.608	35.950	-4.41	35.957	-4.39
Wheat	11.162	11.458	2.65	11.459	2.66
Sorghum	2.099	2.261	7.72	2.261	7.72
Prices ($/metric ton) Corn					
Corn	137.638	172.262	25.16	172.768	25.52
Soybean	321.288	388.889	21.04	389.005	21.08
Wheat	202.677	212.280	4.74	212.277	4.74
Sorghum	107.698	93.259	-13.41	93.028	-13.62
Land use (million hectares) in MARB					
Corn	30.796	27.954	-9.23	27.984	-9.13
Soybean	27.697	23.442	-15.36	23.424	-15.43
Wheat	6.940	7.118	2.56	7.123	2.64
Sorghum	1.357	1.264	-6.85	1.265	-6.78
Land use (million hectares) in CBW					
Corn	0.984	1.109	12.70	1.065	8.23
Soybean	0.829	0.819	-1.21	0.841	1.45
Wheat	0.355	0.341	-3.94	0.342	-3.69
Land use (million hectares) in MRB					
Corn	0.707	0.711	0.57	0.711	0.57
Soybean	0.986	0.984	-0.20	0.984	-0.20
Wheat	0.144	0.143	-0.69	0.143	-0.69
Land use (million hectares) Outside the watersheds					
Corn	6.332	9.447	49.19	9.463	49.45
Soybean	8.095	10.704	32.23	10.708	32.28
Wheat	3.722	3.856	3.60	3.851	3.47
Sorghum	0.742	0.997	34.37	0.997	34.37

	Baseline results (historical and synthetic acreage mix)	45% N Reduction to the Gulf	% change from 45% N Reduction to the Gulf	45% N Reduction to the Gulf and BAU	% change from 45% N Reduction to the Gulf and BAU
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N applied	286.40	325.53	13.66	286.40	0.00
N delivered(Bay)	21109.00	23050.00	9.20	20900.00	0.00
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N delivered(Lake Erie)	3349.20	3589.80	7.18	3342.10	0.00
Production (million metric tons) for the contiguous U.S. Corn					
Corn	383.55	357.59	-6.77	357.21	-6.87
Soybean	119.64	112.11	-6.29	112.10	-6.30
Wheat	31.26	30.70	-1.79	30.70	-1.79
Sorghum	9.49	9.83	3.58	9.84	3.69
Production (million metric tons) for MARB					
Corn	329.48	285.41	-13.38	285.68	-13.29
Soybean	90.05	76.14	-15.45	76.06	-15.54
Wheat	16.10	15.39	-4.41	15.40	-4.35
Sorghum	5.99	5.07	-15.36	5.08	-15.19
Production (million metric tons) for CBW					
Corn	8.01	9.01	12.48	8.44	5.37
Soybean	2.18	2.14	-1.83	2.20	0.92
Wheat	1.33	1.28	-3.76	1.28	-3.76
Production (million metric tons) for MRB					
Corn	7.25	7.45	2.76	7.28	0.41
Soybean	3.57	3.56	-0.28	3.56	-0.28
Wheat	0.64	0.63	-1.56	0.63	-1.56
Production (million metric tons) Outside the water sheds					
Corn	38.82	55.72	43.53	55.78	43.69
Soybean	23.84	30.27	26.97	30.28	27.01
Wheat	13.19	13.40	1.59	13.39	1.52
Sorghum	3.51	4.76	35.61	4.76	35.61


Thank you