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Integrated assessment of nitrogen runoff to the Gulf of Mexico

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ABSTRACT

An integrated hydro-economic agricultural land use model was developed with endogenous and spatially explicit crop planting, nitrogen (N) fertilizer use and irrigation in the Mississippi River Basin (MRB). We used the model to quantify the effects of energy and N fertilizer prices on N runoff to the Gulf of Mexico. Results show a modest effect of energy costs and a more substantive impact of N fertilizer costs on N delivered to the Gulf of Mexico. A 30 % reduction (increase) in N fertilizer price leads to a 3.5 % and 1.5 % increase (2.9 % and 1.5 % decrease) in N use and runoff, respectively. The model was also used to estimate the opportunity cost of N runoff abatement. The opportunity cost of reducing N runoff from crop production to the Gulf by 45 % is estimated to be $6 billion annually, which corresponds to an average cost of $29.3 per kg of N runoff reduction. The results show heterogeneities in the optimal N runoff reduction efforts across counties within the MRB, demonstrating the significance of a targeted abatement strategy.

Abbreviations: N, Nitrogen; MRB, Mississippi River Basin; US EPA, The U.S. Environmental Protection Agency; UMRB, Upper Mississippi River Basin; OTRB, Ohio-Tennessee River Basin; IHEAL, Integrated Hydro-Economic Agricultural Land use; SWAT, Soil and Water Assessment Tool; EPIC, Environmental Policy Integrated Climate; HAWQS, Hydrologic and Water Quality System; MRRB, Missouri River Basin; ARB, Arkansas-White-Red River Basin; LMRB, Lower Mississippi River basin; HUC 8, Eight-digit watershed; MVP, Marginal Value Product; BMP, Best Management Practice; CRP, Conservation Reserve Program; WTP, Willingness To Pay.

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1. Introduction

Nutrient runoff from agricultural production to coastal waters has become a serious problem in many parts of the world including the Baltic Sea in Europe, the Chesapeake Bay in the U.S. and the East China Sea (Diaz and Rosenberg, 2008). As a consequence, many aquatic ecosystems are subject to Hypoxia with significant detrimental impacts (Withers et al., 2014). Diaz and Rosenberg (2008) report that there are over 400 hypoxic zones worldwide, and the number is growing. In regions where agricultural production is a major cause of Hypoxia, assessments of nutrient export from agricultural production and the corresponding costs of runoff abatement are necessary.

One of the largest hypoxic zones that forms as a result of anthropogenic activities is in the northern Gulf of Mexico, USA (US EPA, 2019; Gupta et al., 2021). The use of nitrogen (N) fertilizers for crop production in the Mississippi River Basin (MRB) is a major contributor to eutrophication in the Gulf, which leads to Hypoxia with detrimental consequences for the aquatic ecosystem (Mitsch et al., 2001; US EPA, 2019). Hypoxia in the Gulf of Mexico has been a public concern for decades. The U.S. Environmental Protection Agency (US EPA) established the Mississippi River/Gulf of Mexico Hypoxia Task Force in 2001, which aims to reduce the size of the Hypoxic zone to 5,000 km^2 by 2035 (US EPA, 2014). In 2019, the "dead zone" reached 18,005 km^2, significantly exceeding the Hypoxia Task Force's goal. Robertson and Saad (2013) estimated that 41 % of N delivered to the Gulf originated from farm fertilizer applications.

Numerous studies have investigated Hypoxia in the Gulf of Mexico, N export from agriculture, and strategies to reduce nutrient losses from cropland in the MRB (Ribaudo et al., 2001; Rabotyagov et al., 2010; Robertson and Saad, 2013; Kling et al., 2014; Rabotyagov et al., 2014; White et al., 2014; Jones et al., 2018; Marshall et al., 2018). Previous findings indicate that two sub-basins of the MRB, the Upper Mississippi River Basin (UMRB) and the Ohio-Tennessee River Basin (OTRB), where intensive corn-soybean rotations rely on high use of N fertilizers and/or manure nitrogen inputs, deliver a disproportionate share of N loadings from crop production to the Gulf of Mexico (Kling et al., 2014; White et al., 2014; Jones et al., 2018; Marshall et al., 2018). However, the effects of N fertilizer and energy prices on N runoff to the Gulf have not been addressed.

In recent years, energy and N fertilizer prices have decreased as a result of advances in hydraulic fracturing and the abundance of relatively inexpensive natural gas. Since 2008, crude oil and natural gas prices declined by 61 % and 77 %, respectively (EIA, 2021a,b). As a product of natural gas, N fertilizer prices have dropped by 29 % since 2008 (USDA ERS, 2019). Energy and N fertilizers are important crop production factors for most crops (Marshall et al., 2015). Low energy and nutrient prices affect farmers' crop planting decisions at the intensive as well as extensive margins[1] with corresponding consequences for N loading to the Gulf of Mexico (Pfeiffer and Lin, 2014; Sohngen et al., 2015).

Given the urgent need to mitigate Hypoxia in the Gulf of Mexico, it is vital to understand how variations in prices of energy and related inputs affect farmers' crop acreage and N application decisions, and how these decisions affect water quality in the Gulf of Mexico. Moreover, with eutrophication in the Gulf of Mexico likely to remain a significant challenge (Sinha et al., 2017), it is important to estimate the costs of reducing N runoff from crop production. Since N use and crop production are largely driven by economic incentives, the cost estimates should reflect both economic and biophysical determinants of N runoff.

An integrated model, linking hydrologic and economic components, is necessary to understand the interdependencies between energy-related input costs, land use and N loading (Ribaudo et al., 2001; Rabotyagov et al., 2010; Kling et al., 2014; Rabotyagov et al., 2014; Pennington et al., 2017; Marshall et al., 2018). Therefore, we develop a spatially explicit integrated hydro-economic agricultural land use (IHEAL) model, which combines a price endogenous partial equilibrium model with the Soil and Water Assessment Tool (SWAT) ecohydrological model (Arnold et al., 1998, 2012; Gassman et al., 2007; Williams et al., 2008; Bieger et al., 2017). The IHEAL model is based on county-scale production decisions, including crop planting, fertilizer application and irrigation.

The model can be used to evaluate land use, N fertilizer use, and irrigation under various practice or performance-based policies.[2] Practice-based policies provide guidelines and directions for acceptable production activities while performance-based policies establish bounds for environmental outcomes, like N runoff, and allow for an endogenous determination of adaptation strategy. In this study, we examine the effect of restricting N runoff to the Gulf on optimal spatial distribution of production.

Existing integrated hydro-economic models have relied on fixed fertilizer application specifications (Ribaudo et al., 2001; Rabotyagov et al., 2010; Secchi et al., 2011; Kling et al., 2014; Marshall et al., 2018), and have not been used to examine the effects of N fertilizer prices on farmers' crop planting decisions and corresponding N runoff to the Gulf of Mexico. We extend these studies by including county-scale variable crop yields as functions of per ha N fertilizer use and irrigation as endogenous production factors. This approach adds flexibility to prior specifications with fixed per ha N use in estimating economic and environmental outcomes under various policy and price scenarios.

[1] Intensive margin decisions refer to the use of inputs per acre of crop production, while extensive margin decisions refer to crop acreage adjustments (Elbakidze et al., 2017a; Schoengold et al., 2006; Hendricks and Peterson, 2012; Pfeiffer and Lin, 2014).

[2] Practice based policies refer to particular prescriptive land use restrictions. For example, a practice-based regulation may require producers to fallow a certain proportion of planted acreage, use a particular crop rotation, etc. Conversely, performance-based policies refer to an outcome-focused approach where production decisions are adopted to achieve targeted outcomes. For example, a performance-based policy may set a particular target for environmental emissions and allow production decisions to be adjusted accordingly.

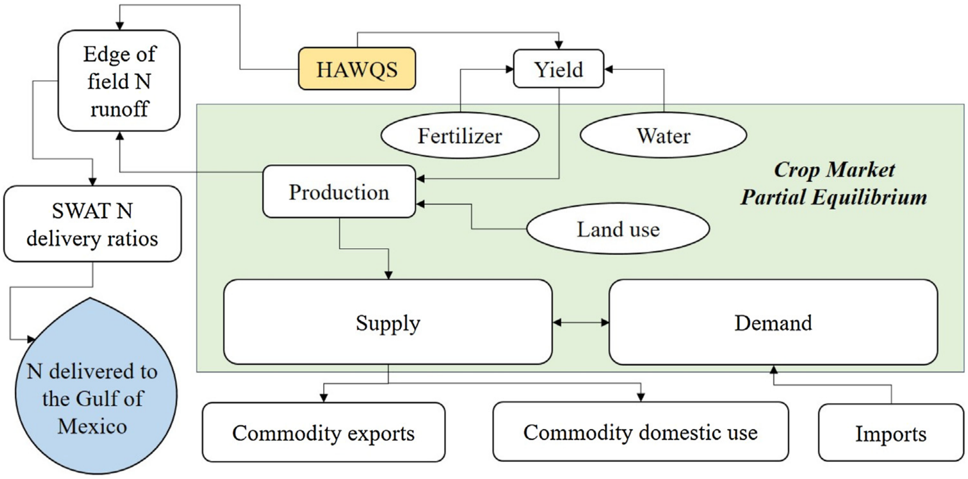

Fig. 1. The IHEAL model schematic.

In addition, IHEAL includes a partial equilibrium modeling framework with supply and demand specifications, which allows for consumer and producer surplus maximization-based assessment of environmental policies and their impacts on changes in land use. Consumer and producer surplus measures are explicitly considered following the recommendations of Griffin (1998) to include consumer and producer welfare measures as part of water related policy cost benefit analysis. This framework is convenient when modeling agricultural production activities in large regions where aggregate production can have a non-zero impact on prices.

Our modeling approach is similar to Ribaudo et al. (2001) and Marshall et al. (2018) in terms of relying on a partial equilibrium economic modeling framework linked with a biophysical model/database to quantify N runoff. However, we introduce several significant contributions. First, we use a county-scale land use representation, which enables a more disaggregated simulation relative to the region scale model in Ribaudo et al. (2001) and Marshall et al. (2018). The county-scale IHEAL model provides a more detailed representation of crop production, N fertilizer application and N runoff potential for policy analysis. Second, unlike Ribaudo et al. (2001) we integrate the parameters obtained from SWAT into the IHEAL model so that economic results and environmental impacts are obtained simultaneously and interdependently under various price and policy scenarios. Land use decisions in our model depend on output prices, costs of production, crop rotation requirements, environmental policy and other constraints as appropriate. N runoff is estimated concurrently with land use in terms of planting, N application, and irrigation. The advantage of this approach is in its ability to evaluate performance-based scenarios where land use and production activities depend on targeted environmental outcomes like the aggregate N runoff to the Gulf of Mexico. Hence, our model can be used for evaluating both practice-based and performance-based environmental policies. Third, we rely on SWAT instead of the Environmental Policy Integrated Climate (EPIC) model (Williams et al., 2008), which was the model applied by Ribaudo et al. (2001) and Marshall et al. (2018). SWAT is a watershed-scale model that simulates all land use within a subbasin and routes the flow of constituents through surface water channels and impoundments to the basin outlet. In contrast, EPIC is a field-scale model that simulates runoff and constituents to the edge of individual land unit. Fourth, unlike Ribaudo et al. (2001) and Marshall et al. (2018), N fertilizer use in our model depends on prices and marginal productivity. Our design enables us to directly assess the effect of changes in N fertilizer market on N runoff to the Gulf.

The primary goal of this study is to develop the IHEAL model for evaluating N runoff from crop production in the MRB to the Gulf of Mexico. Specifically, two objectives are defined: (i) estimate how N runoff into the Gulf of Mexico is affected by energy and fertilizer prices; and (ii) estimate the opportunity cost of reducing N runoff from crop production in the MRB to the Gulf according to the objectives established by the EPA Hypoxia Task Force.

2. Materials and methods

The core of the IHEAL model is an economic price endogenous partial equilibrium model (McCarl and Schneider, 2001; Chen et al., 2014; Yi et al., 2018), which includes crop yield and N runoff outputs generated with SWAT. Fig. 1 provides a schematic overview of the IHEAL model process.

The primary purpose of the modelling system is to enable quantification of the impacts from changes in both environmental policy variables and economic factors. The model endogenously determines annual county crop planting acreage, N application, and irrigation based on constrained maximization of consumer and producer welfare in select crop markets. Within the "crop market partial equilibrium" box (Fig. 1), county production activities generate national commodity supply estimates that are combined with commodity demand functions to produce equilibrium prices and quantities. The demand

and supply balance specifications include import-export data. The estimated equilibrium quantity is split into domestic consumption and exports to the rest of the world.

County-specific crop yields are expressed in terms of N application and irrigation activities using parameters obtained from SWAT simulations executed within the Hydrologic and Water Quality System (HAWQS) on-line platform (HAWQS, 2020). County production activities, including land use and N application, are combined with the watershed-level SWAT N runoff parameters generated within HAWQS and with SWAT delivery ratios that link county N runoff with corresponding N loading in the Gulf, to estimate annual N delivery from crop production to the Gulf of Mexico. For discussion and applications of HAWQS system, including calibration issues, see Fant et al. (2017) and Chen et al. (2020).[3]

2.1. Study area

The price-endogenous partial equilibrium model includes crop production decisions and market outcomes for the contiguous US. The land use component of the partial equilibrium model covers all US agricultural land in 2,788 counties, where the crops included in this model have been produced in at least one year from 2005 to 2019. The numbers of counties within and outside the MRB are 1,620 and 1,168, respectively.

The hydro-economic model component is developed only for the counties within the MRB. The MRB consists of the UMRB, Missouri River Basin (MRRB), Arkansas-White-Red River Basin (ARB), Lower Mississippi River basin (LMRB) and OTRB, and is the largest drainage basin in the U.S. (Aulenbach et al., 2007). The drainage area of the MRB is 3,224,535 km^2, representing 41 % of the contiguous U.S. (US EPA, 2016). The land use in the MRB includes 0.6 % urban land, 58 % agricultural land, 18 % woodlands, 21 % range/barren land, and 2.4 % wetlands and water (Rabalais and Turner, 2011). Only the agricultural land is considered in this study.

2.2. Partial equilibrium and land use

Following Havlík et al. (2011), the objective function (Eq. (1)) maximizes the sum of consumer and producer surplus. The choice variables are national supply, demand, and county scale crop planting acreage decisions with corresponding N application and irrigation schedules.

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

where $P_c^d \left(X_c^d,\ \omega_c\right)$ is inverse demand function; X_c^d is the aggregate demand for crop c; ω_c is the corresponding demand shifter; tc_{ci} denotes the per ha production cost excluding N fertilizer and water use for crop c in county i. L_{cinw} is the acreage of crop c in county i with n kg N fertilizer application and w water use. FC_{ci} and WC_{ci} are total N fertilizer and water costs for crop c in county i, respectively.

The maximization problem is subject to the following constraints:

$$X_c^d + exports \le \sum_{i} X_{ci}^s + imports \,\forall\, c, \tag{2}$$

$$\sum_{n,w} y_{cinw} * L_{cinw} \ge X_{ci}^s \,\forall\, c,\ i, \tag{3}$$

$$FC_{ci} = \sum_{n,w} \theta_{cin} * L_{cinw} \,\forall\, c,\ i, \tag{4}$$

$$WC_{ci} = \sum_{n,w} \mu_{ciw} * L_{cinw} \,\forall\, c,\ i, \tag{5}$$

$$\sum_{n,w} L_{cinw} = \sum_{m} \tau_{mi} * h_{cim} + \sum_{n} \gamma_{vi} * s_{civ} \,\forall\, c,\ i, \tag{6}$$

$$\sum_{m} \tau_{mi} + \sum_{n} \gamma_{vi} = 1 \,\forall\, i. \tag{7}$$

Eq. (2) establishes the supply-demand balance, where total demand for crop c cannot exceed its total supply; X_{ci}^s is the aggregate production of crop c in county i. Eq. (3) restricts total supply of crop c to be no larger than total production, where

[3] Fant et al. (2017) compared predictions of future water quality in the continental US in terms of water temperature, dissolved oxygen, total N and P between US Basins and HAWQS with five climate models and two greenhouse gas mitigation policies. Chen et al. (2020) evaluated the prediction of hydrological process in HAWQS using three weather datasets and two potential evapotranspiration methods for the UMRB.

y_{cinw} is the per ha yield of crop c in county i as a function of the respective fertilizer use, n, and water use, w, which is obtained from the process-based physical model discussed in Section 3.3. Eq. (4) computes total N fertilizer costs for crop c in county i, where θ_{cin} denotes the per ha cost of N fertilizer corresponding to each fertilizer application scenario n. Similarly, Eq. (5) computes total water costs, where μ_{ciw} is the per ha water cost for crop c, in county i and irrigation schedule w.

Eq. (6) restricts land allocation to crop c in county i. The constraint represents a convex combination of historical and synthetic acreages, which allows for flexibility in planted crop acreage decisions for each crop between lower and upper bounds of crop mixes. This formulation implicitly reflects technological, managerial and policy factors that restrict crop planting decisions (McCarl, 1982; Schneider et al., 2007; Elbakidze et al., 2012).

Following Chen and Önal (2012), we use historical and synthetic crop mix specifications to enable greater model flexibility. Synthetic acreages are obtained assuming that a crop acreage response is a function of a vector of crop prices and lagged acreages of competitor crops (Chen and Onal, 2012). Synthetic crop mix estimates are obtained using own and cross acreage-price elasticities, elasticities of own and cross lagged acreages and hypothetical price scenarios. To obtain the own and cross acreage-price elasticities and elasticities of own and cross lagged acreages, we use county production and price data from 2005 to 2019 and the log-log specification of the fixed-effect Arellano-Bond estimator:

$$Acreage_{cit} = \beta_0 + \beta_1 Acreage_{c,i,t-1} + \beta_2 Acreage_{-c,i,t-1} + \beta_3 Price_{c,i,t-1} + \beta_4 Price_{-c,i,t-1} + Climate_{i,t} + TimeTrend_t + \mu_i + \varepsilon_{it} \tag{8}$$

The use of synthetic representation allows acreage to fall outside of historically observed combinations under circumstances that have not been observed previously, including price or environmental impact restriction scenarios. In Eq. (6), county acreage of crop c is the sum of weighted historical and synthetic crop mix acreages. The indexes m and v are respective representations of historical and synthetic crop mixes; 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. Eq. (7) constrains the sum of weights, τ_{mi} and γ_{vi}, to equal to 1, which guarantees that the endogenously determined county crop acreages are convex combinations of acreages observed in the past years and acreages simulated synthetically.

2.3. Crop yields and nutrient runoff

The SWAT model was used within HAWQS to simulate irrigation, N use specific crop yields and watershed-level N loading parameters for counties within the MRB. Subbasins simulated within SWAT were based on eight-digit watersheds (HUC 8), which is one of the simulation unit options available in HAWQS. The simulation time period was from 2000 to 2018. Built-in calibration of SWAT in HAWQS was relied upon or this study (HAWQS, 2020).

There are 822 HUC 8 units with crop production within the MRB. Crop yields and N runoff at the edge of each HUC 8 from 2000 to 2018 were obtained for various scenarios of N application and irrigation. We use area weighted averages of HUC 8 scale crop yields to obtain county scale yields.[4] We use the same procedure to obtain county-scale parameters for optimal irrigation and N runoff. To account for the increase in yields over time (USDA NASS, 2020a) and to account for differences between continuous and alternating crop rotation yields,[5] we calibrate yields using 2018 county yield data obtained from USDA.[6]

We use county-scale N delivery ratios to obtain total N runoff into the Gulf of Mexico from crop production. We obtain the county N delivery ratios using a weighted average of HUC 8 sub-basin N delivery ratios according to the area of each HUC8 in each county. The SWAT HUC 8 sub-basin N delivery ratios are obtained from White et al. (2014). The total N delivered to the Gulf of Mexico is computed as follows:

$$TN = \sum_{i}^{I} \left(dr_i * \sum_{c,n,w} nrf_{cinw} * L_{cinw} \right) \tag{9}$$

where, TN denotes total N delivered to the Gulf of Mexico; dr_i is the N delivery ratio for county i; nrf_{cinw} denotes the per-ha N runoff from planting crop c with fertilizer use n and w in county i. Only the counties in MRB are used in the estimation of N runoff impacts.

[4] For example, 40.0%, 57.7% and 2.3% of McPherson County, KS is located in three HUC 8 units. For these three HUC 8 sub-basins, corn yields with 200 kg/ha N fertilizer application and optimal irrigation are 4.2, 6.5 and 4.0 metric ton/ha, respectively. We estimate corn yield in McPherson County with 200 kg/ha N fertilizer application and optimal irrigation to be 5.5 metric tons/ha (40.0%*4.2+57.7%*6.5+2.3%*4.0=5.5).

[5] SWAT is used to obtain crop yields under various N and water use scenarios assuming continuous rotations. As expected, continuous rotation underestimates yields observed in practice. Corn and soybean yields obtained from SWAT are 30% lower than the observed values in 2018. Therefore, relative yields obtained from SWAT with continuous rotation are used in conjunction with USDA (2020) yield data to obtain calibrated yields used in our model.

[6] Yield calibration is based on the reported county crop yields in USDA NASS. For example, in Champaign County, IL, SWAT mean estimate of continuous rotation corn yield from 2000 to 2018 with 300 kg per ha N application is 12.5 metric ton/ha; USDA NASS reports corn yield in 2018 to be 15.5 ton/ha. Hence, the multiplier used to calibrate corn yield estimated in SWAT for Champaign County, IL is 15.5/12.5=1.24.

2.4. N runoff abatement opportunity cost

We iteratively constrained aggregate N runoff to the Gulf of Mexico (Eq. (8)) to estimate the marginal value of N fertilizer in the MRB. Shadow prices from the Gulf N runoff constraint represent the basin scale marginal value product of N fertilizer which can be used to obtain the opportunity cost of reducing Gulf N runoff. Next, the estimated shadow prices and a Box-Cox specification (Eq. (10)) are used to estimate the Marginal Value Product (MVP) curve of N delivery to the Gulf of Mexico following Elbakidze et al. (2017b). Subsequently, the MVP curve is used to estimate the opportunity cost of decreasing the N delivery relative to the baseline N runoff.

$$y^{(\theta)} = \beta_0 + \beta_1 x, \tag{10}$$

where x is the allowable amount of N delivered to the Gulf of Mexico, and y are shadow prices obtained from the partial equilibrium model at corresponding N bounds. $y^{(\theta)}$ is defined as:

$$y^{(\theta)} = \begin{cases} \frac{y^{\theta}-1}{\theta} \; if \; \left|\theta\right| > 0 \\ \ln(y) \; otherwise \end{cases} \tag{11}$$

Using the regression results based on the Box-Cox specification, we obtain the following MVP curve:

$$y = \left(\theta\beta_0 + \theta\beta_1 x + 1\right)^{1/\theta} \tag{12}$$

To obtain the total opportunity costs (TC_i) of reduced N delivery to the Gulf of Mexico by i % relative to the baseline level, Eq. (12) is integrated between $\bar{x} * (1 - i\%)$ and $\bar{x}$ (baseline).

$$TC_i = \int_{\bar{x}*(1-i\%)}^{\bar{x}} \left(\theta\beta_0 + \theta\beta_1 x + 1\right)^{1/\theta} dx = \frac{\left(\theta\beta_0 + \theta\beta_1 x + 1\right)^{\frac{1}{\theta}+1}}{\left(1+\theta\right)\beta_1}|_{\bar{x}} - \frac{\left(\theta\beta_0 + \theta\beta_1 x + 1\right)^{\frac{1}{\theta}+1}}{\left(1+\theta\right)\beta_1}|_{\bar{x}*(1-i\%)} \tag{13}$$

2.5. Data

The baseline year for the partial equilibrium land use model is 2018. Corn, soybean, wheat and sorghum are included in the model because these crops are major agricultural commodities and are the most fertilizer-intensive crops planted in the US (Marshall et al., 2015; USDA NASS, 2020b). The acreages of corn, soybean, wheat and sorghum account for 27.9 %, 27.9 %, 15.1 % and 1.8 % of total principal crop[7] acreage in the US in 2018, respectively (USDA NASS, 2020c).

We use crop demand elasticities obtained from literature and the observed price-quantity points in 2018 to express inverse commodity demand as a linear function of respective quantities for each crop. We use the 2018 sales, production and price data from USDA NASS (USDA NASS, 2020b). Following previous literature, the demand elasticities for corn, soybean, wheat and sorghum are -0.28, -0.29, -0.34 and -0.3, respectively (Westcott and Hoffman, 1999; Piggott and Wohlgenant, 2002; Ishida and Jaime, 2015).

County-specific historical crop acreage and prices of corn, soybean, wheat and sorghum from 2005 to 2019 are obtained from NASS (USDA NASS, 2020b). We did not include observations from more than 15 years ago to avoid the inclusion of land that may no longer be available for planting. County-scale wheat acreages are not available in NASS after 2008. Therefore, we use CropScape data to fill missing values (USDA NASS Cropland Data Layer, 2020). Crop production costs, excluding energy, fertilizer and water in 2018, are obtained from USDA ERS. These data are available at the farm resource region scale and are converted to county scale through region-county matching provided by USDA ERS (USDA ERS, 2020).

Energy input costs in this analysis include “fuel, lubrication and electricity” related expenses as defined by the USDA ERS (2019). These costs are proportional to energy prices on per ha basis at the county scale, which are converted from data at the farm resource region level.

Fertilizer and water costs are modeled differently for counties within and outside the MRB. Per ha fertilizer application, water use and yields in the counties outside of MRB are fixed, with the data obtained from USDA (USDA ERS, 2020; USDA NASS, 2020b). Yields within the MRB are expressed as a function of N use and irrigation. Hence, within the MRB, these costs vary depending on N use and irrigation. Fertilizer cost is $ 0.98 per kg N element, estimated based on the cost of 30 % N solution and N fertilizer price index obtained from USDA ERS (USDA ERS, 2019).[8] The per-ha cost of the full irrigation is the cost of purchased irrigation water, obtained from USDA ERS (USDA ERS, 2020). Water costs for deficit irrigation are proportionally approximated using costs of full irrigation. For example, if the cost of purchased water for full irrigation is $1 per ha, then 75 % deficit irrigation will cost $ 0.75 per ha.

[7] Principle crops include corn, sorghum, oats, barley, rye, winter wheat, Durum wheat, other spring wheat, rice, soybeans, peanuts, sunflower, cotton, dry edible beans, potatoes, canola, proso millet, and sugarbeets (USDA NASS, 2020b).

[8] The 2018 price of 30% N solution is not available from USDA ERS. The N price index in 2011 and 2018 was 100 and 75.93 respectively. In 2011, the price of 30% N solution was 351 per material short ton. Hence, the 2018 price of a 30% N solution was estimated to be $266.5 per short ton ($351*75.93/100=$266.5). The price of N in 2018 is $0.98/kg (266.5/30%*0.0011=0.98).

Table 1
Validation and baseline results.

	Validation results (historical acreage mix only)	Observed in 2018[a,b]	Baseline results (historical and synthetic acreage mix)
Land use (million hectares) for the contiguous U.S.			
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
Prices ($/metric ton)			
Corn Price	142.8	142	143.5
Soybean Price	312.2	314	320
Wheat Price	187.3	190	198.7
Sorghum Price	118.5	117	110.8
	Model results (historical mixes only)	Values from literature	Model results (historical and synthetic mixes)
N runoff and water use			
N applied within the MRB (1000 metric ton)	9,300 (MRB)	12,610 (U.S.)[c]	8,988(MRB)
Total irrigation water use (million acre-feet)	21.9 (MRB)	83.4 (U.S.)[a]	21.4 (MRB)
N delivered to the Gulf of Mexico from fertilizer application (metric ton)	461,010 (MRB)	796,000 (cultivated agriculture in the MRB)[d,e]	455,570 (MRB)

[a] Source: USDA NASS (2019).
[b] The year of crop demand data used in this study is 2018. Hence, we compare the baseline results with data observed in 2018.
[c] The sum of county-level farm N fertilizer use (Falcone, 2021).
[d] Source: White et al. (2014).
[e] 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).

2.6. Model validation

For validation purposes, the model was solved using observed county historical crop acreage data. We present some of the key baseline model solutions for model validation, including crop production, crop prices, the amount of N delivered to the Gulf of Mexico and the amount of irrigation water used within the MRB, compared with the observed values in the baseline year 2018 (columns 1 and 2, Table 1). The model overestimates cumulative crop acreage for corn and soybean by 6.7 % and 4.7 %, respectively, relative to the acreage observed in 2018. Conversely, wheat acreage is 6.2 % lower than what was observed in 2018. Estimated sorghum acreage matched the value observed in 2018. Crop prices are all close to observed values in 2018 with all deviations less than 2%.

Total water use, N use and N delivered to the Gulf of Mexico are also presented in Table 1. Annual water use within the MRB is 21.9 million acre-feet, which accounts for 26.3 % and 62 % of the observed irrigation water use in the U.S. and in the 31 states, which are at least partially located within the MRB, respectively (USDA NASS, 2019). N applied within the MRB is 9,300 thousand metric tons, which is 73.8 % of the total observed N application in the U.S. N delivered to the Gulf of Mexico from fertilizer applications on corn, soybean, wheat and sorghum fields is 461,010 metric tons, accounting for 57.9 % of N delivered to the Gulf of Mexico from cultivated agriculture in the MRB (White et al., 2014). These solutions provide a firm footing and benchmark for the subsequent analysis of N runoff scenarios.

3. Results

In this section, we first present baseline results followed by the results for the effect of energy and N fertilizer prices on N runoff into the Gulf. Finally, we present the results from the performance-based scenario with targeted N runoff reduction into the Gulf. In particular, we estimate the opportunity cost of reducing N runoff with energy and N fertilizer prices observed in 2018.

3.1. Baseline results

Baseline results are presented in column 3, Table 1. The baseline estimates for the annual N applied within the MRB and the corresponding cumulative N runoff to the Gulf are 8,988,000 and 455,570 metric tons, respectively. These results serve as benchmark estimates for comparison to the scenarios with altered energy costs, N fertilizer costs, and restricted N delivery to the Gulf.

Table 2
Results for alternative energy price scenarios.

Direct energy cost ($/ha)	15 % increase	10 % increase	5 % increase	Baseline	5 % reduction	10 % reduction	15 % reduction
Corn acreage (million ha)	38.0	38.1	38.1	38.2	38.2	38.3	38.3
Soybean acreage (million ha)	37.1	37.2	37.2	37.2	37.3	37.3	37.3
Wheat acreage (million ha)	16.4	16.4	16.4	16.5	16.5	16.5	16.5
Sorghum acreage (million ha)	2.4	2.4	2.4	2.4	2.5	2.5	2.5
Corn production (million metric ton)	378.3	378.6	378.8	379.1	379.4	379.8	380.1
Soybean production (million metric ton)	119.6	119.6	119.7	119.8	119.9	120.0	120.0
Wheat production (million metric ton)	51.8	51.8	51.9	51.9	52.0	52.0	52.0
Sorghum production (million metric ton)	9.3	9.4	9.4	9.4	9.4	9.5	9.5
Corn price ($/metric ton)	144.6	144.3	143.9	143.5	143.1	142.7	142.3
Soybean price (($/metric ton)	321.6	321.3	320.9	320	319.2	318.2	317.7
Wheat price (($/metric ton)	200.1	200.0	199.3	198.7	198.1	197.6	197.3
Sorghum price (($/metric ton)	114.3	112.9	111.7	110.8	109.9	109.2	108.1
N applied within MRB (1000 metric tons)	8,979	8,979	8,982	8,988	8,997	8,995	8,998
Total irrigation water use within MRB (million acre-feet)	21.4	21.4	21.4	21.4	21.4	21.4	21.4
N Delivered to the Gulf of Mexico (metric ton)	455,410	455,460	455,480	455,570	455,660	455,690	455,730

3.2. *Energy costs*

We vary the energy costs from 15 % reduction to 15 % increase with a 5% increment relative to the 2018 value to assess the impact of energy prices on land use and N runoff into the Gulf. Table 2 presents cropland area, crop production, crop prices, irrigation within the MRB, and total N delivered to the Gulf of Mexico under alternative energy cost scenarios. Results indicate that changes in energy costs have modest impacts on the planted area and crop prices, which is consistent with the findings of Marshall et al. (2015). The modest impacts are expected because direct energy costs represent a small portion of total operating costs (excluding irrigation costs and fertilizer), which accounts for 10.33 %, 6.83 %, 7.49 % and 9.82 % of total operating costs of corn, soybean, wheat and sorghum respectively. The small changes in land use result in small changes in N delivered to the Gulf of Mexico (Table 2). In response to a 15 % increase in energy costs, crop acreage and N use decrease by 0.42 % and 0.10 % respectively, resulting in a 0.04 % reduction in N delivered to the Gulf of Mexico. Similarly, a 15 % decrease in energy cost leads to a 0.32 % increase in corn, soybean, wheat and sorghum acreage and a 0.11 % increase in N use, resulting in 0.04 % rise in N loading to the Gulf of Mexico from these crops.

3.3. *Fertilizer costs*

We vary the N fertilizer cost from 30 % reduction to 30 % increase with a 10 % increment relative to its baseline price. Table 3 presents cropland area, crop production, crop prices, total N and water used within the MRB and total N delivered to the Gulf of Mexico under alternative N fertilizer cost scenarios. The results indicate that N fertilizer prices affect land use at the intensive as well as extensive margins. An N fertilizer cost decrease by 30 % leads to an increase in corn, soybean, wheat and sorghum acreages by 1.8 %, 1.1 %, 2.4 % and 8.3 %, respectively. The inverse relationships between fertilizer price and crop acreages are consistent with previous studies (Haile et al., 2016; Li et al., 2019).

As one would expect, cumulative N application in the MRB and N delivered to the Gulf of Mexico increase as N fertilizer costs decline and vice versa. A 10 % decrease in the price of N increases its use by 1% and N delivered to the Gulf by 0.51 %. This result is qualitatively consistent with prior literature (Paudel and Crago, 2021; Sohngen et al., 2015). Paudel and Crago (2021) find that 1% increase in N fertilizer use (kg) increases N concentration (mg/l) by approximately 0.15 % at the HUC8 scale in the U.S. Sohngen et al. (2015) show that a 10 % increase in N prices reduces N outputs (mg/l) by 1.7 %–2.8 %. Similarly, a 10 % increase in Phosphorus (P) prices reduces P outputs (mg/l) by 1.7 %–2.4 % in five U.S. Midwestern watersheds.

Fig. 2 presents the results of N fertilizer application and N delivery to the Gulf of Mexico under various N price scenarios. N use within the MRB and the corresponding N runoff to the Gulf of Mexico increase by 3.5 % and 1.5 %, respectively in response to a 30 % price reduction in N fertilizer price relative to the baseline (Table 3). If N fertilizer price increases by 30 %, then N use within the MRB decreases by 2.9 % and the N delivery to the Gulf of Mexico declines by 1.5 %.

3.4. *Performance-based N reduction costs*

The Box-Cox estimation results for the marginal value product of N runoff into the Gulf of Mexico are presented in Table 4. The corresponding fitted curve and shadow prices are presented in Fig. 3. The upper bound for the N runoff constraint is

Table 3
Results for alternative N fertilizer price scenarios.

N fertilizer cost ($/kg)	30 % increase	20 % increase	10 % increase	Baseline	10 % reduction	20 % reduction	30 % reduction
Corn (million ha)	37.4	37.7	37.9	38.2	38.4	38.7	38.9
Soybean (million ha)	36.9	37.1	37.2	37.2	37.4	37.5	37.6
Wheat (million ha)	16.0	16.1	16.3	16.5	16.6	16.7	16.9
Sorghum (million ha)	2.3	2.4	2.4	2.4	2.5	2.5	2.6
Corn production (million metric ton)	373.0	375.2	377.3	379.1	381.1	383.1	384.9
Soybean production (million metric ton)	118.9	119.4	119.6	119.8	120.1	120.4	120.6
Wheat production (million metric ton)	50.8	51.2	51.5	51.9	52.3	52.7	53.0
Sorghum production (million metric ton)	9.0	9.1	9.3	9.4	9.6	9.7	9.8
Corn price ($/metric ton)	151.6	148.8	146.0	143.5	140.9	138.2	135.9
Soybean price (($/metric ton)	327.9	323.2	321.4	320.0	317.2	314.5	312.4
Wheat price (($/metric ton)	210.3	206.7	202.6	198.7	194.8	190.6	187.0
Sorghum price (($/metric ton)	127.7	123.6	117.7	110.8	105.1	99.5	93.3
N applied within MRB (1000 metric tons)	8,723	8,783	8,883	8,988	9,078	9,196	9,302
Total irrigation water use within MRB (million acre-feet)	24.0	22.6	22.6	21.4	20.9	20.5	19.3
N Delivered to the Gulf of Mexico (metric ton)	448,940	450,550	453,590	455,570	457,920	460,560	462,490

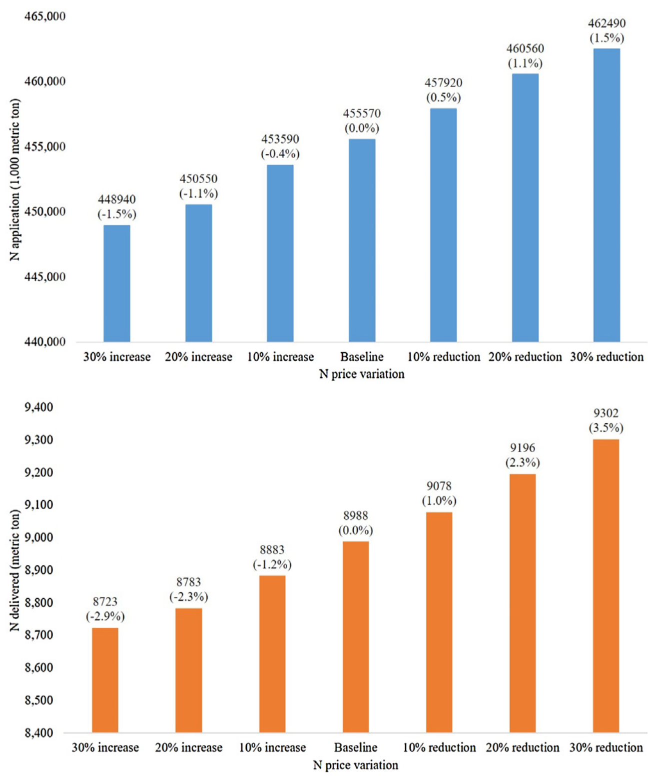

Fig. 2. N applied within the MRB (upper) and delivered to the Gulf of Mexico (bottom).
Note: Percent change relative to the baseline scenario shown parenthetically.

varied between the baseline runoff (455,570 metric tons annually) and 20 % of baseline (91,114 metric tons per year) to obtain the shadow price values.

The results show that the marginal value of reducing N delivery to the Gulf of Mexico by one ton from the baseline runoff is $46. This value increases as the stringency of N runoff restriction is increased.

A 45 % reduction in the N load corresponds to the target of the 2008 Gulf Hypoxia Action Plan (US EPA, 2008). Using Eq. (12) and the coefficient estimates in Table 4, the abatement costs of reducing N loading by 45 % is $6.0 billion. This estimate is higher than the estimate of $2.7 billion in Rabotyagov et al. (2014). The difference may be due to several reasons. First,

Table 4
Derived demand for N use.

VARIABLES	Estimation Results
θ	-0.2742^{***}
Std.Err.	(0.0230)
Z-value	−12.99
β_1	$-4.66E\text{-}07^{***}$
Std.Err.	(0.0000)
$\chi^2(1)$	313.29
β_0	3.5866^{***}
Std.Err.	(0.0000)
Observations	80

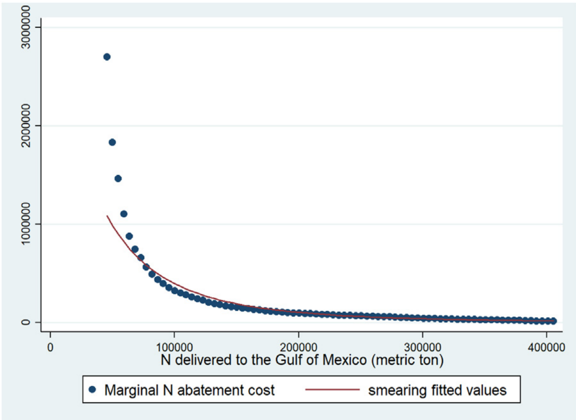

Fig. 3. Marginal value product of N runoff into the Gulf of Mexico.

the estimates in Rabotyagov et al. (2014) correspond to a 19 % reduction in both N and P loads. Conversely, we estimate the annual cost of a 45 % N reduction N in the Gulf of Mexico, following the goal of the 2008 Gulf Hypoxia Action Plan (US EPA, 2008). Second, Rabotyagov et al. (2014) estimated the costs of best management practices (BMPs) on agricultural working land. Our model reduces N runoff through per ha N fertilizer and crop acreage changes without explicit consideration of BMPs. Third, we considered losses in consumer and producer surplus in four major crop markets in the U.S. as opposed to costs estimated in Rabotyagov et al. (2014) that do not include consumer and producer welfare values.

The results for the 45 % N runoff reduction in the Gulf of Mexico are presented in Table 5. The equilibrium prices of corn, soybean and wheat increase by 22.2 %, 14.4 % and 5.7 %, respectively; while sorghum price decreases by 14.4 %. In response to the 45 % N runoff reduction to the Gulf of Mexico, crop production shifts from within to outside the MRB. Within the MRB, acreages of corn, soybean, wheat and sorghum decrease by 8.1 %, 11.2 %, 0.0 % and 16.7 %, respectively. Outside the MRB, acreages of corn, soybean, wheat and sorghum increase by 41.7 %, 25.5 %, 3.4 % and 100 %, respectively. Within the MRB, N use decreases by 20.0 %, and water use increases by 94.6 %, implying that constrained N use may increase the risk of water scarcity.

The cost estimates provided above are obtained with possible relocation of N intensive crop production from within to outside the MRB, which can result in potential N use and runoff increases in counties and waterbodies outside the MRB. To address this, we estimated the costs of 45 % N reduction in the Gulf of Mexico with an additional restriction that limits the relocation of N intensive crops from the MRB to other regions in the U.S. In this scenario, county planted acreage outside of the MRB is fixed at the baseline values. The results are presented in the fourth column of Table 5. The restriction to limit the relocation of N intensive crops reduces total surplus by $0.9 billion ($211.9 - $211 billon), which can be viewed as the cost of environmental quality status quo in other U.S. regions when pursuing the 45 % N reduction goal in the Gulf of Mexico. This restriction results in higher prices of N intensive crops as aggregate supply declines. Although N delivery to the Gulf is reduced by 45 % as intended, total N use in the MRB is greater than the corresponding N use without the crop relocation constraint. N use within the MRB is redistributed to achieve the 45 % reduction in runoff without increasing N use outside of MRB. N use increases (decreases), relative to the scenario without the N intensive crop relocation constraint, in areas with lower (higher) nutrient delivery ratios.

Table 5
Price and acreage results for a 45 % reduction in N runoff to the Gulf of Mexico, with percentage change in parentheses.

	Baseline	45 % N reduction in the Gulf of Mexico	45 % N reduction in the Gulf of Mexico with N use unchanged outside the MRB
Corn price ($/metric ton)	143.5	175.3 (22.2 %)	198.7 (38.5 %)
Soybean price ($/metric ton)	320.0	366.1 (14.4 %)	406.2 (26.9 %)
Wheat price ($/metric ton)	198.7	210.0 (5.7 %)	214.7 (8.1 %)
Sorghum price ($/metric ton)	110.8	94.9 (−14.4 %)	141.4 (27.6 %)
Corn (million ha)	38.2	39.3 (2.9 %)	36.4 (−4.7 %)
within MRB	29.8	27.4 (−8.1 %)	28.0 (−6.0 %)
outside MRB	8.4	11.9 (41.7 %)	8.4 (0%)
Soybean (million ha)	37.2	36.5 (−1.9 %)	34.6 (−7.0 %)
within MRB	27.8	24.7 (−11.2 %)	25.2 (−9.4 %)
outside MRB	9.4	11.8 (25.5 %)	9.4 (0%)
Wheat (million ha)	16.5	16.7 (1.2 %)	16.7 (1.2 %)
within MRB	10.6	10.6 (0.0 %)	10.8 (1.9 %)
outside MRB	5.9	6.1 (3.4 %)	5.9 (0%)
Sorghum (million ha)	2.4	2.7 (12.5 %)	2.3 (−4.2 %)
within MRB	1.8	1.5 (−16.7 %)	1.7 (−5.6 %)
outside MRB	0.6	1.2 (100.0 %)	0.6 (0%)
Corn production (million metric ton)	379.1	355.3 (−6.3 %)	337.8 (−10.9 %)
within MRB	323.1	278.2 (−13.9 %)	281.8 (−12.8 %)
outside MRB	56.0	77.1 (37.7 %)	56.0 (0%)
Soybean production (million metric ton)	119.8	114.6 (−4.3 %)	110.2 (−8.0 %)
within MRB	94.6	83.9 (−11.3 %)	85.0 (−10.1 %)
outside MRB	25.2	30.7 (21.8 %)	25.2 (0%)
Wheat production (million metric ton)	51.9	50.9 (−1.9 %)	50.4 (−2.9 %)
within MRB	28.8	27.5 (−4.5 %)	27.3 (−5.2 %)
outside MRB	23.1	23.4 (1.3 %)	23.1 (0%)
Sorghum production (million metric ton)	9.4	9.8 (4.3 %)	8.7 (−7.4 %)
within MRB	7.5	5.8 (−22.7 %)	6.8 (−9.3 %)
outside MRB	1.9	4.0 (110.5 %)	1.9 (0%)
Social Welfare (million $)	217,900	211,900 (−2.8 %)	211,000 (−3.2 %)
N applied within MRB (1000 metric tons)	8988	7188 (−20.0 %)	7363 (−18.1 %)
Total irrigation water use within MRB (million acre-feet)	21.4	41.7 (94.9 %)	41.2 (92.5 %)
N Delivered to the Gulf of Mexico (metric ton)	455,570	250,564 (−45.0 %)	250,564 (−45.0 %)

4. Spatial distribution of changes in N use and runoff

The modeling exercise in this study corresponds to the social planner problem, where optimal solutions are obtained assuming costless implementation of spatially optimal production decisions. In practice, cooperative optimal solutions are difficult to attain using policy tools like aggregate emissions cap in the absence of institutions that enable implementation of tradeable emission permits (Horan and Shortle, 2011). One option to approximate spatially optimal land use may be to implement spatially explicit mitigation programs that approximate social welfare maximizing production activities. For example, prioritizing areas where the largest decrease in N use is optimal may be an option for approximating the socially optimal spatial configuration of abatement efforts. We disaggregate the results presented in the previous sections into county-scale representation to illustrate spatial heterogeneity in the implications of N price change and runoff constraint scenarios for production within the MRB.

In IHEAL, crop yields, crop acreage rotation requirements, edge of field N runoff, and N nutrient delivery ratios to the Gulf of Mexico are county specific. As a result, the sensitivity of optimal N use to N prices and to N runoff restrictions varies across counties. The results of the current work indicate that targeted N reduction policies and programs can support cost-effectiveness of efforts to reduce N runoff to the Gulf of Mexico. Such a strategy is consistent with previous studies that focused on mitigation of hypoxic zones through targeted BMP recommendations in the MRB (Rabotyagov et al., 2010, 2014; McLellan et al., 2015). Our spatially explicit results for achieving the N reduction goal in the Gulf of Mexico are consistent with Rabotyagov et al. (2014), where the UMRB and OTRB are prioritized for managing N runoff. However, unlike Rabotyagov et al. (2014) our model explicitly includes consumer and producer surplus values as part of the objective function. In addition, since our modeling framework is based on partial equilibrium formulation, we are also able to estimate impacts on commodity prices under various regulatory stringencies and scenario assumptions.

Below, we discuss the results presented in Section 4 under two scenarios: (i). 30 % reduction in N fertilizer cost relative to the 2018 price level, (ii). a 45 % N runoff reduction according to the 2008 Gulf Hypoxia Action Plan (US EPA, 2008). Two

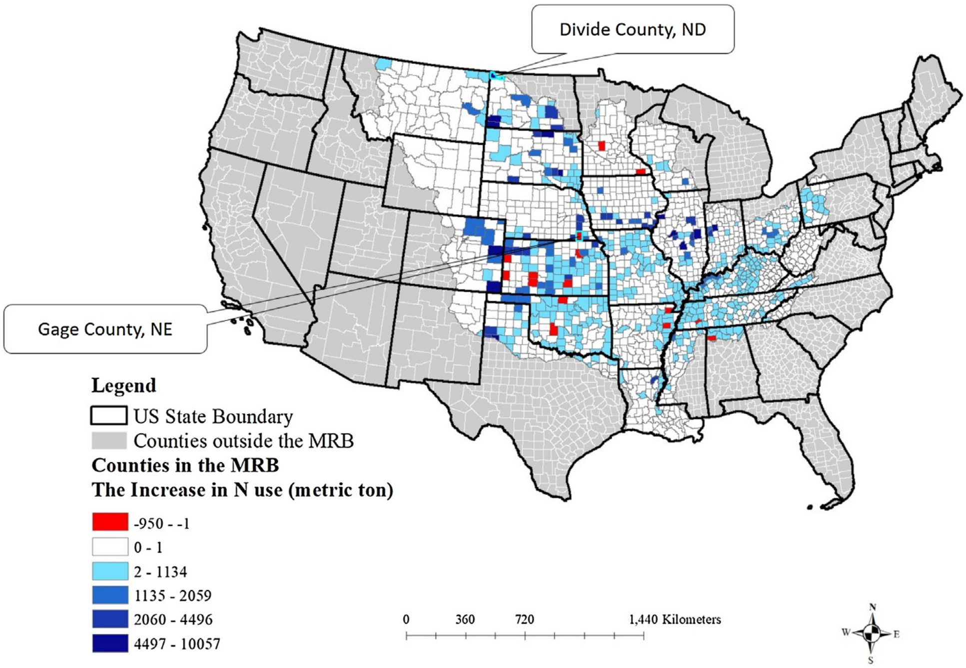

Fig. 4. Changes in N use in response to a 30 % drop in N fertilizer prices.

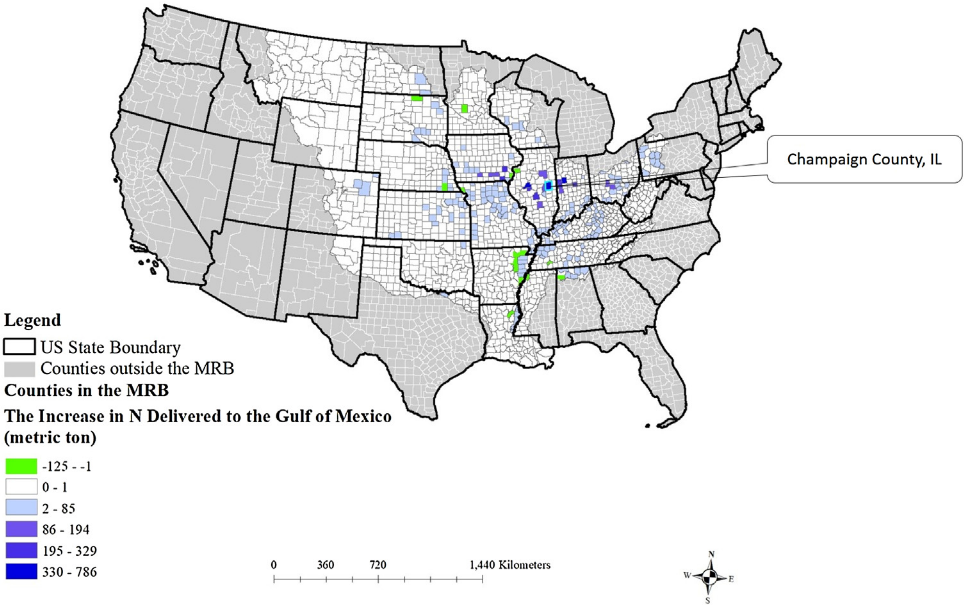

Fig. 5. Changes in N runoff in response to a 30 % drop in N fertilizer prices.

indicators are considered for both analyses: county-scale N use and the corresponding county-specific N runoff to the Gulf of Mexico.

Spatially explicit results for N use and N delivered to the Gulf of Mexico under the 30 % reduction in N price, from $0.98 to $0.69 per kg, are presented in Figs. 4 and 5, respectively. The figures show that (i) the counties with the greatest increase in N use do not necessarily contribute the most N delivered to the Gulf of Mexico, and (ii) while in most counties N use increases in response to lower N prices, in some counties N use declines. Within the MRB, N use increases in 528 counties and decreases in 15 counties in response to a 30 % lower N price.

The decline in N fertilizer prices by 30 % leads to an increase in N delivered to the Gulf from 455,570 to 462,490 metric tons. 74 % of the increased N loading in the Gulf comes from counties located in Illinois, Indiana and Iowa (UMRB). Among

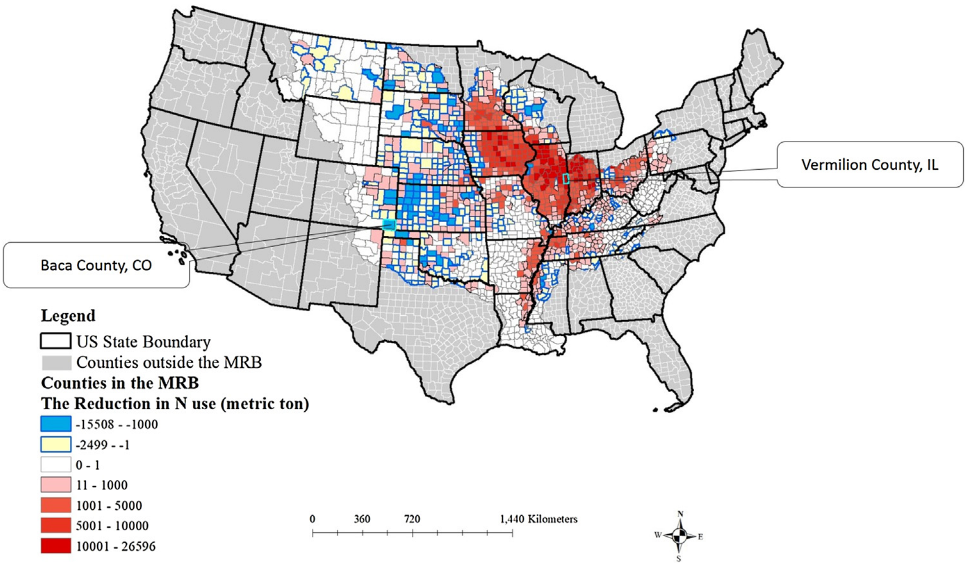

Fig. 6. N use change in response to a 45 % reduction in annual N runoff to the Gulf.

the counties where N use increased, the largest increase from 3,896 to 13,952 metric tons occurs in Divide County,[9] ND. The 10,056 metric tons increase in N application in Divide County leads to an 8 metric tons increase in exported N runoff and a 0.08-metric ton increase in N delivered to the Gulf of Mexico. The highest increase in N delivered to the Gulf (786 metric tons) comes from Champaign County, IL.[10] N use in this county increases from 17,400 to 22,989 metric tons.

N use declines in some counties when the price of N decreases because lower N prices lead to reallocation of N intensive crops to counties with greater productivity of such crops while other counties increase production of less N intensive crops. For example, N use declines the most in Gage county, NE,[11] from 15,572 to 14,622 metric tons. The reduction in N use reflects reduced crop acreages, from 74,925 to 70,024 ha for corn and from 1,134 to 178 ha for sorghum. On the other hand, soybean and wheat acreages increase from 74,115 to 74,844 and from 826 to 1,802 ha, respectively.

Figs. 6 and 7 present optimal spatial distribution of changes in N use and N delivery to the Gulf of Mexico to achieve a 45 % N runoff reduction to the Gulf relative to the baseline scenario. The results illustrate spatial heterogeneity in the distribution of optimal N use change and the corresponding reduction in N delivered to the Gulf. For example, the largest N use reduction (93 %) takes place in Vermilion County, IL.[12] The corresponding reduction in N delivered to the Gulf of Mexico is also the highest with 2,677 metric tons. The results indicate that the counties in dark red in both figures should be prioritized if spatially targeted N use mitigation policies are to be employed. Reduction in N use in these counties is optimal for reducing N runoff to the Gulf. Figs. 6 and 7 indicate that counties with high priority for management of N runoff are mainly located in Illinois, Indiana, Iowa, Ohio and Minnesota (UMRB and OTRB). Consistent with findings from previous studies (Rabotyagov et al., 2014; White et al., 2014; Marshall et al., 2018), the UMRB and OTRB are identified as critical sub-basins which can be prioritized for N and land use changes.

Spatial heterogeneity implies that under restricted N runoff to the Gulf, it may be optimal for some counties to increase N use while others decrease. For example, corn and wheat acreages increase from 7,685 to 26,604 ha and from 1,930 to 120,207 ha, respectively, in Baca County,[13] CO, which leads to a 15,508-metric ton increase in N use (1,492 metric ton in the baseline) and a corresponding 20-metric ton increase in exported N losses. Corresponding N delivery to the Gulf of Mexico increases by 2.4 metric tons. This result is intuitive given the low N runoff, which results in crop production shifting to Baca County and hence an increased N use under the binding constraint for N runoff from the MRB to the Gulf. These results suggest relocation of agricultural production activities as N runoff into the Gulf is restricted.

Land use change in response to the Gulf N runoff restriction is observed within as well as outside of the MRB unless a crop acreage change constraint is imposed outside of the MRB. Outside of the MRB, corn acreage increases in 351 counties (median corn acreage in baseline: 972 ha) and decreases in 11 counties (median corn acreage in baseline: 400 ha) when N

[9] U.S. Geological Survey (USGS) estimates of farm N fertilizer use in Divide County, ND was 5,344 and 9,160 metric tons in 2012 and 2017 respectively (Falcone, 2021).

[10] USGS estimates of farm N fertilizer use in Champaign County, IL was 28,906 and 23,308 metric tons in 2012 and 2017 respectively (Falcone, 2021).

[11] USGS estimates of farm N fertilizer use in Gage County, NE was 14,300 and 14,004 metric tons in 2012 and 2017 respectively (Falcone, 2021).

[12] USGS estimates of farm N fertilizer use in Vermillion County, IL was 18,062 and 18,240 metric tons in 2012 and 2017 respectively (Falcone, 2021). Our results show that optimal N use in this county declines from the baseline N use of 28,396 to 1,800 metric tons.

[13] USGS estimates of farm N fertilizer use for farm production in Baca County, CO is 4,949 and 6,024 metric tons in 2012 and 2017 respectively (Falcone, 2021).

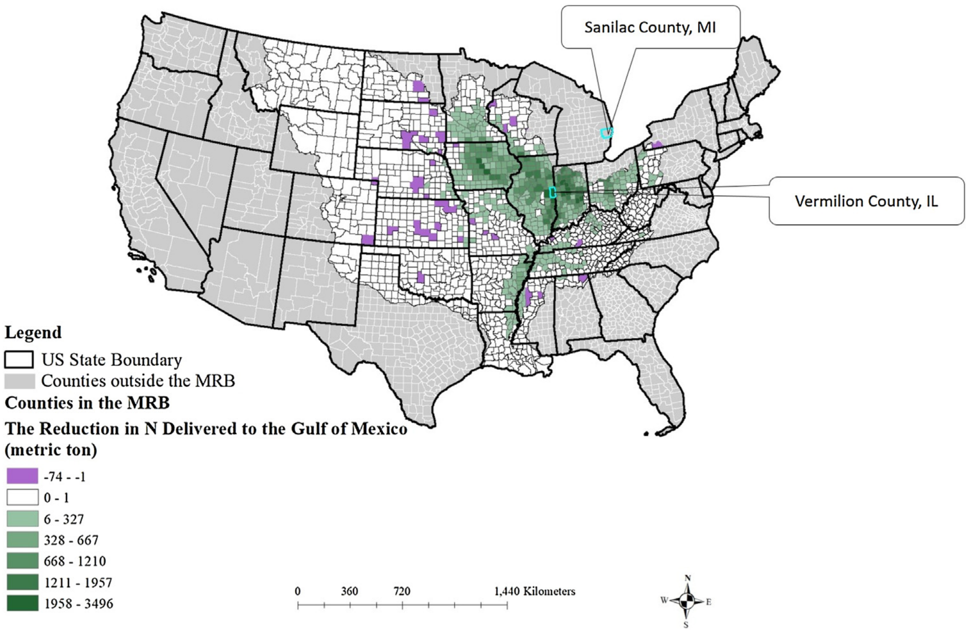

Fig. 7. N delivery change in response to a 45 % reduction in annual N runoff to the Gulf.

runoff into the Gulf is reduced by 45 %. Outside of the MRB, an increase in corn acreage decreases acreages of other crops (soybean, wheat and sorghum) in some counties. Similarly, the reductions of corn acreages are accompanied by increases in soybean, wheat and sorghum acreages. Although the increase in crop production outside of the MRB does not affect water quality in the Gulf of Mexico, other water bodies can be significantly harmed. For example, in Sanilac County, MI, located near the Saginaw Bay, corn production increases from 34,425 to 42,120 ha. This county was ranked second for grain sales in Michigan in 2017 Census of Agriculture. The increased corn production in this county may intensify N fertilizer use and nutrient runoff to the Great Lakes.

These shifts in the acreages of N intensive crops are important because they illustrate how N mitigation policies in one location, such as the Gulf of Mexico, can lead to worsening N outcomes in other locations. These results should serve as impetus for quantifying the extent to which N damages would shift from one location to another as a result of policies aiming to mitigate N damages in particular watersheds like the MRB.

We also observe the potential implications of N runoff abatement efforts for water use within the MRB. With N and irrigation as substitute production factors to some extent (Howitt et al., 2012; Mérel et al., 2014), one can expect irrigation to increase in response to stricter regulation of N use. This outcome, as a co-effect of policies that aim to reduce N runoff, is important to consider because water scarcity is a significant challenge in some regions within the MRB. In particular, agricultural production in Nebraska, westerns Kansas, north Texas and Oklahoma panhandle relies heavily on groundwater pumped from the Ogallala aquifer, where significant challenges with declining water table have been well documented (Ding and Peterson, 2012; Mrad et al., 2020). For the counties located in this region, restricting N use may need to be re-assessed considering the tradeoff between N pollution and local water scarcity.

5. Conclusions

We present the IHEAL model that combines a price endogenous partial equilibrium model with the HAWQS/SWAT to estimate N runoff to the Gulf of Mexico from crop production in the MRB under various input prices and N runoff control scenarios. Building on the previous research that relies on integrated hydro-economic models within the cost minimization framework for deployment of BMPs (Rabotyagov et al., 2010; Kling et al., 2014; Rabotyagov et al., 2014), we develop a price endogenous partial equilibrium model providing key insights grounded in economic consumer and producer surplus maximization in the major agricultural commodity markets. Partial equilibrium framework supports the estimation of the effect of policies on commodity prices. The approach is convenient for evaluating regulatory policies that account for endogenous producer and consumer choices. Producers respond to regulation by adjusting input use, while consumers respond to prices.

With ample availability of cheap natural gas in the U.S., we examine the impact of energy and N fertilizer prices on N use and runoff to the Gulf. Results indicate that the impact of variation in energy prices on N delivered to the Gulf of Mexico is modest. However, the impact of N prices is more pronounced. When N prices are reduced by 30 %, cumulative N use in the MRB and N delivered to the Gulf increase. A 30 % N price drop leads to a 3.5 % increase in N use within the MRB, resulting in a 1.5 % increase in N loading in the Gulf of Mexico. County-specific sensitivities of N use to a 30 % reduction in N price are heterogeneous. N application increases most in counties located in Kansas, North and South Dakota, Illinois, Indiana and Iowa. Counties located in Illinois, Indiana and Iowa contribute 74 % of total increased N runoff to the Gulf. Hence, counties in Illinois, Indiana and Iowa can be prioritized for BMP investment to mitigate water quality degradation in the Gulf.

We also estimate the opportunity cost of N runoff reduction to the Gulf in terms of the value of foregone crop production in the MRB given low energy and N prices in 2018. The estimated opportunity costs include both consumer and producer welfare losses. To reduce N loading in the Gulf of Mexico by 45 %, the average cost of N reduction through N use adjustment and land use change is $29.3/kg, and the total costs are 6 billion U.S. dollars. The results suggest that Illinois, Indiana and Iowa can be prioritized for managing N runoff as part of the strategy to cost effectively attain the N runoff reduction goal set by the EPA Hypoxia Task Force.

Several caveats of our analysis should be mentioned. First, the integrated model corresponds to the social planner's problem with perfect information. Crop production and N use results are obtained based on the maximization of aggregate social welfare. We do not consider non-cooperative behavior of producers across counties within the MRB.

Second, the model considers N runoff reduction only from changing planted acreage and N use without explicitly incorporating BMPs. The adjustment in N use to some degree implicitly reflects BMP outcomes. However, explicit consideration of BMPs may improve the accuracy of the estimates in this study.

Third, this study estimates N runoff only within the MRB. Our results show that production of N intensive crops can shift to counties outside the MRB when N runoff to the Gulf is restricted. This shift may lead to increased damages in the water bodies where production of N intensive crops increases. We do not account for damages in other water bodies as a result of N intensive crop acreage reallocation. To address this limitation, we re-estimate the costs with an additional constraint that restricts crop acreage changes outside of the MRB in response to the required reduction in N runoff to the Gulf and associated land use change within MRB.

Fourth, our analyses focus on the supply side of N runoff reduction by estimating the opportunity cost of achieving the desired decrease in N runoff to the Gulf. We do not address the demand for N runoff management. Full consideration of benefits from N use reduction will need to include not only the values of an improved aquatic ecosystem in the Gulf but also the values of co-benefits beyond the Gulf of Mexico. For example, Downing et al. (2021) assess the global benefits of avoided methane emissions from mitigating eutrophication in Lake Erie. They show that if P loading was reduced by 40 % in 2015 and maintained through 2050, the present value of climate change damage mitigation benefits would be $3.1 billion. The full consideration of benefits from N runoff reduction will also need to include the values of improved regional water quality within the MRB. Some of the benefit values from improved water quality have been estimated in prior literature. For example, Keiser (2019) examines the effects of water pollution on lake recreation demand in the U.S. Using the annual Conservation Reserve Program (CRP) cost of $1.7 billion reported by Hansen (2007), he estimates that water-based recreational benefits can exceed CRP costs by a factor of 2 to 1. Parthum and Ando (2020) estimate willingness to pay (WTP) for local water quality improvement in the Upper Sangamon River Basin, Central Illinois. The average WTP for a 50 % chance of achieving the water quality goal is $48.

Recognizing these caveats, this study offers important insights for mitigation of marine eutrophication and Hypoxia, which pose significant challenges in many agricultural production regions worldwide. Degraded regional water quality can have implications not only locally but also globally (Downing et al., 2021). Addressing the nutrient runoff externality in agricultural production requires policies that balance costs and benefits that include consumer and producer impacts as well as non-market benefits of improved water quality. We provide a model that can be extended to account for additional impacts, including consumer and producer welfare impacts in other markets as well as non-market values of environmental quality when such estimates are available. The framework in this study is particularly suitable for regions with sufficiently large agricultural sectors where changes in production can affect commodity prices. The framework can also be extended to the analysis of nutrient reduction policies in multiple regions simultaneously. Such a specification can be used to examine joint as well as independent nutrient reduction policies across multiple watersheds including comparison of price and quantity instruments.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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