Cross-Watershed Leakage and Agricultural Nutrient Runoff Reduction

Abstract

Agricultural nutrient runoff, particularly nitrogen (N), has been a major contributor to hypoxia in downstream coastal ecosystems. We use an Integrated Assessment Model (IAM) that combines economic and process-based biophysical tools to quantify N runoff leakage across three major US watersheds and to assess losses in consumer and producer surplus from decreased supply and higher prices when nutrient runoff is restricted. Reducing N runoff to the Gulf of Mexico by 45% a) can increase runoff to the Chesapeake Bay and Western Lake Erie by 4.2% and 5.5%, respectively, and b) results in annual surplus losses of $7.1 and $6.95 billion with and without restrictions on leakage to Lake Erie and the Chesapeake Bay, respectively. A coordinated reduction of N runoff to the Gulf by 45% and to the Chesapeake Bay by 25%, with no leakage to other US areas, costs $8.1 billion.

Keywords: Pollution Leakage, Watershed, Nitrogen, Hypoxia, Agriculture, Hydro-economic model, Prices.

Introduction

Agricultural nutrient runoff from individual watersheds has been extensively studied (Bosch et al., 2018; Kling et al., 2014; Liu et al., 2020; Rabotyagov et al., 2014; Rabotyagov et al., 2010; Ribaudo et al., 2001; Secchi et al., 2011). However, due to modeling capability limitations, no structural estimates are available on the interdependencies between nutrient runoff control efforts across watersheds. Ribaudo et al. (2001) demonstrate the potential for nutrient runoff leakage across watersheds due to regional regulation. Xu et al. (2022) also document the need for measuring the cross-watershed nutrient runoff leakage when restricting runoff to the Gulf of Mexico. The authors observe an increase in the acreage of fertilizer intensive crops outside of Mississippi Atchafalaya River Basin (MARB) when runoff to the Gulf of Mexico is restricted. Similarly, Marshall et al. (2018) also observe cross-watershed relocation of fertilizer intensive production in response to limiting runoff to the Gulf. However, none of the prior studies provide estimates for the magnitude of leakage or assess the implications of mitigating cross-watershed leakage for the costs of runoff reduction programs. For example, how significant is the potential increase in runoff to Chesapeake Bay or Lake Erie when runoff to the Gulf is restricted? We address this gap in the literature by presenting an Integrated Assessment Model (IAM) designed to quantify cross watershed nutrient leakage.

Agriculture is a major nonpoint source of nutrient pollution in rivers, lakes, estuaries, and coastal waters (Carpenter et al., 1998; Khanna et al., 2019; Shortle et al., 2022), resulting in eutrophication, harmful algal bloom, and hypoxia (Chang et al., 2021; Camargo & Alonso, 2006; Zillén et al., 2008). Hypoxia disrupts nutrient cycling, increases the acidity of the water column, damages marine habitats, degrades biodiversity, decreases fish catch, and limits recreation opportunities (Chang et al., 2021; Diaz & Rosenberg, 2008; Du et al., 2018). Hypoxic zones are sometimes called "dead zones" because fish either die due to a lack of dissolved oxygen or relocate to other, more habitable areas. Although hypoxia has existed since the earth's formation and can occur naturally, human activities, including agricultural production, increase the size and the number of dead zones. More than 400 coastal marine systems worldwide suffer from hypoxic zones (Diaz & Rosenberg, 2008; Du et al., 2018).

Northern Gulf of Mexico, Chesapeake Bay, and Western Lake Erie suffer from some of the largest and most publicized hypoxic zones in the US. Large portions of nutrient runoff to these ecosystems come from agricultural production in the Mississippi Atchafalaya River Basin (MARB) (Gupta et al., 2021; Rabotyagov et al., 2014; Diaz & Rosenberg, 2008), Chesapeake Bay Watershed (CBW) (Chang et al., 2021), and Maumee River Watershed (MRW) (Liu et al., 2020), respectively (*Figure 1*).

Programs have been established in these watersheds to reduce nutrient runoff. The Mississippi River/Gulf of Mexico Hypoxia Task Force aims to reduce the size of the Hypoxic zone in the Gulf to 5,000 km^2 by 2035 (USEPA, 2014, Rabotyagov et al. 2014). The Chesapeake Bay Total Maximum Daily Load (TMDL) seeks to reduce N loads by 25% relative to 2009 values (Chang et al., 2021). The objective of the revised 2012 Great Lakes Water Quality Agreement (GLWQA) is to reduce total phosphorus (P) loading by 40% relative to 2008 (Liu et al., 2020). Although the objectives of these programs individually have been extensively studied and supported with rich scientific literature, the interdependencies in terms of cross-watershed nutrient runoff leakage have yet to be quantified. We fill this gap by examining the spatial leakage of nitrogen pollution across these watersheds. We also provide the opportunity cost estimates for nitrogen runoff reduction objectives in MARB and CBW with alternate N leakage assumption scenarios.

Cross-watershed nutrient leakage is expected in response to regional agricultural N runoff reduction efforts because a decrease in fertilizer use or adoption of some of the best management practices (Rabotyagov et al., 2014) can increase marginal production costs and/or decrease production. As a result, prices can increase if the regulated region produces a large share of market supply. Higher prices, in turn, can serve as an incentive for producers in other, economically linked, but less regulated regions to increase pollution-producing output. Thus, nutrient runoff can "leak" from more to less regulated regions (Shortle et al., 2022). Similar pollution leakage in response to regional environmental regulation has been documented in other settings, including carbon emissions and deforestation (Babiker, 2005; Aichele and Felbermayer, 2015; Delacote et al., 2016). Mofette and Gibbs (2021) show how Soy Moratorium in Brazil resulted in production spillovers from more to less-regulated regions. Such leakages may (Babiker, 2005) or may not (Villoria et al., 2022) offset pollution reduction from corrective policies in the target region.

We study the interdependence of coastal nitrogen (N) runoff from agricultural production in MARB, CBW, and MRW (*Figure 1*). We examine the reduction of agricultural N runoff from MARB to the Gulf of Mexico by 45% and from the CBW to the Chesapeake Bay by 25%. These policies are examined individually and in combination with explicit control of N runoff leakage from more to less regulated watersheds.

We use a new Integrated Assessment Model (IAM) with an economic framework as the integration platform for biophysical and human systems in examining nutrient leakage across watersheds and estimating the opportunity costs of runoff reduction. We use the Integrated Hydro-Economic Agricultural Land use (IHEAL) model, which combines a price endogenous partial equilibrium commodity market representation, county scale agricultural land use, and process-based Soil and Water Assessment Tool (SWAT) (Xu et al., 2022). The model is extended for this study to include CWB and MRW with associated specifications for downstream coastal nutrient runoff. Unlike previous studies, we explicitly account for price feedbacks and multi-watershed nutrient runoff in leakage interdependencies and costs of runoff reduction (Rabotyagov et al., 2010, 2014; McLellan et al., 2015; Easton et al., 2020; Xu et al., 2022).

IHEAL is used for five scenario analyses that are benchmarked relative to the baseline business-as-usual solutions. In the first scenario, the aggregate N runoff to the Gulf is reduced by 45% relative to the baseline, consistent with the EPA hypoxia task force goal, and quantify the impact on N runoff to the Chesapeake Bay and Western Lake Erie. We dub this scenario as Gulf-45. In the second scenario, runoff to the Gulf is reduced by 45% and runoff to the Chesapeake Bay and Lake Erie is restricted to not exceed the runoff observed in the baseline solution. We refer to this scenario as the Gulf-45-R. In the third scenario, we impose a 25% reduction in N runoff to the Chesapeake Bay relative to the baseline solutions, consistent with the Chesapeake Bay TMDL program, and quantify the impact on N runoff to the Gulf and Western Lake Erie. This scenario is referred to as Bay-25. In the fourth scenario, we combine the 45% N runoff reduction to the Gulf and a 25% N runoff reduction to the Chesapeake Bay with a constraint that prevents additional runoff to Lake Erie relative to the baseline. This scenario is called Gulf-45_Bay-25-R. The last scenario extends the previous one by further constraining the acreage in the rest of the country (ROC) to the acreage observed in the baseline to prevent the relocation of N-intensive production and N leakage to the rest of the country (ROC). This scenario is called Gulf-45_Bay-25-NL.

In each scenario, we estimate the opportunity cost of reducing N runoff with and without constraints restricting N runoff leakage. The opportunity cost includes consumer and producer losses from decreases in the supply and increases in prices of affected major commodities. The analysis does not account for non-market benefits of reducing N runoff such as biodiversity, ecosystem services, recreation, aesthetics, etc. This study should not be interpreted as a cost-benefit analysis of N runoff reduction policies. Instead, our purpose and contribution are narrower, illustrating the potential for cross-watershed leakage and measuring the opportunity costs of various policy objectives in terms of forgone consumer and producer surplus in major commodity markets. N runoff regulations increase costs of production in the regulated region, which can result in lower commodity market supply. Assuming that commodity demand remains unchanged, price is expected to increase as supply declines. While the effect of decreased supply and higher prices on producer surplus can be negative or positive, the combined effect on consumer and producer surplus is negative. In this study, we estimate these combined welfare impacts in the affected commodity markets.

We find that reducing agricultural N runoff to the Gulf of Mexico by 45% can increase N runoff to the Western Lake Erie and to the Chesapeake Bay by 4% and 6% respectively. We also observe that the opportunity cost of reducing agricultural N runoff to the Chesapeake Bay is much lower ($400 million) than the cost of reducing runoff to the Gulf of Mexico ($6.95 billion). This result is expected because agricultural production in the MARB region is much greater than in the CBW.

Gulf of Mexico, Chesapeake Bay, and Western Lake Erie

The annual hypoxic zone in the northern Gulf of Mexico is one of the largest in the world, and MARB is the largest drainage basin in the US (Aulenbach et al., 2007). It includes the Upper Mississippi River Basin (UMRB), Lower Mississippi River Basin (LMRB), Missouri River Basin (MRRB), Arkansas-White-Red River Basin (ARB), and Ohio-Tennessee River Basin (OTRB). Agriculture in MARB represents 70% of US cropland and accounts for 50% of the N runoff to the Gulf. USGS estimates that about 90% of N entering the Gulf originates from the OTRB and UMRB (Goolsby et al., 1999). Despite the Mississippi River/Gulf of Mexico Hypoxia Task Force, initiated in 1997, the hypoxic zone grew from 16,670 km^2 in 2015 to 22,720 km^2 in 2017 (USEPA, 2021; Khanna et al., 2019). The task force's objective is to reduce the dead zone to 5,000 km^2, which requires at least

45% N and P reduction from MARB (USEPA, 2008; Robertson & Saad, 2013). The objectives differ by watershed and state. The Ohio/Tennessee and Upper Mississippi River Sub-basins contribute 80% of the nitrogen that reaches the Gulf of Mexico. Hence, these sub-basins require more attention for reducing nitrogen runoff than other regions (Kling et al., 2014). Numerous studies have examined hypoxia in the Gulf, N export, and best management practices to reduce cropland nutrient runoff (Kling et al., 2014; Rabotyagov et al., 2014; Rabotyagov et al., 2010; Robertson et al., 2019; White et al., 2014; Xu et al., 2022). However, the implications of Gulf N runoff reduction for N runoff to other downstream coastal ecosystems, like the Chesapeake Bay and Western Lake Erie, have yet to be examined.

The Chesapeake Bay receives nutrient runoff from a 165,000 km^2 watershed spanning six states with about 15 million people and is susceptible to eutrophication and hypoxia due to anthropogenic activities (Kemp et al., 2015; Boesch et al., 2001; Du et al., 2018). Approximately $2 billion had been spent as of 2017 on the Bay restoration activities (Kleinman et al., 2019). Over a decade ago, the USEPA collaborated with states in the Chesapeake Bay watershed to implement Total Maximum Daily Load (TMDL) for N, P, and sediment in each tributary draining into the Bay (USEPA, 2017). The TMDL was developed due to inadequate progress and low water quality in the Chesapeake Bay and restricts annual N and P runoff to 84.3 million kg (185.9 million lbs.) and 5.7 million kg (12.5 million lbs.), respectively. Agricultural production contributes over 50% of N runoff to the Bay (Boyer et al., 2002). Although dissolved oxygen in Chesapeake Bay has improved, reducing nonpoint pollution from agricultural production remains a significant challenge (Kleinman et al., 2019; Zhang et al., 2018). Therefore, reducing agricultural nutrient loadings via best management practices remains a major point of interest for water quality in the Chesapeake Bay TMDL (Bosch et al., 2018).

MRW is the largest drainage system in the Great Lakes region and discharges the most nutrient and sediment loads into the Western Basin of Lake Erie, contributing to the toxic algal blooms (Cousino et al., 2015; Liu et al., 2020; Scavia et al., 2017). The watershed includes 17,000 km^2 in three states (northwestern Ohio, northeastern Indiana, and southern Michigan). Eighty-five percent of P loadings in MRW come from agriculture (Liu et al., 2020). The United States (US) and Canada signed the Great Lakes Water Quality Agreement (GLWQA) in 1972to reduce total P loading to the Great Lakes (IJC, 1978). In 1987, the USEPA identified the 2007 km^2 of the MRW as an Area of Concern (AOC) due to agricultural nonpoint pollution (Cousino et al., 2015; US EPA, 2013). While P runoff is the primary contributor to Lake Erie eutrophication, excessive N loadings in late summer can exacerbate the algal bloom (US EPA, 2017; Liu et al., 2020; Scavia et al., 2017). Therefore, avoiding or reducing N runoff to Western Lake Erie is an important element of improving water quality in the bay. Lake Erie's western basin has been listed as impaired under section 303(d) of the Clean Water Act, in 2016, 2018, and 2020 due to nutrient loadings and algae growth. As a result, a proposed consent decree in a lawsuit (Environmental Law & Policy Center et al., v. United States Environmental Protection Agency, No. 3:19-cv-295 (ND Ohio)) requests Ohio to prepare a draft TMDL for the Maumee River Watershed (Maumee Watershed Nutrient TMDL) to address the nutrient and algae impairments for drinking water, aquatic life, and recreational uses in Ohio's Western Lake Erie (USEPA, 2022).

Methods

The Integrated Hydro-Economic Agricultural Land use (IHEAL) model combines an economic price endogenous partial equilibrium commodity market representation with spatial land use and process-based Soil and Water Assessment Tool (SWAT). Similar partial equilibrium economic frameworks have been used in other studies and settings (Havlik et al., 2011; Chen et al., 2014). Previous studies have employed Integrated Assessment Models (IAMs) that include hydrologic and economic components to explore the relationship between energy costs, land, and fertilizer use (Kling et al., 2014; Rabotyagov et al., 2010; Secchi et al., 2011; Xu et al., 2022).

The IHEAL model maximizes the producer and consumer surplus in four major commodity markets. The choice variables are national supply, demand, and county-scale production decisions with corresponding N use and irrigation. Model constraints include commodity-specific supply-demand balance, exports and imports, planted acreage, and land allocation as a convex combination of historically observed and synthetic county crop acreages. We follow Chen & Önal (2012) to obtain synthetic crop mixes from own & cross-price acreage and own & cross-lagged acreage elasticities. These elasticities are estimated from county production and price data from 2005 to 2019 using the fixed effect Arellano-Bond estimator (Xu et al., 2022).

Xu et al. (2022) present IHEAL.1 and use it to evaluate the relationship between N runoff to the Gulf of Mexico, and energy and fertilizer prices. The model includes county-scale agricultural production in the contiguous US and national partial equilibrium commodity market representation for corn, soybean, wheat and sorghum. Other commodities are cumulatively included in the model as part of county scale land use constraints (Chen and Önal, 2012; Chen et al., 2014). We extend Xu et al. (2022) by including the Maumee River Watershed and Chesapeake Bay Watershed to quantify the potential relocation of coastal N runoff from more to less regulated watersheds (*Appendix 1.1*). In this study we explicitly model Maumee River and Chesapeake Bay Watersheds using crop specific nutrient runoff and production functions. Hydrological Response Unit (HRU) "edge of field" nutrient runoff and yield estimates are obtained from the Hydrologic and Water Quality System (HAWQS). HRU-scale process-based SWAT parameters are integrated with county-scale agricultural production in the land use specifications using land area-weighted transformation. Furthermore, we add formulations for spatial downstream N runoff to Western Lake Erie and Chesapeake Bay from the respective watersheds, which allows for explicit modeling of cross-watershed N runoff leakage.

SWAT is a widely used semi-distributed hydrologic watershed quality model that incorporates weather, soil, land cover, and management parameters to quantify the environmental and productivity impacts of various production practices (Abbaspour et al., 2015; Arnold et al., 2012; Gebremariam et al., 2014; Liu et al., 2019; Wagena & Easton, 2018). The SWAT-based HAWQS online platform is used to obtain spatially explicit estimates for crop yields and N leaching as a function of per acre N fertilizer use (HAWQS, 2020). We link county-scale land use and N leaching with SWAT delivery ratios to obtain N loading in the Gulf of Mexico, the Chesapeake Bay, and Western Lake Erie. The delivery ratios are obtained from White et al. (2014), Chesapeake Bay Program (2020), and NRCS (2017) for MARB, CBW, and MRW, respectively. The advantage of SWAT is that it supports a scenario-based assessment of management practices and their environmental and productivity impacts.

The land use model includes 1,590, 157, 24, and 1,017 counties in MARB, CBW, MRW, and the rest of the country (ROC). Land use in the ROC is included to account for aggregate production activities influencing national supply estimates and commodity prices. All counties in the contiguous US where corn, soybean, wheat, or sorghum were produced in at least one year from 2005 to 2019 are included in IHEAL. Production activities in only MARB, CBW, and MWR are integrated with SWAT elements, including corresponding delivery ratios to obtain the downstream N runoff. The simulation period covers 2000-2018.

Four major commodities, including corn, soybean, wheat and sorghum are explicitly modeled to estimate N runoff while other crops are included in land use rotation constraints. Corn, wheat, and sorghum are some of the most N intensive major agricultural commodities produced in the US, while soybean is often planted in rotation with corn. Within MARB, corn, soybean, and sorghum yields depend on per acre N use and irrigation, while wheat depends only on N use. In CBW and MRW, corn, soybean, and wheat depend on N use. No irrigation is used, and no sorghum is produced in CBW and MRW. The commodities explicitly modeled in this study represent more than 90% of major crop acreages in each of the three watersheds and are most relevant for nitrogen runoff (Xu et al. 2022).

Crop prices and county acreages from 2005 to 2019 are obtained from USDA NASS (2020). Energy input, fertilizer, water, and other production costs come from USDA ERS (USDA ERS, 2019). Commodity demand elasticities are obtained from previous literature and are -0.28, -0.29, -0.34, and -0.3 for Corn, Soybean, Wheat, and Sorghum (Ishida & Jaime, 2015; Piggott & Wohlgenant, 2002; Westcott & Hoffman, 1999).

Results

Validation results demonstrate model reliability (see appendix tables A1 and A2), while baseline results serve as a reference point for the policy scenario analyses. The model is calibrated to produce the best possible replication of the observed land use and market data in the business-as-usual setting without the restrictions on N runoff. We include only the observed county historical crop mix data as part of model validation. Baseline solutions include synthetic in addition to the historical crop mix data. Synthetic crop acreages are added to provide greater model flexibility than the specification with only the historical crop mix. The additional flexibility is advantageous for analyzing scenarios where scenario constraints or parameter values differ significantly from the historically observed settings (Chen and Önal, 2012). The model with synthetic and historical crop acreages is used to produce five N runoff reduction scenario results, which are evaluated relative to the baseline results with no restrictions on N runoff.

We present the Gulf, Chesapeake Bay, and Western Lake Erie N runoff results when runoff to the Gulf and/or the Chesapeake Bay is individually or jointly curbed. The results are presented in Tables 1 and 2, and *Appendix, Tables A3 and A4*. Tables 1 and 2 show price, opportunity cost and N runoff results across scenarios. *Appendix, Tables A3 and A4* report corresponding land use and production results, respectively. Each table shows results for the contiguous US, individual watersheds, and the rest of the country (ROC), where applicable. Each table has five scenario results, including baseline, Gulf-45 (reducing N runoff to the Gulf by 45%), Gulf-45-R (reducing N runoff to the Gulf by 45% with a restriction for no increase in runoff to Lake Erie and the Chesapeake bay relative to the baseline), Bay-25 (reducing N runoff to the Chesapeake Bay by 25%), Gulf-45_Bay-25-R (reducing N runoff to the Gulf by 45% and Chesapeake Bay by 25% with a restriction for no increase in runoff to Lake Erie relative to baseline), and Gulf-45_Bay-25-NL (reducing N runoff to the Gulf by 45% and Chesapeake Bay by 25% with no leakage to Lake Erie and ROC).

Model Validation and Baseline Results

Appendix, Table A1 shows model validation outcomes, baseline solutions, and observed 2018 data for crop prices and land use in the contiguous US. Validation results for crop prices and acreages in panels A and B are similar to Xu et al. (2022)[1]. The simulated values are within 4% and 16% of the observed values in 2018. Hence, the validation solutions support using the model for policy scenario analysis. It is also reassuring that baseline results with synthetic crop acreage specification are reasonably close to the observed data.

Panels C, D, E, and F provide disaggregated land use estimates for three focus watersheds and the rest of the country (ROC). In most cases, corn, soybean, wheat, and sorghum acreages are slightly greater than the values observed in 2018. In MARB, land use is within 10% of the observed values. Corn, soybean, and wheat acreages in CBW (MRW) deviate from the observed values by 11%, 16%, and 107% (3%, -0.4%, and 21%), respectively. Although the wheat acreage percent deviations in CVW and MRW appear to be large, in absolute terms, the overestimation is insignificant because baseline wheat acreages in these regions are very small. Overall, the upward marginal bias of acreages for these crops is observed because the objective function explicitly includes consumer and producer surplus measures only for these four commodities. Other commodities, and associated benefits, are not included in the objective function and are instead collectively included in the model as part of the crop

[1] Some differences are observed for production and acreage in ROC because in Xu et al. (2022) MRW and CBW are included in ROC, while in this study these regions are modeled separately. In addition, unlike Xu et al. production activities in MWR and CBW are expressed as functions of N rather than using fixed average per acre yield.

acreage convexity constraints. As a result, the four commodities are slightly overproduced, and the corresponding prices are slightly lower than observed in 2018. However, the bias is insignificant in absolute terms and is unlikely to have a significant systematic impact on the assessment of N runoff leakage across watersheds relative to the baseline scenario, which is the main objective of this study.

Appendix, Table A2 shows validation results, baseline solutions, and estimates from the literature or data from USDA NASS (2019) for N use and runoff. N use in MARB is 6,692 thousand metric tons, approximately 53% of N use in the contiguous US. The corresponding N delivery to the Gulf of Mexico from corn, soybean, wheat, and sorghum production in MARB is 361.6 thousand metric tons, which is approximately 88% of the annual runoff to the Gulf from agricultural production (White et al., 2014; Elbakidze et al., 2022). Similarly, our baseline estimates for N runoff to the Chesapeake Bay and Lake Erie are 21.97 and 3.39 thousand metric tons, respectively. N delivery to the Chesapeake Bay is 55% of agricultural runoff in Ator et al. (2020). Chang et al. (2021) estimate the 2017 N loads to non-tidal CBW at 52 thousand metric tons from all sources, including legacy N. Our N runoff estimate for MRW is about 5% of the cumulative agricultural runoff from US and Canadian drainages to Lake Erie (Robertson et al., 2019).

Gulf-45

In this scenario, N runoff to the Gulf of Mexico is curtailed by 45% consistent with the EPA Gulf Hypoxia Task Force goals, and no additional constraints are imposed on runoff in other watersheds. The results in Table 1 show that corn, soybean, and wheat prices increase by 26.67%, 23.47%, and 5.43%, respectively, while sorghum price decreases by 22.56%. These results are similar to Xu et al. (2022) and are due to decreased (increased) production of more (less) N-intensive corn, soybean, and wheat (sorghum) (*Appendix, Tables A3 and A4*).

US Corn and sorghum acreages increase, while soybean and wheat acreages decrease (*Appendix, Table A3*). In MARB, all crop acreages decline except wheat. However, in the ROC, all crop acreages increase except wheat. In addition, corn acreages increase while soybean acreages decrease in CBW and MRW. Wheat acres move from CBW to MRW. Although US acres for some crops increase, production of all crops except sorghum decreases (*Appendix, Table A4*, Panel A) because production moves to less suitable lands relative to the baseline results. Hence, corn, soybean, and wheat prices increase, while sorghum prices decrease (Table 1). Lower MARB corn production and a consequent price increase result in increased corn production in CBW, MRW, and ROC. Increased production of corn replaces soybean in MRW, wheat and soybean in CBW, and wheat in ROC (*Appendix, Tables A3 and A4*, panels B, C, D, E).

As N-intensive crop production moves from MARB to other regions, so does N use and corresponding N runoff. Table 2 shows that N use in MARB declines by 21.58% to reduce runoff by 45%. N use increases by 5.78% in CBW and 10.19% in MRW. The corresponding N runoffs to the Chesapeake Bay and Western Lake Erie increase by 4.24% and 5.52%, respectively. These results are qualitatively similar to Ribaudo et al. (2001), where a 10% reduction in N use within the MARB increases onsite N loss in other regions by 1% with unclear impacts for downstream runoff.

The annual opportunity cost of 45% N runoff reduction to the Gulf is $6.95 billion (Table 1), representing the difference in consumer and producer surplus across scenarios with and without a 45% runoff reduction constraint. This estimate is greater than the $2.7 billion in Rabotyagov et al. (2014) because of differences in the modeling framework. Our estimates represent the opportunity cost - foregone consumer and producer surplus - of restricting N runoff. Rabotyagov et al. (2014)

estimate the operational costs of implementing best management practices for reducing N runoff. Our approach is similar to Xu et al. (2022), who provide a comparable cost estimate of $6 billion. The difference is that in Xu et al. (2022), MRW and CBW production activities are not modeled explicitly in terms of per acre N use, resulting in a loss of accuracy. They also do not account for N runoff to other areas besides the Gulf of Mexico.

Gulf-45-R

In the Gulf-45-R scenario, runoff to the Gulf of Mexico is curbed by 45% relative to the baseline as in the Gulf-45 scenario, but constraints are added to prevent N runoff leakage from CBW and MRW. That is, N runoff values to Lake Erie and to the Chesapeake Bay are restricted to be at or below the values observed in baseline scenario. Price (Table 1) and aggregate US land use (*Appendix, Table A3*) changes relative to the baseline are qualitatively similar to the previous scenario. However, prices are slightly lower in the Gulf-45-R than in Gulf-45. The lower prices relative to the Gulf-45 scenario are due to greater cumulative production (*Appendix, Table A4*). The additional Lake Erie and Chesapeake Bay runoff constraints effectively flatten the marginal production cost curves by rotating them clockwise, which results in greater output and lower prices, benefiting consumers but harming producers relative to the Gulf-45 scenario.

At the watershed scale, corn production slightly decreases in Gulf-45-R in MARB and increases in CBW, MRW and ROC relative to Gulf-45. Soybean and wheat production decrease in MARB and CBW and increase in MRW and ROC. Sorghum moves from MARB to ROC. These output changes in Gulf-45-R relative to Gulf-45 occur with corn acreage moving from MARB and MRW to CBW and ROC. Soybean acres move from MARB and CBW to MRW and ROC, while wheat acres move to ROC from MARB, MRW, and CBW (*Appendix, Table A3*). Corn production in

MARB increases even though acreage decreases as N use declines (*Appendix, Table A4*) because production moves to more productive MARB lands in Gulf-45-R relative to the Gulf-45 scenario where relocation other watersheds was an option. In the Gulf-45-R scenario, N runoffs to Lake Erie and the Chesapeake Bay are restricted, which limits the opportunity to offset decreased corn production in MARB by relocating to other watersheds when runoff to the Gulf is constrained.

N use in MRW and CBW is lower than in the Gulf-45 scenario but greater than in the baseline, although runoffs to Lake Erie and the Chesapeake Bay are constrained at baseline values (Table 2). Even though N runoffs to Lake Erie and the Chesapeake Bay are unaffected, local water quality may decline as N use increases in some counties. We discuss county scale N use and runoff results in greater detail below.

As expected, the opportunity cost of reducing N runoff to the Gulf by 45% is higher in the Gulf-45-R scenario than in the Gulf-45 scenario. Preventing cross-watershed leakage by restricting N runoff in Lake Erie and the Chesapeake Bay to be at or below the baseline values increases the annual opportunity cost of Gulf runoff reduction by $0.15 billion relative to the Gulf-45 scenario.

Bay-25

In this scenario, runoff to the Chesapeake Bay is curbed by 25% relative to the baseline, consistent with the Total Maximum Daily Load (TMDL) program (USEPA 2010). As expected, this policy has a much smaller impact on prices than the 45% reduction in N runoff to the Gulf (Table 1). Still, prices of N-intensive crops slightly increase while sorghum prices decrease. In percentage terms, corn, soybean and wheat acres and production decrease significantly in CBW (*Appendix, Tables A3 and A4*). As expected, CBW's largest declines are in the acreage (14.57%) and production (16.72%) of corn, the most N-intensive crop. Some corn production moves from CBW to MARB, MRW, and ROC. Soybean and wheat outputs decrease in MARB and increase in ROC. Although sorghum is not produced in CBW, the TMDL program results in a relocation of sorghum production from MARB to ROC as MARB's corn production expands in response to decreased corn production in CBW.

While N use and runoff decrease in CBW as intended, slight increases are observed in MARB and MRW. N runoffs to the Gulf and Lake Erie increase by 360 thousand metric tons (0.08%) and 3.5 thousand metric tons (1.36%), respectively (Table 2). The opportunity cost of the TMDL program in the Chesapeake Bay is $0.04 billion and, as expected, is much smaller than the Gulf N runoff reduction opportunity cost (Table 1). This cost includes foregone consumer and producer surplus and is significantly less than Kaufman et al. (2014) operational best management practice implementation costs for N, P, and sediment reduction in Chesapeake Bay. According to Kaufman et al. (2014), the operational costs of alternative strategies range from $0.36 billion to $0.9 billion.

Gulf-45_Bay-25-R

We evaluate the concurrent 45% and 25% runoff reduction to the Gulf and the Chesapeake Bay respectively with a restriction of no leakage to Lake Erie relative to the baseline. Similar to the results presented above, crop prices increase except for sorghum (Table 1). The magnitudes of price changes are comparable to the Gulf-45-R scenario, where runoff to the Gulf is reduced by 45% without an increase in runoff to Lake Erie and the Chesapeake Bay. The price changes are similar because CBW production represents a significantly smaller share of the commodity market than MARB. Chesapeake Bay's 25% N runoff reduction has a small effect on prices when imposed in isolation or in addition to the 45% reduction to the Gulf. As a result, restricting leakage to Western Lake Erie produces negligible impact on prices when runoffs to the Gulf and to the Chesapeake Bay are curbed by 45% and 25%. A similar resemblance of results between Gulf-45_Bay-25-R and Gulf-45-R is also observed for land use (*Appendix, Table A3*), production (*Appendix, Table A4*), and N runoff

(Table 2). The opportunity cost is $7.19 billion, which is $0.09 billion greater than Gulf-45-R (Table 1). Hence, the marginal opportunity cost of reducing N runoff to the Chesapeake Bay, on top of the 45% Gulf reduction, is more than twice as expensive as reducing Chesapeake Bay runoff independently.

Gulf-45_Bay-25-NL

We reevaluate the Gulf-45_Bay-25-R scenario with an additional constraint that land use in ROC counties remains the same as in the baseline. The purpose of this constraint is to limit the opportunity to relocate the N-intensive crop production from the regulated MARB and CBW to other areas and evaluate the associated impact on consumer and producer benefits. As expected, this scenario produces a significantly greater impact on crop prices as the opportunity to offset the decreased production in MARB and CBW by moving N-intensive crop production to other regions is limited. Prices of corn, soybean, wheat, and sorghum increase by 42%, 40%, 6%, and 14%, respectively, relative to baseline prices (Table 1). Unlike N runoff reduction scenarios presented earlier, even sorghum prices increase when land use change in ROC is restricted. Crop prices increase even though aggregate wheat and sorghum acreages increase. Although runoff leakage to Lake Erie is restricted and runoff to the Chesapeake Bay is curtailed by 25%, some corn acreage moves from the MARB to CBW and MRW (*Appendix, Table A3*). Production of the four crops declines in all areas except for corn in MRW (*Appendix, Table A4*). These changes in production result in an $8.1 billion loss of consumer and producer surplus relative to the baseline scenario (Table 1). Hence, preventing relocation of N runoff from MARB and CBW to other regions as runoff to the Gulf and the

Chesapeake Bay is reduced by 45% and 25%, respectively, costs an additional $0.91 billion annually in consumer and producer benefits.

Spatial N use and N runoff

The IHEAL model produces county-specific crop production, N use, and corresponding N runoff to the Gulf, Lake Erie, and the Chesapeake Bay. Figures.1 and 2 show county scale N use and corresponding runoff to the Gulf of Mexico, Chesapeake Bay, and Lake Erie.

Mississippi Atchafalaya River Basin (MARB)

The MARB is a large agricultural region that includes 1,590 counties where N fertilizers are intensively used to produce corn, soybean, wheat, and sorghum, among other commodities. Figures 2 and 3 show that in the scenarios where runoff to the Gulf is restricted, the most significant reduction in N use takes place in the Upper Mississippi River Basin (UMRB), a major source of nutrient runoff to the Gulf that has been identified for targeted best management prioritization in prior literature (Rabotyagov et al., 2010; Rabotyagov et al., 2014; White et al., 2014; Marshall et al., 2018; Xu et al., 2022). Yet, policies like the support of biofuel production have contributed to corn production and associated N use growth in the UMRB (Secchi et al., 2011). The top five counties with the greatest decline in N use are Champaign, Vermilion, Livingston, Edgar, and DeKalb in Illinois, where N use decreases by 21,950, 17,372, 12,882, 12,749, and 11,498 metric tons, respectively, in all scenarios where runoff to the Gulf is reduced by 45%.

The figures also show that while the key areas in the UMRB decrease N use and runoff, some counties in the MARB increase N use and runoff even with the 45% reduction of runoff to the Gulf. The three counties with greatest increase are Sully, SD, Cheyenne, CO and Deaf Smith, TX, with the increase ranging from 8,708 to 13,869 metric tons. The fertilizer use increases in MARB counties with relatively smaller delivery ratios, which supports nitrogen runoff reduction and agricultural production. Hence, relocation of N use and runoff is important to account not only across the major watersheds like MARB, CBW, and MRW, but also within those regions. Local water quality impacts of reducing N runoff to outlets like the Gulf of Mexico should be considered as part of policy evaluation (Xu et al., 2022).

Chesapeake Bay Watershed (CBW)

The CBW encompasses 157 counties with significant but substantially smaller agricultural production than MARB. Therefore, regulations in MARB have a significant impact on land use, agricultural production and environmental quality in CBW, but not vice versa. The Gulf-45 scenario results in Figures 2 and 3 show that N use in CBW and runoff to the Chesapeake Bay can increase significantly in response to curbing runoff to the Gulf. The greatest increase in corn acreage is found in Washington, MD, Cumberland, PA, and Rockingham, VA. As a result, N use in these counties increases by 1,298, 1,106, and 971 metric tons, respectively. The corresponding runoff from these counties increases by 94, 47, and 58 metric tons.

As expected, the increase in N use in some CBW counties is much smaller in the other scenarios where runoff to the Chesapeake Bay is required to either decrease by 25% or at least not increase relative to the baseline. To accommodate CBW N runoff requirements, fertilizer use is reallocated to counties with smaller delivery ratios. For example, in the Bay-25 scenario, N use decreases in hundred and twenty-one counties and increases in Henrico, VA. In the Gulf-45_Bay-25-R and Gulf-45_Bay-25-NL scenarios, the greatest increase in N use, 24 metric tons, occurs in

Onondaga, NY, as corn and wheat acreages increase by 1,417.5 and 580.37 ha, respectively. The corresponding N runoff from this county to the Chesapeake Bay increases by 9 metric tons.

Maumee River Watershed (MRW)

MRW includes 24 counties where agricultural production generates nutrient runoff to Lake Erie. The primary nutrient of concern in this region is P. However, the potential increase in N runoff can exacerbate algal bloom in Lake Erie. Figure 3 (Gulf-45) shows that without preventative measures, N runoff to Lake Erie increases from most counties in MRW. Even in scenarios where runoff to Lake Erie is constrained at baseline levels, runoff from some counties increases with an offsetting decrease in others (Figure 3 Gulf-45-R, Gulf-45_Bay-25-R, and Gulf-45_Bay-25-NL). The largest increase in N use is observed in Wood, OH, and Hillsdale, MI, with 2,319 and 2,318 metric tons, respectively, in the Gulf-45 scenario. However, these counties have low delivery ratios and only 12 and 16 metric tons propagate to Lake Erie, respectively. Conversely, Hancock and Putnam, OH, increase N use by 1,782 and 1,758, respectively, with 38 and 35 metric tons of additional N delivered to Lake Erie. As expected, leakage of N use to MRW is greater in the Gulf-45 than in Bay-25 scenario.

Conclusions

Nutrient runoff from agricultural production is a major contributor to downstream eutrophication. Reducing nutrient runoff to the Gulf of Mexico, Chesapeake Bay, and Western Lake Erie has been an important environmental objective for state and federal agencies. Initiatives and programs like the Gulf of Mexico Hypoxia Task Force, Chesapeake Bay TMDL, and the developing Maumee Watershed Nutrient TMDL aim to reduce runoff to the respective coastal waters. However, the interdependence of such efforts and the potential leakage of runoff from more to less regulated regions have not been examined, and cross-watershed leakage has not been explicitly factored in policy development. Previous literature documents the potential for non-MARB regions to increase crop production and N use when N runoff to the Gulf is curtailed (Marshall et al., 2018; Xu et al., 2022). However, no empirical leakage estimates have been produced to assess the impacts on downstream coastal waters.

We quantify the leakages of agricultural N runoff to the Gulf of Mexico, Chesapeake Bay, and Western Lake Erie when N runoff is reduced to the Gulf of Mexico and/or Chesapeake Bay. Cross-watershed leakage is estimated when runoff to the Gulf and the Chesapeake Bay is reduced by 45% and 25% individually and jointly according to the objectives of the Gulf Hypoxia Task Force and Chesapeake Bay TMDL (Marshall et al., 2018; Shortle et al., 2022). We evaluate five N runoff management scenarios, including a) a 45% reduction in runoff to the Gulf, b) a 45% runoff reduction to the Gulf and no leakage to Western Lake Erie and the Chesapeake Bay, c) a 25% runoff reduction to the Chesapeake Bay, d) a 45% and 25% runoff reduction to the Gulf and to the Chesapeake Bay, respectively, with a constrained runoff to Western Lake Erie, and e) a 45% and 25% runoff reduction to the Gulf and to the Chesapeake Bay, respectively, with no leakage to rest of the country. For scenarios a) and c), we provide estimates of cross-watershed leakage, and for each scenario, we estimate the opportunity cost in terms of foregone consumer and producer surplus relative to the baseline.

We also contribute to previous literature with a new Integrated Assessment Model, which uses an economic formulation as the core framework for model development, to evaluate cross-watershed leakage interdependencies. The integrated assessment model, IHEAL, estimates N runoff in the three watersheds using a price endogenous partial equilibrium commodity market formulation, spatial SWAT parameters for crop production and N leaching, and county scale delivery ratios for each of the three watersheds. The partial equilibrium model links regional production activities and provides a mechanism by which production in one region is influenced by production in other regions via price feedback, which allows for leakage modeling across watersheds. This approach differs from the previous studies that model best management practices but do not explicitly account for price feedback and pollution leakage, or do not account for price impacts and consumer and producer welfare losses. We model N runoff based on crop production functions expressed in terms of per acre N use via HAWQS/SWAT and an economic welfare maximization framework. Although modeling details differ, our results provide comparable cost estimates and support spatial targeting of critical N source areas for N use reduction documented in previous literature (Rabotyagov et al., 2010, 2014; McLellan et al., 2015; Easton et al., 2020; Xu et al., 2022).

Reducing N runoff to the Gulf by 45% can result in a relocation of N-intensive agricultural production, mainly corn, from MARB to CBW and MRW. Unless the efforts to reduce runoff to the Gulf are accompanied with corresponding programs for Western Lake Erie and the Chesapeake Bay, the N runoff to these water bodies can increase by 4.24% and 5.52%, respectively. This susceptibility highlights the significance of Chesapeake Bay TMDL and underscores the need to explicitly include N into the Maumee Watershed Nutrient TMDL even though P is the primary nutrient of concern. The opportunity cost, in terms of forgone consumer and producer economic benefits, is marginally greater for the coordinated multi-watershed strategy relative to the Gulf only program. The opportunity cost of reducing N runoff to the Gulf of Mexico increases from $6.95 to $7.1 billion if leakages to the Chesapeake Bay and Western Lake Erie are prevented.

Reducing N runoff to the Chesapeake Bay by 25% in isolation results in a small increase of N runoff to the Gulf (0.08%) and Lake Erie (1.36%), with an opportunity cost of $0.04 billion. As expected, the opportunity cost of the Chesapeake Bay N runoff TMDL is much smaller than the corresponding cost of the Gulf of Mexico Hypoxia Task Force goal because agricultural production in MARB is vastly greater than in the CBW. Hence, regulations in MARB have more significant impacts on prices and economic benefits for consumers and producers. The opportunity cost of reducing runoff to the Gulf of Mexico and the Chesapeake Bay by 45% and 25%, respectively, with no leakage to the Western Lake Erie, is $7.19 billion. Hence, the cost of reducing runoff to the Chesapeake Bay by 25%, given that the runoff to the Gulf has to decrease by 45%, costs an additional $0.09 billion relative to the N runoff reduction to the Gulf with no leakage to the Chesapeake Bay and Western Lake Erie. The opportunity cost increases to $8.1 billion in the most restricted scenario, where runoff to the Gulf of Mexico and the Chesapeake Bay is reduced by 45% and 25%, respectively, with no N leakage to other areas of the US, including Western Lake Erie.

The welfare opportunity costs we quantify in this study represent only consumer and producer benefits in the four major commodity markets and do not account for non-market benefits of reducing N runoff. Therefore, the estimates presented in this study should not be interpreted as Cost Benefit Analysis of N runoff reduction. The values of non-market benefits like ecosystem services, biodiversity and others, which motivate the efforts to reduce nutrient runoff to begin with, are outside the scope of this study but important to estimate and include in Cost Benefit Analysis.

References

1. Abbaspour, K. C., Rouholahnejad, E., Vaghefi, S., Srinivasan, R., Yang, H., & Kløve, B. (2015). A continental-scale hydrology and water quality model for Europe: Calibration and uncertainty of a high-resolution large-scale SWAT model. *Journal of Hydrology*, *524*, 733–752. https://doi.org/10.1016/j.jhydrol.2015.03.027
2. Aichele, R., & Felbermayr, G. (2015). Kyoto and carbon leakage: An empirical analysis of the carbon content of bilateral trade. *Review of Economics and Statistics*, *97*(1), 104-115.
3. Arnold, J. G., Kiniry, J. R., Srinivasan, R., Williams, J. R., Haney, E. B., & Neitsch, S. L. (2012.). *Input/Output Documentation Soil & Water Assessment Tool.*
4. Ator, S. W., Blomquist, J. D., Webber, J. S., & Chanat, J. G. (2020). Factors driving nutrient trends in streams of the Chesapeake Bay Watershed. *Journal of Environmental Quality*, *49*(4), 812–834. https://doi.org/10.1002/jeq2.20101
5. Aulenbach, B. T., Buxton, H. T., Battaglin, W. A., & Coupe, R. H. (2007). Streamflow and nutrient fluxes of the Mississippi-Atchafalaya River Basin and subbasins for the period of record through 2005. *Open-File Report*. https://doi.org/10.3133/OFR20071080
6. Babiker, M. H. (2005). Climate change policy, market structure, and carbon leakage. *Journal of International Economics*, *65*(2), 421-445.
7. Boesch, D. F., Brinsfield, R. B., & Magnien, R. E. (2001). Chesapeake Bay Eutrophication: Scientific Understanding, Ecosystem Restoration, and Challenges for Agriculture. *Journal of Environmental Quality*, *30*(2), 303–320. https://doi.org/10.2134/JEQ2001.302303X
8. Bosch, D. J., Wagena, M. B., Ross, A. C., Collick, A. S., & Easton, Z. M. (2018). Meeting Water Quality Goals under Climate Change in Chesapeake Bay Watershed, USA. *Journal of the American Water Resources Association*, *54*(6), 1239–1257. https://doi.org/10.1111/1752-1688.12684
9. Boyer, E. W., Goodale, C. L., Jaworski, N. A., & Howarth, R. W. (2002). Anthropogenic nitrogen sources and relationships to riverine nitrogen export in the northeastern USA. In *Biogeochemistry* (Vol. 57).
10. Camargo, J. A., & Alonso, Á. (2006). Ecological and toxicological effects of inorganic nitrogen pollution in aquatic ecosystems: A global assessment. *Environment International. 2006 Aug;32(6):831-49*. https://doi.org/10.1016/j.envint.2006.05.002
11. Carpenter, S. R., Caraco, N. F., Correll, D. L., Howarth, R. W., Sharpley, A. N., & Smith, V. H. (1998). Nonpoint pollution of surface waters with phosphorus and nitrogen. *Ecological Applications*, *8*(3), 559–568. https://doi.org/10.1890/1051-0761(1998)008[0559:NPOSWW]2.0.CO;
12. Chang, S. Y., Zhang, Q., Byrnes, D. K., Basu, N. B., & van Meter, K. J. (2021). Chesapeake legacies: The importance of legacy nitrogen to improving Chesapeake Bay water quality. *Environmental Research Letters*, *16*(8). https://doi.org/10.1088/1748-9326/ac0d7b
13. Chen, X., Huang, H., Khanna, M., & Önal, H. (2014). Alternative transportation fuel standards: Welfare effects and climate benefits. *Journal of Environmental Economics and Management, 67(3), 241-257*
14. Chen, X., & Önal, H. (2012). Modeling Agricultural Supply Response Using Mathematical Programming and Crop Mixes. *American Journal of Agricultural Economics*, *94*(3), 674–686. https://doi.org/10.1093/AJAE/AAR143

15. Chesapeake Bay Program, 2020. Chesapeake Assessment and Scenario Tool (CAST) Version 2019. Chesapeake Bay Program Office. Last accessed [July 2021] at https://cast.chesapeakebay.net
16. Cousino, L. K., Becker, R. H., & Zmijewski, K. A. (2015). Modeling the effects of climate change on water, sediment, and nutrient yields from the Maumee River watershed. *Journal of Hydrology: Regional Studies*, *4*, 762–775. https://doi.org/10.1016/j.ejrh.2015.06.017
17. Delacote, P., Robinson, E. J., & Roussel, S. (2016). Deforestation, leakage and avoided deforestation policies: A spatial analysis. *Resource and Energy Economics*, *45*, 192-210.
18. Diaz, R. J., & Rosenberg, R. (2008). Spreading dead zones and consequences for marine ecosystems. *Science*, *321*(5891), 926–929. https://doi.org/10.1126/SCIENCE.1156401/SUPPL_FILE/1156401-DIAZ-SOM.PDF
19. Du, J., Shen, J., Park, K., Wang, Y. P., & Yu, X. (2018). Worsened physical condition due to climate change contributes to the increasing hypoxia in Chesapeake Bay. *Science of the Total Environment*, *630*, 707–717. https://doi.org/10.1016/j.scitotenv.2018.02.265
20. Easton, Z.M., K. Stephenson, A. Collick, P.M. Fleming, E. Kellner, J. Martin, M. Ribaudo, and G. Shenk. 2020. Increasing effectiveness and reducing the cost of non-point source best management practice implementation: Is targeting the answer? Chesapeake Bay Science and Technical Advisory Committee Publication Number 20-002.
21. Elbakidze, L., Xu, Y., Gassman, P. W., Arnold, J. G., & Yen, H. (2022). Climate Change and Downstream Water Quality in Agricultural Production: The Case of Nutrient Runoff to the Gulf of Mexico. In American Agriculture, Water Resources, and Climate Change, Edited by G. Libecap and A. Dinar. NBER Chapters. DOI 10.3386/w30153, Available online https://www.nber.org/papers/w30153
22. Falcone, J. A. (2021). Estimates of county-level nitrogen and phosphorus from fertilizer and manure from 1950 through 2017 in the conterminous United States (No.2020-1153). In: US Geological Survey.
23. Gebremariam, S. Y., Martin, J. F., DeMarchi, C., Bosch, N. S., Confesor, R., & Ludsin, S. A. (2014). A comprehensive approach to evaluating watershed models for predicting river flow regimes critical to downstream ecosystem services. *Environmental Modelling and Software*, *61*, 121–134. https://doi.org/10.1016/J.ENVSOFT.2014.07.004
24. Goolsby, D. A., Battaglin, W. A., Lawrence, G. B., Artz, R. S., Aulenbach, B. T., Hooper, R. P., Keeney, D. R., & Stensland, G. J. (1999). *Flux and Sources of Nutrients in the Mississippi-Atchafalaya River Basin Topic 3 Report for the Integrated Assessment on Hypoxia in the Gulf of Mexico.* http://www.cop.noaa.gov
25. Gupta, G. V. M., Jyothibabu, R., Ramu, C. v., Yudhistir Reddy, A., Balachandran, K. K., Sudheesh, V., Kumar, S., Chari, N. V. H. K., Bepari, K. F., Marathe, P. H., Bikram Reddy, B., & Vijayan, A. K. (2021). The world's largest coastal deoxygenation zone is not anthropogenically driven. *Environmental Research Letters*, *16*(5). https://doi.org/10.1088/1748-9326/abe9eb
26. Havlík, P., Schneider, U. A., Schmid, E., Fritz, S., Skalsky, R., Aoki, K., phane De Cara, S., Kindermann, G., Kraxner, F., Leduc, S., McCallum, I., Mosnier, A., Sauer, T., & Obersteiner, M. (2011). Global land-use implications of first and second generation biofuel targets. *Energy Policy,* 39, 5690-5702. https://doi.org/10.1016/j.enpol.2010.03.030
27. HAWQS. (2020). *System and Data to model the lower 48 conterminous US using the SWAT model - HAWQS Dataverse.* https://dataverse.tdl.org/dataset.xhtml?persistentId=doi:10.18738/T8/XN3TE0

28. IJC. (1978). Great Lakes water quality agreement of 1978 with annexes and terms of reference, between the United States and Canada Signed at Ottawa, November 22, 1978. International Joint Commission, Windsor, ON
29. Ishida, K., & Jaime, M. (2015). A Partial Equilibrium of the Sorghum Markets in US, Mexico, and Japan. *2015 AAEA & WAEA Joint Annual Meeting, July 26-28, San Francisco, California* https://doi.org/10.22004/AG.ECON.205708
30. Kemp, W. M., Boynton, W. R., Adolf, J. E., Boesch, D. F., Boicourt, W. C., Brush, G., Cornwell, J. C., Fisher, T. R., Glibert, P. M., Hagy, J. D., Harding, L. W., Houde, E. D., Kimmel, D. G., Miller, W. D., Newell, R. I. E., Roman, M. R., Smith, E. M., & Stevenson, J. C. (2005). Eutrophication of Chesapeake Bay: historical trends and ecological interactions. *Marine Ecology Progress Series Mar Ecol Prog Ser*, *303*, 1–29. www.int-res.com
31. Khanna, M., Gramig, B. M., Delucia, E. H., Cai, X., & Kumar, P. (2019). Harnessing emerging technologies to reduce Gulf hypoxia. *Nature Sustainability*, *2*, 889–891. https://doi.org/10.1038/s41893-019-0381-4
32. Kleinman, P. J. A., Fanelli, R. M., Hirsch, R. M., Buda, A. R., Easton, Z. M., Wainger, L. A., Brosch, C., Lowenfish, M., Collick, A. S., Shirmohammadi, A., Boomer, K., Hubbart, J. A., Bryant, R. B., & Shenk, G. W. (2019). Phosphorus and the Chesapeake Bay: Lingering Issues and Emerging Concerns for Agriculture. *Journal of Environmental Quality*, *48*(5), 1191–1203. https://doi.org/10.2134/jeq2019.03.0112
33. Kling, C. L., Panagopoulos, Y., Rabotyagov, S. S., Valcu, A. M., Gassman, P. W., Campbell, T., White, M. J., Arnold, J. G., Srinivasan, R., Jha, M. K., Richardson, J. J., Moskal, L. M., Turner, R. E., & Rabalais, N. N. (2014). LUMINATE: Linking agricultural land use, local water quality and Gulf of Mexico hypoxia. *European Review of Agricultural Economics*, *41*(3), 431–459. https://doi.org/10.1093/erae/jbu009
34. Kaufman, Z., Abler, D., Shortle, J., Harper, J., Hamlett, J., & Feather, P. (2014). Agricultural Costs of the Chesapeake Bay Total Maximum Daily Load. Environmental Science & Technology, 48(24), 14131–14138. https://doi.org/10.1021/es502696t
35. Liu, H., Zhang, W., Irwin, E., Kast, J., Aloysius, N., Martin, J., & Kalcic, M. (2020). Best Management Practices and Nutrient Reduction: An Integrated Economic-Hydrologic Model of the Western Lake Erie Basin. *Land Economics*, *96*(4), 510‑530. https://doi.org/10.3368/wple.96.4.510
36. Liu, Y., Wang, R., Guo, T., Engel, B. A., Flanagan, D. C., Lee, J. G., Li, S., Pijanowski, B. C., Collingsworth, P. D., & Wallace, C. W. (2019). Evaluating efficiencies and cost-effectiveness of best management practices in improving agricultural water quality using integrated SWAT and cost evaluation tool. *Journal of Hydrology*, *577*(July), 123965. https://doi.org/10.1016/j.jhydrol.2019.123965
37. Marshall, E., Aillery, M., Ribaudo, M., Key, N., Sneeringer, S., Hansen, L., Malcolm, S. & Riddle, A. (2018). Reducing nutrient losses from cropland in the Mississippi/Atchafalaya River Basin: Cost efficiency and regional distribution, , ERR-258, U.S. Department of Agriculture, Economic Research Service.
38. McLellan, E., Robertson, D., Schilling, K., Tomer, M., Kostel, J., Smith, D., King, K., 2015. Reducing nitrogen export from the Corn Belt to the Gulf of Mexico:agricultural strategies for remediating hypoxia. Journal of the American Water Resources Association, 51(1), 263–289, http://dx.doi.org/10.1111/jawr.12246
39. NRCS, 2017. Conservation Practice Adoption on Cultivated Cropland Acres: Effects on Instream Nutrient and Sediment Dynamics and Delivery in Western Lake Erie Basin, 2003-

06 and 2012. Conservation Effects Assessment Project (CEAP), Cropland Special Study Report. Accessed 30th June 2022. Online at https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcseprd1355824.pdf
40. Piggott, N. E., & Wohlgenant, M. K. (2002). Price elasticities, joint products, and international trade. *Australian Journal of Agricultural and Resource Economics*, *46*(4), 487–500. https://doi.org/10.1111/1467-8489.T01-1-00056
41. Rabotyagov, S. S., Campbell, T. D., White, M., Arnold, J. G., Atwood, J., Norfleet, M. L., Kling, C. L., Gassman, P. W., Valcu, A., Richardson, J., Turner, R. E., & Rabalais, N. N. (2014). Cost-effective targeting of conservation investments to reduce the northern Gulf of Mexico hypoxic zone. *Proceedings of the National Academy of Sciences of the United States of America*, *111*(52), 18530–18535. https://doi.org/10.1073/pnas.1405837111
42. Rabotyagov, S., Campbell, T., Jha, M., Gassman, P. W., Arnold, J., Kurkalova, L., Secchi, S., Feng, H., & Kling, C. L. (2010). Least-cost control of agricultural nutrient contributions to the Gulf of Mexico hypoxic zone. *Ecological Applications*, *20*(6), 1542–1555. https://doi.org/10.1890/08-0680.1
43. Ribaudo, M. O., Heimlich, R., Claassen, R., & Peters, M. (2001). Least-cost management of nonpoint source pollution: Source reduction versus interception strategies for controlling nitrogen loss in the Mississippi Basin. *Ecological Economics*, *37*(2), 183–197. https://doi.org/10.1016/S0921-8009(00)00273-1
44. Robertson, D. M., Saad, D. A., Benoy, G. A., Vouk, I., Schwarz, G. E., & Laitta, M. T. (2019). Phosphorus and Nitrogen Transport in the Binational Great Lakes Basin Estimated Using SPARROW Watershed Models. *Journal of the American Water Resources Association*, *55*(6), 1401–1424. https://doi.org/10.1111/1752-1688.12792
45. Robertson, D. M., & Saad, D. A. (2013). SPARROW models used to understand nutrient sources in the Mississippi/Atchafalaya River Basin. Journal of Environmental Quality, 42(5), 1422-1440.
46. Scavia, D., Kalcic, M., Muenich, R. L., Read, J., Aloysius, N., Bertani, I., Boles, C., Confesor, R., Depinto, J., Gildow, M., Martin, J., Redder, T., Robertson, D., Sowa, S., Wang, Y.-C., & Yen, H. (2017). Multiple models guide strategies for agricultural nutrient reductions. Frontiers in Ecology and the Environment, 15(3), 126–132. https://doi.org/10.1002/fee.1472
47. Secchi, S., Gassman, P. W., Jha, M., Kurkalova, L., & Kling, C. L. (2011). Potential water quality changes due to corn expansion in the Upper Mississippi River Basin. Ecological Applications, 21(4), 1068–1084. https://doi.org/10.1890/09-0619.1
48. Shortle, J., Ollikainen, M, and Iho, A., "Water Quality and Agriculture: Economics and Policy for Nonpoint Source Water Pollution" Palgrave Macmillan, Cham, Switzerland.
49. United States Environmental Protection Agency (USEPA), (2022). Proposed Consent Decree: Clean Water Act and Administrative Procedure Act Claims by the EPA. Regulations.gov Accessed online November 14, 2022.
50. United States Environmental Protection Agency (USEPA), (2021). Mississippi River / Gulf of Mexico Hypoxia Task Force (Accessed 26 October 2022) Northern Gulf of Mexico Hypoxic Zone | Mississippi River/Gulf of Mexico Hypoxia Task Force | US EPA
51. United States Environmental Protection Agency (USEPA), (2017). Addressing nutrient pollution in the Chesapeake Bay. https://www.epa.gov/nutrient-policy-data/addressing-nutrient-pollution-chesapeake-bay. (Accessed 24 January 2022).

52. United States Environmental Protection Agency (USEPA), (2014). Mississippi River Gulf of Mexico Watershed Nutrient Task Force New Goal Framework (Accessed 30 December 2021) https://www.epa.gov/sites/production/files/2015-07/documents/htf-goals-framework-2015.pdf.
53. United States Environmental Protection Agency (USEPA), (2013). "Maumee River", Great Lakes Areas of Concern http://www.epa.gov/greatlakes/aoc/maumee/index.html(retrieved 26.01.15).
54. United States Environmental Protection Agency (USEPA), (2010). Chesapeake Bay Total Maximum Daily Load for Nitrogen, Phosphorus, and Sediment (Annapolis, MD: U.S. Environmental Protection Agency) https://www.epa.gov/sites/default/files/2014-12/documents/bay_tmdl_executive_summary_final_12.29.10_final_1.pdf
55. United States Environmental Protection Agency (USEPA), (2008). Gulf Hypoxia Action Plan https://www.epa.gov/sites/default/files/2015-03/documents/2008_8_28_msbasin_ghap2008_update082608.pdf
56. United States Department of Agriculture (USDA) Economic Research Service (ERS). (2019). Fertilizer Use and Price. https://www.ers.usda.gov/data-products/fertilizeruse-and-price. (Accessed 30 Oct 2019).
57. United States Department of Agriculture (USDA) National Agricultural Statistics Service (NASS), (2020). US &All States County Data – Crops. Washington, DC. http://www.nass.usda.gov/. (Accessed 13 May 2021)
58. USDA NASS (United States Department of Agriculture National Agricultural Statistics Service). (2019). 2018 Irrigation and Water Management Data Now. available at https://www.nass.USDA.gov/Newsroom/archive/2019/11-13-2019.php (Accessed March 24, 2023)
59. USGS (United States Geological Survey) (2017). The Challenge of Tracking Nutrient Pollution 2,300 Miles (Accessed 6 Mar 2017) https://www.usgs.gov/news/challenge-tracking-nutrient-pollution-2300-miles.
60. Villoria, N., Garrett, R., Gollnow, F., & Carlson, K. (2022). Leakage does not fully offset soy supply-chain efforts to reduce deforestation in Brazil. Nature communications, 13(1), 1-10
61. Wagena, M. B., & Easton, Z. M. (2018). Agricultural conservation practices can help mitigate the impact of climate change. Science of the Total Environment, 635, 132–143. https://doi.org/10.1016/j.scitotenv.2018.04.110
62. Westcott, P. C., & Hoffman, L. A. (1999). Price Determination for Corn and Wheat: The Role of Market Factors and Government Programs. (No.1488-2016-123383). Market and Trade Economics Division, Economic Research Service, US Department of Agriculture, Technical Bulletin No.1878 https://doi.org/10.22004/AG.ECON.33581
63. White, M. J., Santhi, C., Kannan, N., Arnold, J. G., Harmel, D., Norfleet, L., Allen, P., DiLuzio, M., Wang, X., Atwood, J., Haney, E., & Johnson, M. V. (2014). Nutrient delivery from the Mississippi River to the Gulf of Mexico and effects of cropland conservation. Journal of Soil and Water Conservation, 69(1), 26–40. https://doi.org/10.2489/jswc.69.1.26
64. Xu, Y., Elbakidze, L., Yen, H., Arnold, J. G., Gassman, P. W., Hubbart, J., & Strager, M. P. (2022). Integrated assessment of nitrogen runoff to the Gulf of Mexico. Resource and Energy Economics, 67, 101279. https://doi.org/10.1016/j.reseneeco.2021.101279
65. Zhang, Q., Murphy, R. R., Tian, R., Forsyth, M. K., Trentacoste, E. M., Keisman, J., & Tango, P. J. (2018). Chesapeake Bay's water quality condition has been recovering: Insights

from a multimetric indicator assessment of thirty years of tidal monitoring data. Science of the Total Environment 637-638, 1617-1625. https://doi.org/10.1016/j.scitotenv.2018.05.025
66. Zillén, L., Conley, D. J., Andrén, T., Andrén, E., & Björck, S. (2008). Past occurrences of hypoxia in the Baltic Sea and the role of climate variability, environmental change and human impact. Earth-Science Reviews, 91(1–4), 77–92. https://doi.org/10.1016/J.EARSCIREV.2008.10.001

Figures and Tables

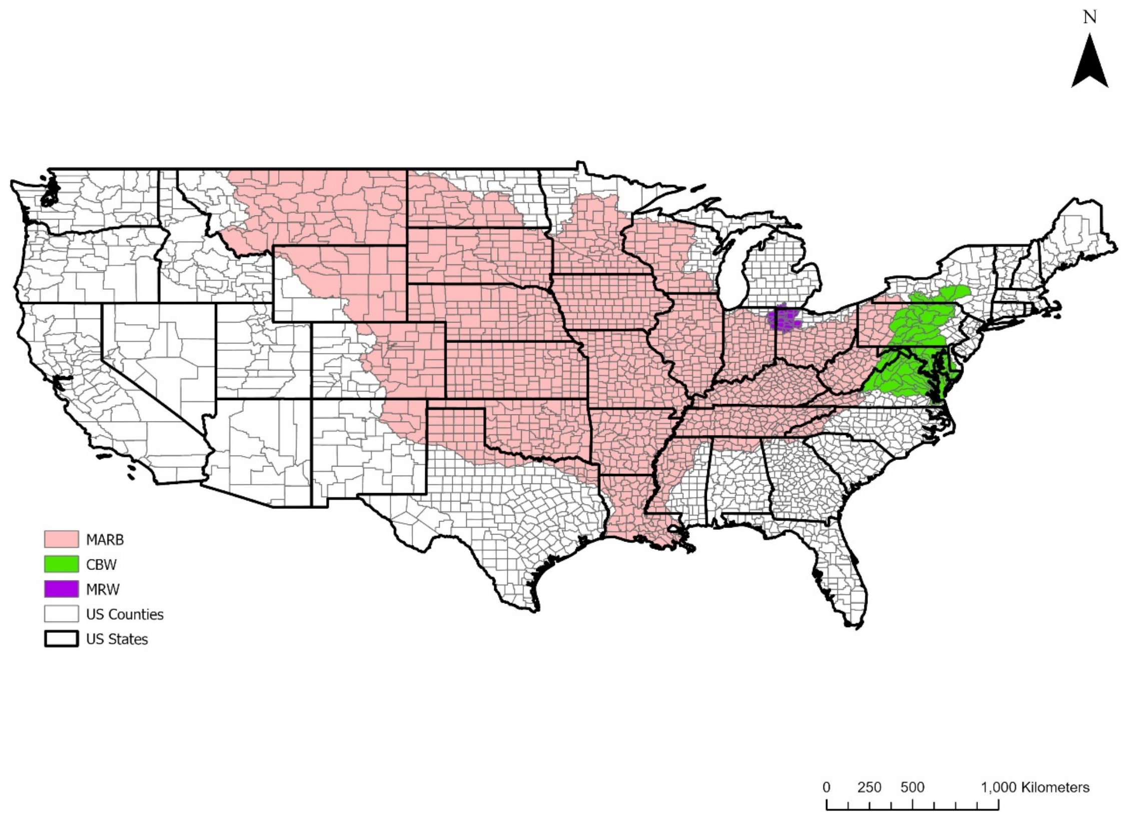

Figure 1. Mississippi Atchafalaya River Basin (MARB), Chesapeake Bay Watershed (CBW), and Maumee River Watershed (MRW).

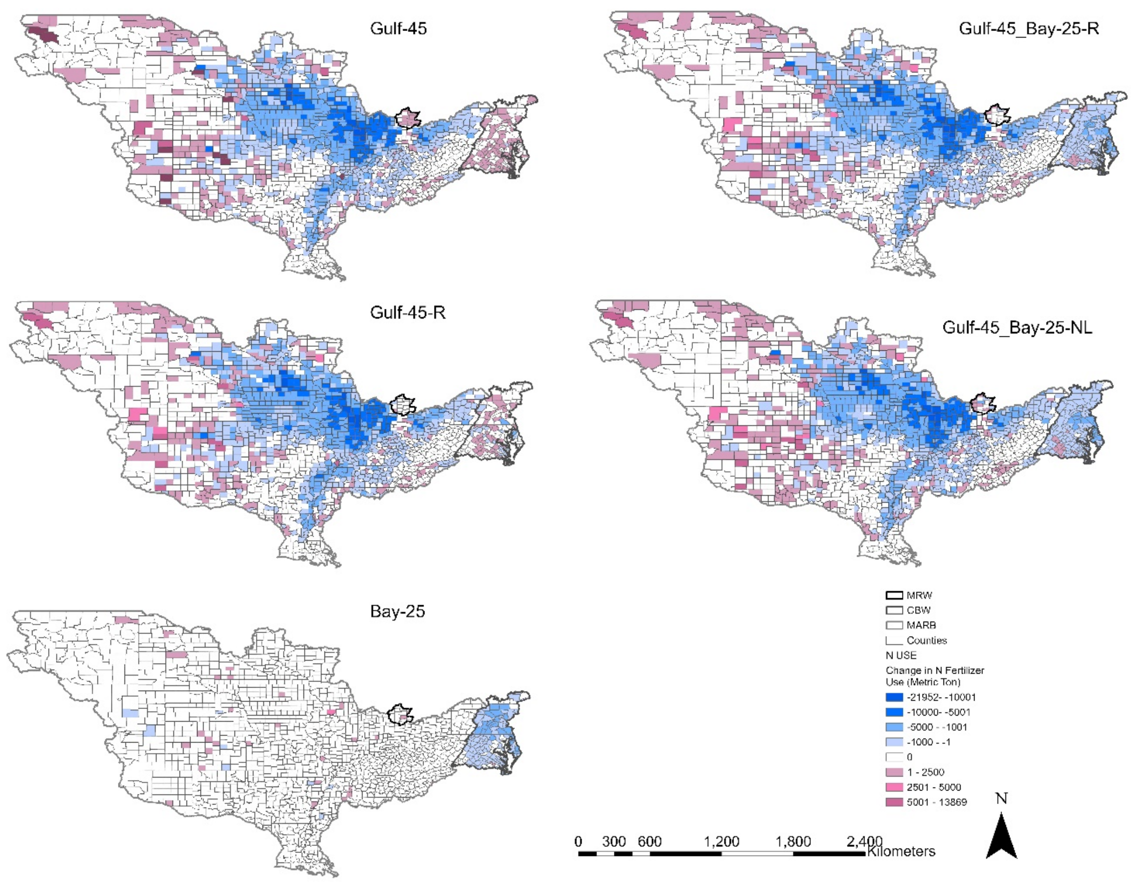

Figure 2. N fertilizer use changes.

This figure presents the county scale N fertilizer use changes in different scenarios. In Gulf-45 scenario, N fertilizer use increases in CBW and MRW in response to the 45% N runoff reduction in MARB. However, in the Gulf 45-R, Gulf-45_Bay-25-R and Gulf-45_Bay-25-NL scenarios, some counties in CBW and MRW reduce N fertilizer use. In the Bay-25 scenario, N fertilizer use in CBW declines with minimal changes in MARB and MRW.

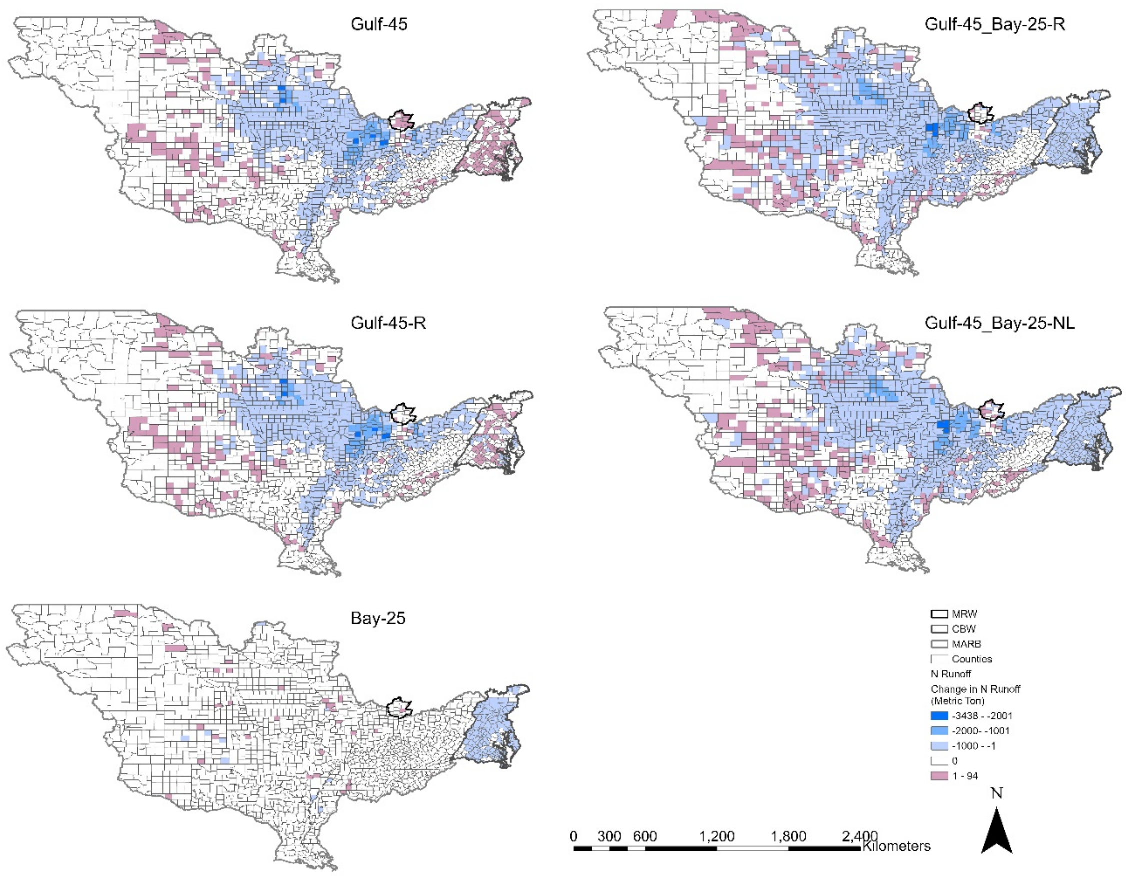

Figure 3. N runoff changes.

This figure shows the county scale N runoff changes in different scenarios to the respective coastal waters. In Gulf-45 scenario, N runoff increases to Western Lake Erie and Chesapeake Bay from most counties in the respective watersheds in response to the 45% N runoff reduction in MARB. In the Gulf 45-R, Gulf-45_Bay-25-R and Gulf-45_Bay-25-NL scenarios, some counties in CBW and MRW reduce N runoff. In the Bay-25 scenario, N runoff from CBW declines with minimal changes from MARB and MRW.

Table 1. Results: Commodity prices and opportunity costs

	Baseline	Gulf-45	Gulf-45-R	Bay-25	Gulf-45_Bay-25-R	Gulf-45_Bay-25-NL
			Prices ($/metric ton)			
Corn	140.772	178.317(26.67%)	177.48(26.08%)	141.402(0.45%)	178.32(26.67%)	199.406(41.65%)
Soybean	317.229	391.676(23.47%)	389.159(22.67%)	317.782(0.17%)	390.238(23.01%)	442.917(39.62%)
Wheat	226.007	238.284(5.43%)	237.225(4.96%)	227.304(0.57%)	239.385(5.92%)	238.966(5.73%)
Sorghum	108.533	84.043(-22.56%)	67.897(-37.44%)	107.71(-0.76%)	67.956(-37.39%)	124.047(14.29%)
			Opportunity Costs ($billions)			
Opportunity Costs		6.95	7.10	0.04	7.19	8.10

Notes: This table presents the commodity prices and opportunity costs for different scenarios. Prices go up for all commodities except for sorghum in Gulf-45, Gulf 45-R, Bay-25, and Gulf-45_Bay-25-R scenarios. However, all prices increase in Gulf-45_Bay-25-NL with the highest opportunity cost.

Table 2. N Use and Runoff

	Baseline	Gulf-45	Gulf-45-R	Bay-25	Gulf-45_Bay-25-R	Gulf-45_Bay-25-NL
	MARB N use and runoff					
N applied within the MARB (1000 metric tons)	6399.2	5018.5(-21.58%)	5006.6(-21.76%)	6413.7(0.23%)	5015.0(-21.63%)	5086.3(-20.52%)
N delivered to the Gulf (metric ton)	358910	197400(-45%)	197400(-45%)	359180(0.08%)	197400(-45%)	197400(-45%)
	CBW N use and runoff					
N applied within the CBW (1000 metric tons)	310.17	328.11(5.78%)	315.57(1.74%)	230.5(-25.69%)	243.76(-21.33%)	245.25(-21.01%)
N delivered to the Chesapeake Bay (metric ton)	22212	23154(4.24%)	22212(0%)	16659(-25%)	16659(-25%)	16659(-25%)
	MRW N use and runoff					
N applied within the MRW (1000 metric tons)	188.93	208.18(10.19%)	194.38(2.88%)	193(2.15%)	195.91(3.74%)	200.09(5.86%)
N delivered to Lake Erie (metric ton)	3420.9	3609.9(5.52%)	3420.9(0%)	3467.5(1.36%)	3420.9(0%)	3420.9(0%)

Appendix

1.1 IHEAL Model

The objective function (Equation 1) maximizes the sum of consumer and producer surplus (Xu et al., 2022).

$$\max_{X,L} \sum_c \int_0^{x_c^d} p_c^d\,(X_c^d, \omega_c) d\,X_c^d - \sum_{c,i,n} tc_{ci} * L_{cinw} - \sum_{c,i} FC_{ci} \;\; - \sum_{c,i} WC_{ci}$$

(1)

where, $P_c^d(X_c^d, \omega_c)$ is the national inverse demand function for crop c and X_c^d is aggregate demand. ω_c is the corresponding demand shifter. tc_{ci} is production cost per ha excluding N fertilizer 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 the N fertilizer and water costs for crop c in county i.

The model is constrained as follows:

$$X_c^d + exports \;\leq\; X_{ci}^s + imports \qquad \forall\, c, \tag{2}$$

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

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

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

$$\sum_n L_{cinw} = \sum_m \tau_{mi} * h_{cim} + \sum_n \gamma_{vi} * s_{civ} \quad \forall\, c, i, \tag{6}$$

$$\sum_m \tau_{mi} + \sum_n \gamma_{vi} = 1 \quad \forall\, i, \tag{7}$$

$$NR_k = \sum_i^{I\in k} \left(dr_{i,k} * \sum_{c,n,w} nrf_{cinw} * L_{cinw}\right) \forall\, k \tag{8}$$

Equation 2 balances the supply and demand for each commodity, where total demand for crop c cannot exceed total supply. Equation 3 shows that the supply of crop c from county i

cannot be greater than the production, where y_{cinw} denotes yield of crop c per ha in county i as a function of fertilizer use n, and water use *w*. Equation 4 estimates N fertilizer costs for crop c in county i, where θ_{cin} is the N fertilizer per ha cost for each fertilizer application scenario n. Equation 5 estimates total water costs for crop c in county i and irrigation schedule w, where μ_{ciw} is the per ha water cost. Equation 6 restricts land allocation to crop c in county i. County acreage of crop c is the weighted sum of historical and synthetic crop mix acreages. The indexes m and v represent historical and synthetic crop mixes, respectively (Chen & Önal, 2012); 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 the convex combination weights determined endogenously. Equation 7 restricts the sum of endogenous crop mix weights, τ_{mi} and γ_{vi} to equal 1, which ensures that the optimal county crop acreages are convex combinations of acreages observed in the past years and acreages simulated synthetically. Equation 8 estimates N runoff to each of the three coastal areas (*k*) using delivery ratios ($dr_{i,k}$) from county *i* to outlet *k*. nrf_{cinw} is the per-ha N runoff from planting crop *c* with fertilizer use *n* and irrigation *w* in county *i*.

Table A1. Validation and Baseline Results for Land Use and Prices

	Validation results	Baseline results	Observed data[2,3]
	A. Prices ($/metric ton)		
Corn	138.159	140.772	142
Soybean	307.444	317.229	314
Wheat	181.514	226.007	190
Sorghum	113.312	108.533	117
	B. Land use (million hectares) for the contiguous US.		
Corn	40.426	39.687	36
Soybean	39.148	38.157	36.1
Wheat	15.369	11.997	13.27
Sorghum	2.425	2.355	2.3
	C. Land use (million hectares) in MARB		
Corn	32.079	31.38	30.247
Soybean	28.859	27.984	30.145
Wheat	10.197	6.679	11.116
Sorghum	1.765	1.588	1.903
	D. Land use (million hectares) in CBW		
Corn	1.072	1.057	0.962
Soybean	0.816	0.819	0.703
Wheat	0.337	0.358	0.163
	E. Land use (million hectares) in MRW		
Corn	0.711	0.719	0.689
Soybean	0.984	0.968	0.988
Wheat	0.143	0.159	0.118
	F. Land use (million hectares) ROC		
Corn	6.564	6.531	9.634
Soybean	8.489	8.385	9.104
Wheat	4.692	4.801	3.359
Sorghum	0.66	0.768	1.9

[2] Source: USDA NASS, 2019

[3] 2018 is used for validation because commodity demand functions are calibrated using 2018 data.

Table A2. Validation and Baseline Results for N Use and N Runoff

	Validation results	Baseline results	Values from the literature
		MARB	
N applied within the MARB (1,000 metric tons)	6,692	6,399	12,610 (US)[4]
N delivered to the Gulf from fertilizer application (metric ton)	361,620	358,910	410,190 (MARB)[5]
		CBW	
N applied within the CBW (1,000 metric tons)	309	310	12,610 (US)
N delivered to the Bay from fertilizer application (metric ton)	21,966	22,212	40,000[6]
		MRW	
N applied within the MRW (1,000 metric tons)	183	189	12,610 (US)
N delivered to Lake Erie from fertilizer application (metric ton)	3,386	3,421	67,425[7]

[4] The sum of county-level farm N fertilizer use (Falcone, 2021).
[5] Source: White et al., 2014, N fertilizer use in crop production 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 operations and legume crops (USGS, 2017).
[6] Source: Ator et al., 2020.
[7] Source: Robertson et al., (2019) which includes total runoff to Lake Erie from US and Canada.

Table A3. Land Use

	Baseline	Gulf-45	Gulf-45-R	Bay-25	Gulf-45_Bay-25-R	Gulf-45_Bay-25-NL
	A: US land use (million hectares)					
Corn	39.687	40.04(0.89%)	40.277(1.49%)	39.663(-0.06%)	40.236(1.38%)	37.296(-6.02%)
Soybean	38.157	36.249(-5%)	36.455(-4.46%)	38.139(-0.05%)	36.403(-4.6%)	34.1(-10.63%)
Wheat	11.997	11.96(-0.31%)	11.984(-0.11%)	11.991(-0.05%)	12.014(0.14%)	12.296(2.49%)
Sorghum	2.355	2.407(2.21%)	2.562(8.79%)	2.358(0.13%)	2.564(8.87%)	2.363(0.34%)
	B: MARB land use (million hectares)					
Corn	31.38	28.456(-9.32%)	28.445(-9.35%)	31.461(0.26%)	28.463(-9.3%)	28.944(-7.76%)
Soybean	27.984	23.742(-15.16%)	23.722(-15.23%)	27.987(0.01%)	23.708(-15.28%)	23.972(-14.34%)
Wheat	6.679	6.855(2.64%)	6.759(1.2%)	6.671(-0.12%)	6.805(1.89%)	7.071(5.87%)
Sorghum	1.588	1.419(-10.64%)	1.365(-14.04%)	1.573(-0.94%)	1.367(-13.92%)	1.596(0.5%)
	C: CBW land use (million hectares)					
Corn	1.057	1.118(5.77%)	1.119(5.87%)	0.903(-14.57%)	1.05(-0.66%)	1.082(2.37%)
Soybean	0.819	0.8162(-0.34%)	0.714(-12.82%)	0.778(-5.01%)	0.79(-3.54%)	0.792(-3.3%)
Wheat	0.358	0.339(-5.31%)	0.337(-5.87%)	0.315(-12.01%)	0.291(-18.72%)	0.272(-24.02%)
	D: MRW land use (million hectares)					
Corn	0.719	0.733(1.95%)	0.729(1.39%)	0.719(0%)	0.733(1.95%)	0.74(2.92%)
Soybean	0.968	0.952(-1.65%)	0.964(-0.41%)	0.968(0%)	0.952(-1.65%)	0.951(-1.76%)
Wheat	0.159	0.162(1.89%)	0.154(-3.14%)	0.159(0%)	0.162(1.89%)	0.152(-4.4%)
	E: ROC land use (million hectares)					
Corn	6.531	9.733(49.03%)	9.987(52.92%)	6.58(0.75%)	9.991(52.98%)	6.531(0%)
Soybean	8.385	10.739(28.07%)	10.956(30.66%)	8.406(0.25%)	10.952(30.61%)	8.385(0%)
Wheat	4.801	4.603(-4.12%)	4.735(-1.37%)	4.847(0.96%)	4.755(-0.96%)	4.801(0%)
Sorghum	0.768	0.988(28.65%)	1.197(55.86%)	0.784(2.08%)	1.196(55.73%)	0.768(0%)

Table A4. Crop Production.

	Baseline	Gulf-45	Gulf-45-R	Bay-25	Gulf-45_Bay-25-R	Gulf-45_Bay-25-NL
	A: US production (million metric tons)					
Corn	381.2	353.04(-7.39%)	353.67(-7.22%)	380.72(-0.13%)	353.04(-7.39%)	337.23(-11.53%)
Soybean	120.09	111.81(-6.89%)	112.08(-6.67%)	120.02(-0.06%)	111.96(-6.77%)	106.11(-11.64%)
Wheat	29.9	29.179(-2.41%)	29.24(-2.21%)	29.82(-0.27%)	29.11(-2.64%)	29.132(-2.57%)
Sorghum	9.47	10.05(6.12%)	10.44(10.24%)	9.49(0.21%)	10.44(10.24%)	9.1(-3.91%)
	B: MARB production (million metric tons)					
Corn	326.14	279.62(-14.26%)	279.71(-14.24%)	326.85(0.22%)	279.87(-14.19%)	282.13(-13.49%)
Soybean	90.101	75.897(-15.76%)	75.806(-15.87%)	90.046(-0.06%)	75.752(-15.93%)	76.224(-15.4%)
Wheat	12.74	12.395(-2.71%)	12.234(-3.97%)	12.733(-0.05%)	12.332(-3.2%)	12.481(-2.03%)
Sorghum	6.482	5.389(-16.86%)	5.168(-20.27%)	6.419(-0.97%)	5.168(-20.27%)	6.112(-5.71%)
	C: CBW production (million metric tons)					
Corn	8.893	9.407(5.78%)	9.33(4.91%)	7.406(-16.72%)	8.466(-4.8%)	8.673(-2.47%)
Soybean	2.155	2.137(-0.84%)	2.133(-1.02%)	2.086(-3.2%)	2.107(-2.23%)	2.112(-2%)
Wheat	1.303	1.239(-4.91%)	1.231(-5.53%)	1.131(-13.2%)	0.914(-29.85%)	0.824(-36.76%)
	D: MRW production (million metric tons)					
Corn	7.708	7.963(3.31%)	7.825(1.52%)	7.737(0.38%)	8.466(9.83%)	7.971(3.41%)
Soybean	3.502	3.448(-1.54%)	3.485(-0.49%)	3.502(0%)	2.107(-39.83%)	3.442(-1.71%)
Wheat	0.681	0.693(1.76%)	0.656(-3.67%)	0.681(0%)	0.914(34.29%)	0.651(-4.41%)
	E: ROC production (million metric tons)					
Corn	38.46	56.052(45.74%)	56.807(47.7%)	38.73(0.7%)	56.827(47.76%)	38.46(0%)
Soybean	24.332	30.329(24.65%)	30.659(26%)	24.39(0.24%)	30.654(25.98%)	24.332(0%)
Wheat	15.176	14.853(-2.13%)	15.118(-0.38%)	15.275(0.65%)	15.171(-0.03%)	15.176(0%)
Sorghum	2.988	4.661(55.99%)	5.272(76.44%)	3.071(2.78%)	5.272(76.44%)	2.988(0%)

Appendix References

1. Ator, S. W., Blomquist, J. D., Webber, J. S., & Chanat, J. G. (2020). Factors driving nutrient trends in streams of the Chesapeake Bay Watershed. Journal of Environmental Quality, 49(4), 812–834. https://doi.org/10.1002/jeq2.20101
2. Falcone, J. A. (2021). Estimates of county-level nitrogen and phosphorus from fertilizer and manure from 1950 through 2017 in the conterminous United States (No.2020-1153). In: US Geological Survey.
3. Robertson, D. M., Saad, D. A., Benoy, G. A., Vouk, I., Schwarz, G. E., & Laitta, M. T. (2019). Phosphorus and Nitrogen Transport in the Binational Great Lakes Basin Estimated Using SPARROW Watershed Models. Journal of the American Water Resources Association, 55(6), 1401–1424. https://doi.org/10.1111/1752-1688.12792
4. USDA NASS (United States Department of Agriculture National Agricultural Statistics Service). (2019). 2018 Irrigation and Water Management Data Now. available at https://www.nass.USDA.gov/Newsroom/archive/2019/11-13-2019.php (Accessed March 24, 2023)
5. USGS (United States Geological Survey) (2017). The Challenge of Tracking Nutrient Pollution 2,300 Miles (Accessed 6 Mar 2017) https://www.usgs.gov/news/challenge-tracking-nutrient-pollution-2300-miles.
6. White, M. J., Santhi, C., Kannan, N., Arnold, J. G., Harmel, D., Norfleet, L., Allen, P., DiLuzio, M., Wang, X., Atwood, J., Haney, E., & Johnson, M. V. (2014). Nutrient delivery from the Mississippi River to the Gulf of Mexico and effects of cropland conservation. Journal of Soil and Water Conservation, 69(1), 26–40. https://doi.org/10.2489/jswc.69.1.26