Reinvestment of Revenue from Carbon Pricing Policies to Mitigate the Severity of Gulf of Mexico Hypoxia

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Abstract

Wetland restoration and construction are recognized as effective means of reducing the Hypoxia zone in the Gulf of Mexico. However, the cost of constructing and restoring wetlands can be high. In this study, we evaluate the impact of allocating carbon revenues generated by three hypothetical carbon prices ($51, $75, and $152 per US per tCO2e) to fund wetland restoration projects in two different scenarios: unconstrained nationwide and constrained state-level revenue allocation. Using an integrated agroecological, economic and hydrologic approach, we estimate the effects of these revenue allocation schemes on nitrate leaching from agricultural activities to the Gulf.

1. Introduction

The Mississippi River, alongside Atchafalaya River, are two major sources of nutrient discharges into the Gulf of Mexico (Goolsby et al., 2001). These rivers together account for more than 90% of nitrogen loads from the US into the Gulf (Lu et al., 2020). Excessive nitrogen fluxes are a primary cause of Gulf Hypoxia. According to the National Center for Coastal Ocean Science (NCCOS), the Gulf of Mexico encompasses the largest hypoxic zone in the US (NCCOS, 2022). As a response to the increased public concern associated with Hypoxia, the US Environmental Protection Agency (US EPA) established the Mississippi River/Gulf of Mexico Hypoxia Task Force (HTF) in 2001 to decrease the average area of the Gulf's Hypoxic zone to less than 5,000 km^2 by 2035 and to reduce total phosphorus and nitrogen loads by 20% by 2025 (US EPA, 2022). Since 1997, numerous conservation practices, including nutrient management, wetland restoration, and riparian buffers have been implemented to reduce anthropogenic inputs such as nitrogen fluxes. Despite these efforts, in 2021, the Gulf's Dead Zone grew to 16,405 km^2, exceeding the measured five-year average (National Oceanic and Atmospheric Administration, 2021). Given the significant increase in the size of the Hypoxic zone in 2021, meeting the 20% reduction target by 2025 may be challenging, and more aggressive measures may be necessary to achieve the overall goal of reducing the Hypoxic zone to less than 5,000 km2 by 2035.

Prior research has proposed various approaches to reduce nitrogen loads into the Gulf of Mexico (Baker et al., 2012; Cheng et al., 2020; Khanna et al., 2019; McLellan et al., 2015; Metaxoglou & Smith, 2022; Petrolia & Gowda, 2006; Rabotyagov et al., 2010; Robertson & Saad, 2013; Ruffatti et al., 2019; Smith et al., 2013; Tan et al., 2021; VanLoocke et al., 2017; Zhang et al., 2022). Some of these approaches include using improved soil erosion control methods (e.g., reduced tillage), reducing the application rate of nitrogen fertilizer, improving management of manure-nitrogen, changing cropping and tillage methods, controlling manure spreading, using nitrification inhibitors, and managing nitrogen application timing as part of precision agriculture practices.

In this study, we investigate the potential of wetland restoration and constructed wetlands on agricultural lands to reduce nitrate fluxes to the Gulf of Mexico and evaluate its cost effectiveness in large-scale policy scenarios. Previous studies have shown that wetlands can effectively remove excess nitrogen from agricultural landscapes (Cheng et al., 2020; Cheng & Basu, 2017; Evenson et al., 2021; Mitsch et al., 2001; Ribaudo et al., 2001; Van Meter et al., 2018), but we take this work a step further by considering its cost effectiveness and investigating its impact in feasible large-scale policy scenarios. Specifically, we develop three experimental policy scenarios that allocate the revenue generated by agricultural activities under a carbon pricing policy to wetland restoration efforts, in essence "doubling down" on the environmental benefits of greenhouse gas (GHG) regulation. We explore carbon pricing policies as a potential solution, given that restoration projects can be costly and funding can often be a limiting factor (Canning et al., 2021; Wylie et al., 2016). Under three carbon pricing scenarios, we estimate the carbon pricing revenue associated with production of corn and soybeans in the Mississippi River Basin (MRB). We allocate that revenue to wetland restoration projects according to different optimality conditions and constraints. Environmental and economic outcomes are then evaluated using a high-resolution gridded model of US corn-soy production and global trade.

Our study objectives are to maximize reductions in nitrate leaching and fluxes to the Gulf of Mexico in the MRB. We use a global computable general equilibrium model (ENVISAGE) to estimate the carbon revenue associated with corn and soybean production in the basin under three different carbon pricing scenarios ($51, $75, and $152 US per tCO2e). The estimated carbon revenue includes fossil fuel-related, electricity-related, and nitrate-related carbon revenues. We then allocate this revenue to wetlands projects according to different optimality conditions and constraints. We consider two allocation schemes reflecting different policy paradigms: a national-scale revenue allocation of the total available budget, unconstrained across the entire basin; and a state-level allocation that constrains funds to be allocated to the same state where revenues are generated. Two cost effectiveness metrics for wetlands are considered when allocating funds: nitrate leaching reduction per dollar of costs, and nitrate flux reduction per unit cost. The nitrate reductions are calculated using a macro-scale, rasterized hydrologic model (Water Balance Model).

Carbon pricing, whether implemented as an emissions trading system (ETS) or a tax, is an efficient policy instrument for reducing GHG emissions (Mankiw, 2009; Nordhaus, 1992; Thube et al., 2021). Through 2021, there have been 68 national and subnational carbon pricing instruments around the world that have generated $84 billion of revenue (World Bank, 2022). Revenues generated from carbon pricing policies are allocated to various sectors including agriculture. For example, the Regional Greenhouse Gas Initiative (RGGI)[1] program in the Eastern states and California's cap-and-trade auction both allocate portions of their revenues to fund wetland restoration projects. The funds are used to achieve fiscal, social, and environmental policy goals, including supporting low-income customers, promoting energy efficiency, and reducing greenhouse gas emissions (Hibbard et al., 2018). In California, most of the proceeds go to the Greenhouse Gas Reduction Fund, which allocates funds to five agencies and programs such as Climate Smart Agriculture, Low-Carbon Transportation, and Wetlands and Watershed Restoration (California Climate Investments, 2021). In 2019, $11.4 million was awarded to seven wetland restoration projects in California (California Department of Fish and Wildlife, 2022).

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[1] RGGI is a market-based program among Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, Vermont, and Virginia to cap power sector's CO_2 emissions (RGGI, 2022).

Carbon revenue can be used to achieve different objectives, such as climate mitigation (Black et al., 2021; Chen et al., 2020; Dolšak et al., 2020; Jakob, 2018; Sonnenschein & Smedby, 2019; World Bank, 2019), preventing carbon leakage (Partnership for Market Readiness, 2015; World Bank, 2019), achieving green economy (Dorband et al., 2022; Edenhofer et al., 2017; Kotchen et al., 2017; Maestre-Andrés et al., 2019; Sommer et al., 2022), investment in development projects (Douenne & Fabre, 2020; Jakob et al., 2016; Kotchen et al., 2017), tax reform (Marron & Morris, 2016; Narassimhan et al., 2018; Parry & Williams, 2010), and debt reduction (Bowen, 2015; Farmer & Steininger, 1999; Rausch, 2013). However, there are benefits and drawbacks to each option (Carbon Pricing Leadership Coalition, 2016; World Bank, 2019). For example, according to World Bank (2019), spending carbon revenues on tax reform can increase economic growth and enhance the efficiency of tax system. This revenue use option, however, requires identifying and targeting groups affected by higher carbon prices and can be less visible than other uses of revenue.[2] Therefore, the decision on how to allocate carbon revenue should align with the government's policy objectives, such as promoting economic growth, efficiency, public acceptance, and equal distribution of resources (Steenkamp, 2021). Overall, various studies highlight the importance of effective revenue management in achieving climate mitigation and environmental conservation goals while minimizing economic costs and promoting economic growth.

2. Creation of wetlands and buffers

In our study, we examine wetlands and their surrounding buffer zones as a means of achieving the Task Force's nutrient-reduction objectives. These techniques entail removing cropland from production. While it may be feasible to offset the loss of production by expanding production in other regions, we assume that land availability will limit this option in most areas. As a result, the decrease in production represents a nutrient abatement expense.

To convert cropland to wetland areas, we consider only land areas within the Mississippi River basin currently farmed with hydric soils. Gridded Soil Survey Geographic (gSSURGO) Database, which indicates areas suitable or unsuitable for wetland restoration (at 30-m resolution), was unprojected to a geographic coordinate system and then aggregated to determine the proportion of each 5 arc-minute grid cell suitable for wetland restoration. Following Cheng et al. (2020); Christianson et al. (2013); Liu et al. (2022), we assume that treating 100 acres of cropland area requires 0.5 acre of restored wetland plus 1.75 acres of wetland buffer. The estimated aggregate feasible area for wetland restoration (including buffer zones) within MRB is 4,500 km^2.

Wetland restoration simulations are based on the work of Zuidema et al. (2023); Liu et al. ((2022; 2022)). Our restoration scenario involves treating all tile-drained corn and soy crop areas with a 0.5% extent of wetlands plus their buffers, as long as the feasible wetland area within a grid cell is not exceeded.

3. Methodology

To assess the economic and environmental impacts of wetland restoration funded with carbon revenues, we employ an integrated agroecological, economic and hydrologic modeling framework. Specifically, we use a model framework that integrates the analysis of climate impacts and mitigation policies (ENVISAGE) with a gridded global partial equilibrium economic model

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[2] For a summary of benefits and limitations of carbon revenue use options, see World Bank (2019) and Carbon Pricing Leadership Coalition (2016).

of corn-soy production that captures yield and N loss responses to changes in nitrogen fertilizer applications (SIMPLE-G-US-CS). In response to input price changes, farmers adjust their fertilizer usage, affecting nitrogen leachate. We route nitrogen leachate through the Mississippi River Basin into the Gulf of Mexico and evaluate the removal of nitrate in wetlands using a process-based gridded hydrologic model (WBM).

Sections 3.1-3.3 detail the models, while Section 3.4 outlines how the cost of wetland restoration is estimated. In Section 3.5, we explain the scenarios for carbon revenue allocation. Section 3.6 describes the scenarios considered in the event of allocating carbon revenues.

3.1. ENVISAGE

Our analysis starts with running the global computable general equilibrium (CGE) model ENVISAGE (van der Mensbrugghe, 2024). The ENVISAGE model used in this study is calibrated to the Global Trade Analysis Project (GTAP) 10 Power Data Base with 2014 reference year, which distinguishes 141 regions and 76 sectors (Chepeliev, 2020). The electricity generation sector in the database is divided into 11 generation technologies, as well as transmission and distribution. For the purposes of this paper, we use an aggregation that includes 14 regions and 41 activities. The main strength of a CGE modelling framework, like ENVISAGE, is the consistent representation of the interdependencies between different sectors, agents, and markets in the global economy. By capturing both the supply and demand sides, the model represents adjustments in quantities and prices following the implementation of a policy shock. For instance, if carbon pricing is implemented in the model, this leads to increasing prices of energy, reducing energy supply and demand, as well as corresponding shifts in the energy supply mix, with increasing share of low-carbon technologies.

We consider three mitigation scenarios each involving a different social cost of carbon: $US 51, 76, and 152/ton CO_2-e, reflecting the underlying uncertainty in the appropriate social discount rate as well as in the science of climate impacts (US Government, 2021). This climate policy action is implemented in the United States only, with the analysis assuming prior implementation of a comparable policy in the European Union. We simultaneously implement a Carbon Border Adjustment Mechanism to protect domestic industries, avoid carbon leakage, and prevent the importation of additional carbon-intensive products (e.g., fertilizer) from countries with less stringent climate policies.

3.2. SIMPLE-G-US-CS

SIMPLE-G is a global partial equilibrium economic model that resolves grid-level details, focusing on agricultural production. SIMPLE-G-US-CS is a specialized version of SIMPLE-G (Baldos et al., 2020) that concentrates on the US, specifically including corn and soybeans. The model encompasses 48,317 grid cells with a resolution of 5 arcminutes and 15 'mega' grid cells representing aggregated regions outside the US. Each grid cell uses a unique multi-nesting CES production structure, allowing inputs to be substituted with a constant elasticity of substitution. Crop output at each grid cell is aggregated to meet national (US) or regional (non-US) demand, with corresponding crop prices. Crop demand, formed in national or regional markets, includes direct consumption, livestock production, biofuels, and processed food sectors. This demand is driven by population growth, income, biofuels policy, and technological changes in the agricultural sector. Agricultural input markets are cleared at the grid level for land and water, and at the national level for fertilizers and other inputs, depending on factor mobility. Converting cropland into wetlands reduces cropland area, affecting the demand for agricultural inputs, total output, and prices.

3.3. Hydrologic model-WBM

The Water Balance Model (WBM) is a macroscale, rasterized hydrologic model that incorporates many anthropogenic processes affecting the water cycle, and provides parsimonious representation of the nitrogen cycle in watersheds. The model simulates fluxes of nitrogen as nitrate such as partitioning leachate between runoff through shallow and deep flow paths, accumulation in groundwater, removal in wetlands, and transports nitrate reaching streams through the river network, accounting for in-stream removal, and ultimately estimates nitrate export to the Gulf of Mexico. Denitrification in wetlands is simulated assuming a well-mixed system with denitrification occurring in the benthic sediments parameterized as a temperature-dependent (Q10 = 2) process undergoing efficiency loss under increasing concentration. Wetlands intercept nitrate leachate from local croplands underlain by tile drainage prior to entering streams and are assumed to be physically separate from non tile-drained groundwater inputs and upstream riverine flow. Agro-IBIS leachate from the root zone provides a boundary condition for simulations spanning 1992 to 2007 at daily time steps. Many landscape features are represented by subpixel processing in the model including impervious and open water area, spatially variable crops, and edge-of-field wetlands.

3.4. Wetland cost estimation

Cost of wetland restoration is divided into two categories: management and maintenance cost and opportunity cost of wetland restoration. Per hectare management and maintenance cost of restoration is obtained from Bravard et al. (2022). These cost estimates include various items such as engineering design; site planning, engineering and preparation; excavation and soil movement; tile redirection; installation of structures; planting; seed costs for wetland; seed costs for buffer; mowing buffer for establishment; mowing buffer for management; monitoring. After personal communication with the authors, the cost items in Bravard et al. (2022) are updated to reflect 2022 inflation. Bravard et al. (2022) estimate annualized cost of restoration over a 20 year time-period using a real 2% discount rate. The average annualized per hectare maintenance and management cost of restoration is $6,500 US.

We define the opportunity cost of wetland restoration as the revenue foregone from corn-soy production due to wetland restoration. We assume that wetlands are constructed on marginal lands that are not well-suited for agricultural production and have low productivity (Kang et al., 2013). We obtain the yield of corn-soy product at a given grid cell from SIMPLE-G-US-CS model and use Lark et al. (2020) estimates to adjust the yields of corn-soy from SIMPLE-G-US-CS. Using nationwide USDA cropland maps and field-level changes, Lark et al. (2020) calculated the difference in yield between pre-existing croplands and lands converted from natural and semi-natural areas to crop production. The authors identified annual changes at a 30-m spatial resolution and combined these results with modeled corn, soybean, and wheat yields to determine the productivity of new croplands in comparison to that of pre-existing fields. The yield differences are calculated at national and local scale. Although Lark et al. (2020) evaluated the crop yield differences between newly converted croplands and preexisting agricultural lands, we utilized their estimates to determine the yield difference between areas converted to wetlands and remaining croplands. This can be supported by assuming that the newly converted land parcels assessed by Lark et al. (2020) are susceptible to various disruptions (e.g., changes in commodity prices, wetland-related regulations, biofuels, etc.), and are thus more likely to be brought on and off the market when policy shifts occur.

Per hectare cost of wetland in grid cell g is shown in equation (1):

$$C_g = p * \bar{y}_g * (1 + \alpha_g) + FC \tag{1}$$

where C_g is defined as per hectare cost of wetland in grid cell g, p is the price of composite corn-soy crop, $\bar{y}_g$ is the yield of composite corn-soy, α_g is the yield differences between marginal and productive lands obtained from Lark et al. (2020), and FC is the per hectare management and maintenance cost obtained from Bravard et al. (2022).

3.5. Carbon revenue allocation

Carbon revenue is allocated to wetland restoration until the revenue is exhausted using an algorithm that maximizes the reduction of nitrate leaching or fluxes to the Gulf by iteratively allocating funding for wetland restoration across all grid cells at the national level or in each state where the revenues are nonbinding. The algorithm prioritizes wetland restoration with the highest nitrate leaching and fluxes reduction per dollar spent, using a heuristic approach. Ultimately, this approach directs the carbon budget to the grid cells ranked highest. We estimate the reduction in nitrate leaching and fluxes under the unconstrained full wetland restoration scenario (baseline) and compare it to the reductions achieved under the national or state level carbon revenue allocation by cost effectiveness.

3.6. Scenario design

Our environmental and economic outcomes are presented under three hypothetical social cost of carbon ($51, $75, and $152 USD) and two different methods of distributing carbon revenues. Similar to Zuidema et al. (2023) the varying costs of carbon reflect the uncertainty surrounding the appropriate social discount rate and the science of climate impacts. It's important to note that our analysis assumes that a comparable climate policy has already been implemented in the European Union. To protect domestic industries, prevent carbon leakage, and curb the importation of carbon-intensive products from countries without a comparable climate policy, we also implement a Carbon Border Adjustment Mechanism (CBAM). This mechanism imposes a levy on the carbon content of imported goods entering the US, equal to the difference in carbon prices between the US and the source of the imports, as proposed by Böhringer et al. (2022). The carbon pricing policy raises energy costs across the board, leading to a significant increase in natural gas prices. This, in turn, causes the price of ammonia - a critical component of nitrogen fertilizer used in agriculture - to rise.

In this study carbon revenue allocation occurs at either the national or state level. In the national-level revenue allocation, the total carbon budget is allocated without constraints across the entire MRB. In contrast, in state-level budget constraints, the funds are allocated within the same state where the revenues are generated. This approach ensures that the benefits of carbon revenue allocation are distributed equitably within the state and can potentially lead to more targeted and effective use of the funds for nitrate reduction efforts.

4. Results

The implementation of climate mitigation policies can result in a permanent increase in costs for the ammonia fertilizer industry. This is due to the industry being taxed for both combustion and process-based emissions, leading to higher natural gas costs and significant impacts on fertilizer prices. Furthermore, the implementation of the Carbon Border Adjustment Mechanism (CBAM) means that importing nitrogen fertilizer from regions with less strict climate policies is no longer advantageous, further increasing prices and reducing fertilizer applications (Zuidema et al., 2023).

These policies can result in a reduction in on-farm nitrate leaching, leading to lower amounts of nitrate percolating into groundwater through recharge, as well as a decrease in concentrations in streams and rivers by approximately 2% (Figure 1). If these climate policies are combined with complete wetland implementation without any budget constraints, the reduction in nitrate leaching to streams and the Gulf can be even greater, up to roughly 3%. This highlights the potential for wetland restoration to have a dual impact on reducing nitrate leaching.

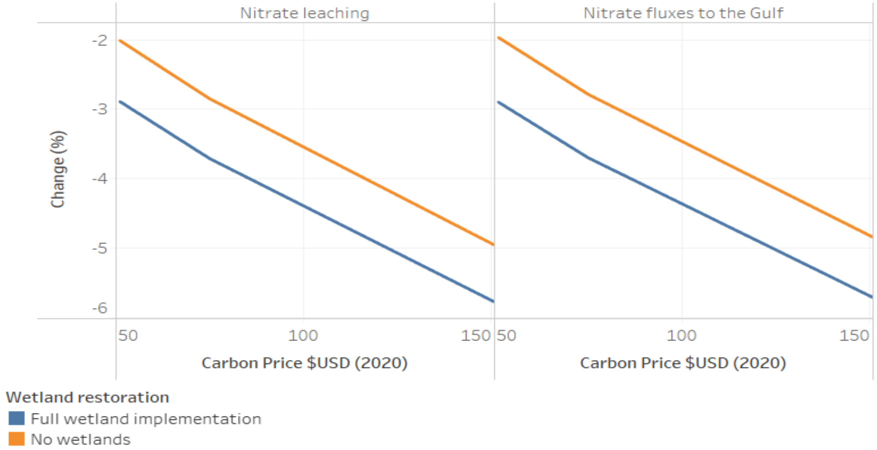

Figure 1: Change in nitrate leaching (left) and nitrate fluxes to the Gulf of Mexico (right). Traces indicate different wetland implementation scenarios: cases without wetland restoration (orange) and full implementation of wetlands (blue).

But what if the budget for wetland restoration projects is limited? Here, we compare the costs of wetland restoration to the revenues generated by process-based CO2 emissions and pricing fossil fuel-based combustion. The national-level carbon revenue generated by three different carbon pricing policies - $51, $71, and $152 per tCO2e - amounts to $2.7, $3.8, and $7.3 billion USD, respectively. The cost of fully implementing wetland restoration according to feasibility is $3.4 billion USD. A comparison of costs and revenues shows that full implementation of wetlands is not feasible if funded by the $51 carbon pricing scenario.

Figure 2 shows the geospatial pattern of cost effectiveness of wetland restoration in terms of marginal nitrate leaching or fluxes change (kg) per dollar spent on wetland restoration across MRB in the baseline. This figure shows the marginal changes in leaching outcomes resulting from wetland restoration, in addition to changes in nitrate leaching and fluxes due to climate policy, if wetlands were restored based on their maximum potentials without any budget constraint. The figure suggests that grid cells located on the edge of MRB experience an increase in nitrate leaching or fluxes due to the disequilibrium effect. For the other grid cells, nitrate leaching and fluxes reduction mainly range from 0 to 2 kg per dollar spent on wetlands.

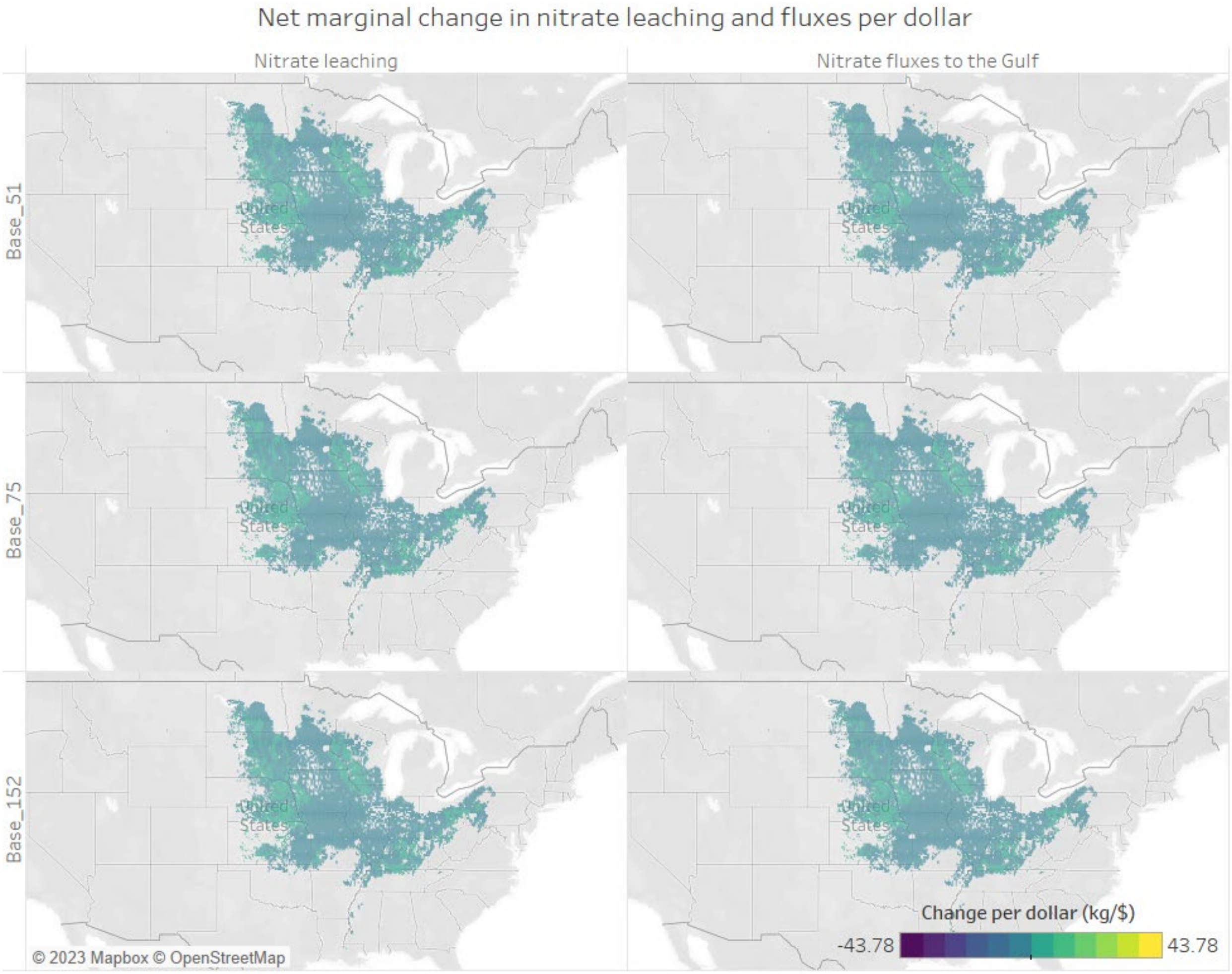

Figure 2: Net marginal change in nitrate leaching and nitrate fluxes to the Gulf of Mexico resulting from wetland restoration per dollar spent on such restoration at the grid cell level.

To allocate the constrained funding, one possible approach is to rank-order grid cells at the national level and select the most marginally cost-effective grid cell until the $2.6 billion constraint is reached. It is important to note that we do not prioritize wetland restoration by rank-ordering grid cells under the $75 and $125 carbon pricing policies at the national level, as there is no budget constraint in these scenarios. Alternatively, the revenues generated in each state could be allocated to fund wetland restoration projects within that state. This approach would result in some states facing state-level constrained budgets, while others have more carbon revenues generated than the cost of their wetland restoration projects. Figure 3 provides a visual representation of the difference between state-level carbon revenue and the cost of wetland restoration. From Figure 3 it is evident that no state faces budget constraint under $152 carbon pricing policy while some states such as Illinois, Indiana and Iowa have constrained funding under $51 and 71 climate policy revenue.

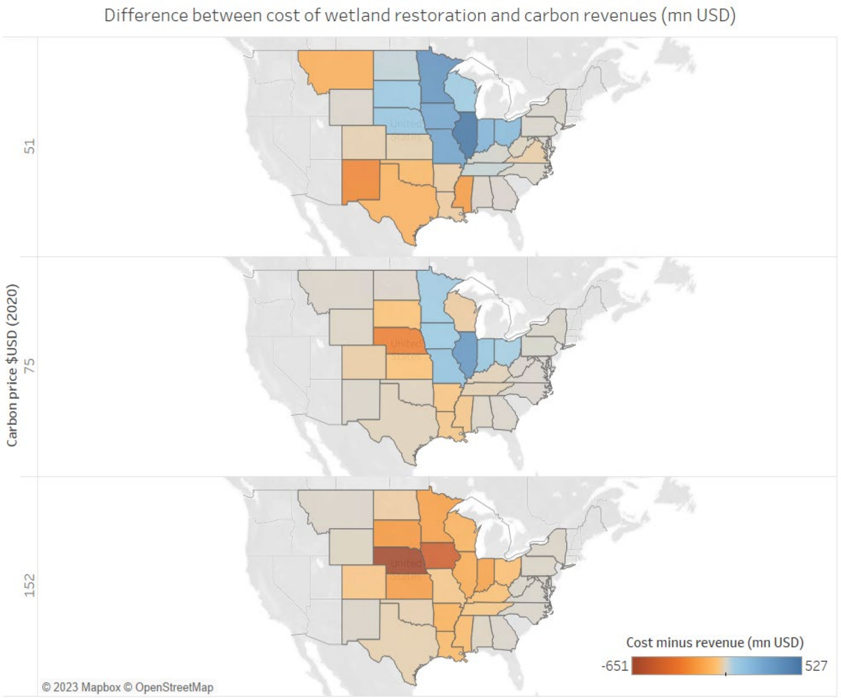

Figure 3: The difference between the cost of wetland restoration in each state and the carbon revenues generated in that state.

Table 1 presents results on the impact of different carbon pricing policies on nitrate leaching and fluxes to the Gulf of Mexico in various states in the Mississippi River Basin. There are three carbon pricing policies considered are those with carbon prices of $51, $75, and $152 per tCO2e. The impact of these policies is compared to the baseline scenario, where wetlands have been implemented fully and carbon pricing is enforced, but carbon revenues have not been allocated. This table provides information on the change in nitrate leaching in each state under the different carbon pricing policies, as well as the achievement rate in nitrate leaching. The achievement rate is calculated by dividing the change in nitrate leaching in a national or state-level scenario by the corresponding baseline scenario.

Table 1 highlights that some states located at the borders of MRB, including Colorado, Kansas, Nebraska, North Dakota, Oklahoma, and Texas, have an achievement rate greater than 100% at the national level revenue allocation scenario. This is due to the complex interplay between wetlands and climate policies in affecting nitrate leaching and fluxes. On one hand, the establishment of wetlands in only a small portion of the Corn Belt can drive up crop prices and lower the cost of nitrogen fertilizer (as lands are taken out of production for wetland restoration), leading to increased production and fertilizer use in other regions (Zuidema et al., 2023). On the other hand, a carbon pricing policy that raises the cost of fertilizer can discourage its use throughout the entire Mississippi River Basin, thereby offsetting some of the imbalanced effects of wetland restoration (Zuidema et al., 2023). At the national level carbon revenue allocation, only grid cells with wetlands that result in reduced nitrate leaching or fluxes will receive funding. This process eliminates the nitrate leaching impact of wetlands in grid cells that are not cost-effective, and only accounts for the effects of carbon pricing policies in those grid cells. In such grid cells, the disequilibrium effect of wetlands may lead to an increase in nitrate leaching, hence allocating revenue only to cost-effective grid cells will result in a marginal benefit and overall greater reduction in nitrate leaching and fluxes across the state. Therefore, for these states the national level carbon revenue allocation will yield the highest achievement rate in nitrate leaching change relative to the state level revenue allocation.

Table 1: Change in nitrate leaching and fluxes to the Gulf of Mexico in the baseline and achievement rate of changes in nation-wide and state level carbon revenue allocation scenarios.

State	Change in nitrate leaching in the baseline (1,000 kg)			Achievement rate in nitrate leaching change (%)			Change in nitrate fluxes to the Gulf in the baseline (1,000 kg)			Achievement rate in nitrate fluxes change (%)		
	Base_51	Base_75	Base_152	N_51	S_51	S_75	Base_51	Base_75	Base_152	N_51	S_51	S_75
Alabama	-166	-232	-415	98	100	100	-133	-185	-328	96	100	100
Arkansas	-966	-1,167	-1,689	58	100	100	-949	-1,136	-1,623	56	100	100
Colorado	-595	-841	-1,438	105	100	100	-450	-630	-1,064	101	100	100
Georgia	-3	-4	-6	93	100	100	-2	-3	-4	92	100	100
Illinois	-11,206	-14,009	-21,118	91	80	88	-10,409	-12,997	-19,552	91	80	88
Indiana	-6,142	-7,685	-11,685	92	84	92	-5,671	-7,091	-10,765	92	84	92
Iowa	-8,488	-10,639	-16,071	91	88	95	-7,801	-9,754	-14,683	91	88	94
Kansas	-5,039	-7,226	-12,789	106	100	100	-4,265	-6,064	-10,633	104	100	100
Kentucky	-1,311	-1,735	-2,816	99	100	100	-1,222	-1,605	-2,582	98	99	100
Louisiana	-12	-16	-26	82	100	100	-12	-16	-25	81	100	100
Maryland	-9	-13	-22	99	98	99	-7	-9	-16	98	97	98
Minnesota	-4,483	-5,361	-7,565	87	80	89	-4,062	-4,838	-6,787	87	80	88
Mississippi	-1,165	-1,505	-2,435	74	100	100	-1,120	-1,424	-2,258	69	100	100
Missouri	-3,689	-4,670	-7,197	94	84	91	-3,356	-4,223	-6,456	93	83	91
Montana	-9	-10	-13	37	100	100	-6	-7	-9	42	100	100
Nebraska	-2,950	-4,087	-6,934	102	100	100	-2,652	-3,649	-6,143	100	100	100
New Mexico	-5	-6	-7	39	100	100	-4	-5	-7	51	100	100
New York	-33	-42	-64	99	100	100	-27	-33	-50	99	100	100
North Carolina	-3	-4	-7	86	100	100	-1	-2	-3	83	100	100
North Dakota	-1,398	-1,819	-2,819	102	102	100	-1,133	-1,468	-2,260	100	100	100
Ohio	-3,853	-4,872	-7,465	94	87	93	-3,378	-4,258	-6,495	93	86	93
Oklahoma	-417	-595	-1,082	104	100	100	-346	-481	-851	98	100	100
Pennsylvania	-205	-271	-446	97	97	99	-172	-226	-368	96	96	98
South Dakota	-1,253	-1,675	-2,701	97	100	100	-1,193	-1,583	-2,534	95	100	100
Tennessee	-792	-1,014	-1,615	87	100	100	-726	-915	-1,423	84	100	100
Texas	-236	-353	-648	125	100	100	-161	-237	-428	118	100	100
Virginia	-6	-8	-13	87	100	100	-3	-4	-6	79	100	100
West Virginia	-17	-21	-31	51	100	100	-17	-21	-31	52	100	100
Wisconsin	-1,642	-2,174	-3,517	100	101	100	-1,401	-1,843	-2,960	98	100	100
Wyoming	-19	-23	-32	56	100	100	-16	-19	-27	56	100	100

Note: Fully_51, Base_75, and Base_152 denote the impact of carbon pricing policy and potential fully implemented wetland restoration on nitrate leaching or fluxes to the Gulf under three social costs of carbon, corresponding to carbon prices of 51, 75, and 152 US dollars, respectively, before allocating carbon revenues. N_51 represents the change in nitrate leaching or fluxes under a $51 carbon pricing policy after carbon revenues are allocated across the entire Mississippi River Basin (MRB). S_51 and S_75 refer to the change in nitrate leaching or fluxes under $51 and $75 carbon pricing policies, respectively, after carbon revenues generated in a state are allocated back to that same state. The achievement rate in nitrate leaching is determined by dividing the change in nitrate leaching in a national or state-level scenario by the corresponding baseline scenario. To illustrate, the achievement rate in nitrate leaching under N_51 is calculated as the nitrate leaching change under N_51 (which is not reported in this table but available from the authors upon request) divided by the nitrate leaching in the Base_51 scenario.

In states where there is not enough state-level carbon revenue to finance their wetland restoration project, the achievement rate typically shows better results or only slightly lower in nation-wide revenue allocation (N_51) than in state-level carbon pricing revenue allocation (S_51 and S_75) (Table 1). This suggests that state-level revenue allocation does not provide strong incentives for these states to reduce nitrate leaching and retain carbon revenues. Among the states considered, Maryland consistently achieves the highest rate of nitrate leaching reduction, ranging from 98% to 99%. This suggests that Maryland is already performing well in reducing nitrate leaching, and further policy intervention may only result in marginal gains. Wisconsin also consistently achieves high rates of nitrate leaching reduction, ranging from 100% to 101%. This indicates that Wisconsin has significant potential for reducing nitrate leaching and benefiting from revenue allocation. Illinois, Indiana, Iowa, Minnesota, Missouri, Ohio, and Pennsylvania have achievement rates ranging from 80% to 97%, indicating that these states have some potential for reducing nitrate leaching and benefiting from carbon revenue allocation.

As expected, results from Table 1 also show that in states located in the heart of MRB with sufficient state-level carbon revenue to finance their state-level wetland restoration project, the achievement rate under state-level carbon revenue allocation is generally higher than that under national revenue allocation. This highlights the importance of giving states with adequate budgetary frameworks control over their carbon revenue, allowing them to allocate it towards specific projects and achieve their restoration goals more effectively.

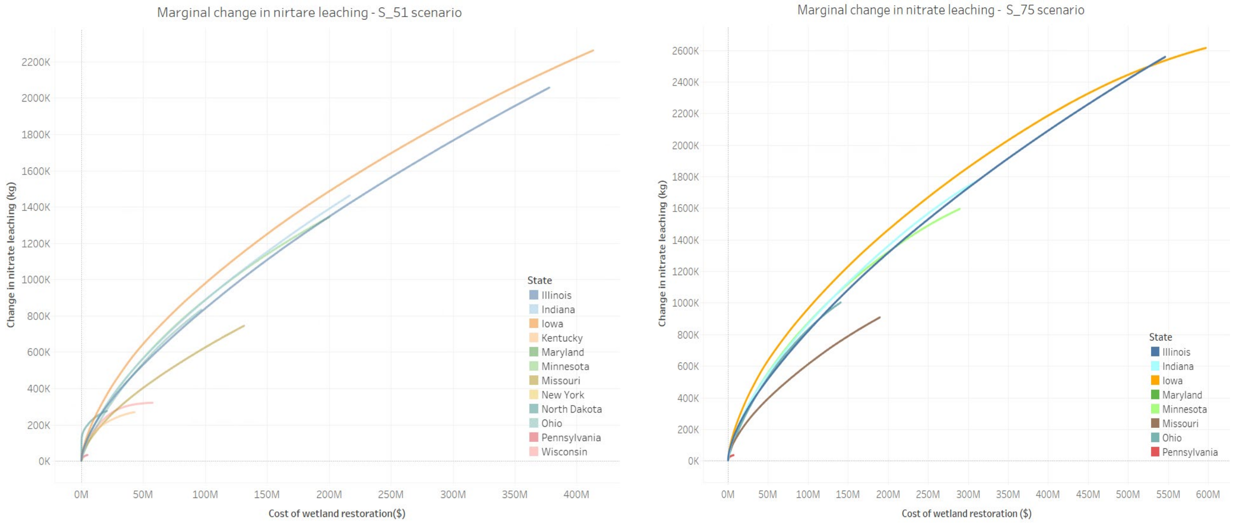

Figure 4: Marginal change in nitrate leaching in state level carbon revenue allocation scenarios.

In order to better understand the cost effectiveness of wetland restoration efforts funded by revenues generated through carbon pricing policies, it is important to compare the cumulative cost of wetland restoration in each state with the cumulative change in nitrate leaching resulting from the implementation of wetlands. This comparison is shown in Figure 4, which illustrates the cumulative cost and nitrate change associated with wetland restoration in each state as marginally cost-effective grid cells are selected.

Figure 4 illustrates the potential marginal reduction in nitrate leaching and flux transfer that can be achieved at a cost equivalent to the revenue generated from carbon pricing in each state. These marginal changes are in addition to any reductions resulting from the implementation of climate policies. For instance, if a carbon tax of $51 ($75) is implemented in Iowa, the estimated revenue generated would be approximately $411 ($595) million USD. Allocating this revenue towards the restoration of wetlands in Iowa would result in a reduction of almost 2.3 (2.6) million kg of nitrate leaching. Similarly, a carbon tax of $51 would generate revenues of $42 million USD. By allocating this revenue to wetland restoration in this state, there would be a reduction of 270 thousand kg of nitrate leaching.

Figure 4 also highlights the impact of different carbon pricing policies on wetland restoration efforts. Specifically, a $51 carbon pricing policy may hinder wetland restoration in certain states such as Iowa, Kentucky, and Wisconsin, where selected grid cells provide little change in nitrate leaching. However, in other states, selected grid cells for wetland restoration add marginally considerable changes to nitrate leaching. On the other hand, a $75 carbon pricing revenue allocation results in the selection of grid cells that add marginally larger changes to nitrate leaching for wetland restoration.

5. Discussion

In this paper, we use a modeling framework that combines economy, agroecology, and hydrology to evaluate the environmental and economic impacts of wetland restoration funded through carbon revenues. Using three different carbon pricing scenarios, we estimate the revenue generated by corn and soybean production in the Mississippi River Basin, which is then allocated to wetland restoration projects based on various optimality conditions and constraints. We then evaluate the environmental and economic outcomes using a high-resolution gridded model of US corn-soy production and global trade.

Our findings indicate that implementing carbon pricing policies can lead to a reduction of approximately 2% in nitrate concentrations in streams and rivers, as well as in nitrate transfer to the Gulf. When combined with wetland restoration, this effect can be further increased to a reduction of around 3%. This highlights the potential synergistic effects of wetlands and carbon pricing policies in reducing nitrate leaching from agricultural activities in the MRB and the Gulf of Mexico. We have also found that the environmental impacts of revenue allocation, whether constrained or unconstrained, vary depending on the states' locations, whether they are situated in the central region of the MRB or on its borders, as well as their financial capability to finance their respective restoration projects.

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