Chapter 14
Tackling Policy Leakage and Targeting Hot Spots Could Be Key to Addressing the “Wicked” Challenge of Nutrient Pollution from Corn Production in the United States

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1 Introduction

Widespread and intensive agricultural activity has resulted in the loss of large amounts of nitrogen (N) from soils (Goolsby et al. 2001; Turner et al. 2007). Elevated N levels in streams and rivers cause a spectrum of challenging problems, including biodiversity loss and threatened human health (Vitousek et al. 1997). Nutrients transported through the Mississippi River Basin (MRB) have been blamed for what are referred to as “dead zones” (i.e., hypoxic or low-oxygen water) that have formed in the Gulf of Mexico (Rabalais et al. 2001; Diaz and Rosenberg 2008). The

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Data availability statement: The files needed to replicate this application are available at https://gtap.agecon.purdue.edu/simple-g/.

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largest hypoxic zone measured since 1985 was 22,730 km^2 (8776 square miles) in 2017 (US EPA Hypoxia Task Force). Reducing the size of this zone to an acceptable level by 2035 will require a reduction of 48% in total nitrogen and phosphorus load (Fennel and Laurent 2018; US EPA 2023).

It is widely recognized that there is no silver bullet for resolving the “wicked” problem of nonpoint source water pollution in the Mississippi watershed (Shortle and Horan 2017; McLellan et al. 2018). To achieve the 48% nutrient reduction goal, in-field nutrient management must be combined with edge-of-field measures as well as downstream nutrient removal practices (Schilling and Wolter 2009; Iowa Nutrient Reduction Strategy 2013; McLellan et al. 2015, 2018). While agronomic and environmental management techniques to control and remove lost N have advanced, there is limited evidence that existing policies effectively facilitate the adoption of these techniques (Shortle et al. 2012; McLellan et al. 2015; Roy et al. 2021). Programs to promote improved water quality in the United States have been found to be largely inefficient, as the incremental cost of water quality protection has exceeded the incremental benefits (Olmstead 2010; Laukkanen and Nauges 2014; Savage and Ribaudo 2016). This low efficiency is often attributed to a failure to identify the proper value of N effluent mitigation (Shortle et al. 2012; Biffi et al. 2021; Fleming et al. 2022). The uniform value assumed in the current policy design does not reflect the spatially varying marginal cost of mitigating water quality damages (Shortle and Horan 2017). Quantifying this cost is challenging in practice because nonpoint source pollution is often not measurable. Without knowing the site-specific biophysical and ecological characteristics of N loss, economic instruments cannot be efficiently deployed.

This chapter introduces a special version of the SIMPLE-G model, called SIMPLE-G-US-CS, that overcomes these problems by estimating and embedding key biophysical relationships in an economic model. Using this integrated multiscale analytic tool, we compare the effectiveness of various policies in reducing nitrate loading in the MRB and the spatial patterns of mitigation.

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2 SIMPLE-G Version Employed for This Study

The version of the model that we created for this application is called SIMPLE-G-US-CS, where CS stands for "corn–soy." Instead of aggregating production across all crops, this model focuses on the two dominant crops in the Midwest: corn and soybeans. Corn is a very N-intensive crop that is often rotated with soybeans. According to the 2017 Census of Agriculture (USDA NASS), these two crops account for 77% of the annual harvested area in the MRB watershed, and 42% of basin-wide N fertilizer use was attributed to the production of corn. The corn–soy model advances the general SIMPLE-G framework by introducing grid-cell-level N loss and crop yield response parameters estimated from the Agro-IBIS model (Kucharik 2003; Donner and Kucharik 2008; Kucharik et al. 2013), as shown in Fig. 14.1. Specifically, the yield responses to N simulated by Agro-IBIS are used to compute the elasticity of substitution (σ) between N fertilizer and augmented land by grid cell and irrigation type. The N loss processes simulated by Agro-IBIS translate the economic equilibrium level of N application into N loss. More information about the two models, validation, and coupling of the two can be found in the supplemental information of Liu et al. (2023).

3 Experimental Design

Our experimental design considers four strategies individually and in combination to study the impacts of different conservation options, as highlighted in Fig. 14.2. The first strategy is an N loss tax that increases the cost of N fertilizer application in proportion to the estimated N loss rate for a given practice in that grid cell. N loss refers to the N fertilizer nutrient that is applied but not taken up by the crop and subsequently leaves the root zone. The final cost is determined by the nationally uniform N fertilizer price (US$/kg of N applied)[1] and the product of a nationwide tax rate of US$1/kg of N loss and the N loss intensity (kg of N loss/kg of N application), which varies by location and practice. After being adjusted by the N loss intensity, the tax imposes the highest penalty on the heavy polluters, whose profit margin will be affected directly by the tax and indirectly by the adverse yield impacts of less N fertilizer application.

Unlike the N loss tax, which reduces N use and nitrate loss via higher input costs, our second strategy achieves the same goal by applying less fertilizer but using it more efficiently. We select two relatively easy—and therefore more likely to be

[1]The N loss tax is a hypothetical nationwide policy that is expected to yield comparable mitigation outcomes as the other nationwide policy—split N application. The base tax rate is set uniformly nationwide for the sake of practical necessity. It is further adjusted by the N loss intensity to create the site-specific N loss tax rate such that the final rate is higher for the locations with higher N loss intensity. See Section B of the SI in Liu et al. (2023) for more information.

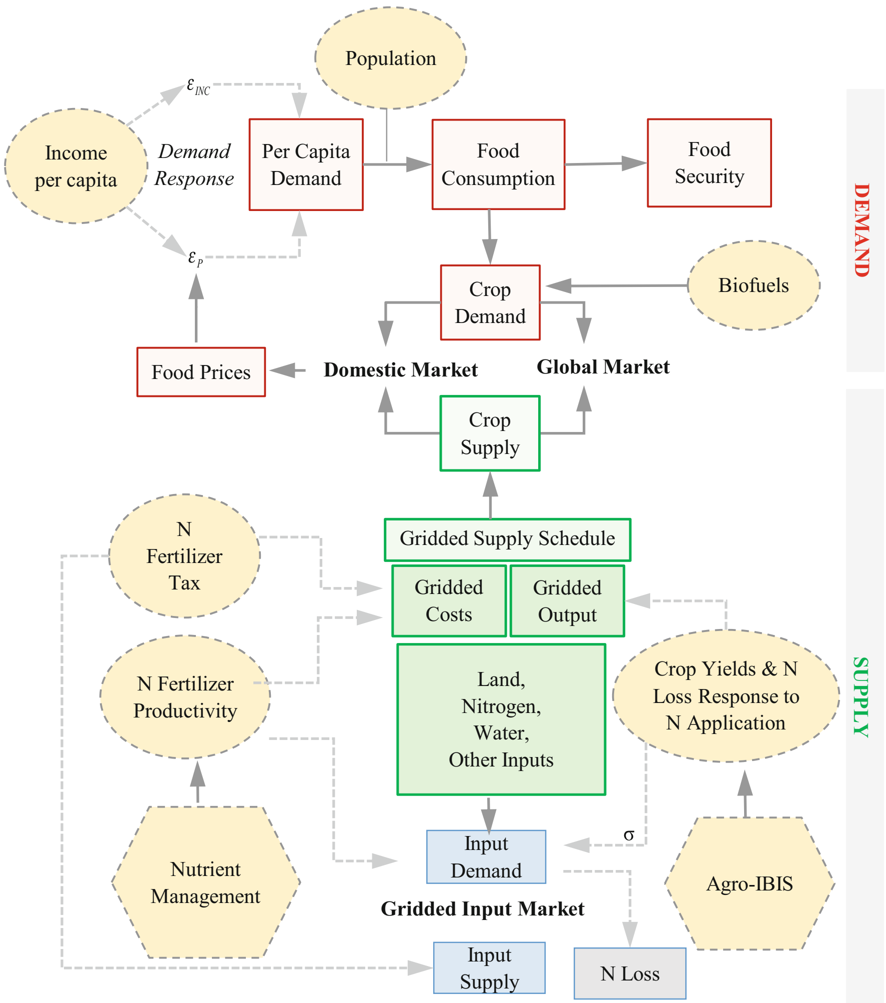

Fig. 14.1 Schematic of the SIMPLE-G-US-CS model
SIMPLE-G-US-CS is a modification of the standard SIMPLE-G model (Fig. 4.1). Key modifications include the interaction between Agro-IBIS and SIMPLE-G and accounting for nitrogen (N) loss resulting from N input use

adopted—practices: split N and side-dressing.[2] According to the Iowa Nutrient Reduction Strategy (2013), moving from fall to spring pre-planting application and side-dressing application reduce nitrate-N loss by an average of 6% and 4%, respectively. These improved practices are implemented in the model by increasing

[2] Split N means that growers make two or more N fertilizer applications during the growing season rather than supplying all of the crop's N requirements with a single treatment prior to or at planting. Side-dressing refers to applying fertilizers in a shallow furrow or band along the side of row crops.

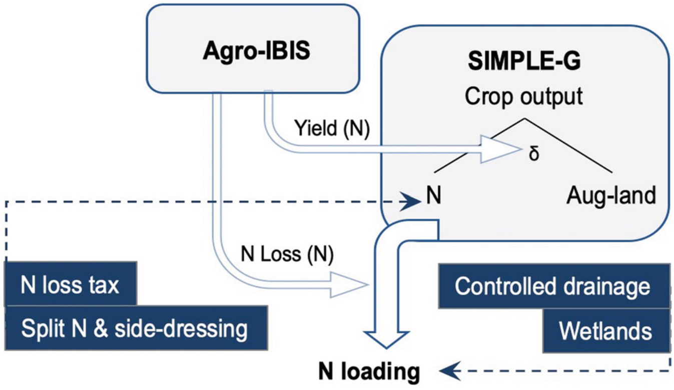

Fig. 14.2 Connections between Agro-IBIS and SIMPLE-G-US-CS and nitrogen (N) loss mitigation policies
Yield (N) and N loss (N) are univariate transfer functions (with respect to N) through which biophysical characteristics are embedded into the economic model. The N loss tax and split N affect N application rates and therefore N loading through the transfer functions. Controlled drainage and wetland restoration affect nitrate loads mainly through post-application nitrate removal

the productivity of N fertilizer to reduce N loss by 10% while keeping the baseline crop output unchanged.

The other two mitigation strategies focus on locally feasible nutrient management practices: controlled drainage[3] and wetland restoration.[4] Both practices yield spatially varying N loss removal rates that are determined by local conditions (e.g., water runoff, subsurface-drained area, and soil and vegetation characteristics). These strategies do not affect N fertilizer application directly but remove pollutants after application before they enter a stream. Additional information for each conservation effort can be found in the supplemental information of Liu et al. (2023).

4 Results

We implement the four policies individually as well as together in the SIMPLE-G-US-CS and explore the results, both at the grid cell level and at more aggregate levels, including states and over the entire Mississippi Basin.

[3] Controlled drainage uses a water control structure to adjust the depth of the subsurface drainage outlet in order to control water in the field.

[4] Wetlands in this paper refer to constructed integrated systems that use the natural functions of vegetation, soil, and microorganisms as well as the environment to improve water quality.

Table 14.1 Nitrogen (N) loss reduction outcomes, impacts on crop output and price, and mitigation efficiency across management strategies

Policy	N application	Crop output	Crop price	N loss	Efficiency	
	Million tons	Million tons	US$/ton	Million tons	US$/ kg N	kg N/ ha
N loss tax	−0.65 (−5.91%)	−9.98 (−2.08%)	4.16 (+1.84%)	−0.34 (−9.02%)	10.09	5.30
Split N	−0.75 (−6.80%)	0.00 (0.00%)	0.00 (0.00%)	−0.42 (−11.18%)	3.57	6.57
Controlled drainage	−0.02 (−0.17%)	−0.88 (−0.18%)	0.36 (+0.16%)	−0.46 (−12.15%)	0.79	31.70
Wetlands	−0.05 (−0.47%)	−2.38 (−0.55%)	1.18 (+0.48%)	−0.58 (−15.41%)	1.81	27.26
Tax + Split N	−1.35 (−12.19%)	−8.99 (−1.87%)	3.74 (+1.65%)	−0.71 (−18.86%)	6.94	11.1
Tax + Split N + Controlled drainage	−1.28 (−11.63%)	−4.78 (−1.00%)	1.97 (+0.87%)	−1.04 (−27.66%)	5.08	16.3
Tax + Split N + Wetlands	−1.36 (−12.30%)	−9.64 (−2.01%)	4.01 (+1.78%)	−1.17 (−31.00%)	5.12	18.2

Mitigation efficiency, measured in US$/kg, indicates the economic efficiency in terms of the direct cost incurred to reduce 1 unit of N loss. Note that this measure abstracts from the potential uses of the tax revenues. The efficiency, measured in kg/ha, indicates the biophysical efficiency regarding the potential for N loss removal per cropland area

4.1 Combining N Loss Tax, Split N Fertilizer Application, and Wetland Restoration Has the Potential to Reduce N Loss from Corn Production by over 30%

Among the four strategies explored, wetland restoration appears to be the most effective single strategy, reducing N loss from corn production by 15%, followed by controlled drainage (12%) (Table 14.1). When combined, wetland restoration—along with the N loss tax and split N application—can raise the reduction potential to 31%. An N loss tax of US$1/kg of N loss boosts the average cost of N fertilizer to corn farms by 28.9% and reduces N fertilizer use by 6% and total N loss by 9%.[5] National crop yields are barely affected by the rate reduction, falling slightly from 7.48 to 7.39 corn-equivalent tons per hectare. However, the local effects are more significant. Figure S2 in Liu et al. (2023) shows that the potential crop yield declines

[5]Results of different tax rates from US$0.1–1/kg of N loss are reported in Section G of the supplemental information of Liu et al. (2023). The N loss charge (in US$/kg of N application) is computed as the product of a charge rate (in US$/kg of N loss) and nitrate-N loss rate (kg of N loss/kg of N application). For example, if a farm loses 30% of the N fertilizer applied, the actual cost of applying 1 kg of N fertilizer increases from the base price of US$1/kg to US$1.3/kg, which includes the US$0.3/kg N loss charge. The 28.9% simply represents the aggregated N loss rate at the national level.

most around the edges of the MRB, where there is a higher dependence on supplementary fertilization is higher. Farms located in the Great Plains are least affected by the tax because of their relatively lower N loss intensity.

At the aggregate level, postapplication treatments such as controlled drainage and wetland construction result in much larger N loss reductions (31 and 27 kg of N/ha, respectively) than split N application and the N loss tax (7 and 5 kg of N/ha, respectively).[6] Removing 1 kg of N loss costs US$1.80 when accomplished via wetlands and US$0.80 when using controlled drainage.[7] It is more costly (US$3.60) to mitigate N loss through the adoption of side-dressing and split N application and even more costly (US$10) by imposing a pollution tax, which is calculated by dividing the total N loss tax collected through N fertilizer sales by the amount of N loss reduced. It is important to note that this economic accounting differs from the implementation costs associated with other practices and must be interpreted with caution should readers wish to compare costs across practices. In addition, the tax revenue can be recycled to support pollution abatement, which could lower the actual cost of the policy. The outcomes of alternative tax recycling schemes (e.g., cutting the existing tax on capital income or subsidizing additional programs to further enhance the mitigation effect) have been more extensively studied in the context of carbon taxation (Timilsina 2018). This work has yet to be done for nutrient management. More information about how each cost is calculated can be found in Liu et al. (2023, supplement Section F).

Crop output falls in almost all cases, albeit modestly, due to the higher input costs associated with the rising N fertilizer price, infrastructure installation and maintenance, or forgone cropland (relevant to wetlands only). The composite corn–soy price increases by no more than 2%, regardless of the scenario, given the modest change in crop output. The sum of the individual scenarios' output and price effects is greater than when they are implemented in concert, indicating the presence of complementarities among the policies.

4.2 The Most Effective Nitrate Loss Mitigation Policy Varies by Location

While total mitigation across the four individual strategies is comparable, the spatial pattern of the N loss reductions varies remarkably (Fig. 14.3). The amount of mitigation is relatively consistent across the US Corn Belt for N loss tax and split

[6] These results are generally comparable to those recorded in the CEAP regional reports, although a straight comparison between the two may not be reasonable given the difference of the actions considered in each study.

[7] This number accounts only the cost for the control system but not the installation of the subsurface-drains itself due to lack of information. The cost of the latter varies depending on the spacing and depth of the drainage pipes.

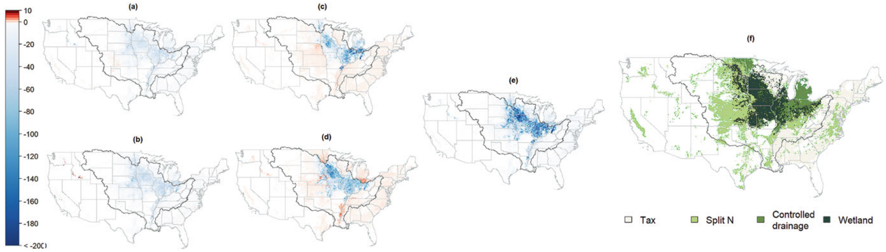

Fig. 14.3 Changes in nitrogen (N) loss under (**a**) an N loss tax, (**b**) split N application, (**c**) controlled drainage, (**d**) wetland restoration, and (**e**) combined strategies of tax, split N, and wetland restoration
Units are tons of N loss per 5 arcmin grid cells. A negative value indicates N loss reduction. Figure **f** shows the most effective single strategy at each grid cell. The maps include only the grid cells where corn and soybeans are grown in the United States

N application, as these are not tied to specific locations. This finding stands in marked contrast to the patterns associated with strategies that are contingent on local conditions. Controlled drainage is only possible in locations where subsurface drainage is installed. Wetland restoration in our analysis is limited to locations where hydric soils and subsurface drainage are present. Results show that N loss mitigation per grid cell is much higher in the heart of the Corn Belt, where controlled drainage and wetland restoration are more prevalent. Compared to N loss tax and split N application, these two strategies also lead to much higher N removal rates.

The gridded results reported in Fig. 14.3a–d allow us to identify the single practice among the four that exhibits the largest N loss reduction (in terms of tons N per grid cell) at each location (Fig. 14.3f). Controlled drainage and wetland restoration dominate the Corn Belt as the most effective practices, except at the western edge, where split N is more effective. Outside of the Corn Belt, the N loss tax stands out as the most effective strategy, especially in the Eastern United States, under the current setting of the experiments (e.g., tax rate, the extent of N fertilizer productivity being increased, and the spatial extent of controlled drainage and restorable wetlands). This stems from a combination of factors, including relatively high N loss intensity and marginal productivity of N applications, as well as the reduced prevalence of subsurface drainage and restorable wetlands in this region.

4.3 Pairing Nationwide Strategies with Site-Specific Conservation Practices Can Remedy Counterproductive Policy Spillovers

Conservation systems such as controlled drainage and wetland restoration incur an additional cost of US$10–US$20 per acre. Despite being a small share of the US $450/acre nonland cost of producing corn (e.g., in Central Illinois circa 2010, Schnitkey et al. 2021), it could still reduce profitability and curb output on adopting farms. By removing land from production, wetland restoration could be more costly, although some lands are intentionally retired due to their low productivity. Considering both factors, output on adopting farms and demand for N fertilizer are likely to fall. When aggregated to the national level, the local effect could boost the corn price while curbing the price of N fertilizer due to the weakened demand for fertilizer. In the long run, the elevated corn price will induce production expansion and additional N application elsewhere.

Figure 14.3c, d clearly show this spatial spillover effect: N loss around the fringes of the Corn Belt rises in response to higher corn prices. Because there is little subsurface drainage in these fringe areas (Valayamkunnath et al. 2020), less of the increased N loss will contribute directly to the hypoxia problem in the Gulf of Mexico, but it could result in groundwater contamination.

To quantify the accumulated spillover effects, we decompose the overall change in N loss into two components: mitigation (a decrease in N loss) and spillovers (an increase in N loss). Although the magnitude of spillover effect is relatively small compared to the mitigation potential, the additional N applications driven by spillovers are more environmentally harmful. This extra N application leads to higher N loss intensity regardless of the measurement method. For example, on average, 41% of the additional N applied to the untreated cropland area is lost, compared to a 33% N loss rate on the same land before wetland restoration is introduced. Both N losses per hectare of cropland and per ton of crop output increase significantly. However, these spillovers are sharply reduced when policies are combined (Fig. 14.3e), as the uniform coverage greatly limits market-mediated leakage.

4.4 Targeting N Loss Hot Spots Would Make Conservation Efforts More Efficient and Cost-Effective

Substantial reductions in N loss are spatially concentrated in areas with extensive corn acreage, intensive N fertilizer use, and/or effective conservation practices. We find that, across the four practices studied, less than 10% of the total 48,317 grid cells contribute 50% of the mitigation, with only a small reduction in crop output (5% or less) (Fig. 14.4). These top-mitigating grid cells shown in Fig. S11 of Liu et al. (2023) account for 39.4% of the corn–soy area and 38.8% of US corn–soy output. They also use 42.5% of N fertilizer and produce 46.7% of N loss in US corn–soy production. Implementing a combined strategy of tax, split N, and wetland restoration to reduce N loss by 30% would cost US$6 billion annually, or approximately US$38/acre/year. Focusing on this 10% of the grid cells that contribute half of the 30% N loss reduction would reduce costs to US$2.4 billion/year, while removing the other half of the 30% would cost more (US$3.6 billion/year) due to lower N removal efficiency. At higher adoption rates, reducing an additional unit of N costs more—

and N removal per hectare also declines—because more "expensive" locations are included, where either the N loss intensity is low, the marginal product of N is high, or both.

Since environmental policies are typically set at the state or federal level rather than by individual grid cells, we also report state-level mitigation potentials in Fig. 14.4. Collectively, these nine selected states produce 80% of US corn and soy output and use 83% of the N fertilizer applied to corn production. These states also account for 80–85% of total N loss reduction under the tax and split N strategies, and almost all the reduction under the controlled drainage and wetland scenarios. Controlled drainage is especially effective for Iowa, Illinois, Indiana, Minnesota, and Ohio, where subsurface drainage is widely used (Valayamkunnath et al. 2020). Wetland restoration is also effective across most of the Corn Belt. However, due to spillover effects, these policies may increase N loss in states lacking controlled drainage and wetland systems. Not surprisingly, policy combinations can outperform individual policies, and this difference is particularly pronounced in Iowa, Illinois, and Minnesota.

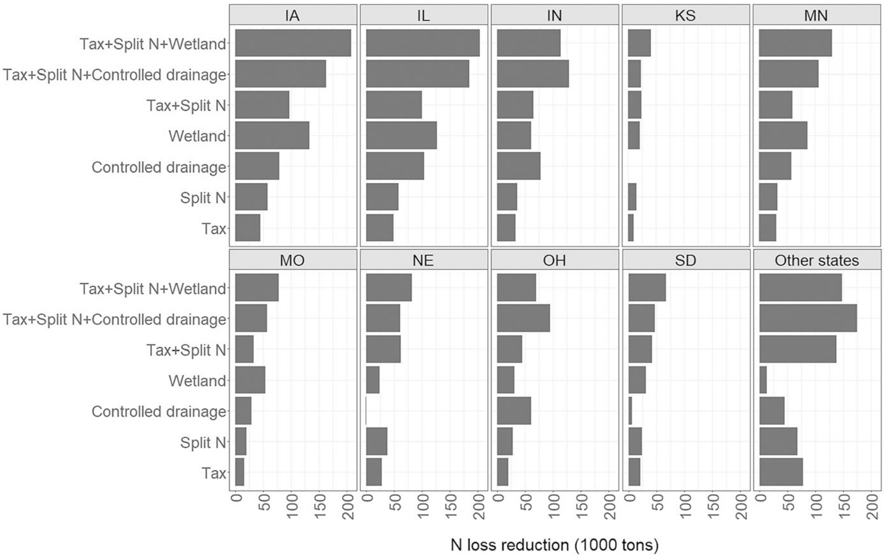

Fig. 14.4 N loss reduction by (**a**) state and mitigation strategy and (**b**) accumulated percentage In Fig. **b**, mitigation at the grid-cell level is first sorted in descending order and then accumulated. Therefore, the order of the grid cells varies by policy. The *light gray, dotted horizontal line* indicates a 50% reduction in total nitrate load

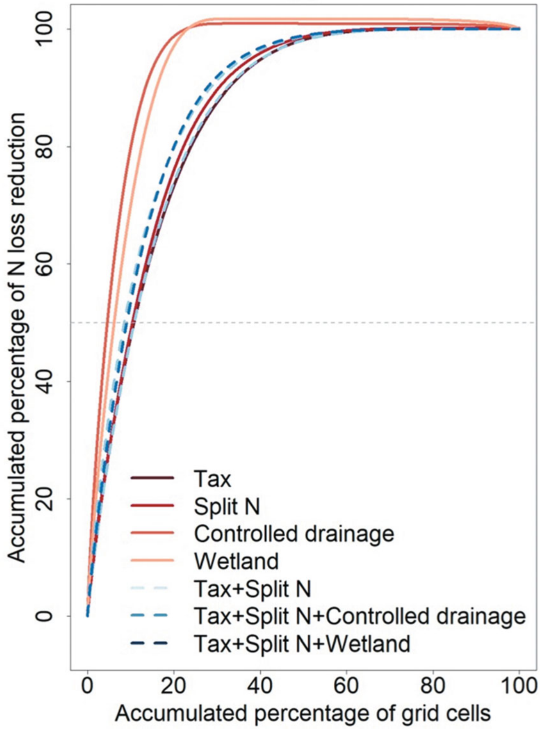

Fig. 14.4 (continued)

5 Discussion

There are several limitations to this study that warrant further investigation. First, we focus only on N loss through water and do not consider nitrous oxide emissions. Therefore, we have not comprehensively evaluated the effectiveness of these conservation policies. A recent study suggests that policies targeting water quality also provide substantial co-benefits by reducing nitrous oxide emissions (Weng et al. 2024). Second, our estimation of the area feasible for controlled drainage and restorable wetlands focus on regions with high potential but does not cover the entire continental United States due to limited data at the time of analysis. Alternative data sources, such as AgTile-US (Valayamkunnath et al. 2020) and Potentially Restorable Wetlands on Agricultural Land provided by EPA EnviroAtlas, could help estimate feasibility in future studies. Third, the N loss reported in our study differs from the amount of nitrate that reaches the Gulf of Mexico, and we do not consider N legacy (Van Meter et al. 2016, 2018; Basu et al. 2022). Both will depend on local hydrological and biogeochemical processes, which will affect the amount of nitrate ultimately reaching the Gulf (Masuda et al. 2021). In future work, it will be valuable to integrate our multiscale analytical framework with hydroecological models to track nutrient movement through ecosystems.

Our study contributes several advancements to the literature. The wider impact of local decisions, or the spillover effect, is the most intriguing result we would like to emphasize. When some—but not all—farms are targeted, the comparative advantage of farms is altered, and the change is transmitted by prices in input and output markets across different scales, leading to unintended displacement of crop production and pollution. Similar "leakage effects" associated with spatially targeted environmental policy intervention have been well recognized in the deployment of climate (Hertel and Tyner 2013; Dou et al. 2018) and air pollution (Fang et al. 2019) policies, but the relevant literature is sparse in the context of water pollution except for a few economic studies (Turner et al. 1999; Xu et al. 2022). A growing concern about governance is that the hidden external cost outside of the target area could offset direct gains (Rajagopal and Zilberman 2013; Dou et al. 2018). However, the spillover phenomenon in policy-making remains poorly understood (Bastos Lima et al. 2019). The coupling of SIMPLE-G-US-CS with Agro-IBIS helps unravel this mechanism by explicitly characterizing production technologies and biophysical characteristics across locations. We find that the spillover effects depend on the cost burden of conservation on farmers. The higher the farmers' burden, the larger the ensuing output reduction and market-mediated spillovers. The magnitude of the spillover depends on the specifics of the policy implementation, including forgone production value, copayments required of farmers, and adoption rates. In our case, leakage is still strongly outweighed by the mitigation efforts but could hinder conservation goals and raise equity and efficiency concerns.

This caveat, however, should not deter the targeting of policy interventions that have been linked to efficiency gains and extensively recommended by the literature (Babcock et al. 1997; van der Horst 2007). Our model's ability to identify areas with high mitigation efficiency provides an empirical foundation for shaping policies that enhance the effectiveness of these interventions (van der Horst 2007). The finding that the leakage effect can be mitigated by combining nationwide and regional strategies offers fresh insights for future policy design. Additionally, our agroecosystem-supported economic model can be used to explore differentiated taxes or subsidies that discourage excessive fertilizer application and compensate farmers for behaviorial changes. While numerous studies have confirmed the effectiveness of conservation practices in improving water quality, much less evidence supports the idea that existing conservation programs succeed in enrolling low-cost adopters or achieve wide adoption of these practices. One possible reason why undifferentiated policies fail is the mismatch between the policy-authorized payment and farmers' expectations, particularly when there are potential negative impacts on yields. And this concern is not unfounded. Roy et al. (2021) show that N application rates in many Midwest counties remain below the N input break point, beyond which crop yield plateaus or declines. Our grid-cell-based analysis also finds locations where nutrient deficiencies could limit crop yields. Assessing this concern requires a thorough understanding of site-specific N balance, the uncertainties associated with climate, production technologies, and the prices of crops and inputs (especially N fertilizer).

6 Conclusion

By integrating a version of SIMPLE-G with the agroecosystem model Agro-IBIS, we evaluate the effectiveness of four conservation strategies—N loss tax, split N application, controlled drainage, and wetland restoration, both individually and in combination—to manage nitrate-N loss from U.S. corn production. Collectively, these practices could reduce N loss from US corn production by 30%, at an estimated annual cost of US$6 billion. Several studies (Rabotyagov et al. 2010, 2014; Tallis et al. 2019; Xu et al. 2022) have reported similar levels of expenditure to achieve comparable mitigation goals.[8] The mitigation effect of each practice varies significantly across regions, highlighting the importance of spatial targeting for both the selection of practices and locations to improve the cost-effectiveness. This aligns with findings from a growing body of research on this topic (Kurkalova 2015; Lintern et al. 2020; Hansen et al. 2021). A successful transition from research to policy and practice requires innovative policy design. Future policies should also consider regulating fertilizer products as a complement to voluntary, farmer-oriented conservation programs. For example, Kanter and Searchinger (2018) propose a municipal minimum sales share of enhanced efficiency fertilizers, akin to how Corporate Average Fuel Economy Standards regulate auto manufacturers to improve fuel efficiency rather than trying to regulate millions of individual drivers. Our modeling framework can be extended to evaluate and test these alternative policy options.

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The findings and conclusions presented in this chapter are those of the authors and should not be construed to represent any official determination or policy of the US Department of Agriculture (USDA), or the National Science Foundation (NSF). Furthermore, we declare that there is no conflict of interest related to this work.

[8]These include the US$1.4 billion/year to reduce N loading in the Upper MRB by 30% through in-field and edge-of-field practices and retirement of land (Rabotyagov et al. 2010), US$2.6 billion/year through market and regulatory instruments to reduce N flows in the Ohio River Basin and Upper MRB by 25% (Tallis et al. 2019), US$2.7 billion/year to reduce the hypoxic zone in the Gulf of Mexico to 5000 km^2 through cropland conservation and fertilizer management practices (Rabotyagov et al. 2014), and US$6 billion/year in opportunity costs in terms of the value of forgone crop production by changing N fertilizer intensification and crop acreage in order to reduce N runoff from crop production to the Gulf by 45% (Xu et al. 2022).

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