Cost-effective targeting of conservation investments to reduce the northern Gulf of Mexico hypoxic zone

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Abstract
A seasonally occurring summer hypoxic (low oxygen) zone in the northern Gulf of Mexico is the second largest in the world. Reductions in nutrients from agricultural cropland in its watershed are needed to reduce the hypoxic zone size to the national policy goal of 5,000 km$^2$ (as a 5-y running average) set by the national Gulf of Mexico Task Force's Action Plan. We develop an integrated assessment model linking the water quality effects of cropland conservation investment decisions on the more than 550 agricultural subwatersheds that deliver nutrients into the Gulf with a hypoxic zone model. We use this integrated assessment model to identify the most cost-effective subwatersheds to target for cropland conservation investments. We consider targeting of the location (which subwatersheds to treat) and the extent of conservation investment to undertake (how much cropland within a subwatershed to treat). We use process models to simulate the dynamics of the effects of cropland conservation investments on nutrient delivery to the Gulf and use an evolutionary algorithm to solve the optimization problem. Model results suggest that by targeting cropland conservation investments to the most cost-effective location and extent of coverage, the Action Plan goal of 5,000 km$^2$ can be achieved at a cost of $2.7 billion annually. A large set of cost-hypoxia tradeoffs is developed, ranging from the baseline to the nontargeted adoption of the most aggressive cropland conservation investments in all subwatersheds (estimated to reduce the hypoxic zone to less than 3,000 km$^2$ at a cost of $5.6 billion annually).

Keywords
Center for Agricultural and Rural Development, eutrophication, hypoxic zone, Gulf of Mexico, agricultural conservation practices, evolutionary computation

Disciplines
Agricultural and Resource Economics | Oceanography | Terrestrial and Aquatic Ecology

Comments
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A seasonally occurring summer hypoxic (low oxygen) zone in the northern Gulf of Mexico is the second largest in the world. Reductions in nutrients from agricultural cropland in its watershed are needed to reduce the hypoxic zone size to the national policy goal of 5,000 km² (as a 5-year running average) set by the national Gulf of Mexico Task Force’s Action Plan. We develop an integrated assessment model linking the water quality effects of cropland conservation investment decisions on the more than 550 agricultural subwatersheds that deliver nutrients into the Gulf with a hypoxic zone model. We use this integrated assessment model to identify the most cost-effective subwatersheds to target for cropland conservation investments. We consider targeting of the location (which subwatersheds to treat) and the extent of conservation investment to undertake (how much cropland within a subwatershed to treat). We use process models to simulate the dynamics of the effects of cropland conservation investments on nutrient delivery to the Gulf and use an evolutionary algorithm to solve the optimization problem. Model results suggest that by targeting cropland conservation investments to the most cost-effective location and extent of coverage, the Action Plan goal of 5,000 km² can be achieved at a cost of $2.7 billion annually. A large set of cost-hypoxia tradeoffs is developed, ranging from the baseline to the nontargeted adoption of the most aggressive cropland conservation investments in all subwatersheds (estimated to reduce the hypoxic zone to less than 3,000 km² at a cost of $5.6 billion annually).

Significance

Hypoxic (low-oxygen) zones threaten an increasing number of marine ecosystems. Hypoxia in the Gulf of Mexico is the second largest in the world. The United States has a policy goal of reducing the average zone to 5,000 km². Reductions in nutrients from cropland in the Mississippi-Atchafalaya River Basin are needed to achieve this goal. We use an integrated assessment model coupled with optimization to identify the most cost-effective locations for that investment and show the tradeoff relationship between the costs that need to be incurred and the expected size of Gulf hypoxia.

In addition to developing a complete baseline of the existing cropland conservation actions and their current effectiveness, the CEAP assessments also identified and modeled the N and P impacts of four additional scenarios for each of the 557 basins and further delineated into more than 800 subwatersheds (these are identified as “HUC-8s” according to the US Geologic Survey nomenclature; ref. 16). Of those subwatersheds, 557 have significant agricultural cropland and are therefore included in our study. If the Hypoxia Task Force’s goal is to be met, significant reductions in the amount of N and P leaving cropland in the Mississippi Basin will be needed, implying that a large investment in new conservation actions will likely be required. In this analysis, we develop an integrated assessment model to identify the most cost-effective locations for that investment and show the tradeoff relationship between the costs that need to be incurred and the expected size of Gulf hypoxia.


The authors declare no conflict of interest.

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agriculturally significant subwatersheds, each incorporating different level and composition of conservation actions. Two cropland conservation action scenarios focused on cropland conservation practices and the other two added better fertilizer management practices. The two cropland conservation practice scenarios differed by the amount of cropland treated within the subwatershed. In the least-intensive treatment option, a set of practices agronomically suited to the watershed was applied only to the most critically undertreated cropland in the subwatershed (high conservation need cropland). The same set of conservation practices were modeled for the second treatment option, but were applied to a larger area of cropland that was identified as having a moderate or high conservation need. Thus, the second option represents a larger spatial coverage of practices within a subwatershed and is therefore more costly. We refer to these two scenarios as Practices-low and Practices-high to indicate that they represent a low and high extent of coverage of cropland conservation practices.

The third and fourth scenarios match the spatial coverage of the first two scenarios, but add better fertilizer management to further reduce nutrient losses. We refer to these additional two scenarios as Practices-Fertilizer-low and Practices-Fertilizer-high. Thus, for each of the 557 subwatersheds, four scenarios depicting different levels of cropland conservation investment were identified and modeled. The specific practices and coverage differ across the subwatersheds to reflect the agronomic conditions. SI Appendix, Table S1 provides a summary of these cropland conservation treatment scenarios and the constituent conservation and fertilizer management practices. The costs associated with each of those levels of investment were also constructed.

To build our integrated assessment model, we combine the detailed modeling of the subwatersheds (a baseline cropland management plus four conservation scenarios each) with an ecohydrological model of riverine N and P fate and transport, and a model of the areal extent of Gulf hypoxia. The ecohydrological model is the HUMUS-CEAP model (10, 17, 18), which simulates how changes in cropland conservation actions in one or more subwatersheds impact the delivery of N and P to the Gulf. This model incorporates the interdependence between hydrologically connected subwatersheds in terms of the effectiveness of cropland conservation investments to reduce N and P loads to the Gulf. For example, depending on a variety of hydrologic factors, nutrient reductions resulting from conservation actions in an upstream subwatershed can differ depending on the cropland management choices in lower subwatersheds.

The final piece of the integrated assessment model is a component that relates the delivery of nutrients from the Mississippi Basin to the size of the hypoxic zone. A statistical model of the Gulf hypoxic zone relating the areal extent of hypoxia and May N and P riverine loads described in ref. 19 was used. The model exhibits good in-sample fit and out-of-sample prediction success on par with (or better than) several other published models (19).

With this set of models and data in place, we are positioned to identify the subwatersheds within the Mississippi Basin and the subwatershed-level cropland conservation actions that should be targeted to achieve the least-cost solution to reducing the size of Gulf hypoxia. The interdependence of effects of cropland conservation between subwatersheds described above means that simple optimization methods cannot be used. Therefore, we use an evolutionary algorithm to solve the optimization problem (20). And, rather than identify the single least-cost solution that achieves the targeted goal, we develop a full tradeoff frontier that represents a range of conservation investments and their associated costs. These cost-effectiveness frontiers can provide policymakers with an understanding of how costly it will be to achieve a given expected reduction in the size of Gulf hypoxia and how those costs can be minimized by targeting both the set of subwatersheds for investment and the level of investment within the subwatershed.

Results

Nontargeted Cropland Conservation Efforts. We begin our analysis with four scenarios where we uniformly apply the four conservation scenarios to all 557 subwatersheds. Fig. 1 shows the expected 5-y average hypoxia zone size for 1988–2006 and the total cost (in $US 1 × 10^9 y⁻¹) under these four counterfactual scenarios relative to the baseline cropland management. The results indicate that if the Practices-low scenario was implemented in all of the 557 watersheds, the mean 5-y size of the zone would decline from the baseline value of approximately 12,500 km² to approximately 11,200 km² and would cost roughly $1.3 billion annually. The only conservation scenario that achieves the goal of reducing 5-y average hypoxia to below 5,000 km² is the Practices-Fertilizer-high scenario, which is predicted to achieve a mean 5-y hypoxia of approximately 2,900 km² at an annual cost of $5.57 billion. Thus, there is one nontargeted strategy that would be expected to (over)achieve the Gulf hypoxia goal. We now turn to the question of whether achieving the hypoxia Action Plan goal can be done at a lower cost by targeting the geographic location and/or the extent of practices more finely across this large landscape.

Cost-Effective Targeting Across Subwatersheds. Fig. 2 shows the full cost-effectiveness frontier depicting the tradeoff between the size of hypoxia and annual costs of conservation when a full advantage of targeting is taken. As expected, to achieve larger reductions in the 5-y running average of hypoxia, a higher annual cost is needed, and this cost increases at an increasing rate (the frontier becomes steeper when moving from right to left, implying increasing marginal costs of hypoxia reductions). The total annual cost ranges from $0 (to achieve no reduction in the hypoxic zone relative to the baseline) to almost $5.6 billion annually to achieve a zone size that is approximately half of the targeted size. The marginal cost, per 1,000 km² reduction in the mean 5-y average hypoxic size, ranges from $270 million y⁻¹ at the baseline to $680 million y⁻¹ for the Action Plan goal of 5,000 km², and rises to approximately $US 1.7 × 10^9 y⁻¹ with an attempt to reduce hypoxia to an average size of 1,000 km².
Of the four nontargeted conservation scenarios, only the Practices+Fertilizer-high scenario appears on the frontier, and the other three uniform scenarios are markedly less efficient than the targeted approaches, suggesting that the same reduction in the size of the zone can be achieved at a lower total cost (or that larger hypoxia reductions can be achieved at the same level of investment in agricultural conservation practices).

A solution of particular interest is the one that is expected to achieve the Gulf hypoxia goal of 5,000 km². This solution corresponds to an approximate 60% reduction in the recent size of the zone (SI Appendix, Table S2). We estimate that the approximate lowest cost of achieving the hypoxia goal over the historical range of climate variability is approximately $US 2.7 × 10^{9}$ y⁻¹. Because each point on the tradeoff frontier represents a specific spatial distribution of cropland conservation scenarios across the Mississippi Basin, the solution can be mapped back to the subwatershed level (Fig. 3). The solution involves large investments in the Practices+Fertilizer-high scenario in large portions of the Upper Mississippi River Basin and the Ohio-Tennessee River Basin, with additional investments in the Missouri River Basin, the Lower Mississippi River Basin, and the Arkansas-White-Red River Basin. Additional investments on ~178,000 km² of cropland (representing 18% of the total cropland area modeled) are required. Of the treated cropland areas, the vast majority (more than 98%) receive the most aggressive cropland conservation treatment consistent with largely maintaining crop production levels (Practices+Fertilizer-high, highlighted in blue in Fig. 3). The remainder of the treated acres are distributed across the Practices-low [approximately 2,000 km² (less than 500,000 acres) treated], Practices+Fertilizer-low [approximately 1,000 km² (less than 250,000 acres) treated], and Practices-high [just over 280 km² (70,000 acres) treated] scenarios. The average annual cost per treated ha (acre) for the solution identified is $153 (S62). A summary of eight other cost-efficient scenarios are displayed in SI Appendix, Table S2, representing ~10% increments in expected hypoxia reductions. The specific spatial configurations of subwatersheds targeted for conservation treatment associated with each of these points are presented in SI Appendix, Figs. S4–S9.

Variability. Variability in the estimated size of hypoxia is large and mirrors large variability in historical measurements of the zone (SI Appendix, Table S2 and Figs. S2 and S3). For example, although the solution depicted in Fig. 3 and SI Appendix, Figs. S2 and S3 achieves the hypoxia goal in expectation, the empirical 95% confidence interval is (220 km², 8,800 km²) when evaluated for 1988–2006.

We evaluate variability for all of the solutions in the tradeoff frontier over the 1988–2006 period. SI Appendix, Fig. S2 depicts the simulated variability in the size of the 5-y average hypoxic zone by considering historical weather over that period. Another way to view the variability is to consider the share of 19 5-y periods (1988–2006) in which the 5-y hypoxia moving average is below the 5,000 km² goal. SI Appendix, Table S2 shows the share of 5-y periods where hypoxia is under the goal, and SI Appendix, Fig. S3 presents these results for the full tradeoff frontier.

The left y axis in SI Appendix, Fig. S3 shows the mean simulated 5-y hypoxia, whereas the right y axis essentially shows the likelihood (in a counterfactual scenario) that a particular spatial assignment of cropland conservation scenarios considered would lead to the hypoxia goal attainment over the period 1988–2006. For example, the solution which achieves the goal on average attains the hypoxia goal 47% of the time (in 9 5-y periods of 19). The most expensive (and effective) solution is represented by the nontargeted application of Practices+Fertilizer-high scenarios across all modeled cropland. It reduces the mean hypoxia by more than 75% and is simulated to have attained the 5,000 km² goal in 16 of 19 (84%) 5-y periods. That solution would have reduced May N and P by approximately 25% each.

Identification of Critical Subwatersheds. A pattern of consistent selection of the subwatersheds emerges when considering the solutions generated by the optimization algorithm. That is, as higher reductions in Gulf hypoxia are desired, requiring larger cropland conservation investments, the same set of subwatersheds tends to be selected as cost-effective. In other words, subwatersheds that are cost-effective to treat if only a small investment in conservation is considered are generally still in the cost-effective set if additional investment is possible (Fig. 4). Sequential investments can be efficient because the same subwatersheds that need treatment to achieve large reductions in the zone also appear in the solutions for small reductions. The efficient subwatershed selection does not change substantially even if the ultimate goal of the size of the zone changes or the willingness to invest in conservation changes. SI Appendix, Table S5 presents the watersheds ranked by the frequency with which they were selected by the algorithm across the entire range of hypoxia reduction values, along with the distribution of the four conservation scenarios across the solutions in which they were selected. The algorithm is fairly consistent both in terms of spatial location of targeted subwatersheds and the conservation scenarios selected (Fig. 4 and SI Appendix, Figs. S4–S9).

Discussion and Limitations

Our results suggest that the Action Plan goal of a reduced Gulf hypoxia zone can be achieved by targeting conservation practices to specific subwatersheds. The estimated hypoxia zone reductions are achieved via a dual nutrient reduction strategy (average of 19% reductions in May mineral N and total P), which is consistent with the approach specified by the Action Plan (9), which, although suggesting that at least a 45% reduction in annual total...
N and total P loads would be sufficient, emphasized that it is likely the more difficult to control spring mineral N, which needs to be targeted. Some authors (21), using a model where Gulf hypoxia depends on N only, estimate that large (approximately 55%) in May total N reductions compared with 1980–1996 average load, or a 62% reduction compared with 2007–2011 loads) would be needed. Given the hypoxia model we use, a maintained dual 45% reduction (in spring mineral) N and P or a 55% reduction in N would drastically reduce the size of the zone. However, given that the hypoxia model we use incorporates the cumulative (up to a 6-y lag; ref. 19) effect of nutrients and nutrient reductions, these percentages are not directly comparable. For example, using 2004 5-y mean hypoxia, uniformly reducing 1999–2004 loads by 19% yields a hypoxia estimate of 5,603 km², which is roughly equivalent to a 32% reduction in N alone for the period 2000–2004 or a dual 27% reductions in N and P. Even with this correction, our findings suggest somewhat lower implied N and P reductions needed to achieve the Action Plan hypoxia goal in expectation, given historic weather variability.

We should also point out (SI Appendix, Table S2) that even applying the most aggressive conservation scenario we consider (Practices+Fertilizer-high) to all modeled subwatersheds reduces spring N and P by approximately 25% on average, so larger reductions would likely require either more effective conservation practices, new cropping systems, retirement of cropland from production, or some combination thereof. This finding highlights the fact that our results are tightly coupled with the agronomically relevant cropland conservation practices and their simulated effectiveness in reducing nutrient loads to the Gulf.

Another limitation is that not all potentially cost-effective conservation actions were simulated in our analysis, including some promising new approaches to retain nutrients on the landscape (e.g., bioreactors, saturated buffers, and cover crops) (22, 23). Likewise, the options we considered were only “working land” options, i.e., cropland conservation scenarios that are consistent with maintaining current crop production levels, because the practices modeled do not require changes in the cropping systems (11–15). Taking land out of production in targeted locations and returning it from farming to more natural conditions (e.g., perennial grasses, wetlands) was not considered in this study. Retiring land from production will be significantly more expensive relative to options that can maintain agricultural land use on a field-by-field basis, but taking land out of production on a targeted basis could be cost-effective. This cost-effectiveness could be further enhanced if ecosystem services (notably flood protection and habitat) from such land use changes are appropriately valued in optimization. Although the development and assessment of new conservation technologies and a better representation of the net cost of agricultural land retirement remain important for further analysis, our findings suggest that the existing suite of “working land” cropland conservation practices can be sufficiently effective to reach the national hypoxia reduction goals. Further, by identifying the most cost-effective locations for treatment, a sequential process of conservation actions can sensibly be developed.

Several other key features of this work should be kept in mind when interpreting the findings. The objective in optimization was to reduce the size of Gulf hypoxia at the lowest cost by using existing and well-established cropland conservation practices. Consequently, the spatial configurations for targeted conservation presented in this study focus only on the consequences for Gulf hypoxia. Many other ecosystem services are produced as a result of these conservation practices including local soil conservation and water quality improvements, flood protection, carbon sequestration, and improvements to wildlife habitat. Multiple ecosystem services could be included in the optimization generating a multidimensional tradeoff frontier rather than a 2D frontier.

Although such an approach would be worthwhile, there are also advantages from focusing on a single environmental concern, particularly for an important national resource such as the Gulf of Mexico. First, a case can be made that given the national interest in the Gulf, federal funds should be geographically targeted to locations that achieve the greatest gain for the dollar with a focus on that national resource. Second, within a planning context, the geographically identified areas could be viewed as the most important locations to begin sequential conservation investments so that both local benefits and improvements to the Gulf occur as quickly as possible.

Other important considerations include the fact that the modeled conservation scenarios and their impact on in-stream water do not account for potentially long nutrient residence times, so even an immediate application of conservation treatments would be unlikely to have an immediate impact on hypoxia. Additionally, although the weather variability data are
Materials and Methods
Effects of Upland Conservation Investments. The basis for this work are a series of data and modeling tools developed as a part of the larger CEAP, which is a major multiagency and multipartner effort with a stated goal to “improve efficacy of conservation practices and programs by quantifying conservation effects and providing the science and education base needed to enrich conservation planning, implementation, management decisions, and policy” (24). Specifically, we use the data and the modeling framework from the Cropland National Assessment, which estimates environmental benefits and effects of conservation practices on cropland. We used the methodology and the results from the CEAP Cropland National Assessment for the basins in the Mississippi-Atchafalaya River Basin (MARB): the Ohio-Tennessee River Basin (11), the Missouri River Basin (12), the Upper Mississippi River Basin (13), the Arkansas-White-Red River Basin (14), and the Lower Missouri River Basin (15). This study integrates (i) the National Cropland CEAP assessments of the in-stream water quality effects of additional conservation investments evaluated at the subwatershed level. However, we use the empirical hypoxia model evaluated in other watersheds. We turn to simulation-optimization methods to approximate the optimal frontier of cost-hypoxia tradeoffs. We use evolutionary algorithms (20) and follow the approach of (30) for optimization. The advantages of evolutionary algorithms include the ability to handle large search spaces, the ability to include dynamic output from complex simulation models as their objectives, and the ability to closely approximate cost-effectiveness frontiers (reflected in to the evolutionary algorithm literature). The N(X) function represents model-estimated impacts, where the impact of assignment of conservation scenarios on nutrient loads are evaluated by the CEAP models (APEX and HUMUS-SWAT), which represent program simulations that cannot be conveniently described in a simple mathematical form. Further, the marginal effect of a conservation scenario adoption in one subwatershed is not independent of the adoption in other subwatersheds. We turn to simulation-optimization methods to approximate the optimal frontier of cost-hypoxia tradeoffs. We use evolutionary algorithms (20) and follow the approach of (30) for optimization. The advantages of evolutionary algorithms include the ability to handle large search spaces, the ability to include dynamic output from complex simulation models as their objectives, and the ability to closely approximate cost-effectiveness frontiers (reflected in to the evolutionary algorithm literature).
hypoxya values, or both. At each iteration, the algorithm creates a Pareto-frontier, demonstrating the set of tradeoffs between hypoxia and the cost of conservation investments. In principle, the algorithm can continue generating such frontiers indefinitely, and a termination criterion needs to be specified. Optimization was stopped by using the consolidation ratio (36 criterion (more than 500 iterations of the search algorithm). Because of computational limitations, we optimize for reducing the size of 2004 hypoxic zone (an average year in the hypoxia series), using 1997–2004 for model simulations to obtain relative nutrient reductions, and then assess the performance of the solutions by resimulating the spatial allocation over the period 1979–2006 (the period of intersection of data availability for USGS nutrient load data and the CEAP data; simulation period starts in 1977 but the first 2 y are discarded to reduce dependence on initial conditions.). Using simulated nutrient reductions, we form the series of hypoxia estimates for the 1984–2006 period (as the empirical hypoxia model requires lagged nutrients as inputs). Following the Action Plan goal, we focus on 5-y averages of hypoxia estimates, obtaining the series for 1988–2006.

The search is initialized with a population of candidate solutions including nontargeted application of all CEAP scenarios to every eight-digit subwatershed under consideration, and with random candidate solutions. **SI Appendix, Table S4** shows the optimization parameters. The algorithm discovered large efficiency gains and appears to exhibit convergence at the time iterations were stopped (**SI Appendix, Fig. 5**). The optimization time was ∼500 h.

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