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

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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 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).

eutrophication | hypoxic zone | Gulf of Mexico | agricultural conservation practices | evolutionary computation

Low-oxygen (hypoxic) zones (oxygen < 2 mg·L^{-1}) in coastal waters are proliferating worldwide, impacting more than 400 coastal marine systems (1, 2). A major cause of their formation and persistence is nutrient pollution (from agricultural, urban, and other sources) delivered from their watersheds. Excess nutrients threaten not only coastal waters (3), but also pose problems within the watersheds (4), diminishing the quantity and quality of the ecosystem services they provide (5–7). For example, 55 percent of US streams are in "poor" condition (4), drinking water supplies are compromised by high nitrate concentrations, harmful algal blooms risk human health, and commercial fisheries are threatened. The second-largest hypoxic zone in the global ocean is in the northern Gulf of Mexico and covers an area averaging more than 14,500 km^2 in the summers of 2004 through 2013 (8). The documentation of this pervasive phenomenon led to the 2008 Action Plan for Reducing, Mitigating, and Controlling Hypoxia in the northern Gulf of Mexico (9). The Action Plan, a joint federal-state effort, set the goal of reducing the size of Gulf hypoxia to less than 5,000 km^2 over a 5-y period.

Current analysis of the sources of nutrient loads from the Mississippi-Atchafalaya River Basin (hereafter referred to as the Mississippi Basin) into the Gulf indicate that agricultural sources in the watershed contribute 80% of the delivered nitrogen (N) and more than 60% of the delivered phosphorus (P) (10). A number of cropland conservation practices can limit the loss of N and P from cropland into waterways and include reduced tillage, terraces, and riparian buffers. Reduced fertilizer application rates, and altered timing and method of application, can also be used to control losses of N and P. A comprehensive analysis of the existing coverage and historical effectiveness of these practices in reducing N, P, and sediment loss across the Mississippi Basin has recently been completed [US Department of Agriculture Conservation Effects Assessment Project (CEAP)] (11–15).

The Mississippi Basin is often divided into five major subbasins and further delineated into more than 800 subwatersheds (these are identified as "HUC-8's" 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.

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

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 km^2. 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 cost-effective locations to target cropland conservation investments across the Basin's 550 agricultural subwatersheds and to identify the nature of tradeoffs between hypoxia and costs of conservation investments. Targeted conservation practice investments are estimated to achieve the hypoxia reduction goal at the cost of \$2.7 billion annually.

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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.

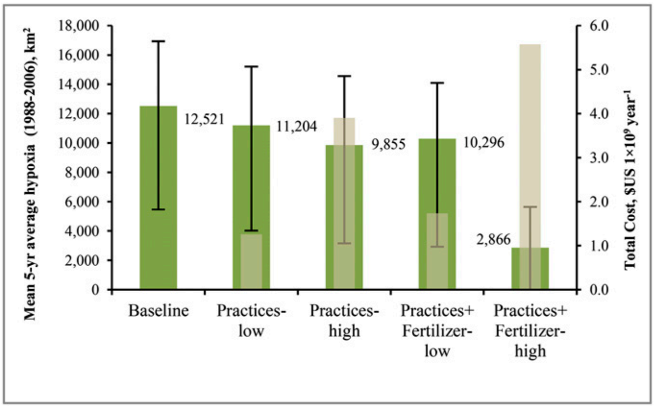

Fig. 1. Cropland conservation scenarios applied in nontargeted fashion to modeled subwatersheds. Green bars (left *y* axis) and data labels represent mean estimated hypoxia; tan bars (right *y* axis) represent annual cost. Additional conservation scenarios modeled are *Practices-low* depicting the low extent of coverage of conservation practices, *Practices-high* depicting the higher coverage of conservation practices, *Practices+Fertilizer-low* depicting low coverage level with both conservation practices and additional nutrient (fertilizer) control, and *Practices+Fertilizer-high* depicting the higher coverage of both conservation practices and nutrient control. Annual hypoxia size estimates are computed for the 1984–2006 period and converted to a moving 5-y average for the period 1988–2006 to provide a better match with the hypoxia Action Plan goal. Whisker bars represent empirical 90% confidence intervals.

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 $1 \times 10^9 \cdot y^{-1}$) 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 km^2 to approximately 11,200 km^2 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 km^2 is the *Practices+Fertilizer-high* scenario, which is predicted to achieve a mean 5-y hypoxia of approximately 2,900 km^2 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 km^2 reduction in the mean 5-y average hypoxic size, ranges from \$270 million$\cdot y^{-1}$ at the baseline to \$680 million$\cdot y^{-1}$ for the Action Plan goal of 5,000 km^2, and rises to approximately \$US $1.7 \times 10^9 \cdot y^{-1}$ with an attempt to reduce hypoxia to an average size of 1,000 km^2.

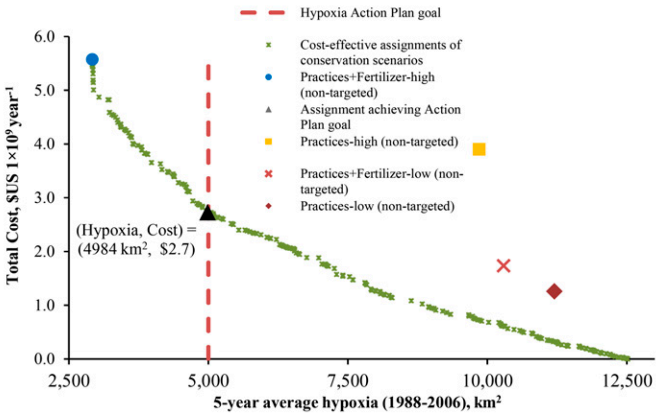

Fig. 2. Cost-hypoxia tradeoff frontier consisting of specific placements of cropland conservation scenarios across subwatersheds, a particular placement (configuration labeled by Δ) that achieves the 5,000 km^2 goal (on average), and nontargeted (simulated at all modeled subwatersheds) applications of cropland conservation scenarios across the Mississippi Basin. *SI Appendix*, Fig. S2 presents the historical simulated variability for each point in the frontier.

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 km^2. 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 × $10^9 \cdot y^{-1}$.* 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 km^2 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 km^2 (less than 500,000 acres) treated], *Practices+Fertilizer-low* [approximately 1,000 km^2 (less than 250,000 acres) treated], and *Practices-high* [just over 280 km^2 (70,000 acres) treated] scenarios. The average annual cost per treated ha (acre) for the solution identified is \$153 (\$62). 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 90% confidence interval is (220 km^2; 8,800 km^2) 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 km^2 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 km^2 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 hypoxic 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

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*One nontargeted scenario with a virtually identical (within 1%) level of hypoxia reduction encountered early in optimization iterations was estimated to cost almost 4.4 × $10^9 \cdot y^{-1}$, providing an estimate of 38% (1.6 × $10^9 \cdot y^{-1}$) cost savings due to targeting (optimization).

[†] It's important to note that, consistent with the National CEAP assessment, the CEAP baseline and alternative scenarios reflect actual farming systems and practices over the 2003–2006 period, and the longer simulations do not represent historical cropland management. Rather, one should interpret these results as counterfactuals only, i.e., under the assumption that a particular set of farming systems and conservation practices is in place and that weather variability follows a pattern observed over 1977–2006; what would have been the impact on nutrients?

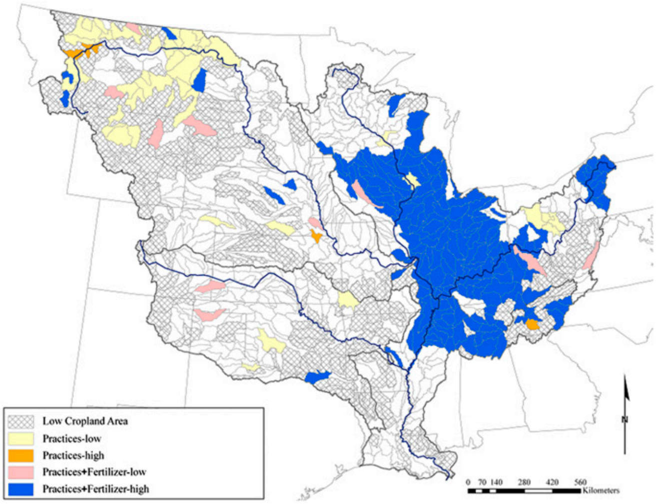

Fig. 3. An identified solution for a 60% reduction in the mean 5-y average hypoxia size (achieves the Action Plan goal, on average). The cross-hatched watersheds were not part of conservation scenario modeling because they have a small fraction of cropland (*SI Appendix*, Table S3).

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 km^2, 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 ecosystems 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

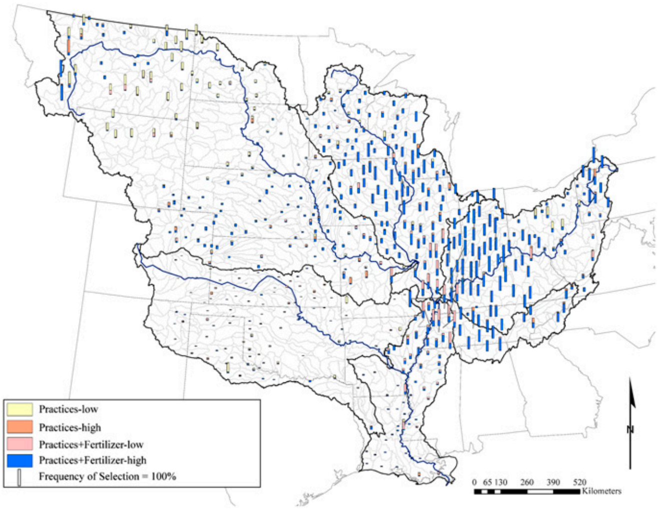

Fig. 4. Spatial distribution of frequency of watershed selection for cost-effective treatment and the distribution by cropland conservation scenario for the instances selected.

drawn from the recent decades, changes in regional climate can affect both the formation of Gulf hypoxia and nutrient loads from upland areas. These and other limitations of the CEAP studies apply equally to our effort, and we refer the reader to the careful disclosure of those in the relevant CEAP literature.

Despite these limitations, the tradeoff frontiers developed here provide insight into the costs and effectiveness of implementing cropland conservation practices to address the problem of eutrophication within the basin and hypoxia in the Gulf of Mexico. The integrated assessment model combined with the tools of evolutionary optimization produce visual depictions of the tradeoffs between the costs of cropland conservation practice investments and the size of Gulf hypoxia, and maps of specific spatial configurations identified by any given solution. This set of tools can provide a powerful backdrop for promoting a scientifically informed discussion among interested parties about the tradeoffs and consequences of action (or inaction) in addressing complex social and environmental problems.

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 Mississippi River Basin (15). This study integrates (*i*) the National Cropland CEAP assessments of the in-stream water quality effects of additional conservation investments for all watersheds in MARB where the CEAP-NRI (25, 26) surveys allowed estimation of cropland acreages considered to be in "high"("critical") or "moderate" need for additional conservation practice treatment, and (*ii*) the CEAP estimates of costs of additional conservation investments. The baseline cropland management and conservation practices were simulated for each CEAP-NRI sample point. Based on the complex evaluation (11–15) of the site conditions and baseline agricultural management and conservation investments, each sample point was categorized as "high ("critical") or "moderate" to describe the need for conservation treatment. For each sample point, additional conservation scenarios were simulated at the field scale (using the APEX model; ref. 27), and edge-of-field nutrient losses were estimated on a per-hectare basis. Four different conservation treatment scenarios were developed for each subwatershed. Although the exact conservation practices simulated vary by site condition and across the basins, the general approach was consistent for the entire MARB. The detailed descriptions of conservation practices simulated are contained in refs. 11–15, with *SI Appendix*, Table S1 providing a summary of the cropland conservation treatment scenarios and the constituent conservation practices and fertilizer management. Weighted per-hectare nutrient loads simulated for the conservation scenarios at the sample point (field) level were scaled up to the watershed level by using cropland expansion factors created from the CEAP-NRI survey weights (25, 26). Subwatersheds are represented by eight-digit USGS watersheds as described in refs. 10 and 16 and *SI Appendix*, Table S3.

Cost Estimates. As a part of the CEAP assessment, estimates of the costs of practices and additional nutrient management treatments were produced for each CEAP-NRI sample point. The costs included the cost of conservation practice planning and installation, maintenance, and repair over time. The costs were annualized because individual conservation practices have different useful lives. The cost estimates include both the farmer costs and the technical assistance costs. We do not make any specific assumptions on the incidence of the costs and focus only on the total cost to society. *SI Appendix*, Table S3 presents the full set of cost data and the area of cropland identified as in critical or moderate need for conservation treatment used in this study.

Linking Modeled Riverine Nutrient Outputs to Inputs to Hypoxia Model. The National Cropland CEAP modeling framework produces simulated in-stream impacts of various spatial assignments of CEAP conservation scenarios across the eight-digit subwatersheds in MARB, including the Basin outlet. Our empirical hypoxia model uses USGS-estimated spring (May) N and P loads at the Basin outlet as inputs.

Using USGS-estimated (28) monthly nutrient values at St. Francisville, LA, we obtain the baseline structural component of model-predicted hypoxia $h_{base} = h(N_{obs})$. To compare the baseline hypoxia estimates with the outcomes from model simulations, which assign CEAP scenarios to 8-digit subwatersheds, we use the "delta change" method (e.g., ref. 29) and modify the observed nutrient values by the ratio of scenario-specific nutrient values to the modeled baseline nutrient values. Doing so allows us to interpret the hypoxia estimate for a particular conservation scenario in a cardinal (as opposed to relative) fashion and to make direct comparisons to the historical observed size of Gulf hypoxia.

Evolutionary Optimization: Approximating the Optimal Placement of Additional Investments Across Subwatersheds. We used the linkage between upland conservation investment scenarios and the estimate of the size of Gulf hypoxia to evaluate the counterfactual scenarios of changes in cropland conservation investments in terms of their consequences for hypoxia and cost. With the four watershed-level conservation scenarios and a baseline option, there are potentially $5^{557} = 2.12 \times 10^{389}$ Mississippi Basin scenarios, each representing a different spatial assignment of conservation scenarios across the MARB. We wish to identify the cost-effectiveness frontier: those watershed configuration scenarios where it is no longer possible to reallocate conservation scenarios across subwatersheds to reduce the size of hypoxia (cost) without increasing cost (hypoxia). In other words, we wish to simultaneously minimize $[C(X), h(N(X))]$, where X represents a particular assignment of CEAP scenarios across the MARB subwatersheds, $h(N(X))$ is the empirical hypoxia model evaluated for a particular spatial assignment X, and $C(X)$ is the estimated cost of a particular assignment of scenarios to MARB subwatersheds. Thus, X can be thought of as a 557×1 vector of decision variables, where each element belongs to the set of CEAP scenarios: $X_i \in (\mathit{Base}, \mathit{Practices\text{-}low}, \mathit{Practices\text{-}high}, \mathit{Practices\ Fertilizer\text{-}low}, \mathit{Practices} + \mathit{Fertilizer\text{-}high})$. The cost of *Base* (baseline cropland conservation) is assumed to be zero (we focus on the need for additional conservation investments and do not consider reducing the baseline cropland conservation investments). The two-objective integer optimization problem could be solved exactly if the objective functions were linear (or at least differentiable). However, although the cost and hypoxia functions satisfy that requirement, the $N(X)$ function represents model-evaluated 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 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 [referred to in the evolutionary algorithm literature as Pareto-frontiers (20) of optimal tradeoffs] in a single optimization run. In particular, an attractive feature of such an approach is the full representation of nonlinearities and interdependencies embedded in the physical process model within optimization, a feature important in spatial optimization by using ecohydrologic models (31–33) and having potential implications for incentive-based conservation policy (33, 34) (*SI Appendix* provides an example of the extent of such nonlinearities by using subwatershed 7040006.). As Vrugt and Robinson (35) argue, "… evolutionary algorithms have emerged as the most powerful approach for solving search and optimization problems involving multiple conflicting objectives." Algorithm description is provided in *SI Appendix, Evolutionary Algorithm description and parameters*. Intuitively, evolutionary algorithms can be thought of as mimicking a simplified process of natural evolution, where individuals (candidate solutions, representing specific spatial assignments of conservation scenarios to watersheds in our application) are evaluated in terms of their performance with respect to the objectives (estimated cost and hypoxia), and those spatial assignments of conservation scenarios that perform well (which are Pareto-efficient with respect to other spatial assignments considered in the current algorithm iteration) are more likely to be selected for "breeding" (creating new spatial assignments) for subsequent algorithm iterations. The process of "breeding," coupled with an element of random search ("mutation"), creates new spatial assignments of conservation scenarios across the MARB that are preferred with respect to having lower hypoxia values for the same cost, lower cost for the same hypoxia 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. S1). The optimization time was ~500 h.

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