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Predicting the response of Gulf of Mexico hypoxia to variations in Mississippi River nitrogen load

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Abstract

The effects of nutrient loading from the Mississippi River basin on the areal extent of hypoxia in the northern Gulf of Mexico were examined using a novel application of a dissolved oxygen model for a river. The model, driven by river nitrogen load and a simple parameterization of ocean dynamics, reproduced 17 yr of observed hypoxia location and extent, subpycnocline oxygen consumption, and cross-pycnocline oxygen flux. With Monte Carlo analysis, we illustrate through hindcasts back to 1968 that extensive regions of low oxygen were not common before the mid-1970s. The Mississippi River Watershed/Gulf of Mexico Hypoxia Task Force set a goal to reduce the 5-yr running average size of the Gulf's hypoxic zone to less than 5,000 km² by 2015 and suggested that a 30% reduction from the 1980–1996 average nitrogen load is needed to reach that goal. Here we show that 30% might not be sufficient to reach that goal when year-to-year variability in ocean dynamics is considered.

The evolution and management of summer hypoxia in bottom waters of the northern Gulf of Mexico have recently received considerable scientific and policy attention because of the enormous size of the hypoxic zone and because of its implications for watershed management within >40% of the continental United States—the Mississippi River Basin (Turner and Rabalais 1994; CENR 2000; Mississippi River/Gulf of Mexico Watershed Nutrient Task Force 2001; Mitsch et al. 2001; Rabalais et al. 2002a). Extensive regions of bottom oxygen concentrations <2 mg L⁻¹ form off the Loui-

siana coast each spring and summer (Rabalais and Turner 2001). These regions have recently extended 600 km westward from the mouth of the Mississippi River past the Texas border. These hypoxic regions averaged 8,300 km² in 1985–1992 and increased to an average of 16,000 km² in 1993–2001 (Rabalais et al. 2002a). An assessment of the causes and consequences of hypoxia concluded that the almost threefold increase in nitrogen load to the Gulf (Goolsby et al. 2001) has driven the long-term increase in hypoxia since the middle of the last century (CENR 2000; Rabalais et al. 2002a). Riverine nitrogen input stimulates coastal algal production and the subsequent settling of organic matter below the pycnocline. Because the pycnocline isolates deeper waters from the surface and inhibits vertical oxygen flux, decomposition of organic matter below the pycnocline consumes oxygen faster than it is replenished, and oxygen concentrations decrease dramatically.

Variability in climate and ocean dynamics control much of the interannual variability in hypoxia extent (Rabalais et al. 1999, 2002a), which can confound the understanding of its response to the management actions being proposed for the basin (Mississippi River/Gulf of Mexico Watershed Nutrient Task Force 2001; Rabalais et al. 2002a). We use a

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biophysical model to explore the relative influence of nitrogen load and ocean variability on changes in hypoxia and provide hindcasts and forecasts of hypoxic area in response to changes in loads, bounded by ranges in potential ocean conditions. Although efforts to model the interactions between nutrient load and oxygen dynamics have successfully simulated temporal variability within one vertical dimension (e.g., Justić et al. 1996, 1997, 2002) and three dimensions (Bierman et al. 1994), this model is the first to successfully predict the direct effect of variable nutrient loads on the areal extent of hypoxia on this shelf.

Methods

The model—The model here is used extensively to simulate oxygen concentrations in rivers and estuaries (e.g., Chapra 1997). The mass balance model simulates concentrations of oxygen-consuming organic matter

$$dB/dt = -v dB/dx - aB$$

and the dissolved oxygen deficit

$$dD/dt = -v dD/dx + aB - bD$$

downstream from point sources of organic load. B is the concentration in oxygen equivalents of the decomposing organic matter (mg L^{-1}), D is the dissolved oxygen deficit (mg L^{-1}), t is time (d), x (km) is the distance downstream from the point source of B , a and b are first-order rate constants for organic matter decomposition and oxygen flux (d^{-1}), respectively, and v is the net downstream advection of subpycnocline waters (km d^{-1}).

The steady state solution for a given point source, ignoring longitudinal dispersion and assuming no upstream oxygen deficit is

$$B = B_0 e^{-ax/v}$$

$$D = [a/(b - a)]B_0[e^{-ax/v} - e^{-bx/v}]$$

where B_0 is the oxygen demand at the point source ($=W/Q$, mg L^{-1}), W is the point source load of B (g d^{-1}), and Q is the flow of the modeled stream ($\text{m}^3 \text{d}^{-1}$). In this application, we calculated annual, summer steady state, subpycnocline oxygen concentration profiles downstream from two sources of oxygen demand—the Mississippi and Atchafalaya rivers.

In this analysis, we assume there is a correspondence between the measured extent of midsummer hypoxia and that which would be achieved at steady state. In reality, the spring and early summer production of organic matter, its subsequent rapid westward movement along the surface, and its settling into the slower moving bottom waters is a dynamic transition into the summer and early fall development of hypoxia. However, our ability to accurately simulate the year-to-year variability with this summer model helps validate the use of point source approximations, parameterized oceanography, and steady state conditions for this application. Expansion beyond these simplifications with, for example, multilayered, time-dependent models could add further insight into the transition periods; however, they also require significantly more parameter estimation, calibration, and field data.

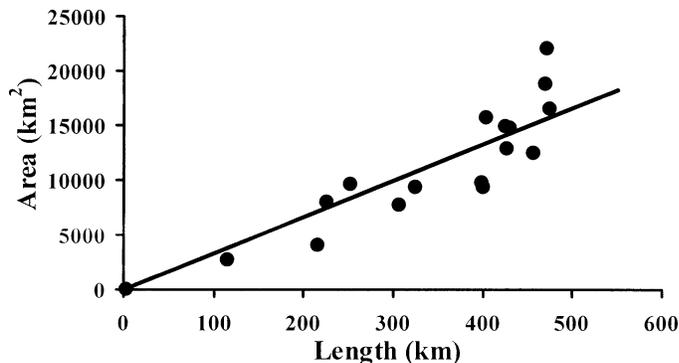


Fig. 1. A linear regression of observed hypoxic area and length. The regression was forced through the origin (slope = 33.13; $r^2 = 0.79$).

In addition to these assumptions of steady state and no dispersion, applying this model to Gulf hypoxia assumes that (1) surface- and bottom-water movement west of the Mississippi River in summer is constrained such that the subpycnocline water movement can be modeled as one-dimensional flow and that hypoxic zone length adequately characterizes its area, (2) river nitrogen load can be used as a surrogate for the load of biological oxygen demand below the pycnocline, (3) subpycnocline oxygen consumption can be modeled as a first-order process proportional to organic matter concentration, and (4) oxygen flux across the pycnocline can be modeled as a first-order process proportional to the oxygen deficit. The validity of these assumptions is discussed in the following paragraphs, as well as in the description of the model calibration results.

Interactions among buoyant river plumes, tidal currents, the Louisiana coastal current, northward excursions of the Loop Current and its eddies, wind-driven circulation, and hurricanes make an analysis of the oceanographic environment in the northern Gulf of Mexico complicated, especially in surface waters over short time scales. However, for the time scales of this analysis, we assume that subpycnocline physics can be captured simply as net westward advection. Whereas surface water currents can be rapid and show significant reversals in flow, bottom waters during summer stratification are fairly isolated from much of the surface dynamics and have typical westward velocities between 0.5 and 1.0 km d^{-1} (DiMarco et al. 1997; Rabalais et al. 1999).

Hypoxia data—The relatively slow, constrained flow, coupled with other biogeochemical and physical processes, produces the characteristic shape of the hypoxic zone. These hypoxic areas typically extend westward from the mouths of the Mississippi and Atchafalaya rivers, sometimes connecting to form one continuous 500–600-km-long zone from the Mississippi River delta, past the Texas border. In contrast to their length, they are typically only 30–60 km wide and <10 m thick. To compare hypoxic zone length and area, contours of bottom-water oxygen concentration $<2 \text{ mg L}^{-1}$ were generated from field data (Rabalais et al. 1999; Rabalais et al. 2002a) using the Kriging interpolation method of Surfer[®] 7 (Golden Software, Inc., 2002). Distances along the length of the hypoxic area(s) were measured using ArcView[®] (Envi-

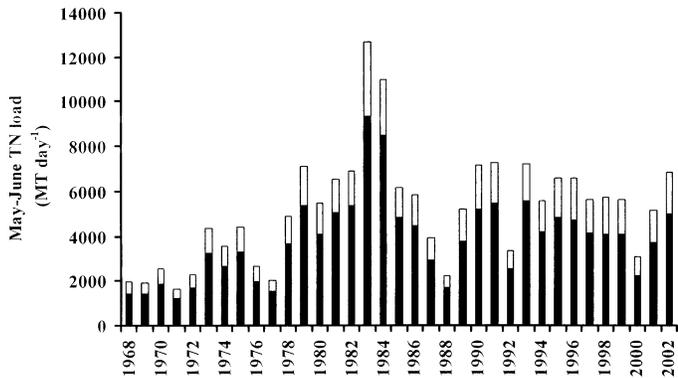


Fig. 2. May–June total nitrogen loads from the Mississippi and Atchafalaya Rivers used in model simulations. Solid bars are Mississippi; open bars are Atchafalaya.

ronmental Systems Research Institute, Inc., 1996) software on imported Surfer-generated contours. The characteristic shape of the hypoxic area, supporting the strong dependence on long-shore transport, leads to a significant, simple linear regression of area with length (slope = 33.13; $r^2 = 0.79$; Fig. 1). This strong correlation and the relatively slow, low-frequency currents observed in the bottom waters appear to justify the assumption of a one-dimensional analysis.

The modeled subpycnocline oxygen concentrations decrease downstream from the mouth of the Mississippi River for 50–100 km and then gradually increase, followed by another decrease downstream from the Atchafalaya. Because the model simulates subpycnocline concentrations, but the observations of hypoxia extent are for areas along the bottom, one has to ascertain for model comparisons a subpycnocline concentration that corresponds to hypoxia along the bottom. Typical vertical oxygen profiles (Rabalais et al. 1999) indicate that subpycnocline average concentrations $<3.0 \text{ mg L}^{-1}$ correspond to the existence of hypoxic waters ($<2.0 \text{ mg L}^{-1}$) at the bottom. Using 3.0 mg L^{-1} in the model to approximate the location of hypoxia, downstream concentration profiles will produce two separate patches or one continuous patch, depending on whether the increasing concentration after the decline from the Mississippi source exceeds 3 mg L^{-1} before approaching the Atchafalaya. Model estimates for the length of the hypoxic zone correspond to the total length of these profiles with subpycnocline concentrations $<3 \text{ mg L}^{-1}$. Area estimates were calculated from the predicted length and the length–area regression.

Nitrogen loads—We considered the load of oxygen-consuming material to be proportional to the loading rate of May–June river total nitrogen (TN) because nitrogen is the most direct stimulant of the spring and early summer plankton blooms that fuel hypoxia (Lohrenz et al. 1997; Justić et al. 1997). The Mississippi River basin drains into the Gulf in two primary locations—the Mississippi main stem and the Atchafalaya River—and nitrogen loads are calculated for stations at St. Francisville and Melville, respectively (USGS 2002). The Old River Control Structure, maintained by the U.S. Army Corps of Engineers, allows 70% of the flow down the Mississippi main stem and 30% down the Atchaf-

alaya. Consequently, the ratio of Mississippi to Atchafalaya TN is $2.95 (\pm 0.34)$ for 1980–2002, the period of record in which TN estimates, calculated as $\text{NO}_3 + \text{NO}_2 + \text{TKN}$, are available. TKN estimates for St. Francisville were not available prior to 1975, and no data were available from Melville prior to 1980. Therefore, we used simple linear regressions to build a complete record for hindcasts to 1968 (Fig. 2). Based on St. Francisville (S) and Melville (M) data from 1980 to 2002, $\text{TN}_M = 2,420 + 0.323\text{TN}_S$ ($r^2 = 0.90$). Based on St. Francisville data from 1975 to 2002, $\text{TKN} = 5,056 + 0.461(\text{NO}_3 + \text{NO}_2)$ ($r^2 = 0.66$).

The model treats these two rivers as point sources and places the Mississippi source at the origin of the model's spatial domain and the Atchafalaya 220 km downstream. We assume that 50% of the Mississippi source is entrained in the westward flowing plume based on a number of considerations (Dinnel and Wiseman 1986; Rabalais et al. 1996, 1999). For example, $\sim 53\%$ of the total flow comprises flows from the westward-oriented passes (South Pass, Southwest Pass, and Grand and Tiger Passes). Coriolis forcing and average wind direction from the southeast enhance westward flow from these passes, and long-shelf profiles of salinity, turbidity, and nutrient concentrations show the clear influence of the westward flow compared to the eastward distributed and offshore flow. The second point source is estimated by calculating a mass balance from B and D , derived from the upstream source, and the new B_0 from the Atchafalaya River. Treating these two rivers as point sources to the subpycnocline is partially justified because a significant portion of the river-stimulated surface algal production settles below the pycnocline within a few tens of kilometers from these sources. Satellite imagery and in situ measurements confirm that, although production continues in surface waters as nutrients are regenerated downstream, both production and surface chlorophyll decrease significantly away from the river mouths, indicating considerable settling below the pycnocline (Rabalais et al. 2002b).

We use the Redfield ratio to convert nitrogen to algal carbon ($5.67 \text{ g C g}^{-1} \text{ N}$), a respiratory quotient of 0.77 for oxygen consumption ($3.47 \text{ g O}_2 \text{ g}^{-1} \text{ C}$), and an estimate that 50% of surface algal production settles beneath the pycnocline (Justić et al. 1996, 1997; Rabalais et al. 2002b). If all river nitrogen entrained in the westward flowing plume is converted to algae and is not recycled and if the average effective westward water flow below the pycnocline is $0.6 \text{ km}^3 \text{ d}^{-1}$ (60 km wide, 10 m thick, 1.0 km d^{-1}), then the nitrogen load ($\text{Mt} [\text{metric tons}] \text{ d}^{-1}$) can be converted to a subpycnocline oxygen demand ($\text{mg O}_2 \text{ L}^{-1}$) at the river source by a factor of 0.016. Although we used this factor in the model, its actual value is not critical because it is held constant across all 17 yr of calibration, and our focus is on simulating the effects of interannual variation in nitrogen load.

Model calibration

The model explains 55% of the variability (calculated as $1 - \sum (P_i - O_i)^2 / \sum (O_i - O_m)^2$, where P_i is the i th prediction, O_i is the i th observation, and O_m is the observation mean)

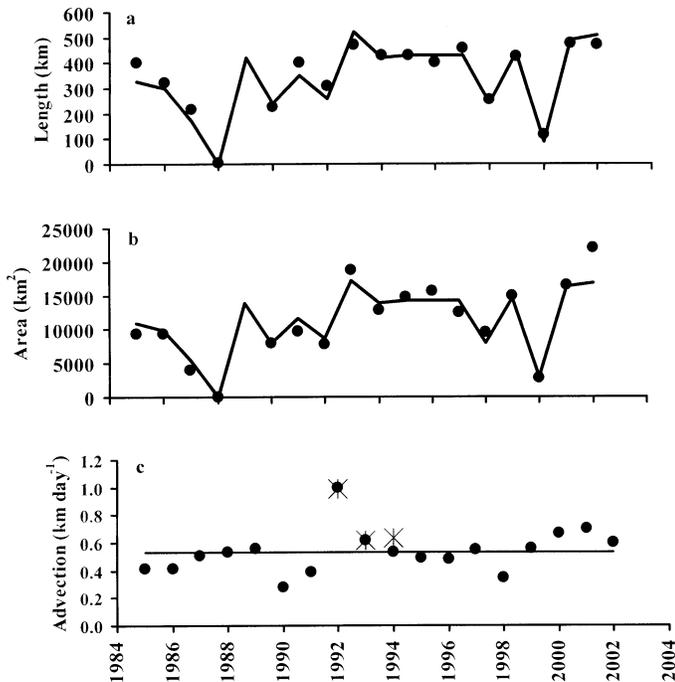


Fig. 3. Simulated hypoxic zone (a) length, (b) area, and (c) calibrated advection terms. Circles in (a) and (b) are observed lengths and areas; there were no comprehensive field data collected in 1989. Circles in panel c are calibrated advection terms; asterisks in panel c are mean bottom-water advection terms from LATEX (Louisiana-Texas Physical Oceanography Program) moorings (DiMarco et al. 1997).

in hypoxic zone length and 45% of the variation in area when the rate coefficients and net westward advection (0.56 km d^{-1}) are kept constant across all years. Holding all coefficients constant assumes that all environmental factors influencing the development of hypoxia, other than nitrogen load, are constant from year to year. Although there is little reason to expect significant interannual variation in the stoichiometric ratios or the first-order rates of subpycnocline oxygen consumption or cross-pycnocline oxygen flux, one would expect significant variations in the physical processes controlling the subpycnocline flow. Parameterizing interannual variation in these dynamics through variations in the net advection term provides a more realistic representation. We estimated the net westward advection of subpycnocline water from current meters located within the hypoxic region (Stas. 15, 16) at depths of 25 and 18 m (DiMarco et al. 1997) by averaging the reported 14-d means for 8 Apr–21 Sep 92, 24 Mar–21 Sep 93, and 23 Mar–20 Sep 94. The results were 0.99 , 0.62 , and 0.63 km d^{-1} , respectively. Using these measured values in the model resulted in simulated patch lengths of 260, 520, and 460 km for 1992, 1993, and 1994, respectively. Given the simplicity of this model, these values compare favorably to the observed patch lengths of 307, 469, and 428 km.

Comprehensive current velocity observations are not available for the remaining years, although current speeds were typically $<0.9 \text{ km d}^{-1}$ for this region in 1993–1997 (Rabalais et al. 1999). Therefore, the advection term was

varied year-by-year to calibrate the model to match the observed hypoxia lengths and areas. By doing so, the calibrated model explains 95% of the variation in hypoxia length and 88% of the variation in hypoxia area (Fig. 3). Faster advection appears to move the decomposing organic matter further downstream, expanding the area of hypoxia. Slower advection retains the organic matter closer to the sources, often resulting in smaller areas, but lower oxygen concentrations. These 17 calibrated advection values (0.53 ± 0.16) are well within the range of observed variation from moorings. Because we do not know historical values for this calibration term and we cannot know their future values, we use the mean and standard deviation from the calibration to represent its natural variability and use them to express such variability in the hindcasts and forecasts in the following sections.

Cross-pycnocline oxygen flux and subpycnocline oxygen consumption are modeled as first-order processes proportional to the subpycnocline oxygen deficit and oxygen demand (organic matter), respectively. Because the values of the first-order rate constants used for flux and consumption (0.01 and 0.003 d^{-1} , respectively) are parameterizations of many processes and thus cannot be derived from direct measurements, they were selected to produce the typical downstream oxygen profiles. However, one can compare the modeled fluxes to those calculated from observations made between 1995 and 1992. Simulated cross-pycnocline fluxes ($0.041 \pm 0.019 \text{ mg O}_2 \text{ L}^{-1} \text{ d}^{-1}$) compare remarkably well to May–August monthly means calculated from measured oxygen balances for the same period and region (0.047 ± 0.008) (Justić et al. 1996, 1997). Simulated subpycnocline loss rates ($0.050 \pm 0.027 \text{ mg O}_2 \text{ L}^{-1} \text{ d}^{-1}$) were also consistent with those determined from these mass balances (0.060 ± 0.032) (Justić et al. 1996, 1997) and with direct respiration measurements (Turner et al. 1998).

The calibrated model predicted the occurrence of single and double patches in most years and placed the hypoxic zone between 10 and 600 km from the mouth of the Mississippi. It reproduced the observed multiple patches in 1986, 1987, 1990, and 1998; single patches in 1993–1997, 1999, 2001, and 2002; and minimal hypoxia in 1988.

Results and discussion

Hindcasts, simulations, and forecasts—The ability to simulate observed hypoxic zone lengths, locations, and areas, as well as rates of oxygen consumption and flux, in response to measured nitrogen loads and measured or calibrated subpycnocline advection makes it possible to assess the effects of potentially altered river nutrient loads under a range of oceanographic conditions. To account for variation in oceanographic conditions, the model was run 1,000 times for each loading scenario between 1968 and 2002 in a Monte Carlo analysis using values for advection drawn randomly from a normal distribution with mean and standard deviation equal to that derived from the 17-year calibration ($0.53 \pm 0.16 \text{ km d}^{-1}$).

Within the bounds of the Monte Carlo error analysis, the model matches the observed hypoxic zone lengths and areas

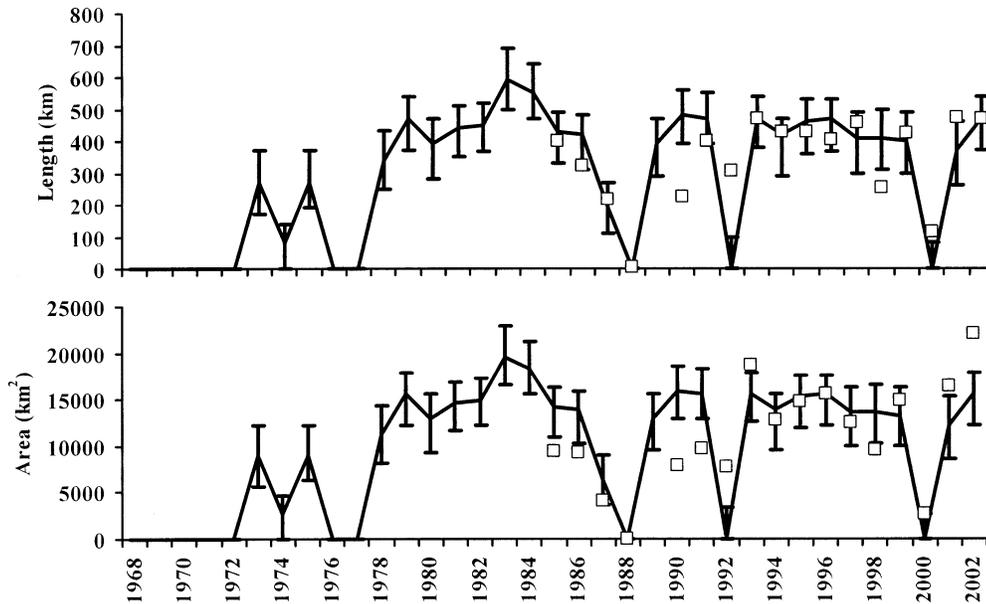


Fig. 4. Simulated hypoxic zone (a) lengths and (b) areas. Lines and error bars represent the first, second, and third quartiles from 1,000 simulations. Open squares are observed lengths and areas; there were no comprehensive field data collected in 1989.

for 1985 to 2002 quite well, with a few notable exceptions (Fig. 4). Hindcasts, using loads between 1968 and 1984, suggest that before the mid-1970s, the nitrogen load was not sufficient to produce significant areas of oxygen-depleted bottom waters. The model hindcasts hypoxic areas of 5,000–10,000 km² in 1973–1975, minimal hypoxia in 1976 and 1977, and significant and persistent large-scale regions between 1978 and the beginning of the shelf-wide cruises. These results are consistent with historic, albeit not comprehensive, surveys of hypoxia on the Gulf shelf (e.g., Turner and Allen 1982; Rabalais et al. 1999, 2002a). The model also suggests that hypoxia might have been more extensive in the mid-1980s than in the following decade. These hindcasts are consistent with those from a one-dimensional vertical model for a region within the hypoxic area between the Mississippi and Atchafalaya Rivers outfalls (Justić et al. 2002) and with the leveling off and significant year-to-year variability in nitrogen loading rates (Fig. 2).

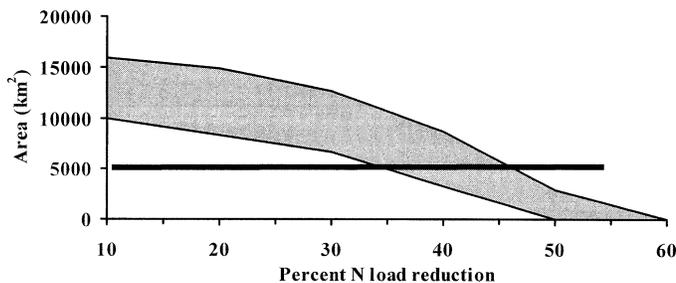


Fig. 5. Ensemble forecasts of the response of hypoxia to changes in riverine nitrogen load. Loads are percent reduction from the 1980–1996 mean May–June total nitrogen loads. The shaded area, representing the ensemble forecast, contains all values between the first and third quartiles from 1,000 simulations. The horizontal bar at 5,000 km² represents the Action Plan goal.

The model was also run 1,000 times for a suite of nutrient load reductions between 10 and 60% to evaluate potential hypoxia responses. The results suggest that load reductions within this range would be effective in reducing the extent of hypoxia. A 30% reduction in load would lead to a 20–60% reduction in areal extent; a 40% reduction in load would lead to a 45–80% reduction in area (Fig. 5).

The Federal–State–Tribal Action Plan for reducing, mitigating, and controlling hypoxia in the northern Gulf of Mexico (Mississippi River/Gulf of Mexico Watershed Nutrient Task Force 2001) agreed on a goal to reduce the 5-yr running average of hypoxic area to below 5,000 km² by 2015. The action plan also suggests that a 30% reduction from the 1980–1996 average nitrogen load would be needed to reach that goal and that most of the reduction would have to come from nonpoint sources as much as 1,000 km north of the Gulf. That goal was based on the best available scientific information at the time and is similar to nutrient reduction goals in other coastal systems in the United States and elsewhere (Boesch 2002). However, the model scenarios outlined here suggest that a 30% reduction might not be sufficient to reach this goal in most years (Fig. 5).

There are at least two important implications from this analysis. First, year-to-year variability in oceanographic conditions can significantly mask, in the short term, the effect of reduced nitrogen loads on the size of the hypoxic zone. Thus, setting a goal based on a 5-yr running average was important. This variability, as well as potential effects of longer term climate change and the relatively slow response time of the basin to changes in land use and management, emphasize the need for taking action now and monitoring carefully, while allowing for policy adjustments over time. Second, although the results here support the initial agenda set in the Action Plan to work toward a 30% load reduction,

that level of reduction might not be enough to reach the goal in some years. In fact, it could take a reduction of 40–45% to assure the goal is satisfied in most years.

These results suggest that policy makers should consider whether to set load reduction goals based on projected average oceanographic and climate conditions or to consider more significant reductions to account for conditions that tend to amplify the load effects. Fortunately, recent reanalyses (McIsaac et al. 2001, 2002) of the effects of potential management actions on nitrogen loads from the Mississippi River Basin suggest that those reductions might be easier to achieve than estimated in the original studies supporting the Action Plan (Doering et al. 1999).

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