2022 Forecast:
Summer Hypoxic Zone Size in the
Northern Gulf of Mexico

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Abstract

A hypoxic water mass with oxygen concentrations ≤ 2 mg l^{-1} forms in bottom waters of the northern Gulf of Mexico continental shelf each spring/summer and lasts into the fall but can be disrupted by strong storms. Nutrients from the Mississippi River watershed, particularly nitrogen, fertilize the Gulf's surface waters to create excessive amounts of algal biomass that sink to the bottom layer and sediments where decomposition leads to oxygen depletion. The low oxygen conditions in the Gulf's most productive waters stresses organisms and may even cause their death so that living resources are threatened, including humans depending on the fish, shrimp and crabs caught there. Various models use the May nitrogen load of the Mississippi River as the main driving force to predict the size of this hypoxic zone in late July. This prediction is from one of these models and predicts the size of the late summer area with an accuracy of 89%.

The June 2022 forecast of the hypoxic zone size for late July 2022 is that it will cover 15233 km^2 (5881 mi^2) of the bottom of the continental shelf off Louisiana and Texas. The 95% confidence interval is that it will be between 13,376 and 17,096 km^2 (5164 and 6601 mi^2). This estimate is based on the assumption that there are no significant tropical storms or unusual wind events in the two weeks before the monitoring cruise, or during the cruise. If a storm does occur, then the size of the zone is predicted to be 56% of the predicted size without the storm, equivalent to 8530 km^2 (3294 mi^2).

The predicted hypoxic area is about the size of Connecticut (14,357 km^2) and 111% of the 1985-2021 average of 13,791 km^2 ($n = 36$ including years with storms; two years had no cruise). If the area of hypoxia becomes as large as predicted, then it will be three times the size of the Hypoxia Action Plan goal to reduce the zone to less than 5,000 km^2 (1931 mi^2). No reductions in the nitrate loading from the Mississippi River to the Gulf of Mexico have occurred in the last few decades, the interval since the formulation of the Hypoxia Action Plan environmental goal.

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Introduction

Hypoxic water masses in bottom waters occur when the oxygen concentration falls below 2 mg l^{-1}. The hypoxic water of the northern Gulf of Mexico is distributed on the continental shelf west of the Mississippi River and onto the northern Texas continental shelf, from near shore to as far as 125 km offshore, and in water depths up to 60 m (Rabalais et al. 2007; Jarvis et al. 2021; Figure 1). It has been found in all months but is most persistent and severe in spring and summer (Turner et al. 2005; Rabalais et al. 2007). The July distribution of hypoxic waters most often is a single continuous zone along the Louisiana and adjacent Texas shelf. Hypoxia also occurs east of the Mississippi River delta but covers less area and is ephemeral. These areas are sometimes called 'dead zones' in the popular press because of the absence of commercial quantities of shrimp and fish in the bottom layer – something that is of economic consequence to the fishery (Purcell et al. 2017; Smith et al. 2017). The number of dead zones throughout the world has been increasing in the last several decades and currently totals over 500 (Díaz and Rosenberg 2008; Rabalais et al. 2010; Conley et al. 2011; Breitburg et al. 2018). The hypoxic zone off the Louisiana coast is the second largest human-caused coastal hypoxic area in the global ocean.
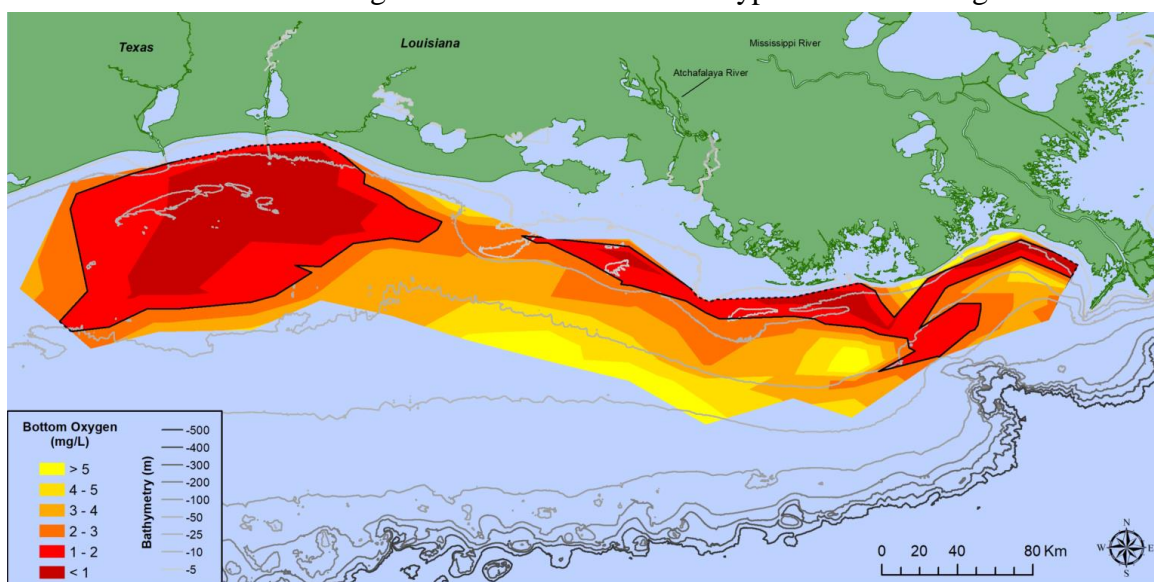
Figure 1. Oxygen concentrations in bottom water across the Louisiana-Texas shelf from July 25 – 31, 2021. Data source: N.N. Rabalais, C.N. Glaspie, and R.E. Turner, Louisiana State University; funded by NOAA, National Centers for Coastal Ocean Science.

Systematic mapping of the area of hypoxia in bottom waters of the northern Gulf began in 1985 at geographically fixed stations (Appendix Figure 1). Its size from 1985 to 2021 ranged between 40 to 22,720 km^2 during late July to early August and averaged 13,863 km^2 (5,616 mi^2) (Figure 2). There are no values for 1989 (no funding available) or for 2016 (incompatible ship with mechanical breakdown); data from 2017 were incomplete at the end of some transects; data for 1978 to 1984 are estimated from contemporary field data. The estimates for before 1978 assume that there was no significant hypoxia then and are based on results from various models and sediment core analyses. There were no shelfwide cruises in 1989 and 2016, and the area was incompletely mapped in 2017. Monthly, and bi-monthly monitoring on two transects off Terrebonne Bay, LA, and the Atchafalaya delta, LA, ended in 2012. The annual number of hypoxia-focused cruises peaked 20 years ago and is now at the bare minimum (Appendix Figure 2).
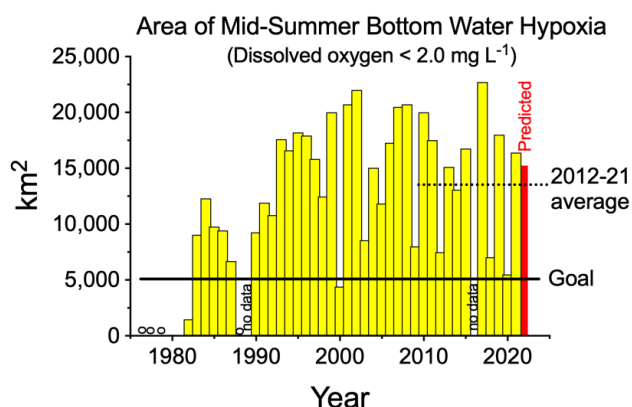

Figure 2. Area of the hypoxic zone from 1979 to 2021 and the predicted value for 2022 (the red bar). The Hypoxia Action Plan restoration 'goal' is 5,000 km^2.

Hypoxic water masses form because the consumption of oxygen in bottom water layers exceeds the re-supply of oxygen from the atmosphere and photosynthesis. The re-aeration rate is negatively influenced by stratification of the water column, which is primarily dependent on the river's freshwater discharge and accentuated by summer warming. The overwhelming supply of organic matter respired in the bottom layer is from the downward flux of organic matter produced in the surface layer. The transport to the bottom layer is the result of sinking of individual cells, as the excretory products of the grazing predators (zooplankton) that 'package' them as fecal pellets, or as aggregates of cells, detritus and mucus. The respiration of this organic matter declines as it falls through the water column (Turner et al. 1998), but the descent rate is sufficiently rapid so that most respiration occurs in the bottom layer and sediments, not within the water column.

The amount of organic matter produced in the surface waters is primarily limited by the supply of nitrogen, not phosphorus (Scavia and Donnelly 2007; Turner and Rabalais 2013), and previous indicators of phosphorus deficiency are not as reliable as they were once thought to be (Fuentes et al. 2014). The evidence for this conclusion is that the supply (loading) of nitrogen (primarily in the form of nitrate-N) from the Mississippi River watershed to the continental shelf within the last few decades is positively related to chlorophyll *a* concentration (Walker and Rabalais 2006; $R^2 = 0.30 – 0.42$), the rate of primary production (Lohrenz et al. 1997, $R^2 > 0.77$; Lohrenz et al. 2008), and the spatial extent of the hypoxic area in summer (Turner et al. 2012; $R^2 > 0.9$). The size of the shelfwide hypoxic zone has increased since it began occurring in the 1970s simultaneously with 1) the rise in carbon sequestration in sediments, 2) indicators of increased diatom production, and 3) shifts in benthic foraminiferal communities (Turner and Rabalais 1994; Sen Gupta et al. 1996; Turner et al. 2008). There is, therefore, a series of cause-

and-effect arguments linking nitrogen loading in the river to phytoplankton production, bottom water oxygen demand, and the formation and maintenance of the largest human-caused coastal hypoxic zone in the western Atlantic Ocean.

The oxygen consumption creates a zone of hypoxia that is constrained by the geomorphology of the shelf, horizontal water movement, stratification, and vertical mixing (Obenour et al. 2012; Justić and Wang 2014). The significance of reducing nutrient loads to these coastal waters is based on the coupling between the organic matter produced in response to these nutrients and its respiration in the bottom layer (MRNGoM HTF 2001, 2008; Rabalais et al. 2002, 2007, 2010; SAB 2007). The nutrient controlling the hypoxia zone size in late July in our model is nitrate loading in May, which is about 70% of the total nitrogen delivered to the northern Gulf of Mexico by the Mississippi River. There is a known period of loading to the Gulf of Mexico, then phytoplankton production, sinking of organ matter, and benthic respiration that links the May nutrient loading to the period of bottom-water in the northern Gulf of Mexico.

Mississippi River Discharge and Nitrogen Loading

Hypoxic conditions are dependent on river discharge because of the influence that water volume and salinity have on the physical structure of the water column and on the nutrients delivered to the coastal zone. The US Geological Survey (USGS) provides monthly estimates of river discharge and nitrogen concentration (http://toxics.usgs.gov/hypoxia/mississippi/), which are used to calculate the nitrogen loading for the Mississippi River watershed into the Gulf of Mexico. The nutrient load is calculated by multiplication of the discharge volume and the concentrations of nutrients, particularly nitrogen.

The discharge from the Mississippi River watershed in May 2022 was 31,900 m^3 s^{-1} (cms), which is the 24th largest in 37 years from 1985 to 2022, and equal to about 109% of the average May discharge. The concentration of nitrate has been declining slightly over the last 20 years, but the increase in river discharge means that the total loading has remained the same in recent decades or is increasing (Figure 3; Sprague et al. 2011; Crawford et al. 2019).
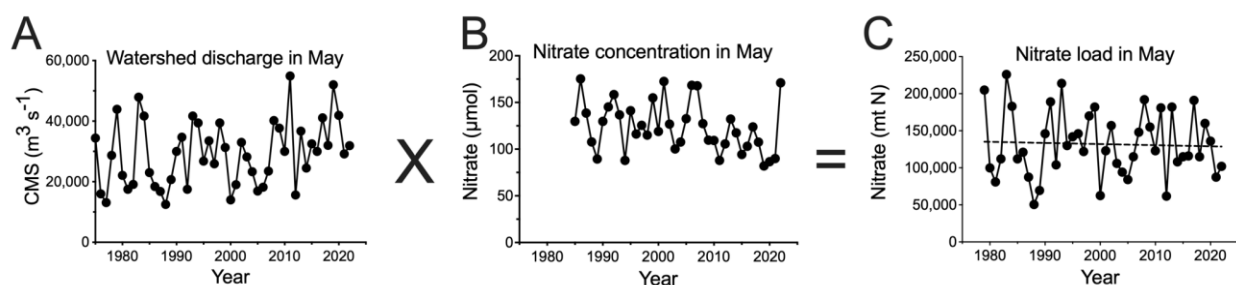

Figure 3. The discharge of the Mississippi River (A), the concentration of nitrate (B), and the resultant nitrate load (C) in May. The discharge and nitrate concentrations are from the United States Geological Survey.
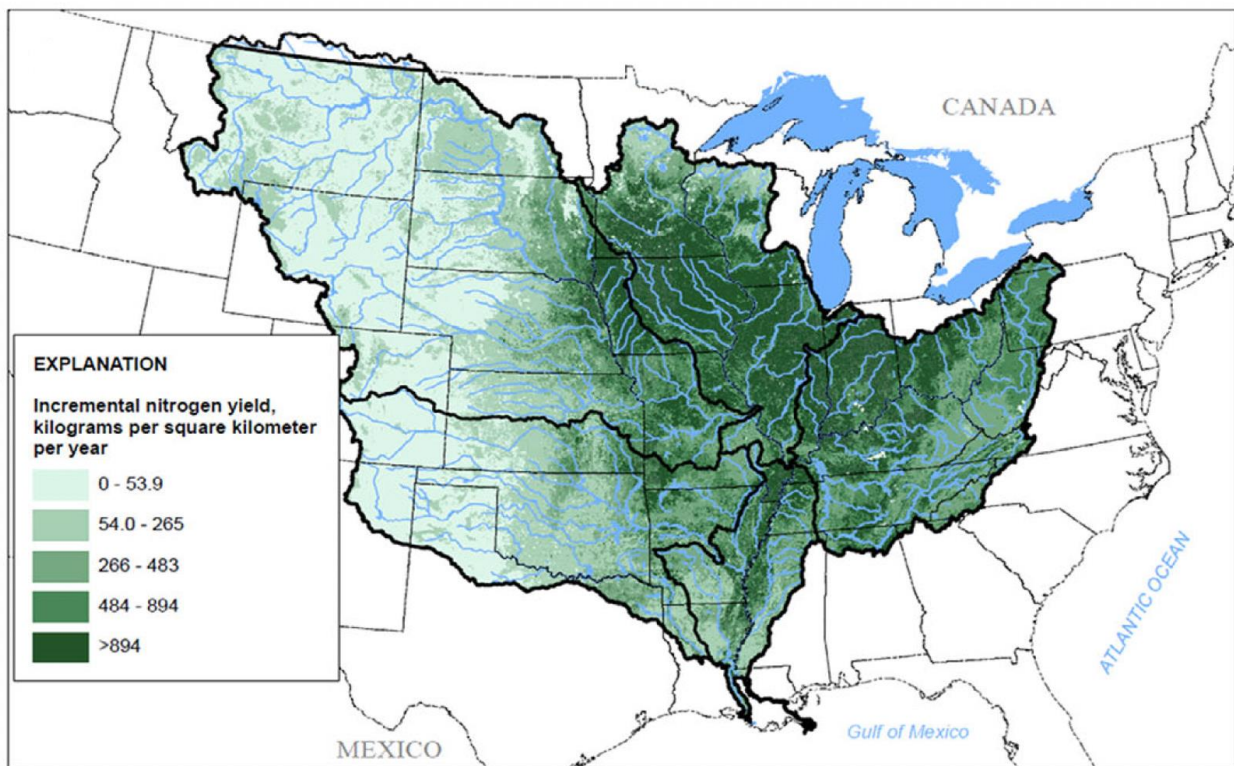
Figure 4. The yield of nitrogen (kg km^{-1}) from land in the Mississippi River watershed (from Robertson and Saad 2021).
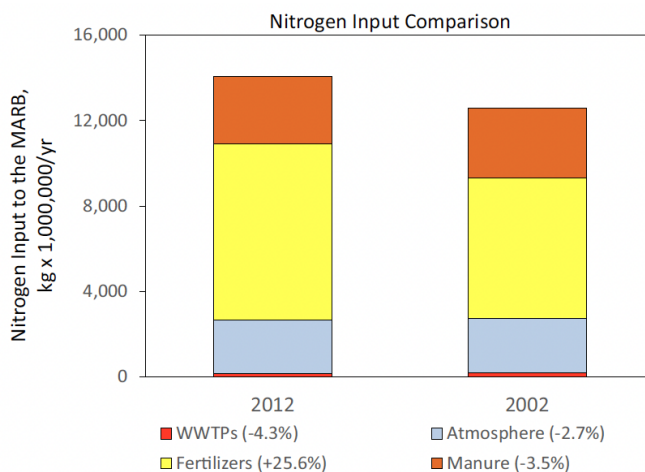

Figure 5. The percent of nitrogen loading in the watershed that is sourced to wastewater treatment plants (WWTP), fertilizers, atmospheric deposition and manure in 2012 and 2002 (from Robertson and Saad 2021).

Some consequences of water quality degradation with nitrate contamination include higher sewage treatment costs (Dearmont et al. 1998), seafood price increases (e.g., Smith et al. 2017), compromises to fish reproduction (Tuckey and Fabrizio 2016) and increased frequency and duration of harmful algae events inshore and offshore (Lopez et al. 2008). There are links between nitrate in drinking water and birth defects [neural tube and spinal cord including spina bifida, oral cleft defects and limb deficiencies (Brender et al. 2013)], and bladder and thyroid cancer (Ward et al. 2018). The strictly nutrient-related issues are co-developing with ocean acidification and climate change whose cumulative and synergistic interactions may be even more socially and ecologically significant than just nitrate contamination (Moss et al. 2011).

Plastics fill oceans (Lavers and Bond 2017), pharmaceuticals are distributed in sewage (Kasprzyk-Hordern 2009; Wilkinson et al. 2022), the COVID-19 virus and other viruses spread in partially treated sewerage wastes from: a) aging septic tanks (Farkas et al. 2020), b) unconstrained wetland treatment systems with insufficient hydrologic controls, and c) overloaded treatment systems.

Hypoxic Zone Size

Models for predicting the size of the hypoxic zone rely on July cruise data, primarily because there are no comparable shelfwide data for other months. Data on the size of the hypoxic zone in late July from 1985 to 2021 are based on annual field measurements (data available at http://www.gulfhypoxia.net). Data for 10 years were not included in the analysis because there were strong storms or unusual wind conditions just before or during the cruise (1998, 2003, 2005, 2008, 2010, 2011, 2013, and 2018 - 2020). These storms or unusual wind conditions, by comparison of pre-cruise and post-cruise sampling to data collected during the cruise, changed currents, disrupted the stratified water column, and re-aerated the water column. It may take a few days to several weeks, depending on water temperature and initial dissolved oxygen concentration, for respiration to reduce the dissolved oxygen concentration to ≤ 2 mg l^{-1} after the water column stratification is re-established. The average reduction in hypoxia size in years with storms compared to years without storms is 56%. Storm frequency has been increasing on more than half of the cruises in recent years (Figure 6).
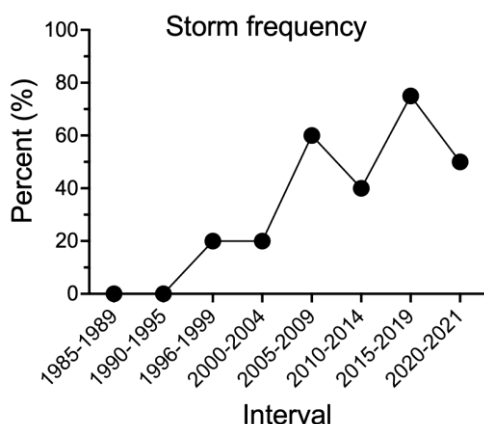

Figure 6. Storm frequency on cruises binned into 5-year increments from 1985 to 2021.

Prediction for 2022

We use several models to forecast the hypoxic zone in the northern Gulf of Mexico in July 2022. The most accurate model prediction, we think, is that it will cover 15,233 km^2 (5881 mi^2) of the bottom of the continental shelf off Louisiana and Texas. The 95% confidence interval is that it will be between 13,776 and 17,096 km^2 (5164 and 6601 mi^2) (Figure 7).

This estimate is based on the assumption that there are no significant tropical storms occurring in the two weeks before the monitoring cruise, or during the cruise. If a storm does occur, then the size of the zone is predicted to be 56% of the predicted size without the storm, equivalent to 8499 km^2 (3294 mi^2).
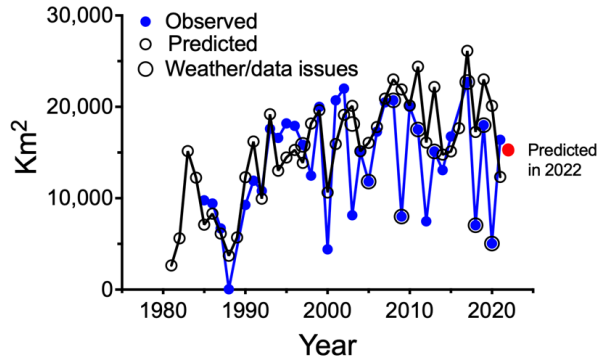
Figure 7. The measured and estimated size of the hypoxic zone from 1981 to 2021 and the predicted size for 2022.

Hypoxia Models and Model Accuracy

We use several models to predict the size of the hypoxic zone in July that are based on the May total nitrite+nitrate nitrogen load (note: concentration × discharge equals the load) to the Gulf from the main stem of the Mississippi River and the Atchafalaya River. The nitrite+nitrate loading will be referred to here as "nitrate" loading because the nitrite component is a minimal component of the two. The residence time of the surface waters along this coast is about 2 to 3 months in the summer, hence the 2 to 3 month lag between the loading rate calculated in May and the size of the hypoxic zone in late July. The stability of these models, however, is not fixed, because the ecosystem is evolving. For example, the size of the hypoxic zone for the same amount of nitrate loading is increasing at about three times over the last 40 years (Figure 8A; Turner et al. 2012).. Further, the models will eventually be adjusted to account for the limited space on the shelf for hypoxia to occur (a geographic constraint). The process-based ecosystem models are a platform to greatly expand understanding how the physical and biological factors interact over all months are increasingly accurate and visually-appealing, but also require additional seasonal data to validate them as conditions change throughout the year and among years.
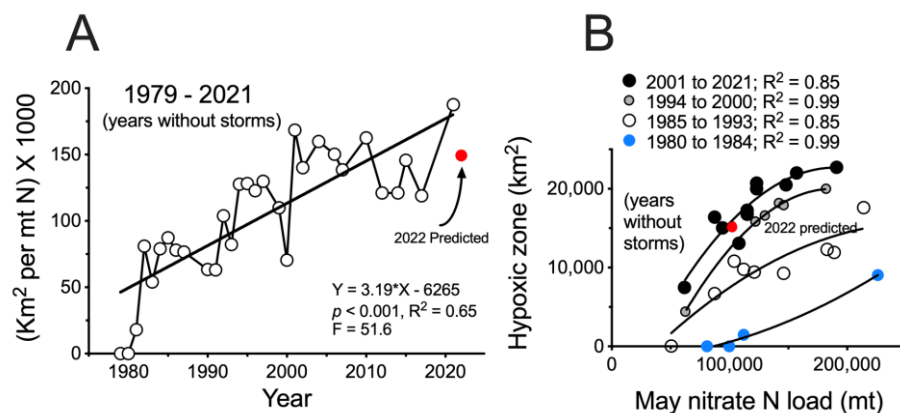
Figure 8. The relationship between nitrate loading in May and the size of the hypoxic zone in July. A. The annual hypoxic zone area per nitrogen loading in May each year. B. The size of the hypoxic zone in different intervals. The red dot is the predicted size in 2022.

The unstated hypothesis implied by these models is that the system can be treated as a chemostat limited by N, in the same way that the chlorophyll *a* concentration or algal biomass in lakes might be modeled by P loading to the lake. The Streeter–Phelps type models initiated by Scavia and colleagues also incorporate this nutrient dose:response framework (Scavia et al. 2003, 2004; Scavia and Donnelly 2007) in their predictive schemes. These models assume that the size of the zone is driven mostly by what happens in the current year and that other influences cause variation around a relatively stable baseline suite of factors. An example of secondary influences might be seasonal or annual variations in wind speed and direction or freshwater volume. Our model is based on the nitrate load of only the current year. The reference point for calibrating the model is the behavior of the system in recent history. We use the last several years of data on the relationship between hypoxic zone size and nutrient loading for this model. Others do something similar. The USGS uses the last five years of data to calibrate the 'LOADSET' model, and Scavia and Donnelly (2007) update the coefficients in their model annually by using rolling 3- to 5-year averages for coefficients (Evans and Scavia 2010). Their recent numerical adaptation has the effect of adjusting model input with each year, but not explaining the biological/physical basis for these changes any better than one of our earlier models did with the 'year' term. The year term in our model is, in other words, descriptive, but not explanatory beyond the simple nitrogen loading = oxygen deficit relationship.

The estimate for 2022 in Figure 8B uses nitrate data that were transformed into their log10 equivalents to avoid the problem encountered in 2012 when the prediction was much larger than the actual size, which is attributable to using a simple linear regression analysis to fit a curvilinear relationship. If there is significant curvature (bowed downward) without this transformation, then both the lower and upper ends of the data field are overestimated. This effect is more dramatic when the relationship is being extended into a sparse data field at the extremes of nitrogen loading, as happened during 2012, which was a drought year with low nitrate loading.

Some of the sensitivity to nitrate loading is carried over from one interval to the next to create a 'legacy' effect that may last decades. A legacy effect can be explained as the result of incremental changes in organic matter accumulated in the sediments one year and metabolized in later years (Turner and Rabalais 1994), by changes in the percent nitrate of the total nitrogen pool, or by long-term increases in bottom-water temperature (Turner et al. 2017).

Our statistical models, and their predecessors, are fairly accurate models based on past performance (Turner et al. 2008, 2012). The model used here describes 89% of the variation since 2000 (non-storm years). The equivalent model for the Baltic Sea low oxygen conditions explains 49 to 52% of the inter-annual variations in bottom-water oxygen concentration (Conley et al. 2007).

Nutrient load models are robust for long-term management purposes, but they are less robust when short-term weather patterns move water masses or mix up the water column (Rabalais et al. 2018). The size of the hypoxic zone this year is expected to follow the relationship with nitrogen loading—as long as there is no 'wildcard' in the form, for example, of a tropical storm before or at the time of the annual summer cruise. Some of the variations in the size of the Gulf hypoxic zone result from re-aeration of the water column during storms. The size

of the summer hypoxic zone in 2008, for example, was less than predicted because of the influence of Hurricane Dolly. Tropical Storm Don was a similar complication in 2011. Climate changes may alter the spring initiation of hypoxia formation, duration and frequency. The timing of hypoxia in the Chesapeake Bay, for example, is earlier with climate warming (Testa et al. 2018). The needed detailed seasonal data necessary to make phenological comparisons for Gulf of Mexico are not known.

The prediction in 2018 was noteworthy for the great disparity between the much larger size of the hypoxic zone predicted by *all* models and the actual size. The predicted size of the forecast from four models ranged from 12,949 to 17,523 km^2, but the measured size was 7040 km^2. Wind data collected during the research cruise indicated a strong change in wind patterns (i.e., from the west instead of the southeast) and elevated wind speeds at the beginning of the cruise. These influences resulted in a short-lived decrease in water column stratification and then oxygenation of the bottom layer, particularly on the eastern end of the mapped area. Winds from the west push the bottom-water hypoxic area more to the east and decrease the bottom-water footprint overall.

Other models predicting oxygen dynamics on this shelf are in Bierman et al. (1994), Justić et al. (2003), Scavia and Donnelly (2007), Forest et al. (2011), Scavia et al. (2003, 2004), Justić and Wang (2014), Fennel et al. (2016), Justić et al. (2017), Testa et al. (2017), Laurent et al. (2018), Fennel and Laurent (2018), and Ou and Xue (2022). Other forecasts for this year will be from the University of Michigan (http://scavia.seas.umich.edu/hypoxia-forecasts/), Dalhousie University (http://memg.ocean.dal.ca/news/), North Carolina State University (https://obenour.wordpress.ncsu.edu/news/), and the Virginia Institute of Marine Science (http://www.vims.edu/research/topics/dead_zones/forecasts/gom/index.php). The NOAA ensemble predictions are based on these models (http://www.noaa.gov/media-releases). These models do not always produce similar results, and model improvement is one focus of ongoing research efforts supported by the NOAA National Centers for Coastal Ocean Science. The general result from an ensemble analysis using the five model results indicates that a 60% reduction in Mississippi River nitrogen load is required to reach the Hypoxia Task Force environmental goal, and that a 25% load reduction is required to have a 95% certainty of observing a hypoxic area reduction within a consecutive 5-year assessment period (Scavia et al. 2017).

A recent description of hypoxia development in the northern Gulf of Mexico is in Rabalais and Turner (2019). We review the past, present, and possible future conditions of hypoxia in the northern Gulf of Mexico and provide some insight into possible management actions. Kirchman (2021) is a well-written and recent overview of low oxygen zones in rivers, lakes, estuaries and oceans.

Beyond the Coast

Hypoxic zones in a dynamic equilibrium of forces, some of which are known or suspected, and others are unexplored or not yet realized. Acidification, climate change, climate change gases, temperature, and fishery targeting are being explored with financial support ranging from meagre to moderate levels. The conditions driving the size of the hypoxic zone in all of these models includes nutrient loading in the Mississippi River. Nutrient loading is

predominantly driven by land use choices in the river watershed. *There has been no reduction in the quantity of nitrogen in the river after the Hypoxia Action Plan (MRNGoM HTF 2001) was forwarded to Congress in 2001*.

Restoration of the coastal waters requires reducing nutrient loading to the coastal zone, and this requires changing farming practices in the Mississippi River watershed (Rabotyagov et al. 2014). Nitrogen loading can be reduced with both agronomic and field nutrient reduction techniques that cover crops, crop rotation and shifts in land under tile drainage (Randall and Mulla 2001; Dinnes et al. 2002). Tile drainage can go into buffer strips before it reaches streams, drains into wetlands, or even not be used if row cropped fields are converted to perennials. The replacement of deep-rooted perennials giving continuous living cover with short-rooted annuals leaving the ground bare for more than half the year results in more soil erosion (Heathcote et al. 2013). Putting perennials back into the landscape will reduce soil erosion and nutrient losses from farm fields.

An excellent example of the use of perennial grains is provided by Liebmann et al. (2013) and Davis et al. (2012) who conducted a 7-year field trial of alternative cropping systems for corn-soybean rotations at Iowa State University. Some key findings were that by using cover crops for 4 years there was a 50% or more reduction in fossil fuel use, a doubling of employment, and the profits remained unchanged. The diversification of crop coverage with small grains and legumes had a 91% reduction in fertilizer use, 97% reduction in herbicide use, and increased carbon storage. Implementing these strategies requires changing significant embedded social, agronomic and political conditions that will benefit the agronomic community, the soil upon which it depends and may be a positive component of climate change adaptation. Maintaining the status quo will not be so helpful.

Post-cruise Assessment

The 2022 mapping cruise is scheduled for July 25 to August 1. The data will be posted as close to daily as possible at http://www.gulfhypoxia.net. Delays will be related to QA/QC of dissolved oxygen data against Winkler titrations. The data from this year's cruise will be used to quantify the relative merits of the assumptions of the models, and to compare them with other models. This is an example of how long-term observations are one of the best ways to test and calibrate ecosystem models, to recognize the dynamic nature of our changing environment(s), and to improve the basis for sound management decisions. The post-cruise assessment will be provided at the end of the summer shelfwide hypoxia cruise and posted on the same website where this report appears.

Acknowledgments

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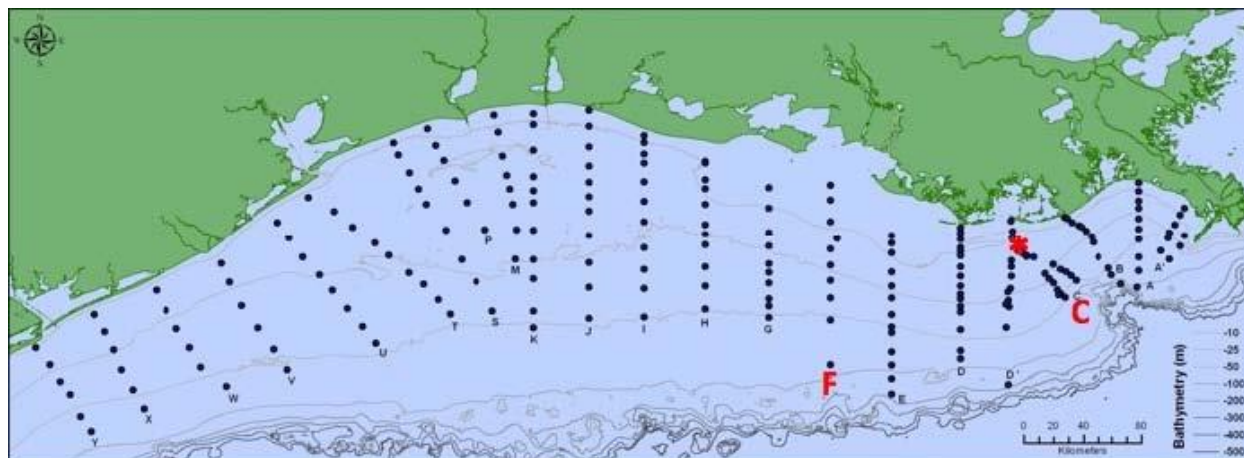
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Appendix

Appendix Figure 1. Location of hypoxia monitoring stations sampled in summer (not every year, depending on location of hypoxic area), the transects off Terrebonne Bay (transect C) and Atchafalaya Bay (transect F), and the ocean observing system (asterisk) off Terrebonne Bay (no longer in operation).
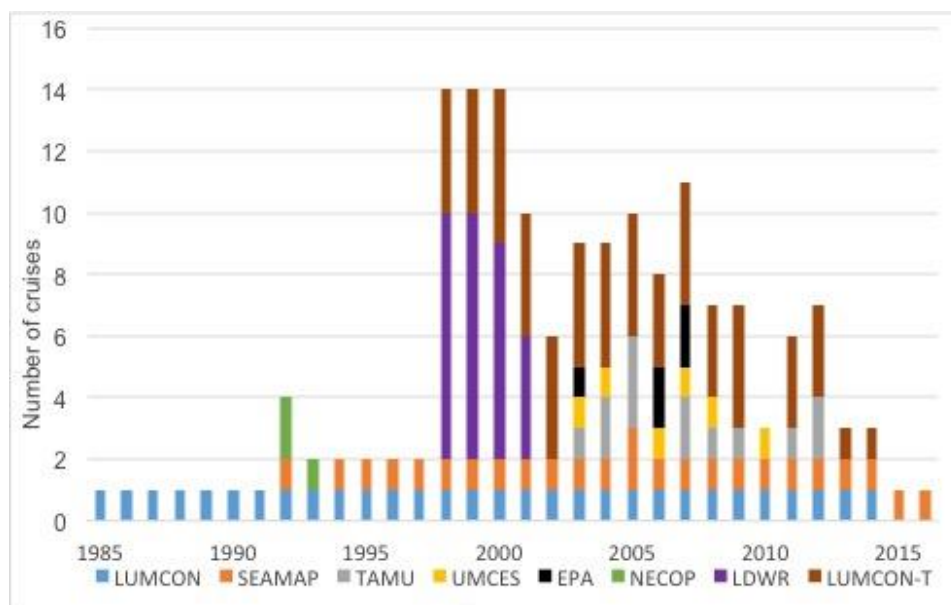
Appendix Figure 2. The number of State, Federal and university cruises associated with hypoxia measurements in the northern Gulf of Mexico from 1985 to 2016. LUMCON = Louisiana Universities Marine Consortium; SEAMAP = Southeast Area Monitoring and Assessment Program; TAMU = Texas A&M University; UMCES = University of Maryland Center for Environmental Studies; EPA = U.S. Environmental Protection Agency; NECOP = Nutrient Enhanced Coastal Ocean Productivity; LDWR = Louisiana Department of Wildlife Research; LUMCON-T = transects sampled during the year by LUMCON. Source: Maiti et al. 2018; used with permission.