2025 Forecast:
Summer Hypoxic Zone Size in the Northern Gulf of Mexico

R. Eugene Turner[1] and Nancy N. Rabalais[1]

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. 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 who depend on the fish, shrimp and crabs caught there. The main driver of the low oxygen zone size is nitrogen from the Mississippi River watershed that fertilizes the Gulf's surface waters creating excessive amounts of algal biomass. This biomass sinks to the bottom layer and sediments where decomposition leads to oxygen depletion. 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. The warming of the continental shelf, however, has altered the phytoplankton-zooplankton-fish food web, and this warming has shrunk the size of the zone created per nitrogen loading. A new model was developed to account for this warming effect.

The June 2025 forecast of the hypoxic zone size for late July 2025 is that it will cover 12,470 km^2 (4815 mi^2) of the bottom of the continental shelf off Louisiana and Texas. The 95% confidence interval is that it will be between 10,900 and 14,266 km^2 (4209 and 5508 mi^2). This estimate is based on the assumption that there are no hurricanes or unusual wind events in the two weeks before the monitoring cruise, or during the cruise.

The predicted hypoxic area is about 90% of the size of Puerto Rico and equal to 88% of the 1985-2024 average of 14,133 km^2 (*n* = 35 including years with storms; two years had no cruise). If the area of hypoxia becomes as large as predicted, then it will be about 2.8 times the size of the Hypoxia Action Plan goal to reduce the zone to less than 5,000 km^2 (1931 mi^2) by 2035. Only minor reductions in the nitrate loading from the Mississippi River to the Gulf of Mexico have occurred since the formulation of the Hypoxia Action Plan environmental goal in 2001.

---

[1] Department of Oceanography and Coastal Sciences
Louisiana State University
Baton Rouge, LA 70803
euturne@lsu.edu
nrabal@lsu.edu

Introduction

Hypoxic water masses occur when the oxygen concentration falls below 2 mg l^{-1}. The hypoxic bottom 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., 2007a; Jarvis et al., 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., 2007a). 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 in oceans and lakes throughout the world has been increasing in the last several decades and are a threat to global stability (Breitburg et al., 2018; Duprey et al., 2024; Rose et al., 2024). A recent overview of low oxygen zones in rivers, lakes, estuaries and oceans is in Kirchman (2021). The hypoxic zone off the Louisiana coast is the second largest human-caused coastal hypoxic area in the global ocean. A recent description of hypoxia development in the northern Gulf of Mexico is in Rabalais and Turner (2019).

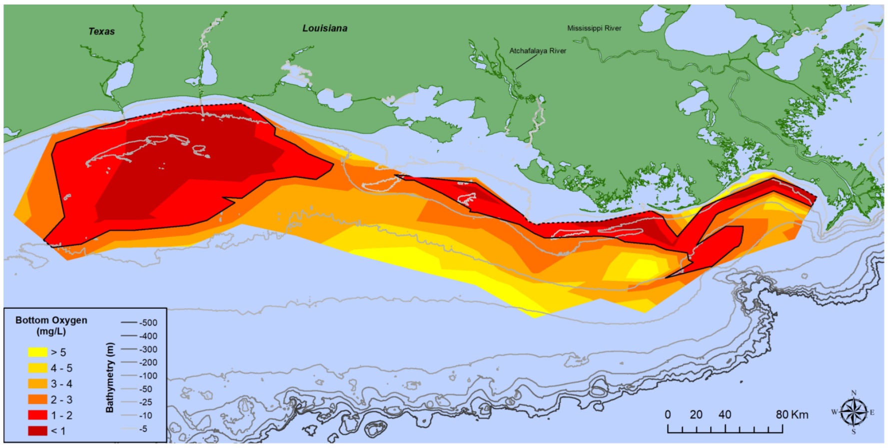


Figure 1. Oxygen concentrations in bottom water across the Louisiana-Texas shelf from July 25 – 31, 2021. Data source: N.N. Rabalais, C.N. Glaspie, R.E. Turner, Louisiana State University. Funding: NOAA, NCCOS (now National Centers for Environmental Information).

.

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 2024 ranged between 40 to 22,720 km^2 during late July to early August and averaged 16,657 km^2 (5533 mi^2). 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).

Hypoxic Water Formation

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 decomposition 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; Rabalais et al., 2007b). 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, 2007a, 2010; SAB 2007).

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 (Figure 2).

The discharge from the Mississippi River and Atchafalaya watershed in May 2024 was 33,000 $m^3 s^{-1}$ (cms), which is the 27th largest in 40 years from 1985 to 2024, and equal to about 62% 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 (Figure 2; Sprague et al., 2011; Crawford et al., 2019). Nitrogen loading is predominately from the Midwest, the upper Mississippi River subbasin, and the Ohio River subbasin (Figure 3) and comes from agricultural land (Figure 4).

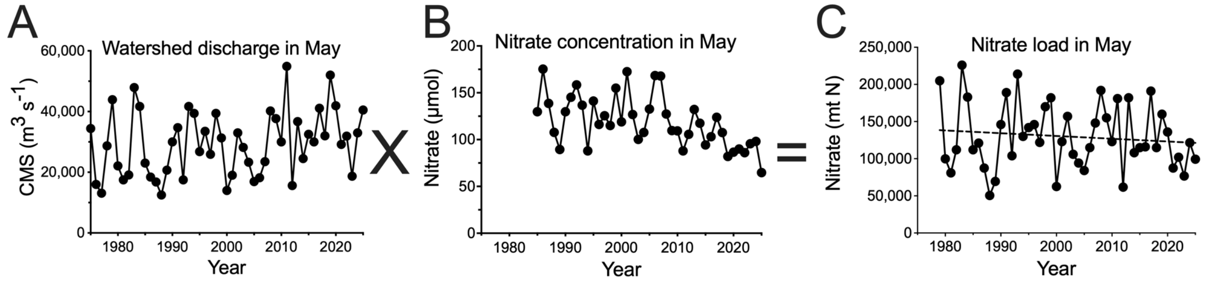


Figure 2. The discharge of the Mississippi River (A), the concentration of nitrate (B), and the resultant nitrate load (C) in May. The discharge and nitrate concentrations are from the United States Geological Survey. N.S. = the simple regression line is not significant.

Some consequences of water quality degradation with nitrate contamination include higher sewage treatment costs (Dearmont et al., 1998), seafood price decreases (e.g., Smith et al., 2017), compromises to fish reproduction (Tuckey and Fabrizio 2016) and increased frequency and duration of harmful algal events inshore and offshore (Lopez et al., 2008). There are links between nitrate in drinking water and birth defects [neural tube and spinal cord defects including spina bifida, oral cleft defects and limb deficiencies (Brender et al., 2013)], bladder and thyroid cancer (Ward et al., 2018), and central nervous system cancers in children (Stayner et al., 2021). The strictly nutrient-related issues are co-developing with ocean acidification and climate change and the 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), and 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.

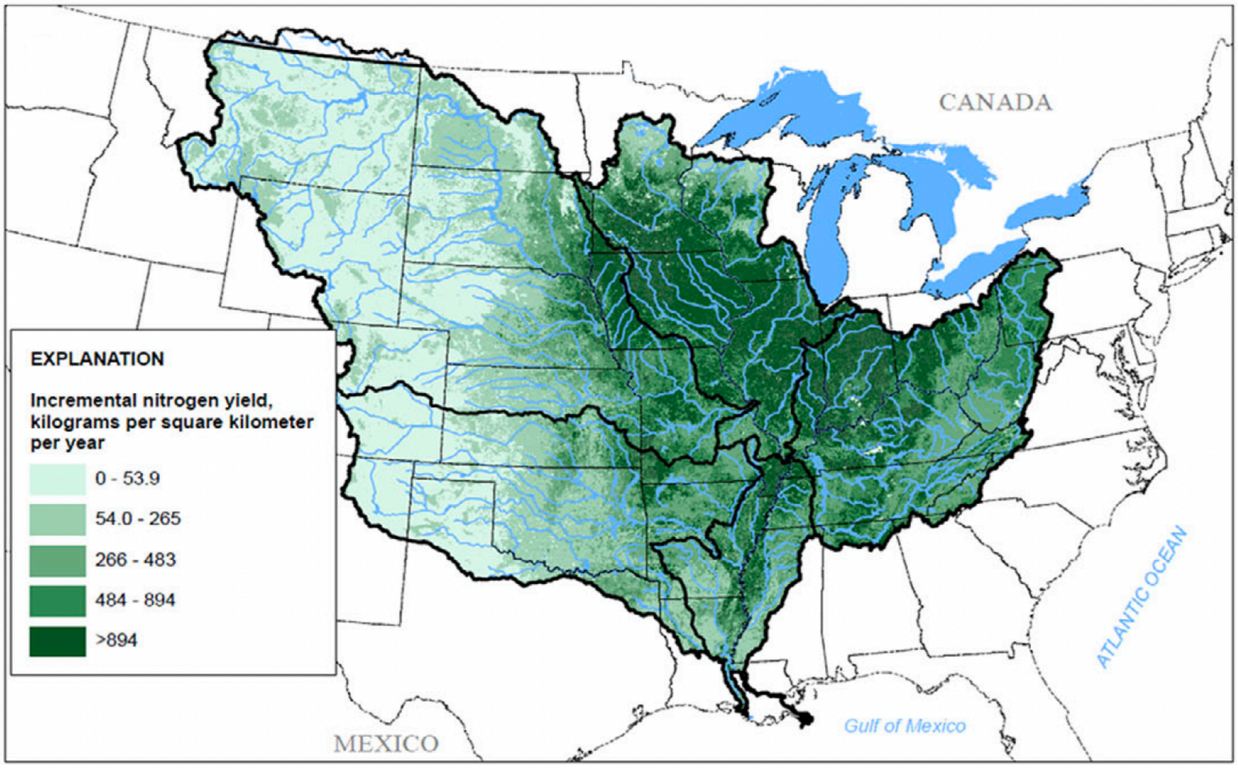


Figure 3. The yield of nitrogen (kg km^{-2}) from the Mississippi River watershed (from Robertson and Saad 2021).

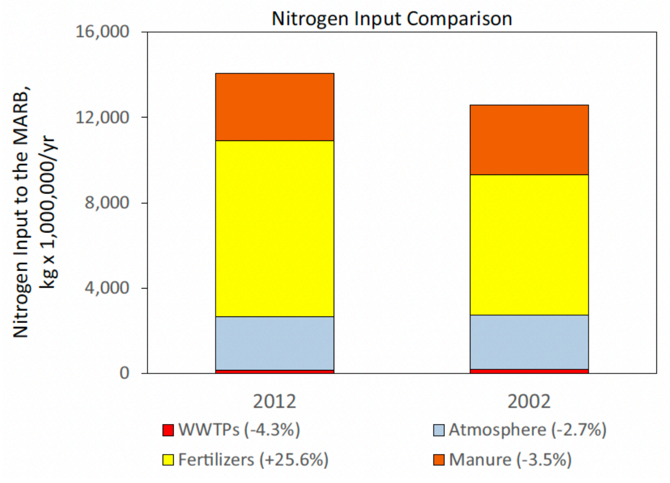


Figure 4. The nitrogen loading in the watershed that is sourced to wastewater treatment plants (WWTP), fertilizers, atmospheric deposition and manure in 2012 and 2002 (from Robertson and Saad 2021).

Hypoxic Zone Size

Models used to predict 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 2024 are based on annual field measurements (data available at http://www.gulfhypoxia.net). Data for 11 years are not included because there were hurricane conditions two weeks before or during the cruise, no funding, no vessel, or the 2010 BP oil spill (1988, 1989, 1997, 2003, 2005, 2008, 2010, 2016, 2019, 2020 and 2024). 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. The storms 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.

Prediction for 2025

We developed a new model to forecast the hypoxic zone size in the northern Gulf of Mexico (Turner et al., 2024). We predict that it will cover 12,470 km^2 (4815 mi^2) of the bottom of the continental shelf off Louisiana and Texas (Figure 5). The 95% confidence interval is that it will be between 10,900 and 14,266 km^2 (4209 and 5508 mi^2).

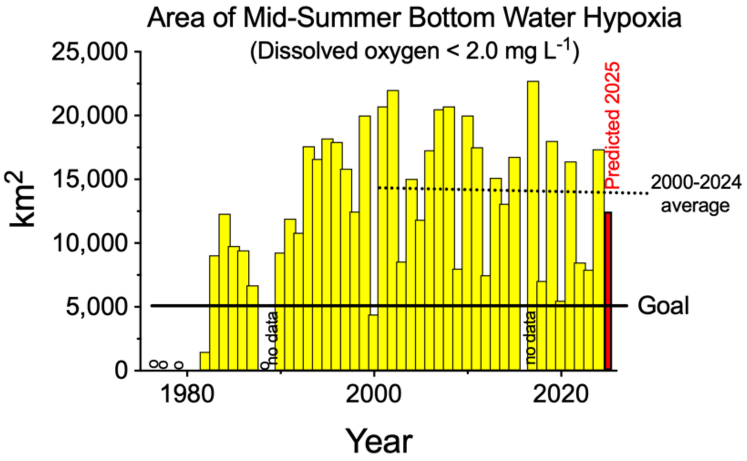


Figure 5. Area of the hypoxic zone from 1979 to 2023 and the predicted value for 2025 (red bar). The Hypoxia Action Plan restoration 'goal' is 5,000 km^2.

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. The 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 (now National Centers for Environmental Information).

Hypoxia Models and Model Accuracy

Previous models predicting the size of the hypoxic zone in July 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]. 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. These models must change as the ecosystem evolves. For example, the size of the hypoxic zone for the same amount of nitrate loading increased about three times over the last 40 years (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 and physiographic constraint). The process-based ecosystem models are a platform to greatly expand understanding how the physical and biological factors interact over all months. They are increasingly accurate and visually-appealing but also require additional seasonal data to validate them as conditions change throughout the year and among years.

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 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. The reference point for calibrating the model is the behavior of the system in recent history. We use the last 24 years of data on the relationship between hypoxic zone size and nutrient loading for this model. Others do something similar. For example, 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.

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). 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 the 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.

Its size in years without storms then has been predicted with great fidelity by using the preceding May's nitrogen loading from the Mississippi River (Scavia et al., 2007; Turner et al., 2012). Ecosystem models with considerably more spatial and temporal detail predict hypoxic areas that include Mississippi River water quality (Justić et al., 2017; Laurent et al., 2018). The prediction in 2022 and 2023, however, severely over-estimated its actual size. The results from

2022 and 2023 indicate that something might be missing in the models, that model coefficients were changing, or perhaps that unrealized non-linear or discontinuous dynamics exist.

Model Insufficiencies

We have been tracking the low oxygen zone off the Mississippi River (MR) delta for several decades. Up until a few years ago there was an excellent relationship between the amount of nitrogen coming down the MR in May and the size of the hypoxic zone on the northern Gulf of Mexico continental shelf in mid-summer. This earlier model described a relationship between fertilizing the phytoplankton, the zooplankton eating phytoplankton (mostly diatoms), and zooplankton fecal pellets (wrapped in a mucous coating) that quickly fall to the bottom where their decomposition uses up the oxygen faster than it can be replaced creating a 'dead zone' that mobile organisms escape from – if they can.

The size of the hypoxic zone (<2 mg O_2 l^{-1}) in the northern Gulf of Mexico during late summer ranged between 4400 to 22,720 km^2 from 2000 to 2021 (http://www.gulfhypoxia.net*)*. Its size in years without storms then has been predicted with great fidelity by using the preceding May's nitrogen loading from the Mississippi River (Fig. 1, Scavia et al., 2017; Turner et al., 2012). There are ecosystem models with considerably more spatial and temporal detail predicting hypoxic area that include Mississippi River water quality (Justić et al., 2017; Laurent et al., 2018). The prediction in 2022 and 2023, however, severely over-estimated its actual size. The results from 2022 and 2023 indicate that something might be missing in the models, that model coefficients were changing, or perhaps that unrealized non-linear or discontinuous dynamics exist. We wondered if something was missing because the relationship between nitrogen loading and hypoxic zone size was not as mathematically satisfying as previously. We wondered if a possible confounding factor was a warming climate.

Ocean Warming

The bottom water temperatures on the continental shelf of the northern Gulf of Mexico (GOM) warmed @ 0.51 deg. C $decade^{-1}$ from 1963 to 2015 (Turner et al., 2017), and fish communities are changing from global warming (Blöcker et al., 2023), and the size-at-age of individual menhaden in the GOM (Turner 2017) and herring and sprat in the Baltic Sea shrank with temperature rises (Daufresne 2009). Temperature increases will affect everything from bacteria to fish (Daufresne 2009; Millien et al., 2006), and so we might anticipate a resulting consequence to an ecosystem undergoing hypoxic water formation, maintenance and dissipation.

A developing and looming future factor potentially affecting hypoxia is climate change. Coastal ocean warming, though it will bring mixing from stronger and more frequent storms, is anticipated to increase hypoxic water formation (Altieri and Gedan 2015; Doney 2010). Oceans are warming this century because they store about 80-90% of the rising heat accumulating in the atmosphere (Levitus et al., 2005). Surface water temperatures in the central Gulf of Mexico have rising from 1970 to 2020 @ 0.0198 deg. C $decade^{-1}$ which is about the same rate as in the global ocean (Wang et al., 2023; Figure 6). The bottom water temperatures on the continental shelf of the northern Gulf of Mexico have been routinely measured on hypoxia cruises during late July to early August and rose about 0.41 deg. C decade^{-1} from 1963 to 2024 (Figure 7). This water warming has been projected to increase the deoxygenation of the ocean because of reduced mixing in more highly stratified layers (Levin 2018) and lower oxygen solubilities. Some models predict that the hypoxic zone in the northern Gulf of Mexico will increase by 1 to 10% (Eldridge and Roelke 2010; Altieri and Gedan 2015; Lehrter 2017). These authors frequently acknowledge that models are insufficient to capture the many biogeochemical processes, omitting temperature effects on biological components or using only one phytoplankton type (diatoms) to simplify modeling.

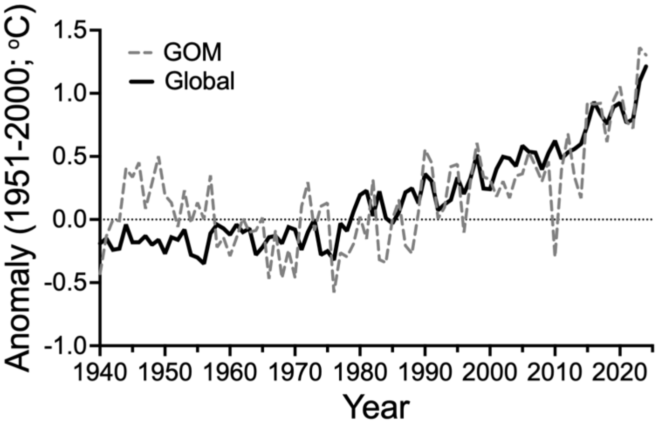
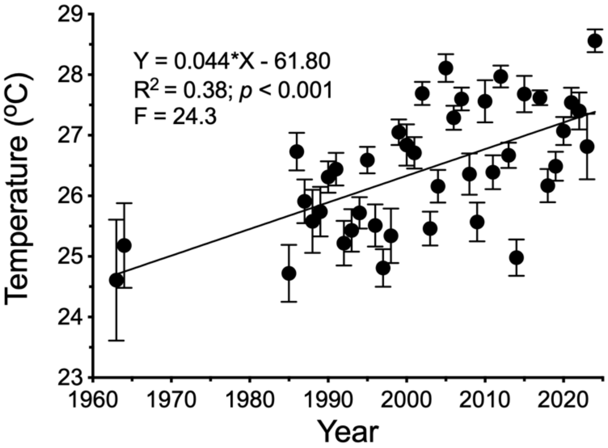


Figure 6. Average annual surface water temperatures in the global surface between 60° S-60° N, and in the central GOM between 20-30° N, and 82-98° W). The data file was generated using Climate Reanalyzer (https://ClimateReanalyzer.org).

Figure 7. The July bottom water temperature on the continental shelf of the northern Gulf of Mexico increased at 0.41 °C decade^{-1} from 1963 to 2024. Updated from Turner et al., (2017).



Temperature increases affect everything from bacteria to fish (Millien 2006; Daufresne et al., 2009). Temperature, for example, is inversely related to size of individual organisms of the same species (the 'temperature-size rule'; Atkinson et al., 2003). Fish communities are changing from global warming (Blöcker et al., 2023), and the size-at-age of individual menhaden in the GOM (Turner 2017) and herring and sprat in the Baltic Sea shrank with temperature rises (Daufresne 2009). The growth rates in ectotherms have a skewed optimum at higher temperatures, beyond which performance drops off rapidly (Thomas et al., 2017; Figure 8), although the shape of the curve varies among species. These relationships can be subtle. Between 20 and 30 °C, for example, the natural mortality of zooplankton and handling time of prey increases, but the intrinsic growth rate of phytoplankton prey and capture rate decreases (Zhao et al., 2002).

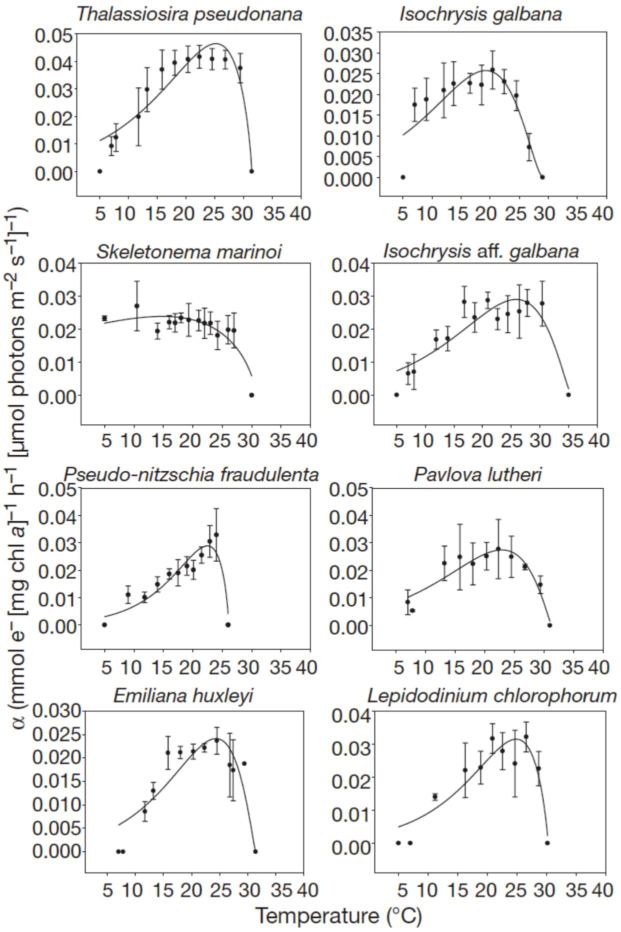


Figure 8. Examples of how the photosynthetic efficiency of eight phytoplankton species changes with temperature. Means ± SE of triplicate cultures are shown (from Claquin et al., 2008).

Warming will have an effect on food web components involved in the creation of the organic matter in surface waters and its downward flux where it is decomposed and deoxygenates the bottom layer. For example, Laws et al.’s (2000) seminal analysis of 11 steady state systems, including polar, Red Sea, Greenland, and open ocean environments, showed that the percent export from surface to deeper water of new primary production of the total production was associated with both temperature and primary production. This transfer from surface to deeper layers is quantified as an export function (*ef*), which is the % of the surface production that sinks to deeper water, and some is buried in sediments. It is commonly known as the ‘biological pump’ that sequesters carbon. They found that temperature was negatively correlated with *ef*, a relationship that explained 86% of the variability in *ef*. Dunne et al., (2005) and Laws et al., (2011) used much larger data sets to show the same outcome. Maiti et al., (2013) demonstrated regional variability in *ef* for the Antarctic, and several groups have demonstrated that there is a stronger effect of temperature in nutrient replete coastal systems like the northern Gulf of Mexico than in nutrient deficient systems such as the open ocean (Cael and Follows 2016; Marañón et al., 2018). Reducing the percent of the carbon produced in aquatic surface layers that is exported into the bottom layers (*ef*) will favor a lower consumption of oxygen and *shrink* the size and duration of oxygen-depleted waters (<2 mgO_2 L^{-1}; 2 ppm) in stratified bottom layers – i.e., a smaller ‘dead zone’.

New Model

Here we demonstrate that the size of the hypoxic zone in the northern GOM is responsive to temperature changes, and that the infidelities of the loading vs. size model for the most recent two years indicates that there is a tipping point beyond which the hypoxic zone size will decrease, even though nitrogen concentrations remain rather static. This sensitivity of the food web to warming may be developing elsewhere in aquatic habitats and resulting in weakened diatom-zooplankton-fish linkages.

We developed a new model incorporating rising oceanic temperatures which are ubiquitously documented on global and local scales in various reports. In general, respiration increases at higher temperatures, but the size of individual organisms declines as temperature increases. The volume to surface area of a cell affects oxygen transfer across the cell surface. There are temperature optimal for food webs, people, bacteria, fish, etc. Like Goldilocks tasting the Bear's food, the temperature could be too cool or too hot or just right. Our new model reflects this optimum hypoxic size with a temperature optimum (Figure 9).

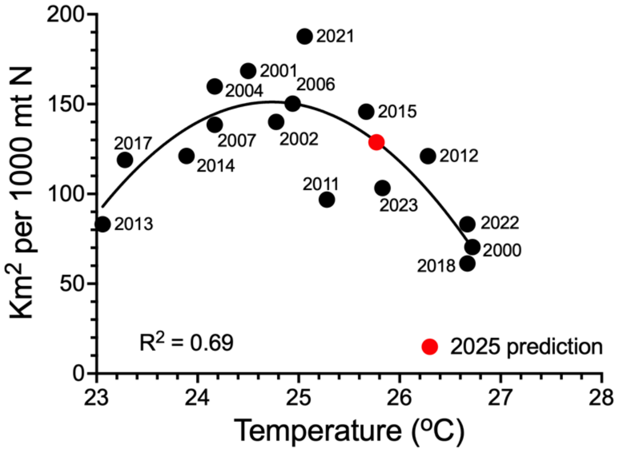


Figure 9. The hyperbolic relationship between the hypoxic zone size per mt nitrate loading and the air temperature in May at the New Orleans International airport.

What seems to be happening is that the warming decreases the individual diatom cell and the zooplankton size; the zooplankton are now eating smaller cells and the fecal pellets holding excretory products of many cells are smaller. Smaller cells now sink more slowly and decompose more on descent to the seabed. So, with warming there is a lower amount of fecal pellets with a smaller amount of carbon respiring in the bottom layer. For the same amount of nitrogen loading we are now getting a smaller hypoxic zone. It is a changing food web. Good, right? But the diatom-zooplankton-fish food chain is what much of the world's fisheries exploit, but at different temperatures. This northern GOM food web is where 25-30% of the US fisheries is landed. The tipping point is telling us that a significant biological shift is taking place potentially risking fish production.

Reducing Nitrogen Loading

The nitrogen loading in the northern GOM is predominantly driven by land use choices in the MR 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*. The rise in nitrate concentration and decline in silicate concentration occurred in the two decades after the 1960s and has become relatively stable over the last 40 years. The average annual nitrate concentration at St. Francisville, LA, for example, has been about the same from 1992 to 2021. The variability of nitrate and silicate concentrations is now moving coincidentally with variations in alkalinity (Turner 2024). The rising nitrate concentrations are often ascribed to changing temporal and spatial applications of fertilizers. This is because fertilization increases loading rates to the land, converting forests to agricultural land, improving drainage, especially by installing subsurface tiles, and increases the percent of the applied nitrogen that goes into drainage channels (Randall and Gross, 2001; Figure 10). The N fertilizer application rate increased almost three orders of magnitude from 1950 to 2015: from less than 0.01 gN m^{-2} yr^{-1} in 1850 to 9.04 gN m^{-2} yr^{-1} in 2015 (Cao et al., 2018) as fertilizer use climbed from 1.5 to 8.1 TgN y^{-1} from 1960 to 2014 (Tian et al., 2020). Nitrogen fertilizer use in the Mississippi River basin now accounts for ~65% of the total fertilizer application in the continental United States (Tian et al., 2020).

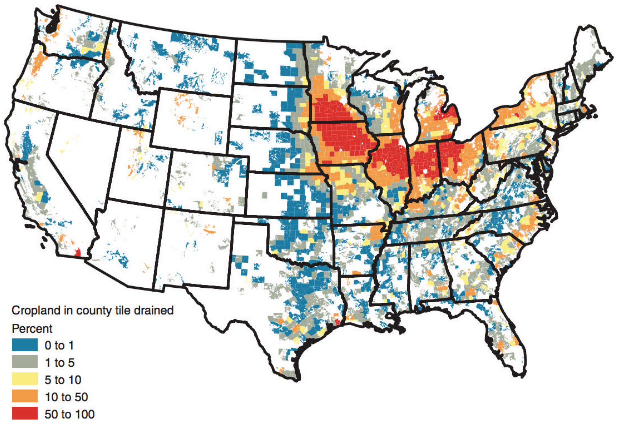


Figure 10. Land under drainage in the US. Source: USDA, Economic Research Service calculations based on data from USDA, National Agricultural Statistics Service, 2013 Census of Agriculture.

Much of the total nitrogen yield in the basin is a consequence of structural changes in the landscape from building swales and tiling, not from solely (or simply) the nitrogen fertilizer application rates (e.g., Kaspar et al., 2003; McIsaac and Hu, 2004; Nangia et al., 2008; Tomer et al., 2003; Randall and Gross, 2001). Land drainage dries soils, as intended, but reduces denitrification, and moves the leached nitrate to waterways that reduce the potential sediment trapping and denitrification in riparian zones (Burt and Pinay, 2005). Randall and Gross (2001) showed that there was a close correspondence between tile drain water yield and nitrate yield, which is visually apparent when maps of the county-level nitrogen yield and drainage are compared. This is why McIsaac and Hu (2004) found that the 1945–1961 riverine nitrate flux in an extensively tile drained region in Illinois averaged 6.6 kgN ha^{-1} $year^{-1}$, compared to 1.3 to 3.1 kgN ha^{-1} $year^{-1}$ for the non-tile drained region, even though the nitrogen application was greater in the non-tile drained region. Arenas Amado et al., (2017) found that tiles “delivered up to 80%

of the stream N load while providing only 15–43% of the water" in the 122 km^2 Otter Creek watershed in Iowa. Ikenberry et al., (2014) estimated that 97% of the nitrate flow occurred during 50% of the highest flows in a 5-year study of the 5132 ha Walnut Creek watershed in Iowa. They reported that two-thirds of row crop land in Central Iowa and the Minnesota Till Prairies Major Land Resources Area had subsurface tile drainage. Measurements of inorganic C concentrations in the intensively farmed Raccoon River, IA, by Jones and Schilling (2013) are another example of the consequence of drainage on nitrate concentrations. The alkalinity there doubled from 2000 to 2011 compared to in 1931 to 1944 (Jones and Schilling, 2013), during which there was an increase in drainage and nitrate concentrations, but not fertilizer applications (Hatfield et al., 2009). In summary, nitrogen yields from field to streams is generally dominated by fertilizer application which increased in the 1960s and stabilized in the last decades. More nitrate escapes farm fields when tiled, and thus drainage improvements are a significant multiplier of these loadings.

Shifting to more diverse crop rotations will be needed to have a major effect on carbon losses and to sustain soil fertility and farming enterprises. Achieving this restoration means that it will result in negative consequences for farmers or consumers. Soil carbon restoration has many benefits important to sustaining agriculture because organic material holds water, minerals, nutrients and organisms giving it soil structure, resistance to erosion and increased soil fertility (Jackson et al., 2017; Chambers et al., 2016). Improving soil health will provide public benefits of improved water quality, flood reduction, enhanced wildlife habitat, reduced air pollutants and reduced global warming potential (Jordan et al., 2007; Boody et al., 2005; Ryan et al., 2018). Plant rotations will include cover crops, especially deep-rooted perennials (Poeplau and Don, 2015; Jungers et al., 2019; Paustian et al., 2019). Land under tile drainage can be a part of these efforts (Randall and Mulla, 2001; Dinnes et al., 2002). Tile drainage can enter buffer strips before reaching streams, drain into wetlands, or even not be used if row cropped fields are converted to perennials. Planting only shallow-rooted annuals leaves the ground without plant cover for more than half the year and results in more soil erosion (Heathcote et al., 2013). Replacement of annuals with deep-rooted perennials provides continuous living cover and reduces soil erosion (Song et al., 2014). Water quality has improved in some sub-watershed streams of the Mississippi watershed because of soil conservation (Rabotyagov et al., 2014, McIsaac et al., 2016; Garcia et al., 2016).

A signature example of alternative management of perennial grains is provided by Liebmann et al., (2013), Davis et al., (2012) and Tomer and Liebmann (2014) who conducted a 7-year field trial of different cropping systems for corn-soybean rotations. 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 no loss of profits. 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. There is much work remaining – half of the US stream and river miles violate water pollution standards (Keiser and Shapiro, 2019). Whole system analyses of land use alternatives for small and large farms are needed to include not only greenhouse gas emissions, but also energy expenditures, wildlife, water quality, and social factors. Boody et al., (2005) found that alternative land management schemes using the same resources could create "improved water quality, healthier fish, increased carbon sequestration, and decreased greenhouse gas emissions, while economic benefits include social capital formation, greater farm profitability, and avoided costs." On-the-ground experiments at a watershed scale that include social governance (Meyfroidt et al., 2022) are recommended.

Fertilizer applications in the watershed are not always directly proportional to nutrient loading in the Mississippi River; their influence is modified by tile drainage, climate variation, plant choices, and farm management. Conversion of natural habitat to agricultural fields with improved drainage reduces plant cover (and increase in evapotranspiration) and more water is shunted into streams. This, in turn, changes the rate of soil accumulation and denitrification as well as alkalinity and the concentrations of alkalinity, nitrate, phosphate, and silicate. The integrated culmination of these land use changes across the watershed over the last 100 years reduced water residence time and nutrient processing in soil but increased concentrations in water bodies; the percent of nitrate exported from soils to water becomes higher as a result. Today agricultural lands are hemorrhaging the carbon needed to build and sustain healthy soil, and a significant carbon sink is not being realized. Examples of accommodations for simultaneous water quality improvements while building soil health exist, but more on-the-ground examples are needed to integrate both the biogeochemical factors and practical socio-political-economic aspects of farming.

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 helpful.

Post-cruise Assessment

The 2025 mapping cruise is scheduled for July 19 to July 29. The data will be posted as close to daily as possible at http://www.gulfhypoxia.net. Delays will be related to the 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 used to predict hypoxic area size, 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

Support is from the NOAA National Centers for Environmental Information through the Northern Gulf Institute at Mississippi State University. The hypoxia area data are from http://www.gulfhypoxia.net, and data sets since 1985 are archived at NOAA's National Centers for Environmental Information. We thank colleagues at NOAA and the USGS for providing the nitrogen loading data for the Mississippi River.

References

Altieri, A.H., K.B. Gedan 2015. Climate change and dead zones. **Global Change Biology** 21(4): 1395-1406.

Arenas Amado, A., K.E. Schilling, C.S. Jones, N. Thomas, L.J. Weber 2017. Estimation of tile drainage contribution to streamflow and nutrient loads at the watershed scale based on continuously monitored data. **Environmental Monitoring and Assessment** 189: 426. doi: 10.1007/s10661-017-6139-4

Atkinson, D., B.J. Ciotti, D.J. Montagnes 2003. Protists decrease in size linearly with temperature: *ca*. 2.5% $°C^{-1}$. **Proceedings Royal Society B Biological Sciences**. 270: 2605–2611. doi:10.1098/rspb.2003.2538

Blöcker, A.M., H.M. Gutte, R.L. Bender, S.A. Otto, C. Sguotti, C. Möllmann 2023. Regime shift dynamics, tipping points and the success of fisheries management. **Scientific Reports** 13(1): 289. doi:org/10.1038/s41598-022-27104-y

Boody, G., B. Vondracek, D.A. Andow, M. Krinke, J. Westra, J. Zimmerman, P. Welle 2005. Multifunctional agriculture in the United States. **BioScience** 55(1): 27-38.

Breitburg, D., L.A. Levin, A. Oschlies, M. Grégoire, F.P. Chavez, D.J. Conley, V. Garçon, D. Gilbert, D. Gutiérrez, K. Isensee, G.S. Jacinto, K.E. Limburg, I. Montes, S.W.A. Naqvi, G.C. Pitcher, N.N. Rabalais, M.R. Roman, K.A. Rose, B.A. Seibel, M. Telszewski, M. Yasuhara, J. Zhang 2018. Declining oxygen in the global ocean and coastal waters. **Science** 359(6571): eaam7240. doi: 10.1126/science.aam72

Brender, J.D., P.J. Weyer, P.A. Romitti, P. Mohanty, M.U. Shinde, et al., 2013. Prenatal nitrate intake from drinking water and selected birth defects in offspring of participants in the National Birth Defects Prevention Study. **Environmental Health Perspectives** 121(9): 1083-1089.

Burt, T.P., G. Pinay 2005. Linking hydrology and biogeochemistry in complex landscapes. **Progress in Physical Geography** 29(3): 297-316.

Cael, B.B., M.J. Follows 2016. On the temperature dependence of oceanic export efficiency. **Geophysical Research Letters** 43(10): 5170-5175.

Cao, P., C. Lu, Z. Yu 2018. Historical nitrogen fertilizer use in agricultural ecosystems of the contiguous United States during 1850–2015: Application rate, timing, and fertilizer types. **Earth Systems Science Data** 10: 969–984. https://doi.org/10.5194/essd-10-969-2018

Chambers, A., R. Lal, K. Paustian 2016. Soil carbon sequestration potential of US croplands and grasslands: Implementing the 4 per Thousand Initiative. **Journal of Soil and Water Conservation** 71: 68A-74A.

Claquin, P., I. Probert, S. Lefebvre, V. Veron 2008. Effects of temperature on photosynthetic parameters and TEP production in eight species of marine microalgae. **Aquatic Microbial Ecology** 51(1): 1-11.

Crawford, J.T., E.G. Stets, L.A. Stets 2019. Network controls on mean and variance of nitrate loads from the Mississippi River to the Gulf of Mexico. **Journal of Environmental Quality** 48: 1789-1799.

Daufresne, M., K. Lengfellenr, U. Sommer 2009. Global warming benefits the small in aquatic ecosystems. **Proceedings of the National Academy of Sciences (USA)** 106: 12788–12793.

Davis, A.S., J.D. Hill, C.A. Chase, A.M. Johanns, M. Liebman 2012. Increasing Cropping system diversity balances productivity, profitability and environmental health. **PLoS ONE** 7(10): e47149. doi:10.1371/journal.pone.0047149.

Dearmont, D., B.A. McCarl, D.A. Tolman 1998. Costs of water treatment due to diminished water quality: A case study in Texas. **Water Resources Research** 34: 849-853.

Dinnes, D.L., D.L. Karlen, D.B. Jaynes, T.C. Kasper, J.L. Hatfield, T.L. Colvin, C.A. Camberdella 2002. Nitrogen management strategies to reduce nitrate leaching in tile-drained Midwestern soils. **Agronomy Journal** 94: 153–171.

Doney, S. C. 2010. The growing human footprint on coastal and open-ocean biogeochemistry. **Science** 328(5985): 1512-1516.

Dunne, J.P., R.A. Armstrong, A. Gnanadesikan, J.L. Sarmiento 2005. Empirical and mechanistic models for the particle export ratio. **Global Biogeochemical Cycles** 19: GB4026.

Duprey, N.N., Foreman, A.D., Carriquiry, J.D., Charles, C.D., Sanchez, S.C., Vonhof, H., Rubach, F., Rabenstein, R., Rohr, M., Reyes-Bonilla, H. and Marconi, D., 2024. Decadal oscillations in the ocean's largest oxygen-deficient zone. **Science** 386(6725): 1019-1024.

Eldridge, P.M., D.L. Roelke 2010. Origins and scales of hypoxia on the Louisiana shelf: importance of seasonal plankton dynamics and river nutrients and discharge. **Ecological Modelling** 221(7): 1028-1042.

Evans, M.A., D. Scavia 2010. Forecasting hypoxia in the Chesapeake Bay and Gulf of Mexico: Model accuracy, precision, and sensitivity to ecosystem change. **Environmental Research Letters** 6: 015001.

Farkas, K., L.S. Hillary, S.K. Malham, J.E. McDonald, D.L. Jones 2020. Wastewater and public health: The potential of wastewater surveillance for monitoring COVID-19. **Current Opinion in Environmental Science & Health** 17: 14–20.

Fuentes, S., G.H. Wikfors, S. Meseck 2014. Silicon deficiency induces alkaline phosphatase enzyme activity in cultures of four marine diatoms. **Estuaries and Coasts** 37(2): 312-324.

García, A.M., R.B. Alexander, J.G. Arnold, L. Norfleet, M.J. White, D.M. Robertson, G. Schwarz 2016. Regional effects of agricultural conservation practices on nutrient transport in the Upper Mississippi River Basin. **Environmental Science and Technology** 50(13): 6991-7000.

Hatfield, J.L., L.D. McMullen, C.S. Jones 2009. Nitrate-nitrogen patterns in the Raccoon River Basin related to agricultural practices. **Journal Soil Water Conservation** 64: 190-199.

Heathcote A.J., C.T. Filstrup J.A. Downing 2013. Watershed sediment losses to lakes accelerating despite agricultural soil conservation efforts. **PLoS ONE** 8(1): e53554. doi:10.1371/journal.pone.0053554

Ikenberry, C.D., M.L. Soupir, K.E. Schilling, C.S. Jones, A. Seeman 2014. Nitrate-nitrogen export: Magnitude and patterns from drainage districts to downstream river basins. **Journal of Environmental Quality** 43(6): 2024-2033.

Jackson, R.B., K. Lajtha, S.E. Crow, G. Hugelius, M.G. Kramer, G. Piñeiro 2017. The ecology of soil carbon: Pools, vulnerabilities, and biotic and abiotic controls. **Annual Review of Ecology, Evolution, and Systematics** 48(1): 419-445.

Jarvis, B., R.M. Greene, Y. Wan, J.C. Lehrter, L.L. Lowe, D.S. Ko 2021. Contiguous low oxygen waters between the continental shelf hypoxia zone and nearshore coastal waters of

Louisiana, USA: Interpreting 30 years of profiling data and three-dimensional ecosystem modeling. **Environmental Science and Technology** 55(8): 4709–4719. https://dx.doi.org/10.1021/acs.est.0c05973.

Jones, C.S., K.E. Schilling 2013. Carbon export from the Raccoon River, Iowa: Patterns, processes, and opportunities. **Journal Environmental Quality** 42: 155-163

Jordan, N., G. Boody, W. Broussard, J.D. Glover, D. Keeney, B.H. McCowan, G. McIsaac, M. Muller, H. Murray, J. Neal, C. Pansing, R.E. Turner, K.D. Warner, D.L. Wyse 2007. Sustainable development of the agricultural bio-economy. **Science** 316: 1570-1571

Jungers, J.M., L.H. DeHaan, D.J. Mulla, C.C. Sheaffer, D.L. Wyse 2019. Reduced nitrate leaching in a perennial grain crop compared to maize in the Upper Midwest, USA. **Agriculture, Ecosystems and Environment** 272: 63-73.

Justić, D., L. Wang 2014. Assessing temporal and spatial variability of hypoxia over the inner Louisiana-upper Texas shelf: Application of an unstructured-grid three-dimensional coupled hydrodynamic-water quality model. **Continental Shelf Research** 72**:** 163-179.

Justić, D., K.A. Rose, R.D. Hetland, K. Fennel (Eds.) 2017. Modeling Coastal Hypoxia: Numerical Simulations of Patterns, Controls and Effects of Dissolved Oxygen Dynamics. Springer, NY. 433 pp.

Kaspar, T., D. Jaynes, T. Moorman, T. Parkin 2003. Reducing nitrate levels in subsurface drain water with organic matter incorporation. Final Report to the American Farm Bureau by the Foundation for Agriculture. National Soil Tilth Laboratory Ames, Iowa.

Kasprzyk-Hordern, B., R.M. Dinsdale, A.J. Guwy 2009. The removal of pharmaceuticals, personal care products, endocrine disruptors and illicit drugs during wastewater treatment and its impact on the quality of receiving waters. **Water Research** 43: 363-380.

Keiser, D.A., J.S. Shapiro 2019. Consequences of the Clean Water Act and the demand for water quality. **The Quarterly Journal of Economics** 134(1): 349-396.

Kirchman, D.A. 2021. Dead Zones: The Loss of Oxygen from Rivers, Lakes, Seas and the Ocean. Oxford University Press. New York. 217 pp.

Laurent, A., K. Fennel, D.S. Ko, J. Lehrter 2018. Climate change projected to exacerbate impacts of coastal eutrophication in the northern Gulf of Mexico. **Journal of Geophysical Research-Oceans** 123: 3408–3426. doi: 10.1002/2017JC013583

Lavers, J.L., A.L. Bond 2017. Exceptional and rapid accumulation of anthropogenic debris on one of the world's most remote and pristine islands. **Proceedings of the National Academy of Sciences (USA)** 114: 6052–6055.

Laws, E.A., P.G. Falkowski, W.O. Smith Jr., H. Ducklow, J.J. McCarthy 2000. Temperature effects on export production in the open ocean. **Global Biogeochemical Cycles** 14(4): 1231-1246.

Laws, E.A., E. D'Sa, P. Naik 2011. Simple equations to estimate ratios of new or export production to total production from satellite-derived estimates of sea surface temperature and primary production, **Limnology and Oceanogr**aphy 9(12): 593–601.

Lehrter, J., D. Ko, L. Lowe, B. Penta 2017. Predicted Effects of Climate Change on Northern Gulf of Mexico Hypoxia . Chapter 8, Modeling Coastal Hypoxia: Numerical Simulations of Patterns, Controls, and Effects of Dissolved Oxygen Dynamics. Springer, New York, NY, 173-214.

Levin, L.A. 2018. Manifestation, drivers, and emergence of open ocean deoxygenation. **Annual Review Marine Science** 3(10): 229–260.

Levitus, S., J. Antonov, T. Boyer 2005. Warming of the world ocean, 1955–2003. **Geophysical Research Letters** 32: L02604.

Liebman, M., M.J. Helmers, L.A. Schulte, C.A. Chase 2013. Using biodiversity to link agricultural productivity with environmental quality: Results from three field experiments in Iowa. **Renewable Agriculture and Food Systems** 28(2): 115–128.

Lohrenz, S.E., G.L. Fahnenstiel, D.G. Redalje, G.A. Lang, X. Chen, M.J. Dagg 1997. Variations in primary production of northern Gulf of Mexico continental shelf waters linked to nutrient inputs from the Mississippi River. **Marine Ecology Progress Series** 155: 45−54.

Lohrenz, S.E., D.G. Redalje, W.J. Cai, J. Acker, M.J. Dagg 2008. A retrospective analysis of nutrients and phytoplankton productivity in the Mississippi River Plume. **Continental Shelf Research** 28: 1466−1475.

Lopez, C.B., E.B. Jewett, Q. Dortch, B.T. Walton, H.K. Hudnell 2008. Scientific assessment of freshwater harmful algal blooms. Interagency Working Group on Harmful Algal Blooms, Hypoxia, and Human Health of the Joint Subcommittee on Ocean Science and Technology. Washington, DC.

Maiti, K., M. A. Charette, K. O. Buesseler, and M. Kahru. 2013. An inverse relationship between production and export efficiency in the Southern Ocean. **Geophysical Research Letters** 40: 1557–1561.

Maiti, V., S. Fang, J. Guinness, N.N. Rabalais, J. Craig, D.R. Obenour 2018. A space-time geostatistical assessment of hypoxia in the northern Gulf of Mexico. **Environmental Science & Technology** 52: 12484-12493 doi: 10.1021/acs.est.8b03474

McIsaac, G.F., X. Hu 2004. Net N Input and riverine N export from Illinois agricultural watersheds with and without extensive tile drainage. **Biogeochemistry** 70: 251-271.

McIsaac, G.F., M.B. David, G.Z. Gertner 2016. Illinois River nitrate-nitrogen concentrations and loads, Long-term variation and association with watershed nitrogen inputs. **Journal of Environmental Quality** 45(4): 1268-75. doi:10.2134/jeq2015.10.0531

Marañón, E., M.P. Lorenzo, P. Cermeño, B. Mouriño-Carballido 2018. Nutrient limitation suppresses the temperature dependence of phytoplankton metabolic rates. **The ISME Journal** 12(7): 1836-1845.

Meyfroidt, P., A. De Bremond, C.M. Ryan, E. Archer, R. Aspinall, A. Chhabra, G. Camara, E. Corbera, R. DeFries, S. Díaz, J. Dong 2022. Ten facts about land systems for sustainability. **Proceedings of the National Academy of Sciences (USA)** 119(7): e2109217118.

Millien, V., S.K. Lyons, L. Olson, F.A. Smith, A.B. Wilson, Y. Yom-Tov. 2006. Ecotypic variation in the context of global climate change: revisiting the rules. **Ecological Lett**ers 9: 853–69.

Moss, B., S. Kosten, M. Meerhoff, R.W. Battarbee, E. Jeppesen, N. Mazzeo, K. Havens, G. Lacerot, Z. Liu, L. De Meester, H. Paerl, and M. Scheffer 2011. Allied attack: Climate change and eutrophication. **Inland Waters** 1: 101-105.

MRNGoM HTF (Mississippi River Nutrient/Gulf of Mexico Hypoxia Task Force) 2001. Action Plan for Reducing, Mitigating, and Controlling Hypoxia in the Northern Gulf of Mexico; Office of Wetlands, Oceans, and Watersheds, U.S. Environmental Protection Agency; Washington, DC.

MRNGoM HTF (Mississippi River Nutrient/Gulf of Mexico Hypoxia Task Force) 2008. Action Plan for Reducing, Mitigating, and Controlling Hypoxia in the Northern Gulf of Mexico. Office of Wetlands, Oceans, and Watersheds, U.S. Environmental Protection Agency, Washington, D.C.

Nangia, V., P.H. Gowda, D.J. Mulla, G.R. Sands 2008. Water quality modeling of fertilizer management impacts on nitrate losses in tile drains at the field scale. **Journal of**

Environmental Quality 37: 296–307.

Obenour, D.R., A.M. Michalak, Y. Zhou, D. Scavia 2012. Quantifying the impacts of stratification and nutrient loading on hypoxia in the northern Gulf of Mexico. **Environmental Science and Technology** 46: 5489–5496.

Paustian, K., E. Larson, J. Kent, E. Marx, A. Swan 2019. Soil C sequestration as a biological negative emission strategy. **Frontiers in Climate** 1: 8. doi*:* 10.3389/fclim.2019.00008

Poeplau, C., A. Don 2015. Carbon sequestration in agricultural soils via cultivation of cover crops—A meta-analysis. **Agriculture, Ecosystems and Environment** 200: 33–41.

Purcell, K.M., J.K. Craig, J.M. Nance, M.D. Smith, L.S. Bennear 2017. Fleet behavior is responsive to a large-scale environmental disturbance: Hypoxia effects on the spatial dynamics of the northern Gulf of Mexico shrimp fishery. **PLoS ONE** 12(8): e0183032. doi.org/10.1371/journal.pone.0183032

Rabalais, N.N., R.E. Turner, D. Scavia 2002. Beyond science into policy: Gulf of Mexico hypoxia and the Mississippi River**. BioScience** 52: 129-142.

Rabalais, N.N., R.E. Turner, B.K. Sen Gupta, D.F. Boesch, P. Chapman, M.C. Murrell 2007a. Hypoxia in the northern Gulf of Mexico: Does the science support the plan to reduce, mitigate and control hypoxia? **Estuaries and Coasts** 30: 753-772.

Rabalais, N.N., R.E. Turner, B.K. Sen Gupta, E. Platon, M.L. Parsons 2007b. Sediments tell the history of eutrophication and hypoxia in the northern Gulf of Mexico. **Ecological Applications** 17(5) Supplement: S129-S143. [Special Issue, Nutrient Enrichment of Estuarine and Coastal Marine Environments]

Rabalais, N.N., R.J. Díaz, L.A. Levin, R.E. Turner, D. Gilbert, J. Zhang 2010. Dynamics and distribution of natural and human-caused hypoxia. **Biogeosciences** 7: 585-619.

Rabalais, N.N., L.M. Smith, R E. Turner 2018. The *Deepwater Horizon* oil spill and Gulf of Mexico shelf hypoxia. **Continental Shelf Research** 152: 98-107.

Rabalais, N.N., R.E. Turner 2019. Gulf of Mexico Hypoxia: Past, present and future. **Limnology and Oceanography Bulletin** 28: 117-124. doi.org/10.1002/lob.1035

Rabotyagov, S., T. Campbell, M. White, J. Arnold, J. Atwood, L. Norfleet, C. Kling, P. Gassman, A. Valcu, J. Richardson, R.E. Turner, N.N. Rabalais 2014. Cost-effective targeting of conservation investments to reduce the northern Gulf of Mexico hypoxic zone. **Proceedings of the National Academy of Sciences (USA)** 111(52): 18530-18535. doi: 10.1073/pnas.1405837111.

Randall, G.W., M.J. Gross 2001. Nitrate losses to surface water through subsurface tile drainage. P. 145-175, In: Nitrogen in the Environment: Sources, Problems, and Management, (Ed.) J.L. Hatfield and R.F. Follett. Elsevier Sciences B.V.

Randall, G.W., D.J. Mulla 2001. Nitrate nitrogen in surface waters as influenced by climatic conditions and agricultural practices. **Journal of Environmental Quality** 30: 337–344.

Robertson, D.M, D.A. Saad 2021. Nitrogen and phosphorus sources and delivery from the Mississippi/Atchafalaya River Basin: An update using 2012 SPARROW models. **Journal of the American Water Resources Association** 57(3): 406-429.

Rose, K.C., E.M. Ferrer, S.R. Carpenter, S.A. Crowe, S.C. Donelan, V.C. Garçon, M. Grégoire, S.F. Jane, P.R. Leavitt, L.A. Levin, A. Oschlies 2024. Aquatic deoxygenation as a planetary boundary and key regulator of Earth system stability. **Nature Ecology & Evolution**, 8(8): 1400-1406.

Ryan, M.R., T.E. Crews, S.W. Culman, L.R. Dehaan, R.C. Hayes, J.B. Jungers, M.G. Bakker 2018. Managing for mulifunctionality in perennial grain crops. B**ioScience** 68: 294-304.

Scavia, D., K.A. Donnelly 2007. Reassessing hypoxia forecasts for the Gulf of Mexico.

Environmental Science and Technology 41: 8111-8117.

Scavia, D., I. Bertani, D.R. Obenour, R.E. Turner, D.R. Forrest, A. Katkin 2017. Ensemble modeling informs hypoxia management in the northern Gulf of Mexico. **Proceedings of the National Academy of Sciences (USA)** 114: 8823–8828. doi/10.1073/pnas.1705293114

Science Advisory Board (SAB) 2007. Hypoxia in the northern Gulf of Mexico, An Update. U.S. Environmental Protection Agency, Science Advisory Board (SAB) Hypoxia Panel Advisory, Report EPA-SAB-08-003, Environmental Protection Agency, Washington, D.C. http://yosemite.epa.gov/sab/sabproduct.nsf/C3D2F27094E03F90852573B800601D93/$File/EPA-SAB-08-003complete.unsigned.pdf

Sen Gupta, B.K., R.E. Turner, N.N. Rabalais 1996. Seasonal oxygen depletion in continental-shelf waters of Louisiana: Historical record of benthic foraminifers. **Geology** 24: 227-230.

Smith, M.D., A. Oglen, A.J. Kirkpatrick, F. Asche, L.S. Bennear, J.K. Craig, J.M. Nance 2017. Seafood prices reveal impacts of a major ecological disturbance. **Proceedings of the National Academy of Sciences (USA)** 114: 1512–1517, doi: 10.1073/pnas.1617948114

Song, Z., K. Müller, H. Wang 2014. Biogeochemical silicon cycle and carbon sequestration in agricultural ecosystems. **Earth-Science Reviews** 139: 268-278.

Sprague, L.A., R.M. Hirsch, B.T. Aulenbach 2011. Nitrate in the Mississippi River and its tributaries, 1980 to 2008: Are we making progress? **Environmental Science and Technology** 45: 7209-7216. dx.doi.org/10.1021/es201221s

Stayner, L.T., J. Schullehner, B.D. Semark, A.S. Jensen, B.B. Trabjerg, M. Pedersen, J. Olsen, B. Hansen, M.H. Ward, R.R. Jones, V.R. Coffman 2021. Exposure to nitrate from drinking water and the risk of childhood cancer in Denmark. **Environment International** 155: 106613.

Testa, J.M., R.R., Murphy, D.C. Brady, W.M. Kemp 2018. Nutrient- and climate-induced shifts in the phenology of linked biogeochemical cycles in a temperate estuary. **Frontiers in Marine Science** 5: 114.doi: 10.3389/fmars.2018.00114

Thomas, M.K., M. Aranguren-Gassis, C.T. Kremer, M.R. Gould, K. Anderson, C.A. Klausmeier, E. Litchman 2017. Temperature–nutrient interactions exacerbate sensitivity to warming in phytoplankton. **Global Change Biology** 23(8): 3269-3280.

Tian, H., R. Xu, S. Pan, Y. Yao, Z. Bian, W.J. Cai, C.S. Hopkinson, D. Justic, S. Lohrenz, C. Lu, W._Ren 2020. Long-term trajectory of nitrogen loading and delivery from Mississippi River basin to the Gulf of Mexico. **Global Biogeochemical Cycles** 34: e2019GB006475.

Tomer, M.D., D.W. Meek, D.B. Jaynes, J.L. Hatfield 2003. Evaluation of nitrate nitrogen fluxes from a tile-drained watershed in Central Iowa. **Journal of Environmental Quality** 32: 642–653.

Tomer, M.D., M. Liebman 2014. Nutrients in soil water under three rotational cropping systems, Iowa, USA. **Agriculture, Ecosystems and Environment** 180: 105-114.

Tuckey, T.D., M.C. Fabrizio 2016. Variability in fish tissue proximate composition is consistent with indirect effects of hypoxia in Chesapeake Bay tributaries. **Marine and Coastal Fisheries** 8: 1-15. doi: 10.1080/19425120.2015.1103824

Turner, R.E. 2017. Smaller size-at-age menhaden with coastal warming and fishing intensity. **Geo: Geography and Environment** 4(2): e00044. doi: 10.1002/geo2.44

Turner, R.E. 2024. Water quality at the end of the Mississippi River for 120 years: The agricultural imperative. **Hydrobiologia** 851: 1219–1239.

Turner, R.E., N. Qureshi, N.N. Rabalais, Q. Dortch, D. Justić, R. Shaw, J. Cope 1998. Fluctuating silicate:nitrate ratios and coastal plankton food webs. **Proceedings of the National Academy of Sciences (USA)** 95: 13048-13051.

Turner, R.E., N.N. Rabalais 1994. Coastal eutrophication near the Mississippi river delta. **Nature** 368: 619-621.

Turner, R.E., N.N. Rabalais, E.M. Swenson, M. Kasprzak, T. Romaire 2005. Summer hypoxia, northern Gulf of Mexico: 1978 to 1995. **Marine Environmental Research** 59: 6577.

Turner, R.E., N.N. Rabalais, D. Justić 2008. Gulf of Mexico hypoxia: Alternate states and a legacy. **Environmental Science & Technology** 42: 2323-2327.

Turner, R.E., N.N. Rabalais, D. Justić 2012. Predicting summer hypoxia in the northern Gulf of Mexico: Redux. **Marine Pollution Bulletin** 64: 318-323. doi: 10.1016/j.marpolbul.2011.11.008 Turner, R.E., N.N.

Turner, R.E., N.N. Rabalais 2013. Nitrogen and phosphorus phytoplankton growth limitation in the northern Gulf of Mexico. **Aquatic Microbial Ecology** 68: 159-169. doi: 10.3354/ame01607.

Turner, R.E., N.N. Rabalais, D. Justić 2017. Trends in summer bottom-water temperatures on the northern Gulf of Mexico continental shelf from 1985 to 2015. **PloS One** 12(9): e0184350. https:// doi.org/10.1371/journal.pone.0184350

Turner, R.E., N.N. Rabalais, C. Glaspie 2025. A temperature tipping point for hypoxia in the northern Gulf of Mexico Hypoxic zone. **Limnology and Oceanography** 69: 54–62. doi: 10.1002/lno.12722

Walker, N.D., N.N. Rabalais 2006. Relationships among satellite chlorophyll a, river inputs, and hypoxia on the Louisiana continental shelf, Gulf of Mexico. **Estuaries and Coasts** 29: 1081–1093.

Wang, Z., T. Boyer, J. Reagan, J., P. Hogan 2023. Upper-oceanic warming in the Gulf of Mexico between 1950 and 2020. **Journal of Climate** 36(8): 2721-2734.

Ward, M.H., R.R. Jones, J.D. Brender, T.M. de Kok, P.J. Weyer, B.T. Nolan, C.M. Villanueva, S.G. van Breda 2018. Drinking water nitrate and human health: An updated review. **International Journal Environmental Research and Public Health** 15: 1557. doi:10.3390/ijerph15071557

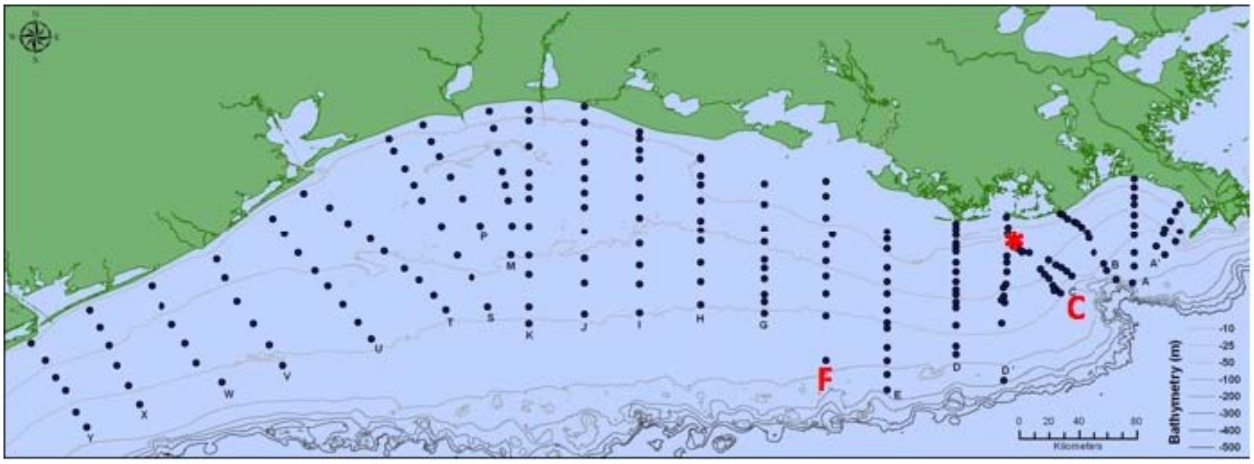
Wilkinson, J.L., A.B. Boxall, D.W. Kolpin, K.M. Leung, R.W. Lai, C. Galbán-Malagón, A.D. Adell, J. Mondon, M. Metian, R.A. Marchant, and A. Bouzas-Monroy 2022. Pharmaceutical pollution of the world's rivers. **Proceedings of the National Academy of Sciences (USA)** 119(8): e2113947119.

Zhao, Q., S. Liu, X. Niu 2002. Effect of water temperature on the dynamic behavior of phytoplankton–zooplankton model. **Applied Mathematics and Computation** 378: 125211.

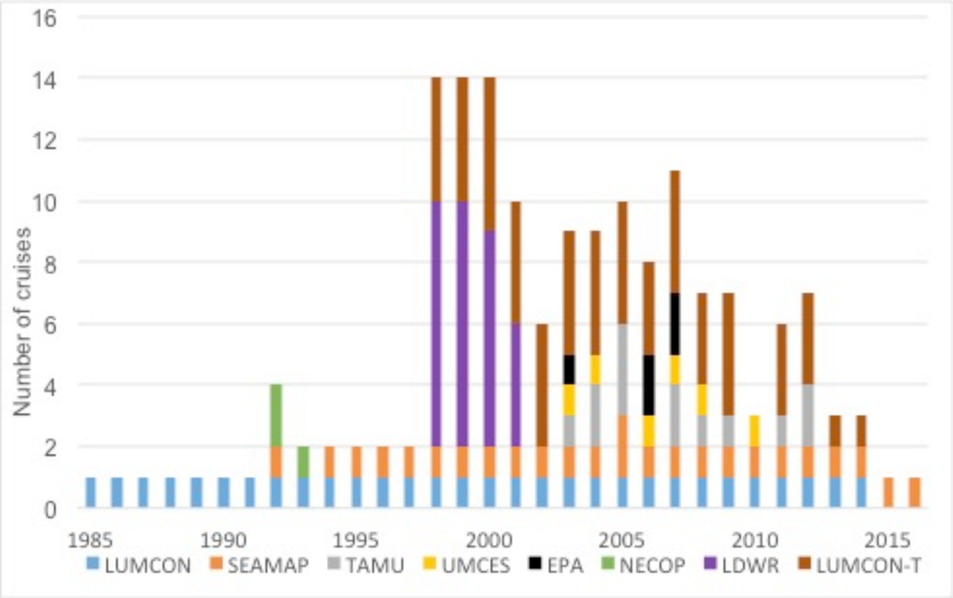
Contacts for Further Information

Cassandra N. Glaspie (LSU wk 225-578-0379; email: cglaspie1@lsu.edu), Chief Scientist
Nancy N. Rabalais (LSU wk 225-578-8531; cell 985-870-4203; email: nrabal@lsu.edu), Co-Principle Investigator
R. Eugene Turner (email: euturne@lsu.edu), Co-Principal Investigator

Appendix



Appendix Figure 1. Location of hypoxia monitoring stations sampled in summer (but not all stations in 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 are 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 and Fisheries; LUMCON-T = transects sampled during the year by LUMCON. Source: Maiti et al., 2018; used with permission.