Gulf of Mexico Hypoxia: Past, Present, and Future

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Abstract

One of the largest human-caused areas of bottom-water oxygen deficiency in the coastal ocean is on the northern Gulf of Mexico continental shelf adjacent to the Mississippi River, which discharges nitrogen and phosphorus loads into its surface waters. The beginnings of seasonal hypoxia (≤ 2 mg l^{-1} dissolved oxygen) in this area was in the 1950s with an acceleration in the worsening of severity during the 1970s. Currently, the bottom area of hypoxic areas can approach 23,000 km^2, and the volume, 140 km^3. Ecosystems, people, and economies are now at risk within the Mississippi River watershed and in the northern Gulf of Mexico. Strengthened nitrogen and phosphorus mitigation, altered agriculture practices, and reduction in carbon and nutrient footprints are key to the recovery of these systems. In this article, we review the past, present, and possible future conditions of the northern Gulf of Mexico and provide insight into possible management actions.

Introduction

There is no doubt that many areas of the coastal ocean are now receiving enriched loads of nitrogen (N) and phosphorus (P) that are implicated in noxious, and often toxic, harmful algal blooms, and in decreasing dissolved oxygen (DO) concentrations in the bottom waters to ecologically depressed levels (Breitburg et al. 2018). These changes began primarily in the mid-1950s when North American watersheds underwent landscape use change or even earlier in European watersheds during the Industrial Revolution and as human population expanded and fossil fuel use increased. One well-documented area for these ecosystem changes is in the northern Gulf of Mexico adjacent to the discharge of the Mississippi River where it discharges its constituents to affect nearshore and mid-depth areas of the adjacent Louisiana continental shelf and lead to bottom-water low oxygen conditions (hypoxia) (Rabalais et al. 2007a; Rabalais et al. 2010; Rabalais et al. 2014). Oxygen deficiency for the purpose of this article is defined as hypoxic when the DO concentration is ≤ 2 mg l^{-1}. Our research findings originate from 30+ years of summertime research cruises across the Louisiana shelf, cruises on two transects 100 and 250 km west of the Mississippi River, continuous bottom-water oxygen measurements on moorings, and analyses of Mississippi River landscape and nutrient load changes revealed on the continental shelf by palaeoindicators in dated sediments.

The present

River/Ocean linkages. The main freshwater sources from the Mississippi River watershed to the northern Gulf of Mexico are through two main distributaries: the birdfoot delta southeast of the city of New Orleans, Louisiana, and the Atchafalaya River 250 km to the west, which is formed by the Red River and the regulated diversion of 30% of the Mississippi River through the Old River Control structure. These two rivers are the primary sources of freshwater, N, and P to the northern Gulf of Mexico, delivering 80% of the freshwater inflow, 91% of the estimated annual N load, and 88% of the P load for the water years 1972–1993 (Dunn 1996). The fresh water and dissolved and particulate constituents flow mostly westward during the spring high river discharge in response to winds primarily from the southeast. The discharge is usually much lower in the summer but shifts in winds and currents from the west retain the fresh water and its constituents on the Louisiana shelf.

Extent. Hypoxia occurs each year in bottom waters of the northern Louisiana continental shelf, at least since consistent late July mapping of the low oxygen zone began in 1985 (Rabalais et al. 2002). The area of low oxygen in bottom-waters is found from very nearshore or adjacent to barrier island beaches to about 50 to 150 km offshore (Fig. 1). The hypoxic water mass sometimes extends into upper Texas coastal waters [(maps of bottom oxygen are at https://www.ncddc.noaa.gov/hypoxia/products/ and http://www.gulfhypoxia.net]. Hypoxia also occurs east of the Mississippi River and is becoming more frequent there (Dzwonkowski et al. 2018).

The area of hypoxic bottom-waters in the Gulf of Mexico west of the Mississippi River can reach up to 23,000 km^2 in mid-summer (http://www.gulfhypoxia.net), making it the second largest human-caused area of hypoxia in the coastal ocean (see Carstensen and Conley, this issue). The bottom-water area dimensions are minimal or lower than average following droughts in the watershed that sometimes occur in spring or summer (Fig. 2). The larger areas are coincidental with higher freshwater discharge, which is a factor in determining the N load (= discharge × concentration). The bottom area of hypoxic waters is best correlated with the nitrate-N load of the Mississippi River in the previous May (Turner et al. 2012). There are summers when the bottom area measured is smaller than predicted in early June. These mismatches occur when (1) a

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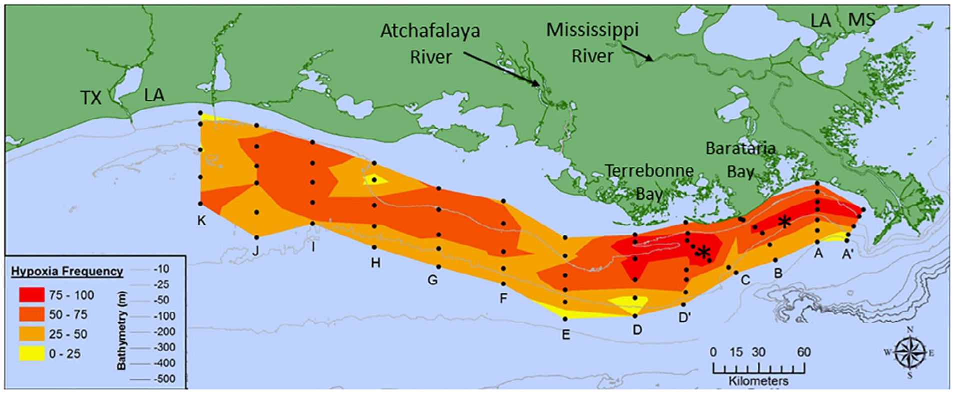

FIG. 1. The frequency of bottom-water hypoxia from shelf-wide hypoxia mapping (1985–2014) (updated from Rabalais et al. (2007b); frequency is determined from stations for which there are data for at least half of all cruises. Asterisks (*) indicate locations of near-bottom oxygen meters; transects C and F identified. Data source: N. N. Rabalais and R. E. Turner.

tropical storm or hurricane disturbance mixes the water column before or during the mapping, or (2) sustained winds from the west push the low oxygen water mass toward the Mississippi River delta so that the bottom area is less than predicted (Rabalais et al. 2018) (Fig. 2). The estimated volume of the hypoxic water mass correlates with the bottom-water area and ranges from negligible (severe summer drought) up to near 140 km^3 (Obenour et al. 2013).

The low oxygen conditions exist in waters of 5 m or less to as deep as 60-m water depth, but are most common in water depths between 10 and 30 m. The distance above the seabed in which hypoxic conditions may persist is in the lower 10 m of a 20-m water column on the eastern Louisiana shelf, but 2 to 5 m above the seabed on the western Louisiana shelf.

Seasonality. The only months in which hypoxia has not been documented are December and January, although there are fewer measurements in those months. Data from transect C (100 km west of the Mississippi delta) and transect F (off Atchafalaya Bay) (locations in Fig. 1) illustrate long-term conditions conducive to the formation of hypoxia and reflect the influence of the two major distributaries (Rabalais et al. 2007a) (Fig. 3). The surface water salinity is lower along both transects during the spring flood season and higher during summer and fall during low flow. Higher concentrations of chlorophyll *a* (as an indicator of phytoplankton biomass) in surface waters on transect C occur after the winter-early spring peak in nitrate-N. The chlorophyll *a* in the surface waters along transect F from nearshore to mid transect increases through spring to maximal concentrations in summer. The high chlorophyll *a* biomass nearshore in July off the Atchafalaya is fueled by high loads of ammonium-N, which favors blooms of dense and often toxic dinoflagellates (Rabalais et al. 2007a). The development of hypoxia along transect C occurs earlier in spring compared to summer along transect F, extends further offshore, and continues into September whereas it has decreased by August off the Atchafalaya.

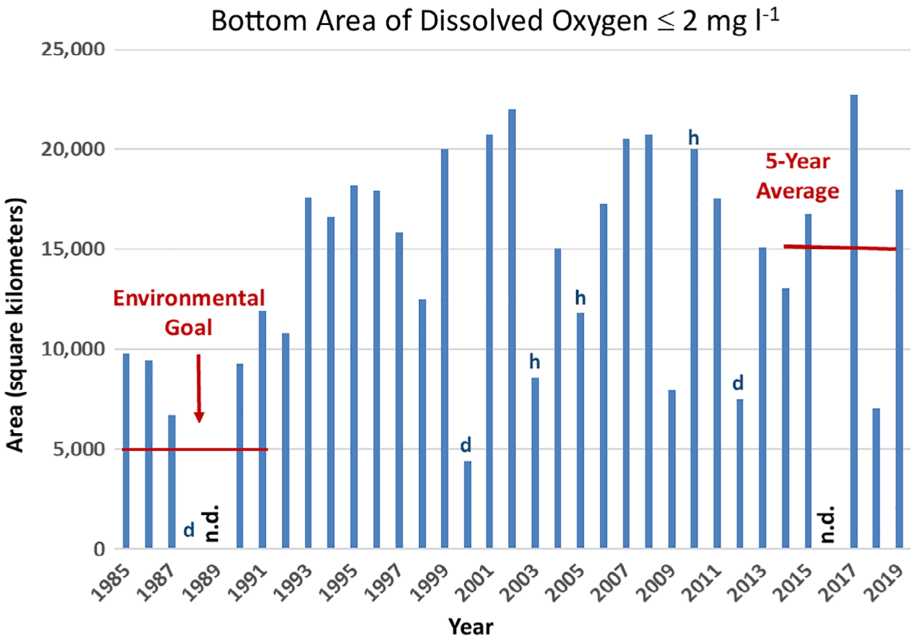

FIG. 2. Histogram of mid-summer bottom-area of dissolved oxygen ≤2 mg l^{-1} on the continental shelf west of the Mississippi River delta since 1985. Events that affect the size of the bottom area are d = drought, h = hurricane or tropical storm activity before or during the cruise to measure the area, w = winds from the west for an extended period before or during the cruise, and n.d. = no data. The only years not included are 1989 (lack of sufficient funding) and 2016 (lack of a suitable vessel).

Duration. Continuously recorded bottom-oxygen concentrations in 20-m water depth, along with other biological and physical parameters, provide insight into the duration and severity of hypoxia, respiration rates, reaeration events, advection, and short-term intrusions of well-oxygenated waters from deeper waters onto the shelf (Fig. 4). The data from oxygen meters (collected every 15 min) deployed near the bottom at a 20-m station 100 km west of the Mississippi River delta document many other physical and biological processes. Strong mixing events of the stratified water column are associated with cold fronts in spring and fall and with tropical storms and hurricanes in summer. These mixing events result in an almost immediate increase in bottom-water oxygen levels from near anoxic to above 6 mg l^{-1} (Rabalais et al. 2007a). Following a mixing event and reoxygenation of bottom waters, there is a gradual decline of bottom oxygen concentrations that are driven by aerobic respiration of organic matter and continue as long as the stratification is maintained. The reduction of the oxygen concentration from about 6 mg l^{-1} to less than 2 mg l^{-1} is 18, 11, or 9 d, in April, May, and July, respectively, as bottom temperatures warm (calculated from data in Fig. 4).

Stratification persists as long as mixing does not occur. Periods of oxygen concentrations less than 1 mg l^{-1} or near anoxia may last from one-half to 2 months from May to September. Short-lived increases in bottom-water oxygen during summer are usually the result of intrusions of higher oxygen content water from depth during upwelling-favorable wind conditions, which are followed by a relaxation of the winds and movement of the higher oxygen water mass offshore (Fig. 4). The DO concentrations at the same depth, but 50 km closer to the outflow of the Mississippi River and for the same period were influenced by tidal advection of oxygenated bottom water onshore and offshore (Rabalais et al. 1994).

Effects on living resources. These low-oxygen areas in the bottom waters of the northern Gulf of Mexico are often referred to as "dead zones" by fishers and the public, because of the lack of trawlable bottom-dwelling shrimp and fishes (Craig 2015). This popular title, however, does not truly describe the ecosystem (Rabalais et al. 2010). Many fish and shrimp are displaced by the low DO waters and move into shallower inshore waters, deeper offshore waters, or higher in the water column (Rabalais et al. 2001a; Craig 2015) (Fig. 5), and a host of microbes thrives in the low-oxygen conditions at the seabed. The organisms living in the sediments, such as polychaetes, burrowing shrimp, and echinoderms, cannot survive if the DO levels remain low enough for long enough (Rabalais et al. 2001b) (Fig. 6). The larger, deeper burrowing infauna are replaced by a community of opportunistic species and low oxygen-tolerant organisms that can survive extremely low oxygen concentrations and often hydrogen sulfide. The abundance and biomass of the remaining infauna remains low after the hypoxic conditions abate, and food resources for returning demersal species are diminished resulting in lowered secondary production.

Past and present nutrient loads

Nitrogen and phosphorus. The dissolved nitrate-N is about 70% of the total N load, and the relative percent is increasing. The total N load of the Mississippi River has increased by threefold since the mid-1950s (Turner and Rabalais 1991), but has not increased substantially in the last decade, and may have stabilized in some tributaries (Stets et al. 2015). The residence time of the surface waters along the northern Gulf of Mexico coast west of the Mississippi River delta is about 2 to 3 months in the summer (Dinnel and Wiseman Jr. 1986), hence the 2- to 3-month lag between the nitrate-N loading rate calculated for May and the predicted size of the hypoxic zone mapped in late July (partially illustrated in Fig. 3). The cause-and-effect relationships are supported by the enhanced primary production (Lohrenz et al. 1997) and the flux of organic carbon from surface to bottom where it is respired (Turner et al. 1998). The nitrate-N load in spring versus summer hypoxia area model is evolving, because the coastal ecosystem is changing. For example, the size of the hypoxic zone for the same amount of nitrate loading is increasing. Further, the models will eventually be adjusted to account for the limited space on the shelf for hypoxia to occur (a physiographic constraint) and climate change (Rabalais et al. 2010).

The data on the changes in P are not as well documented as the changes in N, but the general agreement is that the P load increased by twofold since the mid-1950s (Justić et al. 1995). The dissolved silicate concentration in the Mississippi River has decreased by 50% since the early 1900s (Turner and Rabalais 1991). The result of these changes is that either N or P may limit phytoplankton biomass growth (Turner and Rabalais 2013). Diatom growth may be limited or there may be shifts in diatom composition where the relative proportion of silicate to N is less than the Redfield ratio of 1:1 with potential shifts in the diatom-to-zooplankton-to-higher trophic level food web (Turner et al. 1998). There has been a shift from highly silicified-diatoms to less silicified-diatoms (Rabalais et al. 1996), but with increasing abundance of the latter forms despite the potential for silicate limitation (Parsons et al. 2002).

Nitrogen as a primary focus. We focus on N loading, concentrations, and ratios with other nutrients because the data record is longer, and palaeoindicators from dated sediment cores indicate a close relationship to changes in N and diatoms (Rabalais et al. 2007b). Nutrient limitation experiments with bioassays from 1981 through 2011 were conducted across a range of months, salinities, light conditions, depths, and distance from freshwater and nutrient sources by Turner and Rabalais (2013). They found a combination of N and P was most likely to be limiting to phytoplankton growth, but if a single nutrient was limiting it was more likely to be N than P. The N incorporated into particulate organic N in offshore plankton biomass is clearly a Mississippi River source as identified by stable N isotopes (Rabalais et al. 2014). N remains the primary target of nutrient mitigation, but P also needs to be considered. The methods by which to mitigate the two nutrients are not necessarily the same, but the loading of each will be affected from manipulations of the other.

Carbon. The organic carbon (C) isotopic signature in offshore waters where hypoxia occurs dominates as an atmospheric source rather than a terrestrial C signature (Rabalais et al. 2014). In addition, the $\delta^{13}C$ composition of surface sediments indicates that the terrestrial C flux is located near the river mouth and adjacent to the wetlands (Turner and Rabalais 1994). Wang et al. (2018) verified in situ produced C of marine origin C played the dominant role in near-bottom water and benthic oxygen consumption in the northern Gulf of Mexico shelf west of the Mississippi River. These findings (and those of N sources) point to N pollution as a product of increased N loads to the Louisiana continental shelf, and not terrestrial sources of C that might support bottom-water respiration rates.

The nutrient-enhanced primary production in coastal waters adjacent to the Mississippi River discharge results in a C budget for the upper mixed layer that is a sink for CO_2. It is a sink because of the biological generation of CO_2 (and lowered pH) within the water column and not from air–sea exchanges. Simultaneously below the pycnocline, bacterial respiration of organic matter derived from the surface layer depletes DO, generates CO_2, and contributes to a decline in pH. The duration of low DO and lower pH can persist for a few days, 2 weeks, or several months in the hypoxic zone if stratification persists (Rabalais et al. 2007a). The coastal ecosystem influence by the Mississippi River is overall autotrophic in the surface waters and heterotrophic in the bottom waters for most of the year (Justić et al. 1997). Thus, an imbalance of surface and bottom water pCO_2 and pH conditions can persist for much of the year unlike other

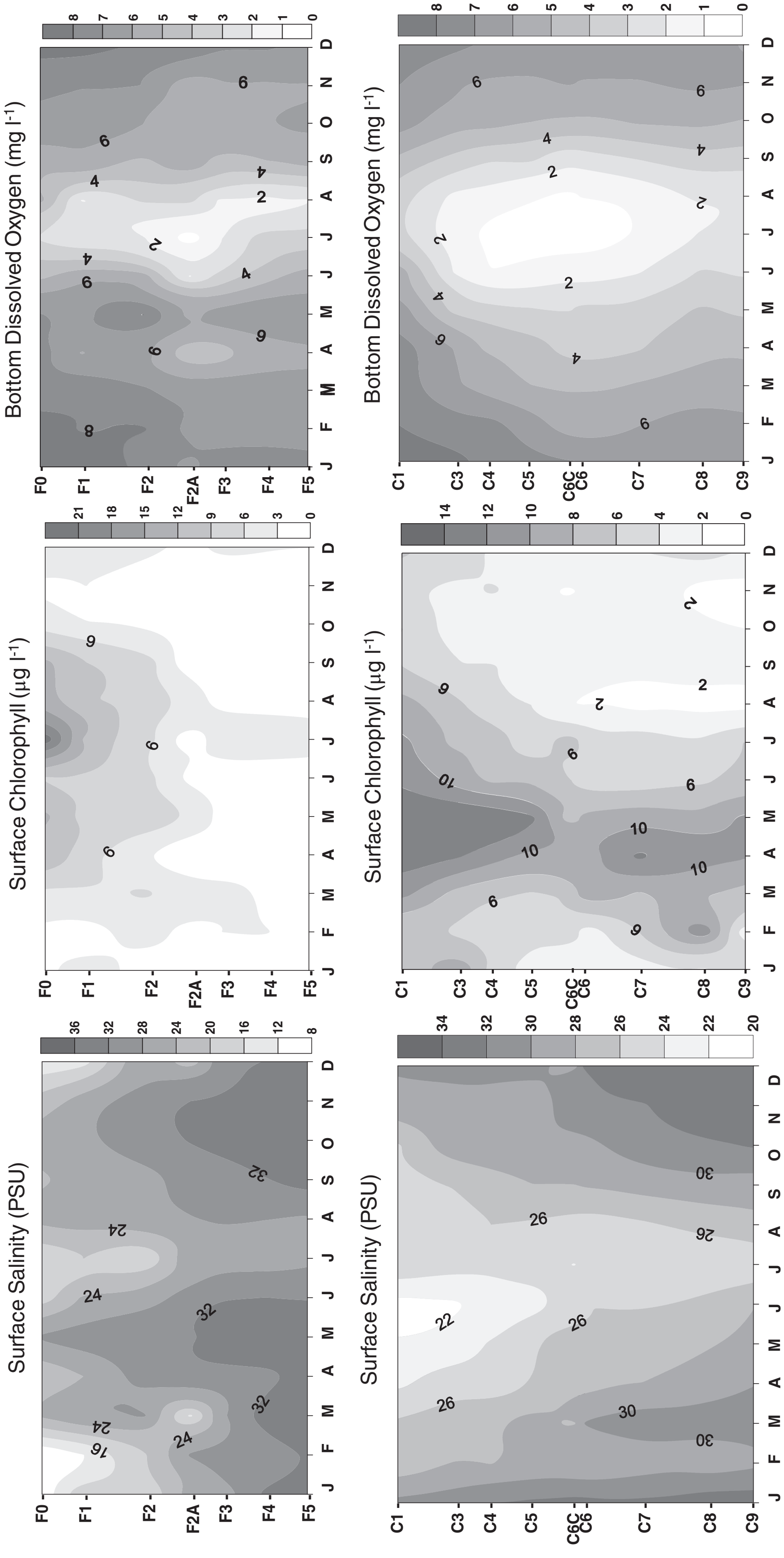

FIG. 3. Water column parameters along transect C (location in Fig. 1) from station C1 inshore at 5 m to C9 offshore at 30 m, January–December 1985–2001 (upper panel), and along transect F (location in Fig. 1) from station F0 inshore at 5 m to F5 offshore 35 m, January–December 2001–2005 (lower panel). Modified from Rabalais et al. (2007a).

areas exposed to only higher pCO_2 concentrations in the atmosphere.

The past

The nearshore coastal waters of the northern Gulf of Mexico adjacent to the Mississippi River outflow are prone to the development of low DO concentrations because of the amount of fresh water and solar heating that support water-column stratification. However, it was not until the N load to the continental shelf caused an ecosystem shift (Turner and Rabalais 1994; Rabalais et al. 2007a) that the typical sequence of processes leading to hypoxia began to occur. Although historic water quality data collection did not begin until oxygen levels began declining (Rabalais et al. 2002), the contents of dated accumulating sediments document the geological, chemical, and biological indicators of increased primary production and declining oxygen conditions at the same time when N loads from the Mississippi River increased beginning approximately 1950s (Turner and Rabalais 1994; Rabalais et al. 1996; Rabalais et al. 2007b). The evidence for increased C production and accumulation is revealed in the accumulation of diatoms and their remnants (Turner and Rabalais 1994), the increase in total organic C in more recent sediments, and the shift to an isotopic signature of the marine-derived C in the sediments (Rabalais et al. 2014). Surrogates for oxygen conditions, including mineral, isotopic, and microfossils, indicate worsening oxygen stress as the N loads from the Mississippi River system increased beginning in the 1950s (Rabalais et al. 2007b), that is, hypoxia has not always been a feature of this coastal ecosystem despite the stratified water column for much of the year. Temporal shifts in this shelf ecosystem parallel the time sequence of similarly eutrophied coastal waters globally and coincide well with the results of sedimentary analyses there.

The future

Climate change. Human activities are changing climates across the globe to affect landscapes, hydrology, the ocean, and related biogeochemical cycles. The predicted higher stream flows for the upper Mississippi River watershed or increasing coastal water temperatures will result in increased nutrient runoff

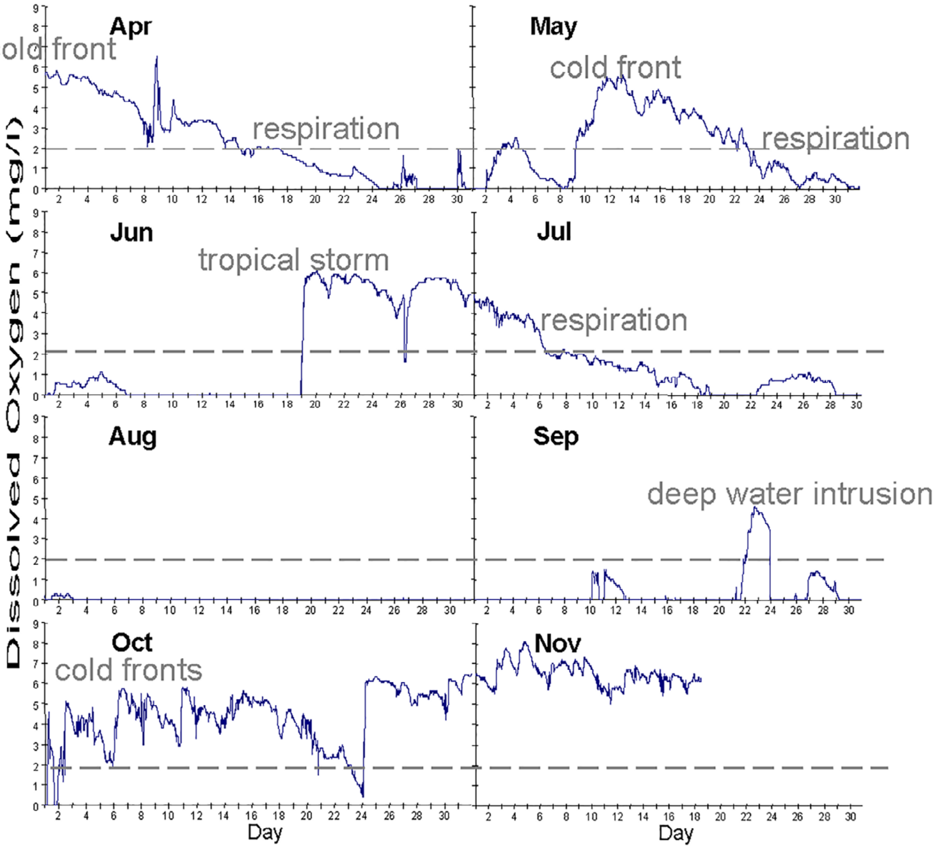

FIG. 4. Continuous bottom-water dissolved oxygen in 20-meter depth on the Louisiana continental shelf about 100 km west of the Mississippi River (April–November 1993). The horizontal dashed line defines hypoxia. Data replotted from Rabalais et al. (2007a).

and stronger stratification gradients, respectively, and increase biological rates offshore and perhaps have other confounding consequences (Rabalais et al. 2010) (Fig. 7). These scenarios, et al, could aggravate hypoxia in the northern Gulf of Mexico, and other eutrophied coastal waters worldwide. Coupled biogeochemical and three-dimensional ocean models (e.g., Laurent et al. 2018) are used increasingly to study the effects of climate change on the northern Gulf of Mexico and are improving the predictability of effects and the related processes.

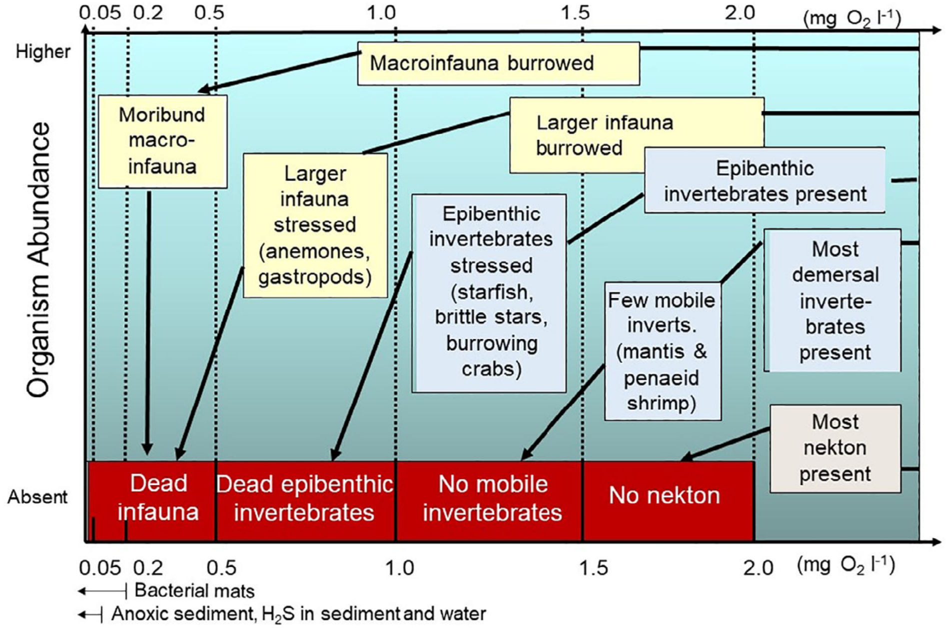

FIG. 5. Progressive changes in fish and invertebrate fauna as the bottom-water oxygen concentration decreases from near 2 mg l^{-1} to anoxia (0 mg l^{-1}). Source: Generated from data in Rabalais et al. (2001a).

While surface water temperatures at a well-monitored station in the hypoxic zone have not increased (from 1963 to 2015) because of land–sea interactions, the bottom-water temperatures have risen over the same period and over a more data-rich period from 1985 to 2015 (Turner et al. 2017). These recent changes in the heat storage on the Louisiana continental shelf will affect oxygen and C cycling. Warmer waters alone hold less DO than do cooler waters, all other parameters held the same.

Although increased temperatures have the potential to strengthen density differences (pycnoclines) in estuarine and coastal waters, lower surface salinity (e.g., from increased freshwater runoff) would be a stronger factor in stratifying the water column. A stronger pycnocline should result in less diffusion of oxygen from the upper water column to the lower water column, leading to less DO in bottom waters.

If the frequency of tropical storms and hurricanes increases as a result of higher water temperatures in the lower to mid-latitudes, there may be, at least, temporarily water column mixing, destratification of the water column, and re-aeration of the bottom water (Rabalais et al. 2010). However, such a disruption of a hypoxic zone would be short-lived. The rates of biological processes, including both photosynthesis and respiration, are expected to increase with higher water temperatures up to a point. Thus, increased precipitation in the watershed will result in more water, sediments, and nutrients reaching the coastal zone where they are likely to augment eutrophication through nutrient-enhanced production, increased stratification, or both.

The combined effects of higher water temperatures in surface and bottom waters, worsening the DO deficiency, lower pH, and the presence of hydrogen sulfide will add to existing formidable and poisonous habitats for sediment inhabitants, attached macrofauna, and demersal organisms. Additional freshwater discharge and potentially increased nutrient loads also contribute to this challenging PRESENT and FUTURE habitat. Human beings are the ultimate drivers for these changes through

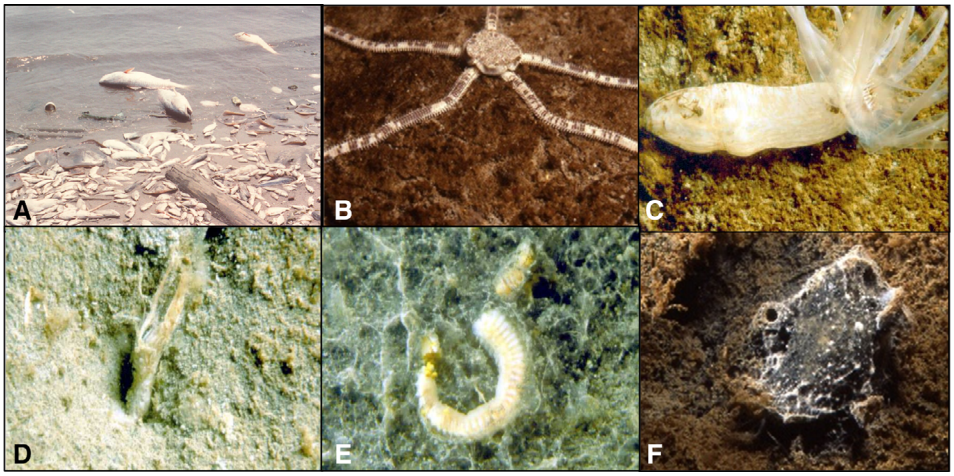

FIG. 6. A range of mortality events and stress behaviors in the Gulf of Mexico hypoxic area. (**A**) Fish kill on grand isle, LA after a hypoxic/anoxic water mass trapped demersal fish near the beach; (**B**) a stressed brittle star trying to reach higher dissolved oxygen levels than available in the sediments, note organic debris on the sediment surface; (**C**) stressed cerianthid anemone out of sediments; (**D**) dead alpheid shrimp at its burrow entrance; (**E**) dead polychaete worm on anoxic sediments with sulfur oxidizing bacteria; (**F**) organic detritus, anoxic sediments, sulfur oxidizing bacteria and burrow of the polychaete *Diopatra cuprea*. Photos from Kerry M. St. Pé, Franklin Viola and Donald E. Harper, Jr.; used with permission of sources.

activities that increase the reactive N in the environment.

Recovery. Increased precipitation under current agricultural practices would result in increased erosion and loss of P, and an increased flux of dissolved inorganic N, primarily as nitrate. Reversing this progression of watershed and coastal water quality damage requires reducing the use of artificial fertilizers, mono- or dual-agriculture systems, intensified animal husbandry, insufficiently treated wastewater, and unnecessary consumption of fossil fuels. There are no easy societal shifts to a less consumptive lifestyle, nor is it an easily achieved political outcome. Reducing both a C and N footprint requires a strong societal and political will.

Some governmental units have successfully implemented multifaceted plans to reduce nutrient loading, for example, countries surrounding the Baltic Sea, Denmark and its neighbors surrounding the Kattegat and Skagerrak, European countries affecting the North Sea, U.S. states comprising the watershed of the Chesapeake Bay (U.S. east coast) and municipalities surrounding Tampa Bay, Florida, U.S. Recovery pathways may take years or even decades to reverse the severity and size of hypoxic conditions adjacent to the Mississippi River outflow (Ballard et al. 2019; Van Meter et al. 2019). This calls for a serious commitment to improve coastal water quality (including improvement of hypoxic conditions) on an individual, community, and political basis.

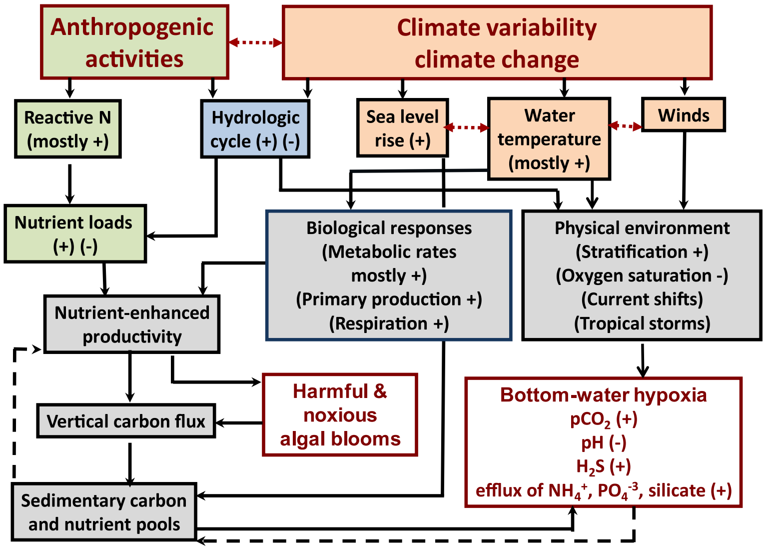

FIG. 7. Conceptual diagram of the impacts of human and climate interactions on nutrient enhanced productivity, harmful and noxious algal blooms, and hypoxia formation (Rabalais et al. 2014). Positive (+) interactions designate a process or parameter that will increase, and negative (−) interactions designate a process or parameter that will decrease. Dashed lines indicate negative feedback processes to nutrient-enhanced production and subsequent hypoxia. The dotted line between "anthropogenic activities" and "Climate variability/climate change" indicates that humans largely drive current climate change, but that climate change can certainly affect human activities.

Restoring coastal water quality by decreasing nutrient loads of the Mississippi River watershed means, in large part, changing farming practices (Rabotyagov et al. 2014) and facilitating natural mechanisms for N removal (Mitsch et al. 2001). The nitrate yield from Iowa streams is directly related to farming practices. Much of the total N yield is a result of tile drainage, that is, pipes placed under croplands to speed water removal, which accounts for much of the rise in nitrate (Randall and Gross 2001). McIsaac and Hu (2004) demonstrated that the 1945–1961 riverine nitrate flux in an extensively tile drained region in Illinois averaged 6.6 kg N ha^{-1} $year^{-1}$, compared to 1.3 to 3.1 kg N ha^{-1} $year^{-1}$ for the nontile drained region, even though the N fertilizer application was greater in the nontile drained region.

The use of cover crops figures prominently as a way to reduce N fertilizer applications. N yields are influenced by the N fertilizer application rate and timing, crop rotation, and tile drainage (Randall and Mulla 2001; Dinnes et al. 2002). Tile drainage can go into buffer strips before they reach streams, drain into wetlands, or even not be used if row cropped fields are converted to perennials. Key findings by Liebman et al. (2013) and Davis et al. (2012) were that, by using cover crops for 4 yr, there was a reduction in fertilizer use by 91%, a 97% reduction in herbicide use, a 50% or more reduction in fossil fuel use, and a doubling of employment—all while profits remained unchanged.

Increased nutrients within the Mississippi River watershed that come into the Gulf also affect ecosystems upstream. Nutrient reductions can benefit caretakers of the land in the watershed and farmers of the sea. Many freshwater lakes and reservoirs suffer from harmful algal blooms comprised of toxic cyanobacteria. They threaten ecosystem functioning and degrade water quality for recreation, drinking water, fisheries, and human health. Similarly, toxic cyanobacterial blooms also plague brackish estuaries in coastal Louisiana (Garcia et al. 2010). The consequences of water quality degradation include higher sewage treatment costs when tertiary treatment is called for to remove nitrate; high nitrate levels in water wells do not receive such treatment. Nitrate in drinking water is implicated in birth defects (Brender et al. 2013) and cancer (Ward et al. 2018).

Do not forget people when considering ways to reduce nutrients in the watershed. Dietary choices can reduce the use of N overall (Howarth et al. 2002). Eating less meat is healthy and requires less N (see Scavia, this issue). Proper wastewater treatment is implicit for human health, but also for reducing N loss into streams and rivers. Fossil fuel emissions generate NO_x emissions and volatile ammonium that travel far or are more localized, respectively, before returning to the landscape as reactive N in the form of nitrate and ammonia. There are some obvious solutions in that regard. Less consumption of fossil fuels and use of nonethanol gasoline avoids many processes that contribute to increased reactive N in the landscape and airshed.

Optimism or pessimism?. Reducing N and P loading into and out of the watershed will have beneficial effects there and in the northern Gulf of Mexico. Water quality has improved in some subwatershed streams of the Mississippi River watershed because of conservation practices (García et al. 2016), but nutrient concentrations and yields have increased in others. A net reduction in the bottom area covered by hypoxia has yet to appear 18 yr after the Mississippi River Nutrient/Gulf of Mexico Hypoxia Task Force (2001) called for reducing the size of the hypoxic zone to 5000 km^2 or less over a 5-year running average by the year 2015 (Fig. 2). The environmental goal was recently extended from 2015 to 2035, with an intermediate goal of a 20% overall reduction in N and P loads into the Mississippi River from the states bordering the Mississippi River and sections of the Ohio River (Mississippi River/Gulf of Mexico Watershed Nutrient Task Force 2015). Many efforts are underway or considered that demonstrate the breadth of attention to local and regional efforts that reduce landscape-scale nutrient loads, but there has not been a demonstrable improvement as of 2019. A deliberate and stronger social and political resolve is mandatory to decrease nutrient inputs to aquatic ecosystems and alleviate the associated ecosystem, human health, and economic difficulties.

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