Supplementary material to “Nutrient Enrichment Drives Gulf of Mexico Hypoxia”

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Organic Matter Sources and the History of Hypoxia

Dagg et al. [2007] and *Bianchi et al.* [2008] suggested that organic matter derived from river discharges or the estuaries (particularly from the massive loss of wetlands that has been experienced along the Louisiana coast) might be responsible for the bottom water hypoxia regularly observed along the inner shelf off Louisiana and Texas. While allochthonous organic matter certainly contributes to the carbon metabolism of the inner-shelf ecosystem, its supply has not increased contemporaneously with the manifestation and expansion of shelf hypoxia. Generalized trends in hypoxic area, wetland loss and nutrient flux are shown in Figure 2. Because both organic carbon delivered by the rivers [*SAB*, 2008] and wetland loss [*Barras et al.*, 2008] were actually on the decline during the development and expansion of recurrent hypoxia. The only source of increasing supply of organic matter to the inner shelf is primary production stimulated by increasing nutrient loads, particularly nitrate.

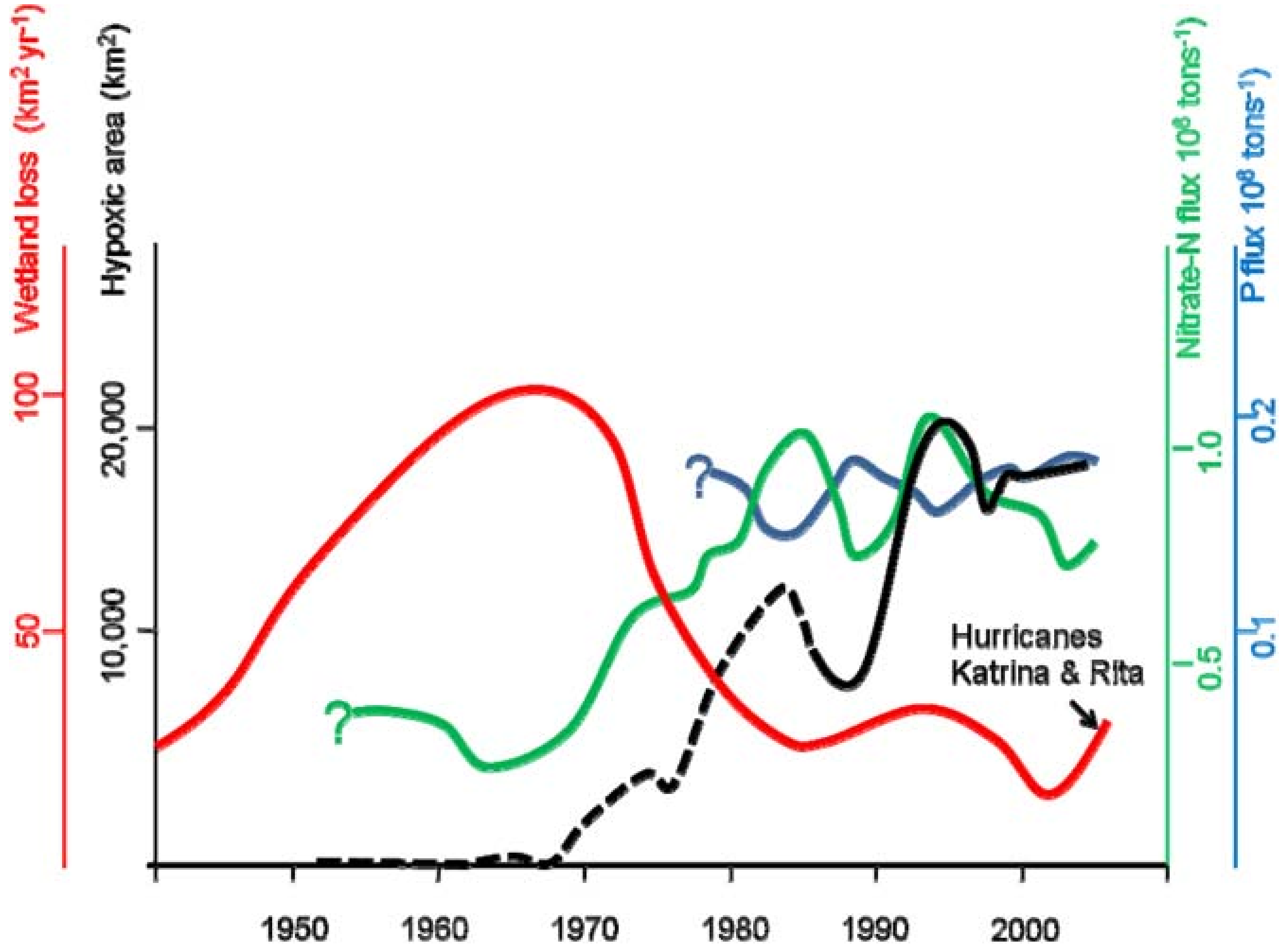

Figure 2. Generalized trends in hypoxic area [*Rabalais et al*, 2007; *Scavia and Donnelly*, 2007], coastal wetland loss rates [*Barras et al.*, 2008] and nitrate-nitrogen and total phosphorus flux [*SAB*, 2008]. Other than for wetland loss rate, the curves are smoothed fits to five-year running means to dampen the effects of river flow variations. Dashed curve for hypoxia indicates fragmentary record reconciled with hindcast model.

Dagg et al. [2007] estimated that the organic carbon annually released due to erosion of marsh soils exceeds that fixed in primary production on the shelf; however, their estimate of organic release from marshes is at least an order of magnitude too high because of: (1) an error made in converting organic matter bulk density to organic carbon, and (2) the use of a wetland loss rate (77 km^2 yr^{-1}) more than double that actually experienced for the entire Louisiana coast [*Barras et al.*, 2008]. *Gordon and Goñi* [2003] found very small contributions by C3 plant debris in organic carbon inventories in surface sediments from water depths greater than 10 m. Shelf sediments are dominated by old and refractory organic carbon derived from Midwestern soils and newer organic carbon fixed in the marine environment. Earlier stable isotope studies by *Fry et al.* [1984] also indicated that the significant wetland-derived organic carbon is incorporated in continental shelf food webs only near shore.

Even in areas near the mouths of the Mississippi and Atchafalaya rivers, the labile organic matter supporting most benthic respiration is derived from marine production [*Turner and Rabalais*, 1994; *Gordon et al.*, 2001; *Green et al.*, 2006]. With greater distance from land-based sources, it is even more likely that labile organic matter needed to consume oxygen in bottom waters is derived from the high phytoplankton production along the inner coast (evident in chlorophyll *a* biomass) that lies atop or adjacent to the hypoxia zone (Figure 1) and is correlated with nitrate loading [*Walker and Rabalais*, 2006; *Green and Gould*, 2008]. However, storage of organic matter in sediments can cause a temporal offset between surface phytoplankton biomass and bottom water hypoxia and may have a residual effect on the next year's hypoxia [*Turner et al.*, 2008].

Modeling Responses to Nutrient Inputs

Hetland and DiMarco [2007] criticize as physically simplistic the application of a Streeter-Phelps model used to relate nutrients loading to extent of hypoxia [*Scavia and Donnelly*, 2007]. While in the original formulation of the model, the calibration term "v" represents net downstream advection, it takes on a different character in this application. The simple steady state model approximates surface production of organic matter, its subsequent westward movement, and settling and decay in subpycnocline waters as if the organic matter were introduced below the pycnocline near the mouths of the rivers and transported westward. Thus, "v" represents both the slow net advection of the bottom waters *and* the more rapid movement of surface waters and settling of organic matter. That single coefficient was used to calibrate across 21 years of observations and, because all model and data errors were collapsed into it, has no simple biophysical analogue, but was used to characterize simulation uncertainty in Monte Carlo assessments [*Scavia and Donnelly*, 2007].

Effects on the Ecosystem and Valued Resource Species

Bianchi et al. [2008] describe as arbitrary the goal of reducing the average size of shelf hypoxia to 5,000 km2. While not linked to a fisheries recovery metric, this goal is implicitly linked to one of expanding suitable habitat (i.e., increasing the area where benthic fish, crustaceans and their prey can live during the summer) and was chosen by a task force of diverse constituents as a goal that would have significant benefits achievable over time. *Bianchi et al.* also intimate that hypoxia has not had negative impacts because fisheries landings increased during 1985-2007. Catch-per-unit-effort of highly valued brown shrimp (*Farfantepenaeus aztecus*) actually declined from the 1970s to the 1990s [*Zimmerman and Nance*, 2001] when annually recurrent shelf hypoxia was developing (Figure 2). Brown shrimp landings in both Louisiana and Texas are negatively correlated with the extent of hypoxia [*O'Connor and Whitall*, 2007] and fishery-independent data show that populations are displaced both inshore and offshore from their optimal habitat [*Craig et al.*, 2005], leading to a loss of about 25% of formerly productive habitat. Hypoxia also affects net energetic gains and production in shrimp and demersal fish [*Craig and Crowder*, 2005]. Dramatic changes in the fish communities have occurred since the 1930s [*Chesney and Baltz*, 2001] as a result of multiple stressors, including hypoxia. As late as the 1960s, surveys showed the highest summer biomass of demersal fish in regions of the Louisiana shelf [*Darnell et al.*, 1983] now occupied by hypoxia rather than summer fish aggregations.

The diminished habitability by demersal fish and crustaceans and reduced prey benthic biomass [*Rabalais et al.*, 2001] over 10,000 to 20,000 km^2 of seabed each summer cannot be presumed to be without consequences to the ecosystem's resources and services. Moreover, a recent global comparative analysis showed that thresholds of lethal and sublethal effects vary greatly among marine benthic organisms and that the conventional definition of 2 $mg\ l^{-1}$ of dissolved oxygen to designate waters as hypoxic is below the empirical sublethal and lethal thresholds for half the species tested [*Vaquer-Sunyer and Duarte*, 2008]. This implies that the effects of hypoxia on marine biodiversity have been generally underestimated.

Management Implications

Bianchi et al. [2008] recommend that the goal of managing for an "acceptable" hypoxic zone should be restricted to the region between the Atchafalaya and Mississippi rivers and not the inner shelf extending to the west "where many other physical and biogeochemical factors complicate management projections." Presumably, this is because they believe it is not caused by nutrient-enhanced production and, therefore, will not respond to changes in river nutrient loads. In our paper, we demonstrate why marine organic production is required for oxygen depletion in this region. Furthermore, observations over many years suggest that hypoxia in this western area is more responsive to variations in nutrient loading than areas to the east, where hypoxia is more frequent and intense [*Rabalais et al.*, 2007].

Bianchi et al. further assert that policy makers need to be more open in considering other controls on hypoxia in addition to river nutrients, but it is not obvious what other controls could be employed. As the floods of 2008 demonstrate, one can hardly keep the river from reclaiming its floodplain much less from flowing to the Gulf of Mexico. River diversions for coastal wetland restoration are mentioned, but nutrient removal by wetlands receiving diversions could possibly achieve only a small portion of the required load reductions compared to improved agricultural practices or wetland restoration within the MARB [*Mitsch et al.*, 2001]. Diversions that inject large amounts of fresh water and sediments presently discharged via the deep-water Balize delta of the Mississippi into the nearshore zone, such as recommended by the *National Research Council* [2005], are likely to result in larger nutrient loads reaching the regions of the inner shelf susceptible to hypoxia and, at the same time, to increase stratification. Deterioration of deltaic wetlands and shelf hypoxia are both manifestations of the complex and pervasive human alteration of the MARB, including its catchment, course and delta, and clearly require integrated solutions [*Boesch*, 2006]. Requiring acceptance of worsening hypoxia as a condition for restoring functioning Mississippi and Atchafalaya river deltas is an unreasonable and unnecessary predicate. Thus, there is added urgency to reducing nutrient loads so that restoration of the deltas can proceed without collateral impacts on water quality and ecosystem health.

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