White Paper

Ecological Impacts of Hypoxia on Living Resources Workshop

March 26-29, 2007
Bay St. Louis, Mississippi

WORKSHOP RATIONALE

Scientific Background

Hypoxia is a common symptom of degraded water quality that often results from anthropogenic activities (e.g. nutrient pollution). Over the last few decades, eutrophication of coastal waters has been linked to increases in the frequency, duration, and aerial extent of hypoxic events. Hypoxia is now recognized as one of most important environmental problems worldwide (Diaz et al. 2004) with the potential to significantly impact coastal fisheries (Diaz 2001). The national scale of the problem is evidenced by passage of the Harmful Algal Bloom and Hypoxia Research and Control Act (HABHRCA) in 1998 and its recent reauthorization in 2004 (www.cop.noaa.gov/stressors/extremeevents/hab/habhrca/welcome.html). Despite this recognition, management of the problem is hampered by a poor understanding of the quantitative relationship between hypoxia and populations of commercially and recreationally important living resources. This information gap limits assessment of ecological and socio-economic impacts of hypoxia and is the single most significant scientific barrier to informed management of this problem nationally. The *Ecological Impacts of Hypoxia on Living Resources Workshop* aims to assess the current state-of-knowledge of the quantitative ecological impacts of hypoxia on living resources with a focus on application of the science to coastal decision-making.

Ecological effects of hypoxia in coastal systems can vary in both degree and scale, often reflecting a graded response to the level of eutrophication (Diaz 2001). Few species of commercial and recreational value can survive dissolved oxygen conditions below 2 mg l^{-1}(Rabalais et al. 2006), although this threshold varies between species. The most apparent and extreme effects of hypoxia are fish kills; however, these events are often limited in scale. More common effects of hypoxia include shifts in spatial distribution and benthic and nekton community structure through mortality (primarily sessile benthic organisms) and emigration (fish and mobile invertebrates). Changes in community structure and loss of habitat can have bottom-up effects on food web structure resulting in further ecological effects (Diaz 2001). Additionally, exposure to hypoxic conditions can lead to reductions in growth (Taylor and Miller 2001), reproductive fitness (Marcus et al. 2004), and other physiological effects. These effects due to hypoxia have contributed to the collapse or impairment of a number of commercially important fisheries including the Norway lobster (*Nephrops norvegicus*) fishery in the Kattegat Sea (Baden et al. 1990) and demersal fish fisheries in the Baltic and Black Sea (Breitburg et al. 2001, Diaz et al. 2004).

While progress has been made on determining the effects of hypoxia on living resources, significant knowledge gaps remain, especially with regard to sub-lethal population level effects. Determining the ecological consequences of hypoxia is often complicated by interactions with a variety of anthropogenic stressors (such as over-fishing), and the cumulative effects of these interactions are largely unknown. Effects of hypoxia on commercially important species are often likely to be indirect, resulting from changes in food web structure and sub-lethal individual effects. Quantification of these indirect effects and their translation to populations are needed by managers in order to improve coastal management and policy decision making. To this end, application and advancement of spatially explicit and species specific models would allow for better forecasting of the current and future socio-economic costs and benefits of coastal hypoxia.

The *Ecological Impacts of Hypoxia on Living Resources Workshop* (March 28-29, 2007) will convene leading scientists and managers with knowledge of, and experience with, hypoxia and living resources in three coastal centers noted for seasonally recurring hypoxic zones: Chesapeake Bay, Gulf of Mexico, and Lake Erie. Additional systems will also be examined for comparative purposes. A symposium will be held prior to the *Workshop* (March 26-27, 2007) that includes sessions titled:

- Historical perspective on research and management: development of problem, link to eutrophication and other anthropogenic stressors;

- Direct and indirect effects of hypoxia: interactions with climate, overfishing, or other stressors, and impacts on food web structure and function;

- Management tools applied to hypoxia issues: indicators, models.

Workshop participants will then work to evaluate current knowledge of the impacts of hypoxia on ecologically, commercially, and recreationally important fish and shellfish, and to identify future science and management strategies for coastal decision making.

WORKSHOP OBJECTIVES

1. Develop an informational database of physical, chemical, and biological hypoxia data;

2. Compile, present, and evaluate the state-of-knowledge of hypoxia effects on living resource populations and communities in three systems in a manner that can be used in evaluating the resource, and potential economic impacts of alternative management decisions;

3. Develop recommendations for selecting and applying management tools (e.g. indicators, predictive models) that quantify the effects of hypoxia on living resource populations in a manner that can be used to inform the management of

hypoxia in coastal systems;

4. Identify research priorities needed to further advance the state-of-knowledge of hypoxia effects on living resources in a manner that can be used in evaluating the resource and socioeconomic impacts of alternative management decisions in coastal systems impacted by hypoxia.

TARGETED OUTCOMES

The *Ecological Impacts of Hypoxia on Living Resources Workshop* will result in two publications. A NOAA Technical Report of the workshop will be produced shortly after the meeting, and a special issue peer-reviewed publication will result from symposium presentations. These publications will provide a framework for guiding research directions and management strategies aimed at assessing and mitigating the effects of hypoxia on living resources

RELATIONSHIP WITH REGIONAL AGREEMENTS

Numerous regional and local agreements have been developed to assess and control the effects of hypoxia on living resources. For example:

- Northern Gulf of Mexico: The 2001 *Action Plan for Reducing, Mitigating and Controlling Hypoxia in the Northern Gulf of Mexico* calls for the hypoxic zone in the Gulf of Mexico to be reduced to an annual average size of 5,000 km^2 by 2015, down from the 2000-2005 average of 15,600 km^2. A key indicator of successful mitigation, as outlined in the *Action Plan*, is the return of bottom communities in the hypoxic zone to normoxic condition, in terms of diversity and biomass, and the return of normal migratory patterns for key species. Additionally, increasing water quality for living resources is an inherent driver behind *Action Plan* goals.

- Chesapeake Bay: The Chesapeake 2000 Agreement, built from the 1987 Chesapeake Bay Agreement and amendments in 1992, set a goal of improving water quality through a 40% reduction in nitrogen and phosphorus in an effort to remove the Bay from the list of impaired waters under the Clean Water Act. A prominent vision in the *Agreement* is oxygen rich waters resulting from large reductions in nutrient pollution to support abundant fish and shellfish populations. In 2003, dissolved oxygen criteria were established for various space and time scales in the Chesapeake Bay and its tributaries. Many of these criteria were subsequently adopted as standards in the watershed states to further drive implementation of nutrient controls.

- Lake Erie: The *Great Lakes Water Quality Agreement* of 1972 was negotiated between Canada and the United States in part to remediate hypoxia within the central basin of Lake Erie. Within the *Agreement*, both governments made a commitment to restore the biological integrity in the Great Lakes and year-round aerobic conditions in the bottom waters of the Central Basin of Lake Erie. A prominent goal of this *Agreement* was to reduce phosphorus loading within the lake to 11,000 metric tonnes a year, a goal that was met in the late 1980's (Hawley et al. 2006). However, in the 1990's, both phosphorus concentrations and the frequency and scale of hypoxic events began to increase, with high phosphorus loadings and summer hypoxia continuing to the present.

REGIONAL STATUS OF HYPOXIA AND EFFECTS ON LIVING RESOURCES

Gulf of Mexico

The largest zone of oxygen-depleted coastal waters in the United States, and the second largest for the world's coastal ocean, is in the northern Gulf of Mexico on the Louisiana continental shelf. Retrospective analyses of sedimentary records and model hindcasts suggest that hypoxia in this region has intensified since the 1950s, and that large-scale hypoxia began in the 1970s (reviewed in Justić et al. subm., Rabalais et al. subm.). The areal extent of the hypoxic zone, monitored in mid-summer since 1985, has increased from an average of 6,900 km^2 from 1985-1992 to 13,600 km^2 from 1993-2004, with a peak of 22,000 km^2 in 2002 (Rabalais et al. 1999, Rabalais and Turner 2006). The intensification and expansion of Gulf hypoxia over recent decades have been related to increases in nitrate loading, and scientific consensuses (CENR 2000, Rabalais et al. subm.) support the conclusion that the worsening hypoxia in this region is eutrophication-induced.

Significant research gaps on the effects of hypoxia on living resources exist in the Northern Gulf of Mexico, especially with respect to non-sessile species, although significant hypoxia-associated reductions in benthic macrofaunal biomass, species richness, and abundance have been well documented (e.g. Rabalais et al. 2001). The region supports some of the United States' most valuable commercial and recreational fisheries (Diaz and Solow 1999, Chesney et al. 2000, Zimmerman and Nance 2001). For example, Texas and Louisiana lead all states in catches of the largest U.S. commercial fishery, shrimp (NOAA 2006). Zimmerman and Nance (2001) suggest that severe hypoxic conditions may block the migration of shrimp from near-shore to offshore habitats. Additionally, brown shrimp are subjected to a significant amount of habitat loss due to hypoxia (Craig et al. 2005), congregating along suboptimal environments along the hypoxic zone edge, possibly causing a reduction in growth (Craig and Crowder 2005). Limited information exists on the effects of this hypoxic zone on finfish, but Craig and Crowder (2005) also found that Atlantic croaker congregated in sub-optimal conditions along hypoxic zone edges, possibly resulting in a reduction of body mass. However, Chesney and Baltz (2001) hypothesize that finfish and mobile invertebrate populations have thus far been resilient to hypoxia effects, with other anthropogenic stressors (e.g. fishing) possibly having larger consequences.

These studies highlight the high level of uncertainty associated with population level effects of hypoxia on non-sessile living resources in the northwestern Gulf of Mexico, and the strong need for elucidating the consequences of indirect effects, such as exclusion from physiologically optimal foraging or breeding habitat. As in all coastal systems, trophic interactions along the Louisiana shelf are complex, requiring detailed food web models. Application of these models would allow managers to assess the effects of hypoxia-induced changes in food availability and predation pressure to commercially and recreationally important species. Further, quantifying the level of interaction between hypoxia and other environmental or anthropogenically mediated perturbations (e.g. coastal wetland loss, fishing pressure) is needed to assess the cumulative effects of these stressors on living resources.

Chesapeake Bay

The Chesapeake Bay system includes deep central channels in the mainstem Bay and some of its larger subestuaries, and extensive shallow-waters with benthic habitat within or above pycnocline depths. The mainstem Chesapeake Bay is about 300 km long, varies from about 5.5 to 25 km in width, and has an average depth of only 6.5 m. Hypoxia and anoxia develop in subpycnocline waters of the mainstem Bay and several of its larger tributaries during late spring through about mid-October. Approximately 18% of the bottom area of the system (including mesohaline portions of tributaries) has bottom oxygen concentrations ≤ 3 mg/L during summer. Some degree of seasonal oxygen depletion is natural in deep stratified waters of the mainstem, but both paleoecological studies (e.g., Cooper and Brush 1993) and reconstructions of historical field data (e.g., D'Elia et al. 2002), indicate substantial increases in the severity and spatial extent of hypoxia beginning in the mid-20th century (summarized in Kemp et al. 2005). Surface waters in most years and bottom water south of the Rappahannock River typically remain above 3 mg L^{-1} and often have substantially higher dissolved oxygen concentrations. However, increased monitoring in shallow creeks and small subtributaries in recent years has resulted in a growing awareness of the particularly troublesome problem of shallow water hypoxia, which may have important ecological consequences.

Hypoxia affects the abundance, distribution, growth, behavior, and fisheries landings of both mobile and sessile consumers in Chesapeake Bay where hypoxic or anoxic bottom waters occur (Breitburg et al. 2002). Bottom habitat and portions of the water column directly affected by hypoxia have reduced abundances of all fauna (Weisberg et al., 1997 Roman et al. 2005, Keister et al. 2000; Latour: http://www.fisheries.vims.edu/multispecies/), mortality of fish eggs (Breitburg et al., 2002), reduced growth rates, altered predator-prey interactions (Pihl et al. 1992; Breitburg et al. 1997, 1999; Seitz et al., 2003), reduced habitat suitability (Niklitschek and Secor , 2001), increased success of invasive species (Jewett et al., 2005), and conditions that increase the prevalence and intensity of the pathogen that has devastated Chesapeake oyster populations (*Perkinsus* marinus; Anderson et al., 1998). Areas of Chesapeake Bay with bottom-layer hypoxia or anoxia are characterized by altered vertical distributions of plankton and nekton (Keister, et al., 2000). Because the Chesapeake Bay food web includes species with very similar diets but vastly different tolerances to low oxygen and values as prey for piscivores (e.g., bay anchovy vs. the ctenophore *Mnemiopsis leidyi*), hypoxia has the potential to strongly influence food web dynamics in affected waters (Breitburg 2002). In general the severity of effects increases with increasing severity of hypoxia, and thresholds in responses are common.

In spite of numerous examples of negative effects at the local or individual scale, there are no well-substantiated system-wide declines of fish or benthic macroinvertebrates due to hypoxia in Chesapeake Bay (see also Diaz 2001). Experiments and bioenergetics modeling (summarized in Niklitschek and Secor , 2001) indicate that reintroduction of sturgeon to Chesapeake Bay may be hampered by hypoxia. However, the initial decline was due to overfishing. In a cross system comparison including 30 estuaries and semi-enclosed seas, Chesapeake Bay had the highest landings of finfish and mobile macro-invertebrates km^{-2} (Breitburg et al., in review and to be presented). The effects of oxygen depletion on system-wide production of upper trophic level organisms and fisheries landings needs to be considered in the context of a spatial pattern that includes both oxygen-depleted bottom waters and surface and shallow habitat the has high oxygen concentrations and high prey production. This does not preclude the possibility that hypoxia has contributed to the declines seen in some harvested species, but points to both the importance of the spatial patterning of hypoxia effects and the complexity of isolating effects of hypoxia from other effects of nutrient enrichment and co-occurring stressors.

Lake Erie

Late-summer hypoxia is a natural phenomenon in Lake Erie, likely having occurred in the hypolimnion of Lake Erie’s central basin for hundreds, if not thousands, of years (Delorme 1982). Because central Lake Erie is deep enough to stratify (maximum depth = 25.6 m), but shallow enough that the thermocline can set up relatively close to the lake bottom (typically < 6 m from the bottom; Rosa and Burns 1987), the volume of hypolimnetic water that is cut off from surface aeration is small. In turn, dissolved oxygen can be depleted before fall turnover, thus leading to bottom hypoxia during late summer through early fall (Charlton 1980, Rosa and Burns 1987). By contrast, hypolimnetic volume of the deeper east basin (maximum depth = 64.0 m) is relatively large and does not become hypoxic before fall re-mixing (turnover), whereas the shallower west basin (maximum depth = 20.4 m) typically does not become hypoxic, owing to wind-driven circulation and storm events that keep that basin well mixed during summer (but see Bridgeman et al. 2006).

While hypoxia is a natural phenomenon in central Lake Erie, research has indicated that the rate of oxygen depletion, as well as the extent of hypoxia, can be modified by human activities (Rosa and Burns 1987, Bertram 1993). Owing to excessive phosphorus inputs from both point- and non-point sources that stimulated pelagic and benthic algal production, summer oxygen depletion rates increased during the 1950s and 1960s, thus leading to formation of a hypoxic zone as large as 11,000 km^2 in the central basin (Beeton 1963). In addition, during the height of cultural eutrophication (late 1950s through early 1970s), even the shallow western basin of Lake Erie could become hypoxic during wind-free periods in summer (Hartman 1972, Leach and Nepszy 1976).

In an effort to mitigate bottom hypoxia, as well as other water quality impairments (e.g., reduced water clarity), phosphorus abatement programs were initiated as part of the *Great Lakes Water Quality Agreement* of 1972 (Dolan 1993). These programs are thought to have led to an observed decline in bottom anoxia in both western and central Lake Erie through the early 1990s (Bertram 1993, Makarewicz and Bertram 1991, Charlton et al. 1993, Neilson et al. 1995). Since the late 1990s, however, the extent of bottom hypoxia has increased to levels on par with those during the height of cultural eutrophication (Hawley et al. 2006; U.S. EPA and Environment Canada, unpub. data). The exact causal mechanisms for this increase are not fully understood, although the recent increase coincides with increased nutrient inputs from non-point sources (R. Peter Richards, Heidelberg College, unpub. data) and warmer temperatures.

The effects of hypoxia on Lake Erie's food web remain largely enigmatic. It is known for certain that bottom hypoxia can regulate benthic macroinvertebrate community structure and production, as demonstrated by the elimination and then the recovery of important benthic macroinvertebrate prey species (e.g., burrowing mayflies, *Hexagenia limbata* and *H. rigida*) during the 1950s and 1980s, respectively (Britt 1955, Carr and Hiltunen 1965, Krieger and Ross 1993, Krieger et al. 1996). Hypoxia-driven losses of thermal and foraging habitat available to cool- and cold-water benthic fishes in the central basin also are believed to have contributed to the decline of several commercially valuable benthic fishes (e.g., lake whitefish *Coregonus clupeaformis*, burbot *Lota lota*) in central Lake Erie by the 1960s (Hartman 1972, Leach and Nepszy 1976, Laws 1981). Likewise, recovery of these species and other benthic fishes, including smallmouth bass *Micropterus dolomieu* (a sport fish) and silver chub *Macrhybopsis storeriana* (a prey fish), has been partly attributed to the implementation of phosphorus abatement programs during the early 1970s that enhanced bottom oxygen levels through the mid-1990s (Ludsin et al. 2001). However, until initiation of NOAA's International Field Years on Lake Erie (IFYLE) Program during 2005, no research had been conducted to explore how hypoxia can influence Lake Erie fishes; all previous studies concerning hypoxia's effects on fishes were speculative. In turn, Lake Erie management agencies are only now beginning to understand what role hypoxia might play in regulating growth, survival, and production of their fisheries.

WORKSHOP APPROACH

The *Ecological Effects of Hypoxia on Living Resources Workshop* will convene leading scientists and managers with knowledge of and experience with hypoxia and living resources to develop a framework for guiding future research and management of the issue. The *Workshop* participants will use existing literature and information from the previous 2-day *Symposium* to develop consensus conclusions and recommendations centering around four themes: 1) Current Knowledge of Hypoxia Effects on Living Resources, 2) Management Needs, 3) Management Tools, and 4) Research Gaps and Recommendations. The discussions and outcomes (technical report, journal special issue) will focus on three coastal centers with seasonally recurring hypoxic zones: Chesapeake Bay, Gulf of Mexico, and Lake Erie, but comparative information from other systems will be included.

Session 1: Current Knowledge of Hypoxia Effects on Living Resources

This session will compile the state-of-knowledge of hypoxia effects on living resources. Ecologically and economically important species affected by hypoxia will be compiled, including benthos, shellfish, demersal and pelagic fish, and plankton. Quantifiable direct and indirect effects of hypoxia will be discussed. Direct effects include fish kills or other mass mortality events, loss of habitat, altered spatial distribution, sublethal effects (physiological, reproductive, or energetic), and observed reductions on populations. Indirect effects of hypoxia include food web alterations due to effects on prey and/or predator populations, changes in susceptibility to fishing and/or predation, and altered short- or long-term migratory patterns. Evidence for adverse and beneficial indirect effects from hypoxia will be discussed. Participants will also discuss quantifiable interactive effects of hypoxia with other stressors, including chemical contaminants, climate change, overfishing (target species) and bycatch (non-target species), and habitat loss (e.g. wetlands, oyster bars). The evidence for large-scale ecological regime changes related to chronic hypoxia will be presented (e.g. through changes in species composition and/or species diversity). This session will conclude with a discussion of economic costs associated with hypoxia impacts on living resources.

Session 2: Management Needs

Management of hypoxia will be addressed from perspectives that include the management goals and management information needs. Management goals will include those related to assessing and controlling the magnitude of hypoxia (e.g. periodicity, spatial extent, and volume), and those related to mitigating the effects of hypoxia on living resources. Information needs will be discussed that would allow a quantifiable assessment of the relationship between hypoxia magnitude and resource impact and the risks of these impacts on economies.

Session 3: Management Tools

Discussion will focus on the models and indicators available or proposed that would improve effectiveness in managing hypoxia and its effects. The application of models to assessing and predicting the quantitative effects of hypoxia on living resources will include consideration of different types of models and their integration. These include population dynamics models for economically important species, individual and community energetic models, and food web models. The efficacy of available and emerging indicators will be explored, including those that provide evidence of individual or population impacts.

Session 4: Research Gaps and Recommendations

This session will develop recommendations for future research directions that would lead to better informed management of the effects of hypoxia on living resources. Consensus will be derived on research priorities needed to further advance the state-of-knowledge of hypoxia effects, and models and indicators that can be most effective in evaluating and predicting the resource and socioeconomic impacts of alternative management decisions used to control or mitigate hypoxia. Recommendations will also be made for the development of bio-economic models to assess the cost-benefit of hypoxia mitigation.

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