Synthesis Report on Gulf of Mexico Hypoxia Impacts on Living Resources

An output form the 3rd Annual Gulf of Mexico Hypoxia Research Coordination Workshop to inform the Scientific Reassessment of the Action 5 of the 2008 Gulf Hypoxia Action Plan

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Introduction

Development of the quantitative relationship between nutrients, hypoxia, and living resource populations represents an important milestone that will allow for improved goal setting and nutrient reduction targets. During the scientific reassessment that preceded the 2008 Task Force Action Plan, understanding of the living resource impacts of hypoxia in the Gulf of Mexico was relatively limited and quantification of population level impacts proved elusive (see Rose et al. 2009). This relative lack of knowledge was reflected in the science reassessment by U.S. EPA Science Advisory Board (U.S. EPA 2008), who limited much of their review of impacts to a brief discussion of possible ecosystem regime shifts based largely on findings from other systems that experience that seasonal hypoxia and in a series of abstracts provided in an appendix. However, many of the studies represented in the SAB report provided some of the fundamental information required to make some of the significant advances that have been seen in recent years.

This scientific assessment of Action 5 provides an overview of the activities and major research findings that have occurred since the release of the 2008 Action Plan and outlines the significant progress that has been made on understanding the impacts of hypoxia in the Gulf of Mexico. In addition, remaining research needs are outlined, with an emphasis on those required to quantitatively link nutrient reduction scenarios with resulting changes in living resource population and ecosystem changes.

Activities to Address Action 5

Much of the progress on understanding living resource impacts since 2008 can be traced to a NOAA sponsored workshop convened in 2007. This workshop was the result of a growing recognition during the last scientific reassessment of the need to advance impacts research and focused on the development of a state of knowledge and outline future research priorities. The workshop resulted in several significant outputs. Based on science advances identified at the workshop, a special issue publication of the Journal of Experimental Marine Biology and Ecology (Kidwell et al. 2009) was developed containing peer-reviewed publications on the latest research of hypoxia impacts. Research and management priorities identified at the workshop informed the activities and critical needs outlined in Action 5 of the 2008 Action Plan. These priorities were also used to inform the development of a

2009 Federal Funding Opportunity that resulted in the funding of three large multi-institution, multi-disciplinary research studies that directly address Action 5 science needs.

Since the 2007 workshop, living resource impacts have been the focus of two Hypoxia Research Coordination Workshops (2010 and 2012). These workshops have centered on coordinating ongoing research activities, sharing findings and outputs, and engaging the management community. To improve capabilities to examine hypoxia impacts, these workshops have leveraged existing research projects, particularly those focused on characterizing and modeling the hypoxic zone, to improve year-to-year research capabilities and provide realistic modeling scenarios. In 2012, the Coordination Workshop focused on providing an update on the state of the science and remaining research priorities in order to inform the scientific reassessment of the 2008 Action Plan. Findings from the 2012 workshop have been integrated with peer-reviewed literature to develop the following assessment of research findings and remaining science needs related to hypoxia impacts.

Significant Research Findings

Altered Spatial Distribution and Composition

It has been well documented that bottom-dwelling species, particularly Atlantic croaker and brown shrimp, are displaced from optimal habitat along the Louisiana shelf as a result of hypoxia (Craig and Crowder 2005, Craig et al. 2005), This displacement often results in a congregation of species around the edges of the hypoxic zone, creating what has been termed the 'halo-effect', with many species being pushed both offshore and inshore of the hypoxic zone. Bottom-dwelling species are typically displaced horizontally, while pelagic species are typically forced higher in the water column.

Craig (2012) quantified this displacement for a number of species and found that many were found relatively close to the 2mg/l hypoxic edge, often within 1 to 2 km. While most individuals for each species were found within this range, or further from the edge, a smaller number can be found within the hypoxic zone proper. Craig (2012) found avoidance thresholds for the 10 species analyzed were often below 2 mg/l. For example, Atlantic croaker typically avoids waters with 1.24 to 2.04 mg/l, shrimp 1.07 to 1.57 mg/l, and Atlantic bumper 0.66 to 1.31 mg/l of dissolved oxygen. Much of the range of avoidance reflects interannual variability that is possibly a response to varying severity of hypoxia (i.e., areal extent). While the low avoidance thresholds for most species may indicate a relative tolerance to hypoxic conditions or ability to vertically migrate, these threshold values are likely close the minimum dissolved oxygen levels required to avoid mortality for many species. Further, mortality avoidance thresholds of dissolved oxygen appear to be significantly lower than thresholds for sub-lethal physiological effects (P. Thomas pers. comm.).

In addition to horizontal displacement, studies have indicated that many species, particularly plankton, are vertically displaced. Zooplankton typically make daily vertical migrations in association with diel cycles, inhabiting deeper, darker waters during daylight hours to avoid predation and migrating to surface waters at night in order to feed. However, zooplankton found over hypoxic bottom waters limited their daytime depth to an average of 7m higher in the water column than zooplankton inhabiting normoxic waters (Roman et al. 2012). The forcing of hypoxia higher into the water column likely increases their susceptibility to predation and may improve, at least temporarily, food availability for planktivorous fish. This vertical displacement of zooplankton is not uniform, however, and is likely dependent on the severity and percent of water column that is hypoxic (Pierson et al. 2009). Acoustical scans also found aggregations of pelagic fish concentrated higher in the water column during hypoxia relative to normoxic waters (Hazen et al. 2009).

Sub-lethal Physiological Effects

Mounting evidence is indicating that Atlantic croaker aggregated along the edges of the hypoxic zone, where waters often contain sub-optimal oxygen levels, are exhibiting a suite of sub-lethal physiological impacts, even in species considered hypoxia-tolerant, such as Atlantic croaker. Comparative field and laboratory studies have isolated and established the expression of the hypoxia inducible-factor (HIF) 1α as a useful biomarker for hypoxia exposure in Atlantic croaker (Thomas et al. 2007, Murphy et al. 2009, Thomas and Rahman 2009a,b). Upregulation of the HIF mRNA and proteins serves as a mechanism for suppression aerobic metabolism under low oxygen conditions (Thomas and Rahman 2009a,b) and can lead to significant increases in reactive oxygen species that have been associated with cell damage and other oxidative stresses (Rahman and Thomas 2011) . Molecular analysis has shown that the hypoxic-induced oxidative stress can impact the regulation of CYP1A, an enzyme indicative of a toxicity response to chemical contaminants (Rahman and Thomas 2012). Although these efforts have focused on the relatively hypoxia tolerant Atlantic croaker, it is likely this biomarker or physiological response is not species specific nor is it likely limited to the Gulf of Mexico. For example, expression of the HIF 1α biomarker was also recently found in mantis shrimp and dragonet exposed to hypoxia in Tokyo Bay, Japan (Kodama et al. 2012a,b).

Additional research on the physiological impacts of hypoxia has focused on endocrine disruption and reproductive impairment. Exposure to sub-optimal dissolved oxygen conditions, varying from just below to just above 2mg/l, has been attributed to disruption of the key enzyme tryptophan hydroxylase (TPH) in the hypothalamus of Atlantic croaker (Thomas et al. 2007, Rahman and Thomas 2009, Rahman et al. 2011). This disruption of the endocrine system responsible for regulating the gonadal system can have significant impacts to the reproduction that can be widespread. Thomas and Rahman (2010) found that male Atlantic croaker collected from sites associated with the Gulf hypoxic zone had significant testicular impairment relative to male Atlantic croaker collected from normoxic reference sites. Males from the hypoxic zone had 26.2% fewer sperm than males from references sites leading to an approximately 50% decrease in testicular growth. Subsequent analysis of female croaker from the hypoxic zone found similar impairments. While ovaries of female Atlantic croaker from normoxic sites were normal, 19% of croaker ovaries from hypoxic sites contained male germ cells, a sign on masculinization. In addition, croaker ovaries from hypoxic sites were smaller, less developed, and produced fewer viable eggs. These findings were confirmed through laboratory experiments, which also showed that ovaries did not recover once normal dissolved oxygen conditions returned. Further, a spawning trial indicated that impaired gamete maturation was accompanied by a dramatic decline in numbers of fertilized eggs (Thomas and Rahman 2009c). Widespread analysis of croaker sex ratios indicates a strong bias towards males around the hypoxic zone relative to croaker from normoxic waters (Thomas and Rahman 2011). As expected, impacted masculinized female croaker exhibited significantly reduced endocrine function as well as aromatase, an enzyme responsible for the production of estrogen.

With high spatial overlap with other additional fish species (see Craig 2012), Craig and Bosman (2012) suggest that the sublethal impacts found in croaker likely extend to the broader demersal, and possibly pelagic, community.

Evidence for Fisheries and Socioeconomic Effects

Research into the socioeconomic impacts of hypoxia in the Gulf of Mexico has primarily focused on brown shrimp and results remain preliminary. However, research on the economic impacts of hypoxia on the brown shrimp fishery in the Neuse River, North Carolina likely provides a useful perspective to the Gulf. In the Neuse River, Huang et al. (2010) estimated a 12-15% increase in revenues to the shrimp fishery if hypoxia were eliminated. However, Huang et al. (2012) suggests the effect of eliminated hypoxia would be lower. Since the shrimp supply in the United States is dominated by imports, improvements in the Neuse River fishery would have no effect on overall shrimp prices. For shrimpers, any gains in shrimp harvest would likely be short-lived or minimal due to current fishery management policies and since shrimpers typically respond to a suite of factors in addition to shrimp supply (e.g., weather and prices). It should be noted that these analyses examined only the Neuse River fishery, although hypoxia likely impacts a broader suite of species and ecosystem functions. Therefore, the economic benefits of nutrient reductions would have to be integrated across impairments (K. Craig, pers. comm.).

A broader analysis of the socioeconomic impacts to the shrimp fishery in the Gulf of Mexico is currently under way, including the development of a suite of economic models. Preliminary results from this study have found that shrimpers in the northern Gulf respond to hypoxia in a similar pattern to shrimp and croaker, with shrimpers fishing in a halo pattern around the edge of hypoxic zone (K. Criag, pers. comm.). The large congregation of demersal species around hypoxic zone coupled with targeted fishing along the edge by shimpers has been suggested to cause an increase in bycatch of non-target species (K. Craig 2012). In addition, alterations in movements have also been observed in Gulf menhaden fishers and studies are underway (K. Craig, NOAA) to examine the role of hypoxia in movements of the menhaden fishing fleet (J. Rester Gulf States Marine Fisheries Commission, pers. comm.).

Next Steps and Remaining Needs

Relative to the 2008 Action Plan Reassessment, knowledge of the ecological impacts of hypoxia has increased greatly and many research efforts are beginning to mature. Many of these efforts are beginning to transition their findings from laboratory and field based assessments into integrative modeling platforms that will allow for examination of multiple stressors and hypoxia scenarios. For example, results on reproductive impairments in croaker coupled with data on distribution relative to the hypoxic zone are being integrated into an individual based model of Atlantic croaker in the northern Gulf of Mexico (S. Creekmore and K. Rose, Louisiana State University, pers. comm.). Once fully developed, this model will allow an examination of hypoxia effects on croaker populations under varying scenarios and provide a framework for modeling impacts to additional Gulf species. Similarly, ecosystem-based models such as EcoSim with EcoPath (EwE) and Atlantis are currently under development that allow for multi-species assessments of hypoxia impacts, trophic dynamics, and nutrient effects.

In addition, integration of these modeling efforts with physical/biogeochemical hypoxia models will also allow for a holistic assessment of ecosystem effects from nutrient abatement and reduced hypoxia. While it is widely accepted that reduced hypoxic area will improve overall ecosystem health, an emerging theory indicates there will be possible trade-offs with some species benefiting more than others. In Lake Erie, Brandt et al. (2011) suggested that walleye, an important recreational fishery, may be benefiting from hypoxia as a result of concentrated plankton biomass above hypoxic waters. Similar theories have been suggested for planktivorous fish in the Gulf, such as juvenile menhaden, anchovies, and Atlantic bumper, though the additive effect of fishing pressure remains a critical unknown. Elucidating these ecosystem-wide implications through integrated model applications represents a critical frontier in hypoxia impacts research.

To enable these modeling capabilities, a suite of targeted research needs remain a priority. In general, these needs center on expanding the suite of species analyzed for hypoxia impacts and on improving ecological modeling capabilities. Most of the needs identified in Kidwell et al. (2009) remain gaps in research and should be addressed. However, advancement of the field has resulted in the identification of specific priority needs required to advance modeling efforts. These needs include:

1. Refined assessments of Atlantic croaker sub-lethal and indirect hypoxia impacts and targeted research to examine possible sublethal impacts in additional species.

2. Multi-stressor assessments of cumulative ecosystem and species impacts.

3. Improved quantification of long-term population-level impacts of key living resources, such as brown shrimp and red snapper.

4. Integration into regional ecosystem planning and fisheries management efforts.

5. Improved species modeling capabilities, including incorporation of movement patterns in relation to the hypoxic zone and bioenergetic implications of altered foraging habits and sub-optimal oxygen levels.

6. Refinement of ecosystem modeling capabilities that incorporates spatially explicit effects of hypoxia and subsequent changes in predator-prey relationships.

7. Refined quantification of socioeconomic effects and expansion to additional species.

8. Coupling of ecological models with scenario-based hypoxia models.

9. Improved understanding of the relationship between nutrient loads, hypoxia spatial and temporal dynamics, and living marine resources through integrated modeling and assessments.

Appendix 1: Hypoxia Impact Publications Since 2008

Baustian, M.M. and N.N. Rabalais. 2009. Seasonal composition of benthic macrofauna exposed to hypoxia in the northern Gulf of Mexico. Estuaries and Coasts 32: 975-983.

Baustian, M.M., J.K. Craig, and N.N. Rabalais. 2009. Effects of summer 2003 hypoxia on macrobenthos and Atlantic croaker foraging selectivity in the northern Gulf of Mexico. Journal of Experimental Marine Biology and Ecology 381 (S1): S31-S37.

Baustian, M.M., N.N. Rabalais, W.L. Morrison, and R.E. Turner. 2011. Seasonal microphytobenthos on the hypoxic northern Gulf of Mexico continental shelf. Marine Ecological Progress Series 436: 51-66.

Brady, D.C., T.E. Targett, and D.M. Tuzzolino. 2009. Behavioral responses of juvenile weakfish (Cynoscion regalis) to diel-cycling hypoxia: swimming speed, angula correlation, expected displacement, and effects of hypoxia acclimation. Canadian Journal of Fisheries and Aquatic Science 66: 415-424.

Brandt, S.B., M. Constantini, S.E. Kolesar, S.A. Ludsin, D.M. Mason, C.M. rae, and H. Zhang. 2011. Does hypoxia improve habitat quality for Lake Erie walleye? A bioenergetics perspective. Canadian Journal of Fisheries and Aquatics Sciences 68: 857-879.

Craig, J.K. 2012. Aggregation on the edge: effects of hypoxia avoidance on the spatial distribution of brown shrimp and demersal fishes in the northern Gulf of Mexico. Marine Ecological Progress Series 445: 75-95.

Craig, J.K. and S.H. Bosman. 2012. Small spatial scale variation in fish assemblage structure in the vicinity of the northwestern Gulf of Mexico hypoxic zone. Estuaries and Coasts DOI 10.1007/s12237-012-9577-9.

Craig, J.K., P.C. Gillikin, M.A. Magelnicki, and L.N. May. 2010. Habitat use of cownose rays (*Rhinoptera bonasus*) in a highly productive, hypoxic continental shelf ecosystem. Fisheries Oceanography 19(4): 301-317.

Elliott, D.E., M.J. Pierson, and M.R. Roman. 2012. Relationship between environmental conditions and zooplankton community structure during summer hypoxia in the northern Gulf of Mexico. Journal of Plankton Research: doi: 10.1093/plankt/fbs029

Hazen, E.L., J.K. Craig, C.P. Good, L.B. Crowder. 2009. Vertical distribution of fish biomass in hypoxic waters on the Gulf of Mexico shelf. Marine Ecological Progress Series 375: 195-207.

Huang, L., L.A.B. Nichols, J.K. Craig, and M.D. Smith. 2012. Measuring welfare losses from hypoxia: the case of the North Carolina brown shrimp. Marine Resource Economics 27: 3-23.

Huang, L., M.D. Smith, and J.K. Craig. 2010. Quantifying the economic effects of hypoxia on a fishery for brown shrimp *Fafantepenaeus aztecus*. Marine and Coastal Fisheries: Dynamics, Management, and Ecosystem Science 2: 232-248.

Kidwell, D.M.,A.J. Lewitus, E.B. Jewett, S. Brandt, and D.M. Mason. 2009. Ecological impacts of hypoxia on living resources. Journal of Experimental Marine Biology and Ecology 381 (S1): S1-S3.

Kimmel, D.G., W. Boicourt, J. Pierson, M. Roman, X. Zhang. 2010. The vertical distribution and diel variability of mesozooplankton biomass, abundance, and size in response to hypoxia in the northern Gulf of Mexico, USA. Journal of Plankton Research 10: 1185-1202.

Kimmel, D.G., W.C. Boicourt, J.J. Pierson, M.R. Roman, X. Zhang. 2009. A comparison of the mesozooplankton response to hypoxia in Chesapeake Bay and the northern Gulf of Mexico using biomass size spectrum. Journal of Experimental Marine Biology and Ecology 381: S65-S73.

Kodama, K. M.S. Rahman, T. Horiguchi, and P. Thomas. 2012a. Assessment of hypoxia-inducible factor-1α mRNA expression in mantis shrimp as a biomarker of environmental hypoxia exposure. Biology Letters 8: 278-281.

Kodama, K. Md.S. Rahman, T. Horiguchi, and P. Thomas. 2012b. Effects of environmental hypoxia exposure on transcript levels of two hypoxia-inducible factor α genes (HIF-1α and HIF 2-α) in a marine teleost dragonet *Callionymus valenciennei* from Tokyo Bay. Marine Pollution Bulletin 64: 1339-1347.

Murphy, C.A., K.A. Rose, M.S. Rahman, and P. Thomas .2009. Testing and applying a fish vitellogenesis model to evaluate laboratory and field biomarkers of endocrine disruption in Atlantic croaker (*MIcropogonias undulates*) exposed to hypoxia. Environmental Toxicology and Chemistry 28(6): 1288-1303.

Pierson, J.J., M.R. Roman, D.G. Kimmel, W.C. Boicourt, X. Zhang. 2009. Quantifying changes in the vertical distribution on mesozpoplankton. Journal of Experimental Marine Biology and Ecology 381: S74-S79.

Rahman, Md.S. and P. Thomas. 2012. Effects of hypoxia exposure on hepatic cytochrome P450 (CYP1A) expression in Atlantic croaker: molecular mechanisms of CYP1A down-regulation. PLOS One 7(7): e40285.

Rahman, Md.S. and P. Thomas. 2011. Characterization of three IGFBP mRNAs in Atlantic croaker and their regulation during hypoxic stress: potential mechanisms of their upregulation by hypoxia. *American Journal of Physiology- Endocrinology and Metabolism* 301:E637-E648.

Rahman, Md.S. and P. Thomas. 2009. Molecular cloning, characterization and expression of two tryptophan hydroxylase (TPH-1 and TPH-2) genes in the hypothalamus of Atlantic croaker: down-regulation after chronic exposure to hypoxia. Neuroscience 158(2): 751-765.

Rahman, Md.S., I.A. Khan, P. Thomas. 2011. Tryptophan Hydroxylase: A Target for Neuroendocrine Disruption. Journal of Toxicology and Environmental Health, Part B 14: 473-494.

Roberts, J.J., S.B. Brandt, D. Fanslow, S.A. Ludsin, S.A. Pothoven, D. Scavia, and T.O. Höök. Effects of hypoxia on consumption, growth, and RNA:DNA ratios of young yellow perch. Transactions of the American Fisheries Society: 140(6): 1574-1586.

Roman, M.R., J.J. Pierson, D.G. Kimmel, W.C. Boicort, and X. Zhang. 2012. Impacts of hypoxia on zooplankton spatial distribution in the northern Gulf of Mexico. Estuaries and Coasts 35(5): 1261-1269.

Rose, K.A., A.T. Adamack, C.A. Murphy, S.E. Sable, S.E. Kolesar, J.K. Craig, D.L. Breitburg, P.Thomas, M.H. Brouwer, C.E. Cerco, and S. Diamond. 2009. Does hypoxia have population-level effects on coastal fish? Musing from the virtual world. Journal of Experimental Marine Biology and Ecology 381 (S1): S188-S203.

Switzter, T.S., E.J. Chesney, and D.M. Baltz. 2009. Habitat selection by flatfishes in the northern Gulf of Mexico: implications for susceptibility to hypoxia. . Journal of Experimental Marine Biology and Ecology 381 (S1): S138-S50.

Thomas, P. and M.S. Rahman. 2012. Extensive reproductive disruption, ovarian masculinization and aromatase suppression in Atlantic croaker in the northern Gulf of Mexico hypoxic zone. Proceedings of the Royal Society B 279: 29-38.

Thomas, P. and M.S. Rahman. 2009a. Region-wide impairment of Atlantic croaker testicular development and sperm production in the northern Gulf of Mexico hypoxic dead zone. Marine Environmental Research 68: S59-62.

Thomas, P. and M.S. Rahman. 2009b. Biomarkers of hypoxia exposure and reproductive function in Atlantic croaker: A review with some preliminary findings from the northern Gulf of Mexico hypoxic zone. Journal of Experimental Marine Biology and Ecology 381: S38-S50.

Thomas, P. and Md.S. Rahman. 2009c. Chronic hypoxia impairs gamete maturation in Atlantic croaker induced by progestins through nongenomic mechanisms resulting in reduced reproductive success. Environmental Science and Technology 43: 4175-4180.

Thomas, P., Md.S. Rahman, I.A. Khan, J.A. Kummer. 2007. Widespread endocrine disruption and reproductive impairment in an estuarine fish population exposed to seasonal hypoxia. Proceedings of the Royal Society B 274: 2693-2701.

U.S. EPA. 2008. Hypoxia in the northern Gulf of Mexico: An update by the EPA Science Advisory Board. Washington, D.C. EPA-SAB-08-003

Weissberger, E.J., L.L. Coiro, and E.W. Davey. 2009. Effects of hypoxia on animal burrow construction and consequent effects on sediment redox profiles. Journal of Experimental Marine Biology and Ecology 371: 60-67.

Zhang, H. S.A. Ludsin, D.M. Mason, A.T. Adamack, S.B. Brandt, X. Zhang, D.G. Kimmel, M.R. Roman, and W.C. Boicourt. 2009. Hypoxia-driven changes in the behavior and spatial distribution of pelagic fish and zooplankton in the northern Gulf of Mexico. Journal of Experimental Marine Biology and Ecology 381: S80-S91.