NGOMEX 2016: User-driven tools to predict and assess effects of reduced nutrients and hypoxia on living resources in the Gulf of Mexico

Kim de Mutsert and Kristy A. Lewis, George Mason University; Matthew Campbell, NMFS Mississippi Laboratories; Stephen Brandt, Oregon State University; Arnaud Laurent, Dalhousie University; Joe Buszowski and Jeroen Steenbeek, Ecopath International Initiative

ABSTRACT

Expansive hypoxia in the Northern Gulf of Mexico (NGOMEX) will continue to affect ecologically and economically important living resources, but the magnitude, predictability and even the direction of these changes remain elusive. Managers and stakeholders need readily available and quantitative tools to predict and evaluate the effects on living resources of planned nutrient reduction strategies aimed to minimize the hypoxic zone. We plan to develop user-friendly, management-scale relevant forecasting tools and quantitative indictors. We will also assess the minimum data needs (monitoring or modeling parameters, and time and space scales) to ensure these forecasts produce accurate and useful data required by managers and stakeholders. Previous work in the region by the P.I.s and colleagues resulted in three tested models and expansive datasets from seven cruises, which will be used to estimate effects of reduced nutrient inputs and hypoxic volume on living resources in the NGOMEX, and will form the basis of user-friendly tools to be transferred to resource managers. The coupling of two different fisheries modeling approaches (physiological-based and ecosystem-based) with the same 3D hydrodynamic/water quality model ensures that questions of varying levels of resolution can be addressed. Both coupled "physics to fish" approaches will assess the trade-offs of nutrient loading, namely the combined effects of increased productivity through bottom-up fueling, and altered habitat capacity or quality due to hypoxia. Interactive effects of other anthropogenic stressors such as fishing and climate change will be evaluated, as will the degree of model detail required. Outputs include species-specific fish growth rate potential as a measure of Essential Fish Habitat (EFH), and biomass and catch of ecologically and economically important living resources. Simplified indicators of ecosystem change will be developed. A high degree of interaction with both managers and stakeholders will be an integral part of the program. Frequent meetings with a team of advisors complemented with annual workshops will ensure the utility of the work for management purposes, and the transfer of tools to resource managers and stakeholders. The primary target audience is NOAA-NMFS coupled with the NOAA Center for Sponsored Coastal Ocean Research, Regional Sea Grant Extension and their fisheries stakeholders, the Northern Gulf Institute, the interagency Mississippi River/Gulf of Mexico Hypoxia Task Force, the NOAA RESTORE Act Science Program, and key state agencies. An initial workshop will define both manager needs and stakeholder expectations and answer the question of the requisite predictions and frequency of product delivery needed. The second workshop will include training and testing of the developed management tools, whereas the last workshop will focus on technology transfer and applications. This approach, and the use of adaptive science where feedback during workshops will be incorporated into work priorities, ensures transition of research to management throughout the scope of this project. The outcomes of this project will be an improved capability to assess the effects of alternative management strategies on ecosystem function, living resources, and fisheries revenue.

INTRODUCTION

A characteristic feature of the Louisiana continental shelf region is the presence of two major sources of freshwater, the Mississippi and Atchafalaya Rivers, that strongly influence the physics (Wiseman et al. 2004), biology (Hanson 1982, Wiseman et al. 1986) and chemistry (Ho and Barrett 1977) of the Northern Gulf of Mexico (NGOMEX). The nutrient-rich waters entering the NGOMEX in this manner fuel high primary production on the coastal shelf, which in turn stimulates the secondary production of this marine ecosystem (Nixon and Buckley 2002). The Louisiana coastal area has indeed been referred to as the *Fertile Fisheries Crescent* (Gunter 1963); fisheries landings in Louisiana are the highest of the Gulf States, and contribute significantly to the total commercial and recreational catch in the US (Chesney et al. 2000). Gulf commercial fisheries are valued at near $1B USD.

High levels of primary production on the Louisiana shelf and the resulting bacterial respiration during the decay of large amounts of organic matter, in combination with summer stratification of coastal waters, causes formation of an extensive region of hypoxic bottom water each summer (Rabalais and Turner 2001, Rabalais et al. 2001)). The areal extent of the affected region is positively related to Mississippi River discharge, and has had an average size of 13,650 km^2 over the past 30 years (1985-2014, http://www.gulfhypoxia.net/Overview/). Expansive hypoxia in the NGOMEX will affect ecologically and economically important living resources, but the magnitude, predictability and even the direction of these changes remain elusive (Rose 2000, Breitburg 2002, O'Connor and Whitall 2007). **Does hypoxia in the NGOMEX affect fish and fisheries to such an extent that it needs to be included in stock assessment and fisheries management?** The best tools to address this overarching question are spatially- and temporally-explicit and linked water quality-fisheries models. With ongoing monitoring and sample collection efforts by NOAA and others in the NGOMEX, the system is data-rich and highly suitable for representation with simulation models. The advantages of using a modeling approach include the ability to decouple the bottom-up fueling effect of high levels of primary production on higher trophic levels, and the negative effects of hypoxic events on these consumers related to the same high levels of primary productivity. Importantly, models provide the framework within which we can test alternative management strategies and evaluate the relative value of indicator metrics. Models provide a forum for experimentation that cannot easily be replicated under field conditions.

Since both bioenergetics models (species and physiological-based modeling) and ecosystem models (ecosystem-based modeling) have different strengths and outputs, we propose a project that uses both methods in a comparative and complementary approach. **Our goals are to predict effects of reduced size of the hypoxic zone and reduced nutrient loading on fish and shellfish growth rate potential, biomass, and catch using simulation models, and develop management tools that can be used to weigh costs and benefits of alternative management strategies, and improve resource assessments.**

SCIENTIFIC OBJECTIVES

The proposed research builds on existing simulation models developed to determine population to ecosystem-level effects of Gulf of Mexico hypoxia both spatially and temporally on ecologically and commercially important aquatic species. We are dedicated to the goal of connecting model predictions and management actions in an adaptive-management and (uniquely) adaptive-science framework with continuous feedback for improvement. Our overall objective is to provide tools for forecasting Fish Habitat Quality, Essential Fish Habitat, and biomass and catch estimates of key ecological and economical living resources across the NGOMEX in response to 1) changes in nutrient loading strategies, 2) inter-annual variations in flow, hypoxia and temperature and 3) long-term changes in climate. These user-driven ecological forecasting (vis a vi Brandt et al. 2006) tools will enable managers to assess alternative management strategies and their consequences to key fisheries and provide understandable metrics useful for stakeholder expectations and adaptations.

With the delivery of practical management tools as our main objective, our project goals are:

- Determine effects of nutrient loading and hypoxic volume reduction scenarios on growth rate potential, habitat quantity and quality, fish population biomass and catch, and fisheries revenue.
- Improve species bioenergetics, food web, and spatially/temporally explicit modeling capabilities of key living resources in the NGOMEX in response to changing hypoxic and climatic conditions.
- Determine minimal data requirements, and develop quantitative indicators (including uncertainty) for when changes in above-mentioned parameters are expected.
- Develop management tools in collaboration with fisheries managers that can be readily applied to test alternative management strategies to reduce hypoxic volume, and investigate subsequent effects on fish growth, population dynamics (e.g. abundance and biomass), and fisheries catches.
- Evaluate whether incorporation of hypoxia improves resource assessments, and develop/refine the tools for implementation.

PROJECT BACKGROUND AND RATIONALE

Effects of Hypoxia on Higher Trophic Levels and Fisheries

It has been suggested that the formation of the hypoxic zone could lead to altered food web dynamics on the Louisiana shelf (Chesney et al. 2000, Rabalais & Turner 2001). Effects may be both direct via increased mortality through prolonged exposure to low dissolved oxygen (DO) concentrations (Breitburg et al. 1999, Turner 2001, Breitburg et al. 2003) or indirect via alteration of benthic (Turner 2001) and water column (Breitburg et al. 1999, Chesney et al. 2000, Turner 2001) habitat availability and food web structure including, perhaps, increased abundances of gelatinous zooplankton predators (Graham 2001, Grove and Breitburg 2005).

Several studies have described the effects of hypoxia on feeding, growth, behavior and mortality of fishes from a variety of taxonomic groups in NGOMEX and elsewhere. In particular, sub-lethal effects of hypoxia have been shown to result in decreased feeding (Chabot and Dutil 1999, Tallqvist et al. 1999, Pichavant et al. 2001) and growth rate (Bejda et al. 1992, Secor and Gunderson 1998, Chabot and Dutil 1999, Taylor and Miller 2001), changes in activity level (Crocker and Chech 1997, Schurmann and Steffensen 1992), and spatial distribution (Pihl et al. 1991, Breitburg et al. 1999, 2003, Keister et al. 2000, Wannamaker and Rice 2000). Studies have also demonstrated direct effects of severe or chronic hypoxia on mortality (Schurmann and Steffensen 1992, Tallqvist et al. 1999, Miller et al. 2002); specific DO levels that can elicit sub-lethal effects have been shown to be species-specific (see reviews by Davis 1975, USEPA 2001, Miller et al. 2002). Fish have also been shown to shift distributions laterally (e.g. Switzer et al. 2015) or vertically, which can move fish into different thermal habitats, change predator-prey encounter rates and have both negative or positive consequences (e.g. Craig and Crowder 2005, Zhang et al. 2009, 2014, Brandt et al. 2009, 2011). Thus model evaluations need a high level of spatial (and temporal) resolution.

The hypoxic zone could also have economic consequences, when hypoxia reduces production of commercially and recreationally valuable fish and shellfish (Diaz and Rosenberg 1995, Breitburg 2002, O'Connor and Whitall 2007). Aggregation near hypoxic edges has been shown for gulf shrimp and finfish, which may enhance their susceptibility to commercial shrimp trawls and thereby magnify fishing mortality (Craig 2012). Mechanisms such as those that result in aggregation can result in hyperstability issues where population trajectories are masked by fisheries dependent data used to determine stock size (Hilborn and Walters 1992). Positive correlations could also occur as a result of the bottom-up effect that nutrient enrichment has on higher trophic levels (Nixon and Buckley 2002, Breitburg et al. 2009).

Defining Living Resource Habitat Quantity and Quality

One of the fundamental challenges in ecology is to predict species distributions in an environment and to evaluate the consequences of that distribution to survival, reproductive success and population dynamics. Understanding habitat quality is at the very core of our ability to predict a species' persistence in an ecosystem (e.g. Austin 2002, 2007, Braunisch et al. 2008, Christensen et al. 2008, Cogan et al. 2009, Holt 2009, Lehodey et al. 2010, McInerny and Etienne 2013, Warren 2012). How do we define the habitat quality an ecosystem affords a particular species? Is there a way to look at a habitat and quantitatively evaluate and, map the habitat quality and quantity for a given species and evaluate the impacts of changes in that habitat?

We argue that habitat quality must be defined from the perspective of an individual species or life stage of a species since the physiological and behavioral requirements differ across species. Habitat quality must also be a function of both abiotic and biotic factors that prevail in a particular ecosystem. But, how do we weigh biological and abiotic characteristics of the environment in a meaningful way **from the fish's perspective**?

We will quantify fish habitat quantity and quality as a function of environmental conditions such as temperature, salinity, DO, and food concentrations in the NGOMEX using a spatially-explicit bioenergetics approach. Bioenergetics-based, spatially-explicit growth rate potential (GRP) modeling (e.g. Brandt et al. 1992, Mason et al. 1995) offers the means to evaluate how non-linear interactions between oxygen availability and other important habitat features (e.g., temperature, prey densities) influence growth (production potential) of an organism (Luo et al. 1996, Brandt and Mason 2003).

Fish growth, itself, has often been considered a valid or even proxy measure of the habitat quality for fish (e.g. Able et al. 1999, Adamack 2003, Walters and Martell 2004, Annis et al. 2011, Beauchamp et al. 2007, Booker et al. 2004, Craig and Crowder 2005, Daewel et al. 2008, Searcy et al. 2007 and many more). It is an integrative response of fish performance and higher growth rates can be directly linked to higher survival rates and reproductive capacity. In many ecosystems and species, high growth rates are correlated with reproductive success and reduced natural mortality because larger fish have fewer predators. Fish growth rate is a common and accepted component of habitat quality indices; it is often used in fisheries management to identify Essential Fish Habitat – EFH (e.g. Delong and Collie 2004, Gilliers et al. 2006, Minns et al. 2011) and the Habitat Suitability Index – HSI (e.g. Rosenfeld 2003, Hirzel et al. 2006, Hirzel and Lay 2008). Growth rate is not only a robust and integrative measure but it is also a measure of nonlinear response to the combined physical and biological habitat.

Spatially-explicit modeling of fish growth rate potential and predation rates is a quantitative tool for directly linking species- and size-specific production to the physiological and behavioral requirements of fish and to the prevailing or predicted biological and physical conditions of the environment experienced (Brandt et al. 1992, Brandt and Kirsch 1993, Brandt and Mason 2003, Mason et al. 1995). This approach has been widely applied to examine how physical complexities and gradients affect fish growth and production (e.g. Luo et al. 2001, Brandt et al. 2002, Brandt and Mason 2003). Output from these types of models can be used to explore how specific habitat stressors (e.g., hypoxia, oil) would directly or indirectly influence habitat suitability for an organism in a modeled region. Modeled areas of high GRP would be reflective of high habitat quality, and vice versa for modeled areas of low GRP.

Ecosystem-based approach to fisheries

The concept of ecosystem models in fisheries science and ecology is to include effects of environmental parameters, trophic interactions of multiple species and fishing on the biomass of all species included in such models. Ecopath with Ecosim (EwE) is on the forefront of ecosystem modeling in fisheries science and was developed as an open source ecosystem modeling software (Polovina 1984). The intent of (initially just) Ecopath was to model trophic interactions and to estimate mean annual biomass on a coral reef ecosystem and has since been greatly improved and used to model ecosystems worldwide (Christensen & Pauly 1992, Walters et. al. 1997, Walters et al. 1999, Walters et al. 2000). Ecopath is a virtual representation of the foodweb of an ecosystem, including flows and pools of biomass within this foodweb. Ecosim then allows for temporal simulations of changes in biomass of groups in the model (which could be species or species guilds) in response to changes in environmental variables (such as nutrient loads and salinity) and fishing over time. Because of the trophic interactions represented with the initial foodweb, both direct and indirect effects of these drivers and forcing functions are made evident. Lastly, Ecospace allows for spatial and temporal simulations of biomass change of each of the groups in response to spatially and temporally explicit drivers, and habitat characteristics. This feature not only provides information on the spatial distribution of each group in the model, it also improves estimates of total biomass and catch of each group because movement of consumers and fishing fleets, and spatially-explicit habitat characteristics of the system are taken into consideration. Inclusion of ports and fishing fleets allows for the simulation of the added effect of catches on the abundance of living marine resources, while simultaneously providing an estimate of landings and revenue.

New developments in Ecospace allow for the inclusion of an unlimited number of environmental layers that affect groups in the model through response curves, allowing for e.g., avoidance of hypoxia by marine nekton and reduced feeding of organisms in response to low oxygen levels. Ecospace determines the ‘habitat capacity’ of each grid cell for each group per time step, equivalent to habitat suitability, which in turn affects movement and feeding rates. This new feature is called the habitat capacity model, and has already been used to develop models in support of management decisions in coastal Louisiana (De Mutsert et al. 2015a, 2016) and elsewhere (Christensen et al. 2014, Navarro et al. 2015). Figure 1 shows an example of using the habitat capacity model to investigate effects of Mississippi River diversion openings on fish species in Louisiana coastal estuaries. When four diversions are opened, Gulf menhaden (*Brevoortia patronus*) respond both to direct effects of salinity reductions, and indirect effects of total suspended solids, which limits phytoplankton growth in the near-field of the diversions, and subsequently limits Gulf menhaden biomass through a bottom-up foodweb effect.

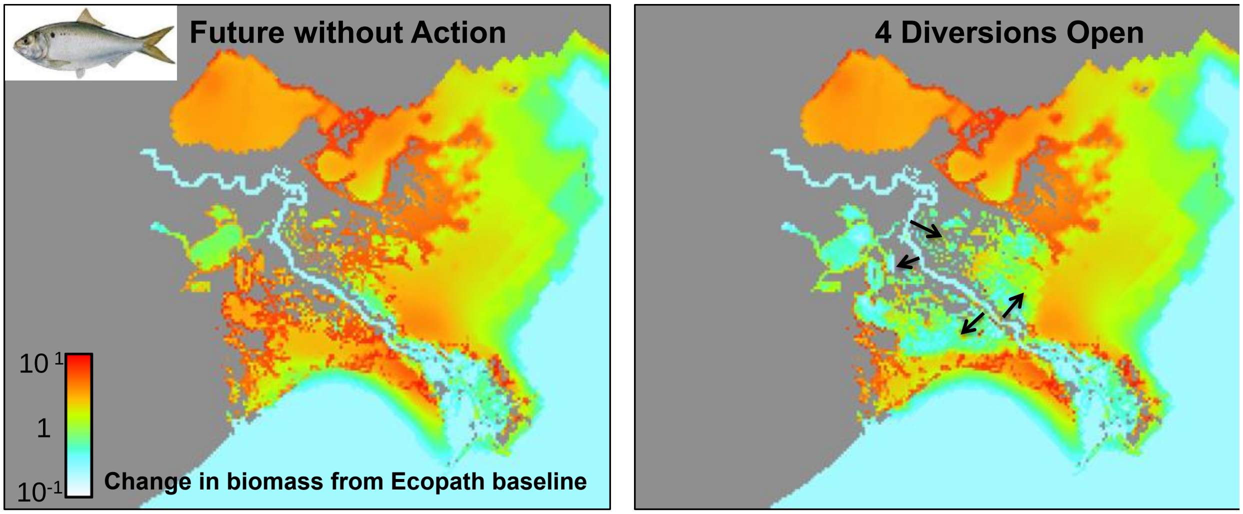

Figure 1. *Spatial distribution of juvenile Gulf menhaden biomass in the Mississippi River Delta in a hypothetical diversion operation plan with four diversions open from Feb-July (right panel), compared to no diversions (left panel).*

The NOAA-NMFS Southeast Fisheries Science Center has made progress in including environmental indices into stock assessments and has a high interest investigating whether incorporating hypoxia and other Mississippi river outflow effects in the Northern Gulf of Mexico improve their ability to provide tactical management advice. Previous successes of an ecosystem-based approach to fisheries management in the Gulf of Mexico include the incorporation of red tide mortality for gag grouper (SEDAR 2013) and red grouper (SEDAR 2014), and recruitment anomalies due to oceanographic factors for red snapper (SEDAR 2013).

Previous Research in the NGOMEX

The P.I.s and colleagues have spent a number of years investigating coastal hypoxia and effects of hypoxia on consumer groups in the NGOMEX and other aquatic ecosystems (See Accomplishments from Prior Federal Support). With NOAA and NSF funding, our research team (and colleagues, principally M. Roman) conducted seven summer mapping and process cruises across the NGOMEX (> 15 inshore-offshore [100km] transects between the Texas border and the Bird's Foot Delta) to gather high-resolution data to define the spatially-explicit relationships between environmental conditions and pelagic zooplankton and fish distributions (Figure 2). We have one of the most comprehensive, synoptic data sets on temperature, salinity, oxygen, phytoplankton, zooplankton and fish in the NGOMEX under a range of environmental conditions including differing hypoxic volume/area, freshwater input from the Mississippi River, and climatological forcing. All of these data are available for this project (Roman, pers. comm.) and are currently being incorporated into a comprehensive data management system by other funding (see Data Management Section).

Our data products, many of which have been published in peer-reviewed papers and are publicly available at BCO-DMO.org, include hydrological conditions; species composition and biomass of phytoplankton, zooplankton and fish; biomass size distribution of zooplankton and fish; comprehensive measures of pelagic fish densities, fish diet data (over 3,000 entries); and fish growth potential models to quantitatively assess fish habitat requirements. These data are comprehensive from physics to fish, are spatially-explicit throughout the water column and span the coastal area of NGOMEX across 7 years. Thus we have an extremely valuable dataset to integrate with other ongoing and historical oceanographic, plankton, and fish collections in the NGOMEX region to produce integrated and synthetic metrics that can be used in a variety of models to improve our understanding of the NGOMEX pelagic foodweb and assess potential responses to stressors.

Previous research has also resulted in several models that we aim to use in our proposed program. A coupled physical-biological model that has shown to reliably reproduce patterns of hypoxic area and volume (Fennel et al. 2011), has already been used to determine effects of Mississippi River nutrient load reductions on hypoxic volume, phytoplankton and lower tropic level consumers (Laurent and Fennel 2014). Growth rate potential models for several relevant species such as bay anchovy (e.g. Luo et al. 1996, Zhang et al. 2009) and Gulf menhaden (Luo et al. 2001, Brandt and Mason 2003) have been developed and can be readily applied to this project, while models for a few additional key species such as brown shrimp and red snapper will be added. An Ecospace model of the NGOMEX representing the foodweb with 57 consumer groups has been developed and already used to determine effects of hypoxia on biomass and catch of living resources. **With this rich toolbox we are ready to take the next step and work directly with managers to develop management tools.**

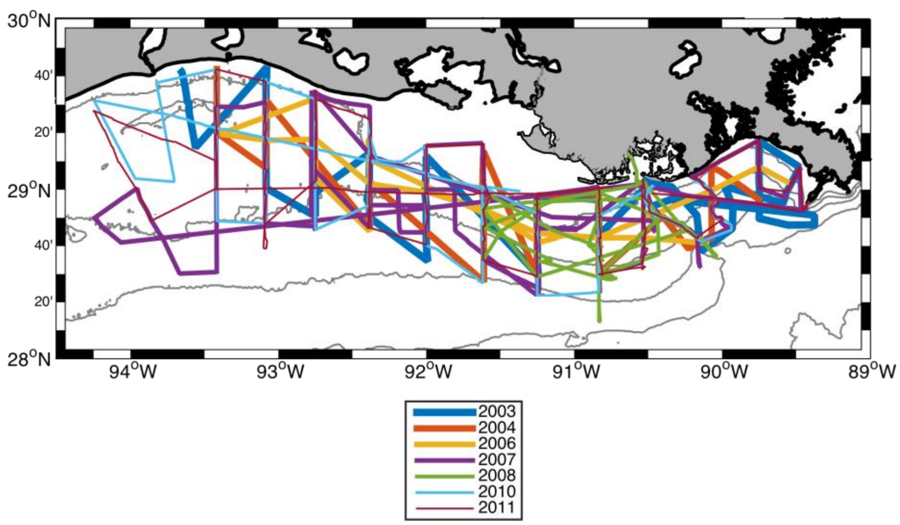

Figure 2. *Map of cruise tracks from each of seven cruises conducted in the northern Gulf of Mexico from 2003 - 2011 (from Roman, Peterson and Brandt).*

RESEARCH APPROACH

Our proposed program will couple spatially-explicit water quality, bioenergetics, and ecosystem models to evaluate alternative management strategies, inter-annual differences in water flows, nutrient loading and water temperatures, and longer-term climate changes on living resources. The work will focus on the development of user friendly, management-scale relevant forecasting tools. We will also assess the minimum (monitoring or modeling parameters, and time and space scales) data needs to make these forecasts to the degree of accuracy required by decision-makers and stakeholders. Previous work in the region by the P.I.s and colleagues resulted in three published and well-tested models and expansive datasets from seven cruises, which will be used to estimate effects of reduced nutrient inputs and hypoxic volume on living resources in the NGOMEX, and will form the basis of user-friendly modeling tools to be transferred to resource managers. In this iteration, we will use hypoxic volume rather than area as a driver to ensure hypoxia is included as a 3D feature, while the temporal and spatial dynamic nature of hypoxia is explicitly represented by the proposed modeling approaches. The use of two different fisheries modeling approaches (linked to the same physical-biological model) ensures that questions of varying levels of resolution can be addressed and compared.

Both coupled "physics to fish" approaches will incorporate the trade-offs of nutrient loading, namely the combined effects of increased productivity through bottom-up fueling, and reduced habitat capacity or quality due to hypoxia. Interactive effects of other anthropogenic stressors such as fishing and climate change will be evaluated, as will the degree of model detail required. Simplified indications of ecosystem change will be developed. **A high degree of interaction with both managers and stakeholders will be an integral part of the program.** A management advisory team and annual workshops will ensure the utility of the work for management purposes, and the transfer of tools to resource managers and stakeholders.

Simulation scenarios

The federal action plan goal is to reduce the geographic size of the hypoxic zone to 5000 km^2 over a 5-year running average (USEPA 2008), down from the most recent 5-year average of 15,000 km^2 (http://www.gulfhypoxia.net/Research/Shelfwide%20Cruises/). Since the hypoxic zone has been shown to be resistant to moderate nitrogen reductions, it is clear that larger nutrient reductions including phosphorus are needed (Laurent and Fennel 2014). With the 3D physical-biological model we aim to use during this project, nutrient reduction scenarios have been performed that include various levels of nitrogen and/or phosphorus load reductions (Laurent and Fennel 2014). More than 50 simulations have already been completed for the years 2001-2007 with varying combinations of nitrogen and phosphorus reductions in addition to the baseline run (Figure 3) of no nutrient reduction. During the first Annual Workshop the advice of managers and other participants will be solicited as to which scenarios would be most useful to run with our coupled approach to test effects on fish growth potential, biomass, and catch. New simulations can be run as well if e.g., output of a different time period is deemed useful. With hindcasting output of this model going back as far as 1990, we also aim to create scenarios based on previous years. Options include e.g., creating scenarios from warm years as a proxy for the anticipated rise in sea surface temperature, and scenarios of years that had a hypoxic zone of 5,000 km^2. The following are some of the simulations planned for this project:

- A repeated 10+ year time series of the years with a hypoxic zone smaller than 5,000 km^2 (e.g., the year 2000).
- A combination of different years that represent a hypoxic zone of 5,000 km^2 on average over a 5 year period, for a duration of 5, 10, 20 and 50 years.
- Nutrient reduction scenarios, including a 60% reduction of both N and P, simulated over 5, 10, 20 and 50 years.
- Scenarios based on years with high (or low) Mississippi River outflow, and years with warmer and cooler Gulf thermal conditions.

It is important to note that the physical-biological model estimates hypoxic area as well as hypoxic volume. This way we can create scenarios that relate to the federal action plan goal, which is based on hypoxic area, while the hypoxic volume (and seasonal timing and duration) output of that scenario drives fish growth rate potential, biomass, and catch. Details of the models used in these simulation scenarios are described below.

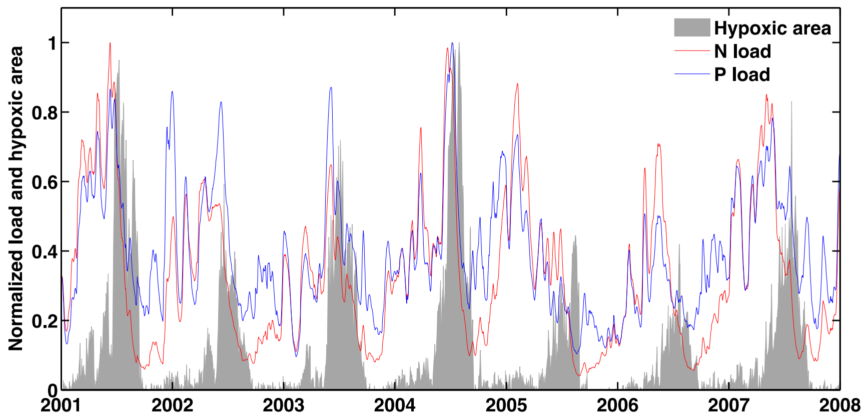

Figure 3. *Normalized baseline output of the physical-biological model of hypoxic area and nutrient load for the years 2001-2008.*

3-D Physical-Biological Model

The water quality model is a coupled circulation-biogeochemical model based on a high-resolution, regional circulation model configured with the Regional Ocean Modeling System (ROMS, Haidvogel et al. 2008). The model grid covers the Louisiana Shelf, with 20 layers and a horizontal resolution that varies from ~ 20 km offshore to up to 1 km near the Mississippi River delta (Figure 4). The circulation model, set up and validated by Hetland and DiMarco (2008, 2012), is coupled with the pelagic N-cycle model of Fennel et al. (2006, 2008, 2011) that includes two forms of dissolved inorganic nitrogen (DIN), nitrate and ammonium, as well as phytoplankton, chlorophyll, zooplankton and two detritus pools (small and large). The N-cycle model was extended to include dissolved inorganic phosphorus (DIP) (Laurent et al. 2012) and O_2 (Fennel et al. 2013). The water quality model provides daily and spatially resolved outputs of the 9 biological state variables, as well as temperature, salinity and velocity. Primary production, limited by light, temperature, and the most limiting nutrient, either DIN (N limitation) or DIP (P limitation) is also available from the model output. In the model, freshwater input from the Mississippi and Atchafalaya Rivers are prescribed using freshwater transports estimated by the US Army Corps of Engineers at Tarbert Landing and Simmesport, respectively. Nutrient and POM loading are based on monthly nutrient flux estimates from the U.S. Geological Survey (Aulenbach et al. 2007). The water quality model was recently used to investigate nutrient reduction strategies to mitigate hypoxia (Laurent and Fennel 2014). All output generated by this coupled physical-biological model is available to test effects of nutrient reduction scenarios on fish growth potential, biomass, and catch using the two models described below, including the nutrient reduction strategy scenarios.

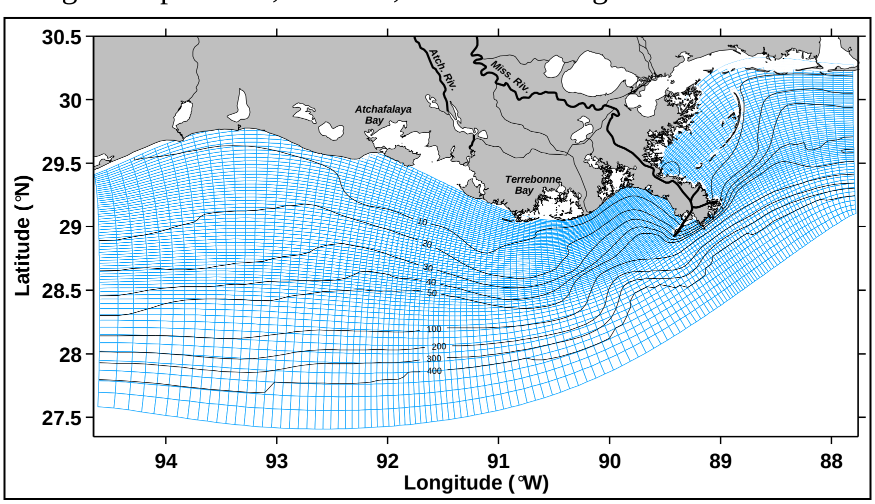

Figure 4. *The model domain of the physical-biological model used for nutrient reduction scenarios. In addition to the visible horizontal grid, the 3D model includes 20 vertical layers.*

Growth Rate Potential Models

Spatially-explicit GRP is a grid-based approach where the aquatic habitat is divided up into spatial cells (depth by location), and where each cell (defined on a volume) is characterized by a specific set of measured or modeled attributes such as water temperature, DO, and prey density (Figure 5). Foraging and physiological growth models are run in each cell to calculate GRP of an organism in that cell. Inputs into the foraging model can include prey density, size and condition, water temperature, DO, or oil, with consumption rate as the output. The growth model uses consumption rate from the foraging model, temperature, and DO as inputs and estimates growth rate potential. Thus, the GRP is defined as the growth rate of a particular size and type of organism in that cell for a specific unit of time, and is a measure of the habitat quality perceived by the fish.

Overall distributions of GRPs reflect the heterogeneity of habitat quality and quantity, which can be summarized in several ways (e.g. volume of habitat (quantity) capable of supporting growth, cumulative frequency distribution of GRP). Moreover, integration of GRP across space may provide an index of system production relative to the target species. The advantage of using a spatially-explicit, bioenergetics-based GRP approach is that it captures the spatial complexity in the environment as a "snap shot" and provides a physiological measure on the quality of the pelagic environment. Sequences of these snap shots through time provide the temporal component. This approach provides critical insights into a fish's physiological tolerances and behavioral response to changes in the biological and physical environment and may directly link population dynamics to habitat quality. Example output of the bluefish GRP model is shown in Figure 6.

The GRP models will focus on some of the key ecologically and economically important species of the region. In particular we will look at Gulf menhaden, bay anchovy, and bluefish for which GRP models have been developed already, and red snapper, brown shrimp, and Atlantic croaker for which new models will be developed using available data (e.g. Switzer et al. 2015). We have an abundance of data and bioenergetics information on these fish species that span phytoplanktivores, zooplanktivores, benthic feeders, pelagic feeders and piscivores. During the first Annual Workshop of this project, advice of managers and other participants will be solicited to determine which species should be added to this list, and new models will be developed for those species.

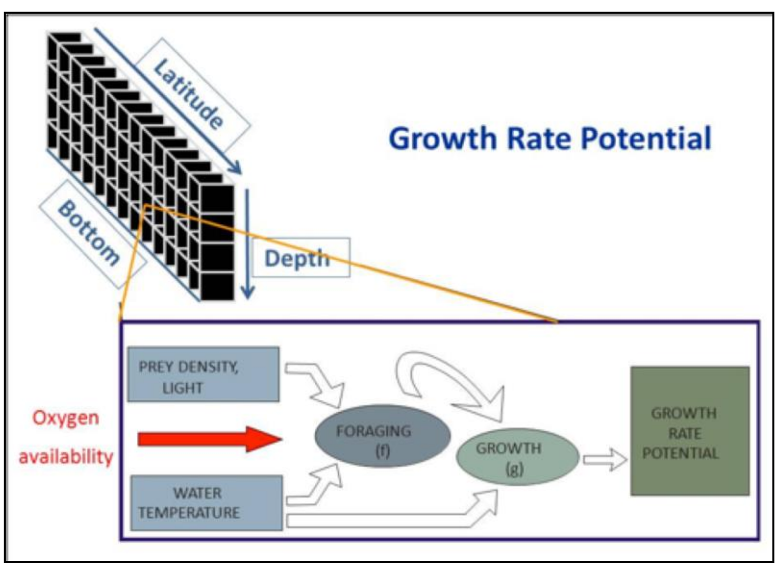

Figure 5*. Growth Rate Potential (GRP) model schematic showing grid cells, input data, foraging and growth functions and output.*

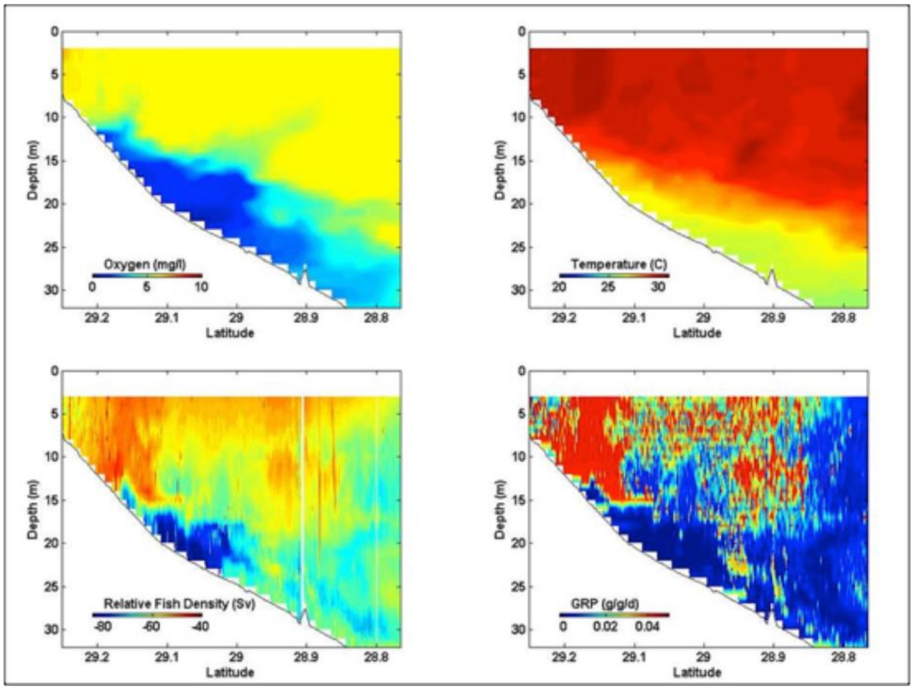

Figure 6. *Example of output from fish growth rate potential showing high-resolution data from the Gulf of Mexico on water temperature, dissolved oxygen, prey density and modeled growth rates of bluefish (Pomatomus saltatrix).*

We will run the GRP model for each species on a daily basis for each spatial cell in the 3D hydrodynamic/water quality model. Using various scenarios projected by the hydrodynamic model we can calculate growth rate potential at a family of assumed prey density estimates. We can evaluate the overall impact of changes in prey density on estimated growth potential. In addition, we will reconstruct the inter-annual fish habitat quality for each of the key species. The NGOMEX has an abundance of historical (largely NOAA) data on temperature and oxygen conditions. We can compile these baseline data on temperature, salinity and oxygen and evaluate changes in annual indices of habitat quality for each of the key species. Annual indices will be compared to historical catches as well as monitoring information of fish sizes (e.g. from SEAMAP). This information will provide a good baseline for comparison with modeled output.

We have already done this for Chinook Salmon in the Pacific Ocean (Sellinger and Brandt 2015). We constructed a georeferenced database of 37,838 XBT and CDT data from 1929 – 2013 from the National Ocean Data Center and used these to calculate Adult Salmon Growth Rate Potential on an annual basis (Figure 7). Note the regime shift in growth rates**. These data match the annual catches of adult salmon well**. Figure 8 shows an example of the annual (January – December) growth profiles at a deep station off Oregon in a warm year and a colder year. We can do the same analyses for key Gulf species using the same database/modeling system by including NGOMEX data. These types of analyses will provide a long-term record, a basis for comparison with the hydrodynamic model and a framework for using planned monitoring.

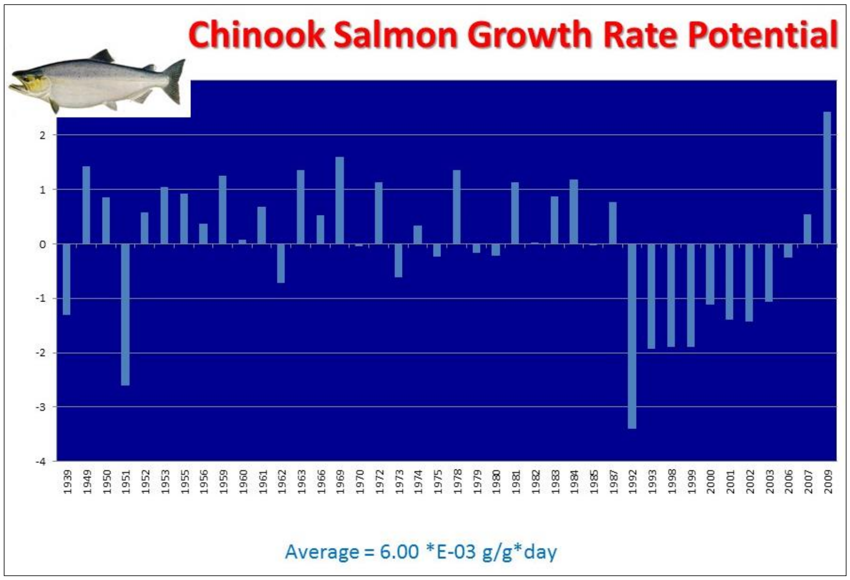

Figure 7. *Adult Chinook salmon growth rate potential in an annual basis in the Pacific Ocean.*

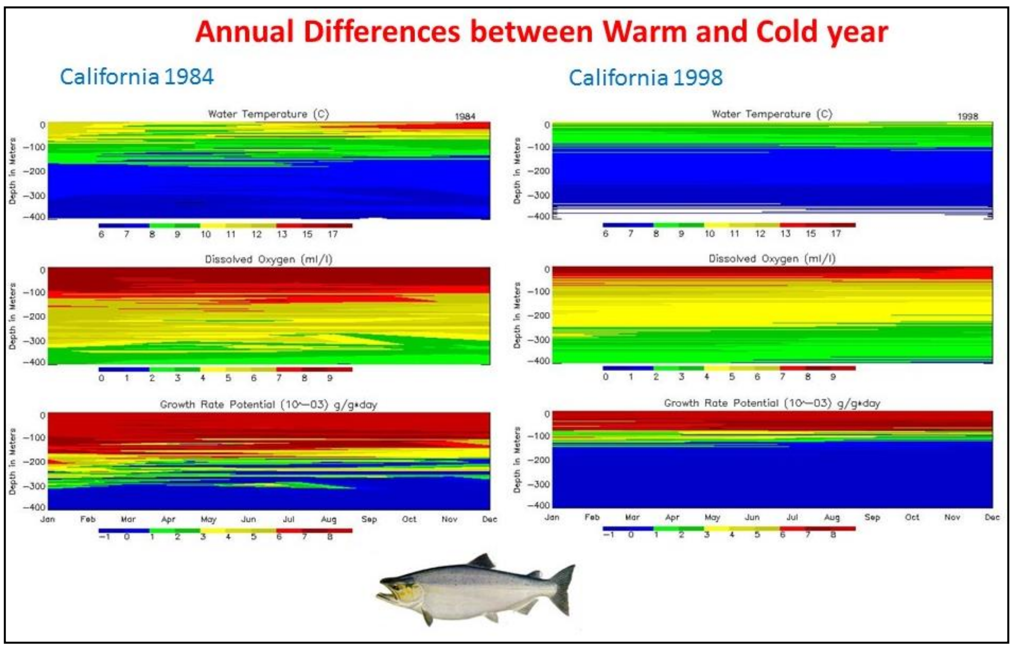

Figure 8. *Water temperature, dissolved oxygen, and growth rate potential profiles with a monthly resolution of Chinook salmon at a deep station off Oregon in a warm year (1984) and a cold year (1998).*

NGOMEX Ecospace model

The NGOMEX Ecospace model is developed using Ecopath with Ecosim (EwE, ecopath.org), and modified from a previous model developed for the Gulf of Mexico by Walters et al. (2008). Modifications included, but were not limited to, adjusting the species list and recalculating species density (biomass in t km^{-2}) to represent the relevant portion of the NGOMEX based on SEAMAP data (www.seamap.org) collected within the model area (Figure 9). Groups in the model vary in resolution from species aggregates to life stages of species, depending on the presence of pertinent ontogenetic shifts in diet. The split in multiple life stages (referred to as the multistanza approach) also enables the representation of selective targeting of size classes of fisheries species. The total of 60 groups in the model include species of commercial and/or recreational importance such as Gulf menhaden, brown shrimp, white shrimp, and red snapper; species that are dominant in the model area such as Atlantic croaker; and additional forage species and predators important to the foodweb in this area. The model is calibrated and published (de Mutsert et al. 2015b), while further modifications to this model will be included in this project. One important modification is the use of the habitat capacity model (Christensen et al. 2014). The habitat capacity model calculates the suitability of each model cell for each species based on its environmental conditions (using various response curves), and then modifies dispersal rates and prey availability. The habitat capacity model has been successfully applied in two Ecospace models used to test effects on fish and fisheries of restoration projects in Louisiana estuaries (De Mutsert et al. 2015a, 2016). The habitat capacity model allows for the inclusion of an unlimited number of environmental driver layers that vary spatially and temporally by reading in a parameter value (e.g. hypoxic volume) per grid cell, per month over a simulation period. In addition, the resolution of the model grid will be increased from 5 km^2 to 1 km^2. Outputs of the model are biomass and catch in t km^{-2} for each group in the model. Results from these analyses can be directly compared to those from the GRP Habitat Quality model.

In this spatial (and temporal) model, both reduced feeding and movement in response to low oxygen conditions can be simulated. This functionality has consequences for both the biomass and the catch of groups in the model. Fishing is included explicitly in the model with fleets that have the ability to move. Fleets move over the model grid with a gravitational model based on revenue. This means that fleets do not just gravitate to the cells with the highest biomass of the target species when the price per pound and the cost of fishing (fuel charges) are included in the calculations. In this way, the movement of fisheries species away from shore and the aggregation of species in response to hypoxia can have an effect on fisheries revenue, even when it doesn't have an effect on biomass. With the availability of the extensive data collected during seven cruises from 2003-2011 (see Figure 1 and Data Management Plan), validation of the model is made possible, and will be part of the proposed project.

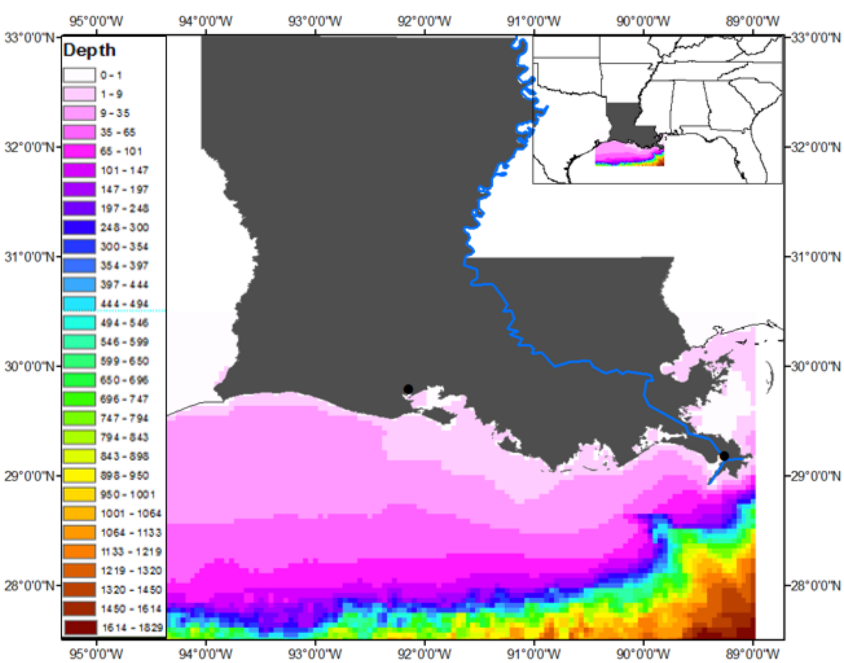

Figure 9. *Model domain of the NGOMEX Ecospace model. The model area will be extended to the east to match the areal extent of the physical-biological model.*

Indicators and Management Tools

Quantitative ecological indicators (or actual metrics) are a valuable management tool to monitor and assess ecological 'health' as well as evaluate the impacts of management decisions of changes in environmental drivers. In most cases these indicators have substantial weight based on scientific evidence and are 'good enough' for management decisions and stakeholder understanding. By 'good enough' we mean that the indicator is exactly that, an indicator metric.

The status of NGOMEX hypoxic conditions is measured by the geographic extent (in km^2) of bottom hypoxia as determined by an annual research cruise. Whole scale management is based on reducing this acreage to 5000 km^2 over a 5-year running average (USEPA 2008) and forecasting models are being used to predict the annual extent (Scavia et al. 2013). This annual measurement approach has been used to make management decisions, set long-term goals, and provide a stakeholder reference to assess current conditions. The determination of the extent of bottom hypoxia is valuable because it is easy to measure, has a common sense feel to it and has some direct biological consequences particularly for those organisms that are near bottom during the time the measurements are taken. Yet, bottom hypoxic acreage is not robust enough to make quantitative biological predictions of consequences because 1) hypoxic volume is a better indicator of hypoxic conditions since the vertical extent of hypoxia can differ across locations or years and sometimes hypoxia extends into midwater without a bottom signature, 2) hypoxic conditions are transient and can move with ocean circulation or changes in response to storms and 3) the seasonal duration of hypoxia is critical for assessing biological impact. We can conclude that hypoxic acreage has proven a valuable management tool but that far more information is required to make accurate, quantitative biological predictions.

Assessing, understanding and monitoring fish habitat quality and its dynamics are, perhaps, the keystone challenge of fish management at both the state and federal level. Two of the management applications of habitat are formal; **Habitat Suitability Indices – HSI** (Baker and Coon 1995, 1997: Brown et al. 2000, Budy and Schaller 2007, Crowder and Diplas 2006, Dieterich and Fulford 2012, Hirzel et al. 2006, Hirzel and Lay 2008, Kuhn et al. 2008, Railsback et al. 2003, Rosenfeld 2003, Smith et al. 2010) and **Essential Fish Habitat – EFH** (DeLong and Collie 2004, Gilliers et al. 2006, Green et al. 2006, Minns et al. 2011, Valavanis et al. 2008) and a critical part of regional fisheries management decisions. Both HSI and EFH are part of the legal management structure of aquatic ecosystems.

EFH is defined as habitat that is needed for growth, reproduction and survival. We argue that Fish Growth Potential is a measure of EFH. Indeed, using historical data, our extensive field data, or model output, we can quantitatively calculate fish habitat quality in 3D at a high spatial resolution and across time. This information is crucial for assessing how changes in hypoxic conditions will affect fish populations. Is there an indicator that we can develop for this measurement? We contend that we can evaluate this parameter across time and space to search for indicator stations or conditions (e.g. mean summer values based on CTDs from the annual hypoxic cruises) that can provide an annual, predictable and management relevant indictor of 'habitat health' for key species.

NOAA has also recently introduced a Habitat Blueprint Plan that stresses the importance of fish habitat quality in ecosystem-based management and, in part, introduces strategic approaches to habitat science that will inform effective decision-making. We contend that the Growth Rate Potential approach be directly adopted into these sorts of indices and decision-making processes. For example, NOAA routinely collects fisheries acoustics data of the type we are using here. Can these data provide the basis for more direct measures of fish habitat quality potential and can GRP maps be a new product for NOAA?

Another tool to be transferred to NOAA is the Ecospace ecosystem model. Our initial simulation runs with the coupled water quality model will serve to advance knowledge on the effects of hypoxia on fish and fisheries, and to gain insight into effects of various nutrient reduction scenarios. Before hypoxia is incorporated in stock assessment, the Ecospace model can be used to determine if hypoxia is a driver, and what other environmental factors might be drivers and helpful to assessment. With feedback from the workshops and the management advisory committee, the model will be modified and simplified to only allow for the loading of environmental parameters when a new scenario is to be tested.

While our current proposed work restricts forecasting to what-if scenarios (e.g., the nutrient reduction simulations), we are set up to perform now-casting. Since most of the assessments operate on a 1-3 year time lag, the current year and even some previous years are the future to the NOAA-NMFS stock assessment models. The more the fishery quotas are derived from the previous couple of years or recruits (short-lived species such as penaeid shrimp and Gulf menhaden, the most important fisheries in the NGOMEX) the more important these now-casts become to management.

PROJECT OUTPUTS AND OUTCOMES

Our overarching goal is to develop user-friendly tools that both provide indices of the health of a population of fishes as well as indicators of the direction and magnitude of fish population response to management decisions in relation to nutrient loading. Currently, there are simple annual forecasts of the expected size of the hypoxic area. Our intent is to provide forecasts of changes in essential fish habitat, and biomass and catch estimates in response to hypoxic area or volume forecasts. **The outputs that are direct results from our proposed program are:**

- Advanced knowledge and expectations on the effects of nutrient reduction (and its subsequent effect on hypoxic volume) on fish growth rate potential, population biomass, and fisheries catch
- Publications in scientific journals
- Annual workshops with managers and stakeholders for the duration of the program (3 years)
- New management tools in the form of simplified simulation models and new indicators of essential fish habitat
- Presentations at scientific meetings including the annual hypoxia meetings
- Special sessions at national conferences
- Outreach products developed in collaboration with the Sea Grant Extension Program

Our intent is that our program and its outputs change the knowledge and the actions of the end-user, in our case NOAA-NMFS fisheries managers. Our success will be gaged by actually management use of our tools. The overall intended outcome of our proposed research is improved management effectiveness. **More specifically, our anticipated outcomes are the management application of:**

- The newly gained knowledge described in outputs

- The results of our annual workshops
- New ecological forecasting tools that will be transferred to NOAA-NMFS
- Improved methodology that include the new tools for estimating essential fish habitat, fish biomass, and catch

The management agency targeted is NOAA-NMFS, which is heavily involved in our proposed project through participation in an advisory committee and annual workshops. The eventual **environmental and societal outcomes** we strive to achieve with our program are the improved sustainability of fisheries of the Northern Gulf of Mexico, and the increased acceptance of management strategies that reduce nutrient loading, when effects on fisheries can be demonstrated with new tools, and have been incorporated in the decision process. Stakeholder use of ecological indicators will be another important outcome.

THE RESEARCH TEAM

All personnel in this project will work as a team and jointly be involved in publications, the special workshops and scientific session, scientific presentations and the broader impacts. We would plan regular meetings and conference calls.

Dr. **Kim de Mutsert** (George Mason University) is the Lead Scientific PI. She will administer the project and communicate with the Federal Program Manager on all pertinent verbal or written information. She will be in charge of Ecospace modifications and simulations, and adaptation of the model into a management tool. De Mutsert has extensive ecosystem modeling experience using Ecopath with Ecosim, and is involved in the management application of this tool through two projects with the Coastal Protection and Restoration Authority of Louisiana and the US Army Corps of Engineers by simulating effects on fish and fisheries of planned coastal restoration projects. De Mutsert's synergistic activities in coastal Louisiana include serving on the technical team of Changing Course (http://changingcourse.us), on the modeling team of Louisiana's Coastal Master Plan, and as working group participant on the Mississippi River/Gulf Interactions project of the NOAA RESTORE Act Science Program.

Dr. **Matthew Campbell** (NOAA-NMFS Southeast Fisheries Science Center, Mississippi Laboratories) is a SEFSC reef fish unit leader and the Application PI. He will serve as the management liaison, will be the head of the management advisory committee, and will lead the organization of the annual workshops.

Dr. **Kristy A. Lewis** (George Mason University; Co-PI) will perform Ecospace simulations, coordinate long-term model output storage, work with Dr. Campbell to organize the annual workshops, and help transfer the scientific output to management. She has expertise in ecosystem modeling, statistical methods, and general quantitative ecology.

The bioenergetics modeling will form the primary thrust of Professor **Stephen Brandt**'s (Oregon State university; Co-PI) research agenda. Brandt has extensive fisheries acoustics research experience in marine and freshwater systems, pioneered development of spatially-explicit bioenergetics-based GRP modeling for quantifying habitat suitability and has ongoing programs (publications phase) on the Gulf of Mexico, Chesapeake Bay and Lake Erie. He also has strong ties to NOAA and the National Sea Grant Extension Network and extensive experience linking research to agency and stakeholder needs. Brandt helped develop the concepts of Ecological Forecasting in NOAA (e.g. Brandt et al. 2006). He has led NOAA projects in the Gulf of Mexico and sat on the Louisiana Coastal Authority Science Advisory Board. Brand's role will be to lead the spatial habitat quality modeling and development of predictive indices, to integrate modeling with existing field data as described and help to ensure that information and tools that can benefit resource managers, NOAA and regional stakeholders. His current appointment is 25% extension so he remains active with stakeholders.

Cynthia Sellinger (OSU) has over twenty years of environmental modeling experience and handling large spatial arrays of data. She also had major responsibilities in database management, developing computer programs and working with stakeholders. She is proficient in Interactive Data Language (IDL). And, more recently, at Oregon State University, Ms. Sellinger reprogrammed the fish-acoustics analyses and Growth Rate Potential model into a more graphic and dynamic computer language. She will be responsible for creating all software for the fish models, integrating models with the extensive field data, and data management.

An additional **Postdoctoral Scholar** at OSU with expertise in fish bioenergetics and spatial ecology with focus on developing the specific-specific bioenergetics models and evaluating summary spatial statistics and predictive indices.

Consultants to the project are Dr. **Arnaud Laurent** (Dalhousie University) who will deliver or generate the physical-biological model output and assist in the model linking process, and **Joe Buszowski** and **Jeroen Steenbeek** (Ecopath International Initiative) who will assist with EwE programming and trouble-shooting.

Of course other colleagues that helped collect the original physical data will be included in publications (e.g. Roman, Pierson, Mason, Boicourt, Adamack and others).

DATA MANAGEMENT PLAN

Type of data and information created

Data management is a critical component of this project, although no new data will be collected. Data management will encompass 1) extensive field collections from various oceanic surveys, 2) model parameters and spatially-explicit output, 3) compilation of historical physical and chemical data from the region and 3) software IDL modeling framework. These data include model-derived and in situ measurements of physical, water quality, and biological data.

Data management for the extensive field data for use in the GRP model will be fully leveraged by a new grant (2016-2017) to Roman, Peterson and Brandt from the National Academy of Sciences Gulf Research Program's Data Synthesis grants. This grant will compile and manage all of these data into a user-friendly database. The field data are already currently within an extensive database and since it was funded by NSF and NOAA, falls within their database requirement framework. GRP model output generated during this project will be stored there as well. The CTD and temperature oxygen data are already housed at NSF's BCO-DMO.org. Data management for other GRP modeling products will largely be done through our funded project through the use of EDaMaMe, the Environmental Data Management Mechanism. Developed at UMCES, EDaMaMe uses a MySQL relational database back end that facilitates the upload, annotation, discovery, and download of scientific data. EDaMaMe stores a wealth of metadata associated with each entity, including descriptions, geospatial and temporal boundaries, units of measure, citations, publications, associated files, and contributors.

The biological and environmental data used to develop the Ecospace model includes species-specific biomass and diet information, in addition to growth, production and consumption parameters. SEAMAP fisheries survey data (http://seamap.gsmfc.org/) were used to incorporate species biomasses in the modeled area, and to develop oxygen response curves. Data from this survey are available to the public by direct request. Fisheries data were included in the model using annual landings obtained from the NOAA Fisheries Annual Commercial Landings Statistics (http://st.nmfs.noaa.gov) and from the Louisiana Department of Wildlife and Fisheries (LDWF). The NOAA data are freely available on the website and the LDWF landings data are available by direct request.

At the project's end, all Ecospace model inputs and outputs will be archived using services provided by George Mason University. Using the George Mason University (GMU) Dataverse (http://arc.irss.unc.edu/dvn/dv/gmu), all data and modeling software will be made openly accessible. The metadata will be indexed by search engines to encourage discovery. These products will be stored in this location in perpetuity, and will be openly accessible and publically available through Dataverse at George Mason University within a year of the projects end. For more information or to make a data request, please contact Dr. Kim de Mutsert (kdemutse@gmu.edu) or Dr. Kristy A. Lewis (klewis22@gmu.edu).

Since both of the fisheries models will be used to evaluate various scenarios of water quality and hydrodynamic conditions, it will be important to store and manage the common inputs between models. The inputs generated from the physical-biological model are an example of these data and will be stored using a cloud database service that can be accessed by all collaborators. This central location will ensure the modeling teams are using the same temporal and spatial scales for generating model scenarios. These data will then be archived using Dataverse at the project's completion. We will also manage a publicly accessible project website for the duration of our research. The website will be updated to track the progress of our work, and will provide links to the various sources and locations of our data.

Standards for format and content

Output from our modeling efforts will be in common, easily accessed data formats. Non-georeferenced information will be output as .CSV and .TXT files. Examples of these data types include time series data, diet matrices, model summaries, and log files. Spatially-explicit data will be output as ASCII grid files or other raster formats that can be easily imported into GIS software for exploration. We will include the appropriate metadata alongside the data output from each scenario. For the Ecospace model, the metadata will be automatically generated with each model run and output as .TXT files. These files specify when the model was run, what scenario was tested, and various other aspects of that specific model run.

APPLICATION TO MANAGEMENT

Due to the large number and wide variety of species managed by the SEFSC there are always ecosystem level considerations that flow into and result from management decisions. NOAA has adopted ecosystem-based fisheries management (EBFM) as the approach for meeting the agency's mandates and the National Marine Fisheries Service (NMFS) has taken several steps to advance EBFM as a strategic programmatic goal. Currently the SEFSC is building capacity to conduct ecosystem science and work EBFM products into assessments. Historically there have been many efforts from across the SEFSC to conduct ecosystem science.

Additionally various fisheries independent surveys have contributed data to ecosystem models and modeling efforts (e.g. SEAMAP) but survey data collection is currently tuned to feed information into single species stock assessments that are conducted by the SEFSC through the SouthEast Data, Assessment, and Review (SEDAR) process. Coordinated implementation of EBFM across mandates will lead to greater efficiency and will enable NOAA Fisheries to assess the interaction between fisheries, and other ecosystem components (e.g. species, habitats) and processes.

SouthEast Data, Assessment, and Review (SEDAR, http://sedarweb.org/) is a cooperative Fishery Management Council process initiated to improve the quality and reliability of assessments of fishery resources in the southeastern United States, including the South Atlantic, Gulf of Mexico, and US Caribbean. Recently SEDAR has begun including an integrated ecosystem assessment (IEA) group in the process. For example during SEDAR 33 (gag grouper) the IEA group developed estimates of natural mortality due to episodic events (e.g. red tide) and estimates of recruitment strength due to factors other than spawning stock biomass (SEDAR 2014) and relied on Ecopath with Ecosim (EwE) modeling products. We've contacted Dr. Michael Schirripa, Dr. John Walter, Dr. Mandy Karnouskas, and Dr. Skyler Sagarese who were the NMFS representatives of the IEA group within the SEFSC to begin coordinating this proposed work, and so that modeling products and outcomes are maximally useful for a fisheries assessment. Additionally we will coordinate workshops with the IEA groups. Finally and most importantly we will coordinate with the IEA group to ensure that model products and outcomes are understood and included for review during the SEDAR assessment process.

Since the inception of fisheries independent sampling programs within NMFS (70's and 80's) the focus has always been on delivering indices of relative abundance for use in single species stock assessments. Over the years the underlying research designs have undergone intense scrutiny in regards to sample sizes, power, spatio-temporal coverage, and gear selectivity with an ultimate goal to ensure the development of standardized survey protocols. **Recognizing that NMFS includes EBFM as a critical component to meet the agency's mandates, data collection resources might require retooling or redirection to meet those needs.** However this is not a quick and easy redirect given a lengthy history of programmatic structure designed for fairly explicit purposes. Given that ecosystem modeling is fairly new and that EBFM in particular is not well defined, individuals assigned to guide the fisheries independent surveys have received little direction on how to retool surveys to meet EBFM data needs. Therefore we intend to include individuals from fisheries independent survey laboratories in the workshops, as well as specifically in the project itself (Drs. Matthew Campbell and Walter Ingram, NMFS Mississippi Laboratories). This enables direct access to various SEFSC and SEAMAP data sets, improved understanding of the underlying survey designs and collection methods, and most importantly a clearer understanding of the limitations of those data. Additionally, the size and strength of the hypoxic regions of the Gulf of Mexico may prove to be important drivers of fish abundance and thus have the potential to modify catch rates (i.e. CPUE) that are used to estimate relative abundance indices and applied directly in assessments. For instance the SEAMAP trawl data is one of the most important indices used to index red snapper abundance and that survey historically and currently operates throughout the hypoxic region that stretches from Louisiana to Texas (SEDAR 2013).

There is strong evidence that hypoxia leads to lower catch rates within affected areas and subsequent loading of biomass along the edges of hypoxic zones (Craig and Crowder 2005). Because of this trait we believe that management of the hypoxic zone will have important considerations for the Gulf of Mexico shrimp fishery and the associated groundfish community. The NMFS Galveston office is the primary office conducting shrimp assessments for the Gulf of Mexico fishery and therefore we will include individuals from that office in our workshops and communications about model development (Drs. Rick Hart and Jim Nance). While our main target end-user group is NOAA NMFS, we aim to include personnel from key state agencies, especially those in Louisiana such as the Louisiana Department of Wildlife and Fisheries (LDWF), and the Coastal Protection and Restoration Authority (CPRA) who have extensive experience in researching and managing Mississippi River effects on the coastal ecosystem.

We will conduct three separate workshops with the intent to educate user groups on model inputs, capabilities, and output and receive their input to help guide our work plan and define tools and indicators. An initial workshop will define both manager needs and stakeholder expectations and answer the question of how accurate and how often predictions are needed. The next major workshop will include training and testing of the developed management tools, whereas the last workshop will focus on technology transfer and applications. This approach, and the use of adaptive science where feedback during workshops will be incorporated into work priorities, ensures transition of research to management throughout the scope of this project.

Additionally, we will form an advisory committee within NMFS to provide a mechanism to centralize discussions, people, and resources that will facilitate the use of model outputs. The goal is to deliver usable end products to test potential outcomes under various management scenarios that have the potential to modify the extent and influence of the hypoxic region of the Gulf of Mexico, and thus impact fisheries resources that NMFS is managing. The laboratories and individuals listed in Table 1 have been contacted and identified as potential end-users and will be invited to take part in the workshops and advisory committee. The advisory committee and the PIs will hold quarterly conference calls throughout the proposed project. We established this initial list to gauge support for our proposed project among our primary target group (see letters of support included in the application package), and plan to extend the invitation to other institutions such as state agencies (e.g., LDWF, CPRA) once funded.

Table 1. Individuals and their affiliation that have agreed to (or have been invited to) participate in our workshops and/or serve on the advisory committee, and that support our proposed work.

Affiliation	Participants
NMFS – SEFSC – Miami	Dr. Michael Schirripa, Dr. Mandy Karnouskas, Dr. John Walter, Dr. Skyler Sagarese
NMFS – SEFSC – Mississippi Laboratories	Dr. Matthew Campbell, Dr. Walter Ingram
NMFS – SEFSC – Galveston	Dr. Rick Hart, Dr. Jim Nance
NOAA Habitat Program	Dr. Buck Sutter (invited)
Northern Gulf Institute	Dr. Steven Ashby
Louisiana Sea Grant	Prof. Robert Twilley

OUTREACH AND EDUCATION

As mentioned above, a high degree of interaction with both managers and stakeholders will be an integral part of the program. A management advisory team and annual workshops will ensure the utility of the work for management purposes, and the transfer of tools to resource managers and stakeholders. Connections between nutrient loading and fisheries are vital to management and stakeholder interests, economics, jobs, and even lifestyle for people living in the region and the watershed. It is thus essential they know what is going on, have an input at an early stage, and understand enough of the science to accept its validity (and uncertainty), and take action based on predictions. We believe that the engagement process, whereby communication and input from managers and stakeholders are used to help define the tools, products, direction, and outputs from this project, is essential.

We need to determine whether the types of forecasts and models we are using are appropriate for management, and how we can bring these predictive models into active use. We intend to engage regional Sea Grant Extension in this activity and invite participation of other scientists funded by this NOAA program, particularly those funded to model the causes of the hypoxia as that information will help inform our statistical and meta-analysis models. We will be able to use findings from our workshops to modify and improve our original analytical and comparative modeling approaches and to facilitate further communication and collaboration among researchers and agencies.

We will make sure the tools we propose receive broad dissemination to management agencies through our workshops, scientific publications and presentations, and our project's website. It also is important to inform fisheries stakeholders of the potential applications. We will work directly through and with existing outreach networks, starting with the National Sea Grant Extension network and the Gulf Regional Extension Network (Robert Twilley pers. comm.) to effect these engagements (e.g., see Rand et al. 1997). Dr. Brandt's appointment is 25% extension so he is active with stakeholders.

Education will be a prominent component of our proposed work as well; we have included funding for two post-doctoral scholars, two graduate students, and an undergraduate student who will reside at Oregon State University or George Mason University. Dr. de Mutsert teaches several classes at the graduate and undergraduate level in estuarine and coastal ecology and fisheries science, in which she will educate students about coastal hypoxia and the implications for ecosystems.

In addition, we aim to publish our work in scientific journals, present our work at scientific meetings, and organize two special sessions at national conferences. We aim to plan one session at the beginning of year 2 of this project at the biannual Coastal and Estuarine Research Federation meeting, bringing together physical oceanographers and fisheries scientists on the topic of effects of hypoxia on living resources. The second session will occur at the beginning of year 3, and will largely target fisheries managers (and stakeholders) and fish habitat scientists. This session would be proposed for the Annual meeting of the American Fisheries Society. The general theme of this discussion would be to look at integrated quantitative indices of fish habitat quality and quantity such as HSI, EFH and food webs and will include invited speakers to address management needs for habitat science in this context, specifically related to hypoxia. We expect this will be an opportunity for engagement and allow us to improve our original analytical and comparative modeling approaches and to facilitate further communication with agencies to help make our results more meaningful to applicable to decision-makers.