Science for Solutions

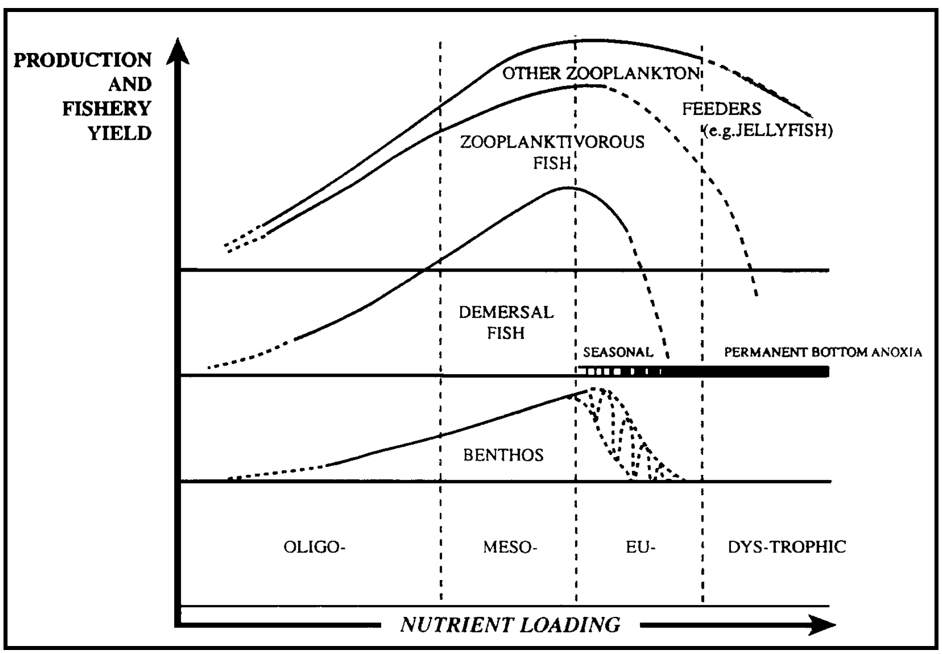
NOAA COASTAL OCEAN PROGRAM
Decision Analysis Series No. 16

Ecological and Economic Consequences of Hypoxia

Topic 2 Report for the Integrated Assessment on Hypoxia in the Gulf of Mexico

Robert J. Diaz and Andrew Solow

May 1999



U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Ocean Service
Coastal Ocean Program

GULF OF MEXICO HYPOXIA ASSESSMENT

This report is the second in a series of six reports developed as the scientific basis for an integrated assessment of the causes and consequences of hypoxia in the Gulf of Mexico, as requested by the White House Office of Science and Technology Policy and as required by Section 604a of P.L. 105-383. For more information on the assessment and the assessment process, please contact the National Centers for Coastal Ocean Science at (301) 713-3060.

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Cover image: Comparative evaluation of fishery response to nutrients based on data from around the world (modified and redrawn from Caddy 1993).

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Contents

List of Figures and Tables

FIGURES

TABLES

Acknowledgments

We would like to acknowledge the assistance of many managers and scientists who have contributed insight and/or data on the ecological and economic effects of hypoxia, particularly the Task 2 Ecological Effects and Economic Effects Working Group members.

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Foreword

Nutrient overenrichment from anthropogenic sources is one of the major stresses on coastal ecosystems. Generally, excess nutrients increase algal production and the availability of organic carbon within an ecosystem—a process known as eutrophication. Scientific investigations in the northern Gulf of Mexico have documented a large area of the Louisiana continental shelf with seasonally depleted oxygen levels (< 2 mg/l). Most aquatic species cannot survive at such low oxygen levels. The oxygen depletion, referred to as hypoxia, forms in the middle of the most important commercial and recreational fisheries in the conterminous United States and could threaten the economy of this region of the Gulf.

As part of a process of considering options for responding to hypoxia, the U.S. Environmental Protection Agency (EPA) formed the Mississippi River/Gulf of Mexico Watershed Nutrient Task Force during the fall of 1997, and asked the White House Office of Science and Technology Policy to conduct a scientific assessment of the causes and consequences of Gulf hypoxia through its Committee on Environment and Natural Resources (CENR). A Hypoxia Working Group was assembled from federal agency representatives, and the group developed a plan to conduct the scientific assessment.

The National Oceanic and Atmospheric Administration (NOAA) has led the CENR assessment, although oversight is spread among several federal agencies. The objectives are to provide scientific information that can be used to evaluate management strategies, and to identify gaps in our understanding of this complex problem. While the assessment focuses on hypoxia in the Gulf of Mexico, it also addresses the effects of changes in nutrient concentrations and loads and nutrient ratios on water quality conditions within the Mississippi–Atchafalaya River system.

As a foundation for the assessment, six interrelated reports were developed by six teams with experts from within and outside of government. Each of the reports underwent extensive peer review by independent experts. To facilitate this comprehensive review, an editorial board was selected based on nominations from the task force and other organizations. Board members were Dr. Donald Boesch, University of Maryland; Dr. Jerry Hatfield, U.S. Department of Agriculture; Dr. George Hallberg, Cadmus Group; Dr. Fred Bryan, Louisiana State University; Dr. Sandra Batie, Michigan State University; and Dr. Rodney Foil, Mississippi State University. The six reports are entitled:

> ***Topic 1: Characterization of Hypoxia.*** Describes the seasonal, interannual, and long-term variations of hypoxia in the northern Gulf of Mexico and its relationship to nutrient loadings. *Lead: Nancy N. Rabalais, Louisiana Universities Marine Consortium.*

Topic 2: Ecological and Economic Consequences of Hypoxia**.** Evaluates the ecological and economic consequences of nutrient loading, including impacts on the regional economy. *Co-leads: Robert J. Diaz, Virginia Institute of Marine Science, and Andrew Solow, Woods Hole Oceanographic Institution, Center for Marine Policy.*

Topic 3: Flux and Sources of Nutrients in the Mississippi–Atchafalaya River Basin. Identifies the sources of nutrients within the Mississippi–Atchafalaya system and Gulf of Mexico. *Lead: Donald A. Goolsby, U.S. Geological Survey.*

Topic 4: Effects of Reducing Nutrient Loads to Surface Waters Within the Mississippi River Basin and Gulf of Mexico. Estimates the effects of nutrient-source reductions on water quality. *Co-leads: Patrick L. Brezonik, University of Minnesota, and Victor J. Bierman, Jr., Limno-Tech, Inc.*

Topic 5: Reducing Nutrient Loads, Especially Nitrate–Nitrogen, to Surface Water, Ground Water, and the Gulf of Mexico. Identifies and evaluates methods for reducing nutrient loads. *Lead: William J. Mitsch, Ohio State University.*

Topic 6: Evaluation of the Economic Costs and Benefits of Methods for Reducing Nutrient Loads to the Gulf of Mexico*.* Evaluates the social and economic costs and benefits of the methods identified in Topic 5 for reducing nutrient loads. *Lead: Otto C. Doering, Purdue University.*

These six individual reports provide a foundation for the final integrated assessment, which the task force will use to evaluate alternative solutions and management strategies called for in Public Law 105-383.

As a contribution to the Decision Analysis Series, this report provides a critical synthesis of the best available scientific information regarding the ecological and economic consequences of hypoxia in the Gulf of Mexico. As with all of its products, the Coastal Ocean Program is very interested in ascertaining the utility of the Decision Analysis Series, particularly with regard to its application to the management decision process. Therefore, we encourage you to write, fax, call, or e-mail us with your comments. Our address and telephone and fax numbers are on the inside front cover of this report.

David Johnson, Director
Coastal Ocean Program

Donald Scavia, Chief Scientist
National Ocean Service

Executive Summary

In this report we have attempted to evaluate the ecological and economic consequences of hypoxia in the northern Gulf of Mexico. Although our initial approach was to rely on published accounts, we quickly realized that the body of published literature dealing with hypoxia was limited, and we would have to conduct our own exploratory analysis of existing Gulf data, or rely on published accounts from other systems to infer possible or potential effects of hypoxia.

For the economic analysis, we developed a conceptual model of how hypoxia-related impacts could affect fisheries. Our model included both supply and demand components. The supply model had two components: (1) a physical production function for fish or shrimp, and (2) the cost of fishing. If hypoxia causes the cost of a unit of fishing effort to change, then this will result in a shift in supply. The demand model considered how hypoxia might affect the quality of landed fish or shrimp. In particular, the market value per pound is lower for small shrimp than for large shrimp.

Given the limitations of the ecological assessment, the shallow continental shelf area affected by hypoxia does show signs of hypoxia-related stress. While current ecological conditions are a response to a variety of stressors, the effects of hypoxia are most obvious in the benthos that experience mortality, elimination of larger long-lived species, and a shifting of productivity to non-hypoxic periods (energy pulsing). What is not known is whether hypoxia leads to higher productivity during productive periods, or simply to a reduction of productivity during oxygen-stressed periods.

The economic assessment based on fisheries data, however, failed to detect effects attributable to hypoxia. Overall, fisheries landings statistics for at least the last few decades have been relatively constant. The failure to identify clear hypoxic effects in the fisheries statistics does not necessarily mean that they are absent. There are several possibilities: (1) hypoxic effects are small relative to the overall variability in the data sets evaluated; (2) the data and the power of the analyses are not adequate; and (3) currently there are no hypoxic effects on fisheries.

Lack of identified hypoxic effects in available fisheries data does not imply that effects would not occur should conditions worsen. Experience with other hypoxic zones around the globe shows that both ecological and fisheries effects become progressively more severe as hypoxia increases. Several large systems around the globe have suffered serious ecological and economic consequences from seasonal summertime hypoxia; most notable are the Kattegat and Black Sea. The consequences range from localized loss of catch and recruitment failure to complete system-wide loss of fishery species. If experiences in other systems are applicable to the Gulf of Mexico, then in the face of worsening hypoxic conditions, at some point fisheries and other species will decline, perhaps precipitously.

Catch per unit effort for brown shrimp, while variable, has trended down since the late 1970s. While fish and shrimp may avoid hypoxia, the effects of avoidance on metabolism and predator avoidance are unknown, including the time and space scales over which avoidance is possible. In fact, a major difference between the northern Gulf of Mexico hypoxic zone and other such zones around the world is that for the last few decades, the Gulf ecosystem has managed to maintain energy flow to productive fisheries (crabs and shrimps) that depend on the bottom.

Any effect of hypoxia in the northern Gulf of Mexico is intertwined with other environmental stressors. To understand specifically how hypoxia affects populations in the Gulf, we first need to determine the contribution of all natural and anthropogenic sources of mortality and growth to population dynamics. We also need to determine what functional aspects of the ecosystem are specifically affected by hypoxia. A comprehensive research plan is needed as a focus for efforts directed at assessing both the ecological and the economic effects of hypoxia in the Gulf. This plan must include elements for both directing new research and synthesizing existing data. Our efforts to identify hypoxia-related problems were severely hampered by lack of published data. A total ecosystem approach to the problem will be the only successful approach. Consideration of how hypoxia and other stressors interact with all aspects of the Gulf ecosystem is essential for planning restoration efforts.

CHAPTER 1

Introduction

1.1 SCOPE OF THIS REPORT

An important goal of the CENR hypoxia science assessment was to document the state of knowledge of the extent, characteristics, causes, and effects (both ecological and economic) of hypoxia in the northern Gulf of Mexico. This report specifically deals with the ecological and economic effects of annual hypoxia, which is apparently procreated by excess nutrient loading delivered to the Gulf via the Mississippi River Basin. It also examines the impacts of hypoxia on Gulf of Mexico fisheries and the regional and national economies, and articulates both the ecological and the economic consequences and, to the extent appropriate, their interaction.

Other reports in the assessment series compiled existing information on nutrient sources, identified alternatives for reducing nutrient inputs, and examined the costs and benefits associated with reducing the nutrient loads. The ecological and economic assessment was built from the work of many Gulf of Mexico researchers.

1.2 LINKING LAND AND SEA

The direct connection between land and sea is best exemplified by the relationship between estuarine and coastal fisheries production and land-derived nutrients. The most productive fisheries zones around the world are always associated with significant inputs of either land- (runoff) or deep oceanic- (upwelling) derived nutrients. The basic nutrients carried by land runoff and oceanic upwelling are essential elements that fuel primary production passed through marine food webs to species of economic importance. This basic scenario has been played out for eons around the world, including the northern Gulf of Mexico (Rabalais et al. 1996). The importance of the linkage between land and sea is clearly seen in the Gulf of Mexico, which in 1996 accounted for 16% of the total commercial landings in the United States, with over half of this total harvested from waters surrounding the Mississippi River Delta (Holliday and O'Bannon 1997).

Problems begin when the nutrients entering the system exceed the capacity of the food chain to assimilate them. At first, increased nutrients lead to increased fisheries production. But as production of organic matter production increases, changes occur in the food web that leads to different endpoints. These changes are very predictable and have followed the same path in many marine ecosystems (Figure 1.1). The relationship between nutrient loads delivered to the northern Gulf of Mexico and basic ecological responses (e.g., increased primary productivity in the water column, increased flux of organic matter to the bottom, bottom-water hypoxia, altered energy flow, and stressed fisheries) are typical of other systems' responses around the world (see

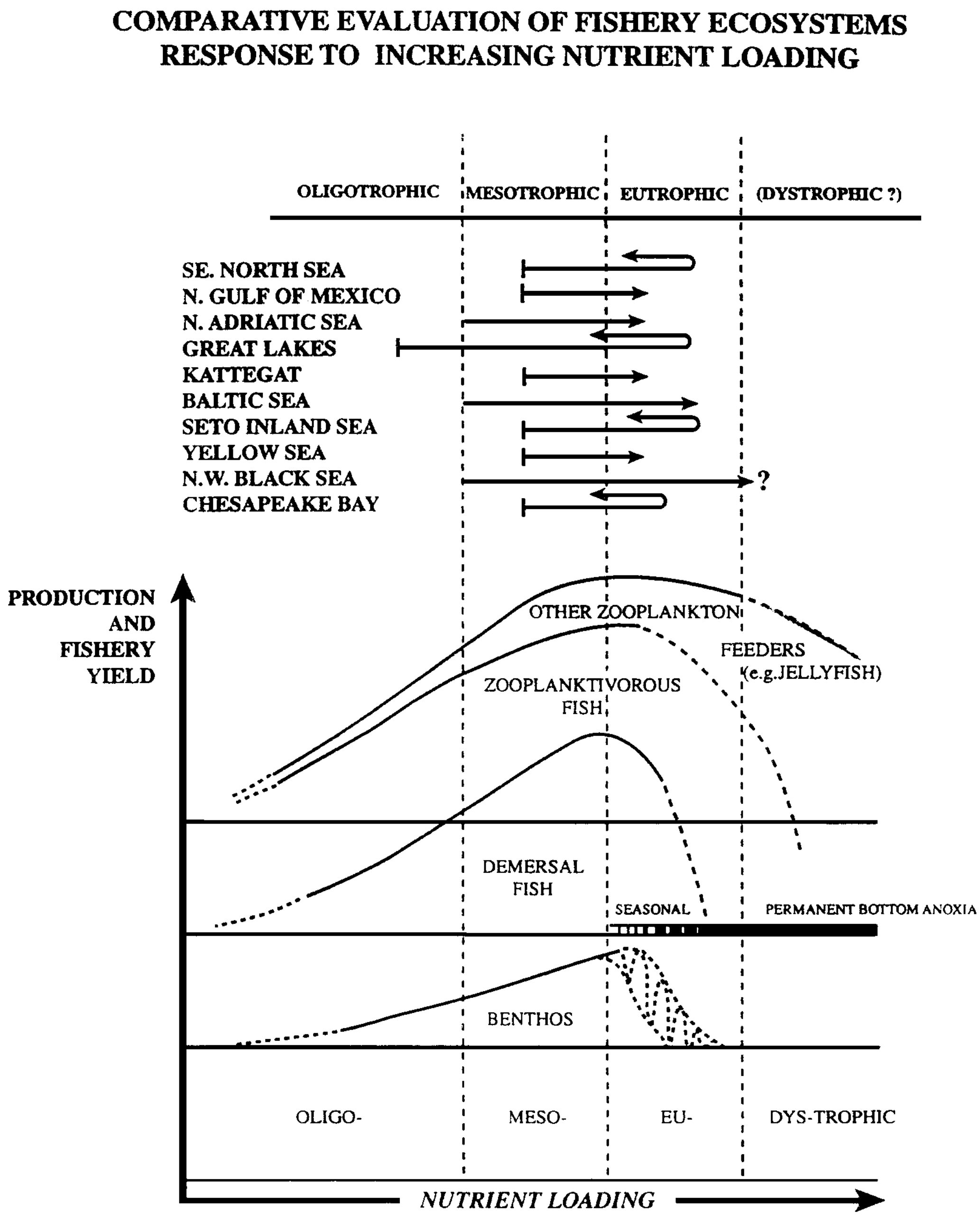

FIGURE 1.1. Comparative evaluation of fishery response to nutrients based on data from around the world (modified and redrawn from Caddy 1993). NOTE: Each curve represents a general guild of species and their reaction to increasing nutrient supplies. The top part of the figure lists recent trends for various systems around the world. Vertical dashed lines separate general categories of organic production that result from different levels of nutrients.

reviews by Brongersma–Sanders 1957; Caddy 1993; Diaz and Rosenberg 1995). Basically, the northern Gulf of Mexico hypoxic zone, popularly know as the "Dead Zone," is a secondary manifestation of the larger problem of excess nutrients, which leads to increased production of organic matter and, in the case of the Gulf of Mexico, hypoxia. (For details, see the Topic 1 report, *Characterization of Hypoxia*.) The increased loading of organic matter is referred to as eutrophication (Nixon 1995).

1.3 ASSESSING EFFECTS

Many marine species in the northern Gulf of Mexico are targets of commercial and recreational fishing and, therefore, have direct economic value. These species deserve special attention in an assessment of the ecological and economic consequences of hypoxia. Moreover, the information on which such an assessment could be based is generally more detailed for commercially exploited species.

Despite considerable concern and speculation, to date there appears to have been no rigorous assessment of ecological or economic effects. Accordingly, the decision was made to focus on identifying economic effects in existing fisheries data for selected commercial stocks that could reasonably be attributed to hypoxia. For identifying ecological effects, the focus was on fisheries-independent data and other environmental studies conducted primarily for oil and gas development. Although this focus is certainly narrow, it was necessitated by a combination of the requirement for some level of scientific rigor and limitations on project resources.

The economic assessment was originally envisioned as consisting of two steps: identifying effects in the fisheries data that could be attributed to hypoxia, and attaching an economic value to those effects. There appears to be only one quantitative assessment of the effects of hypoxia on a commercial fishery in the Gulf of Mexico (Zimmerman et al. 1996). Briefly, the main findings of that study were that (1) there is a weak relationship between shrimp catch and a measure of the frequency of hypoxic conditions, and (2) catch per unit effort is unrelated to the frequency of hypoxia.

In the absence of an existing body of analysis, the study described here involved what should be viewed as an exploratory or preliminary analysis of existing data to identify possible hypoxic effects. As described in more detail below, this analysis uncovered only weak evidence of such effects. In interpreting these results, it is important to emphasize three points:

- First, the failure to identify hypoxic effects does not necessarily mean that they are absent. Rather, it only suggests that their magnitude is small in relation to the overall variability in the data. In technical terms, given the data and sample size, the statistical power of this analysis may be low. There are many potential sources of variability in the fisheries data other than hypoxia. These include measurement errors and other problems with the data; variation due to weather and the compounding effects of coastal habitat modifications; and economic and other factors affecting fishing behavior, including variation through time and between localities in fisheries regulations.
- Second, in connection with the first point, the ability to account empirically for different sources of variability in the fisheries data is limited by information about these sources. Notably, consistent quantitative data on the severity of hypoxic conditions were limited to estimates of the area experiencing oxygen concentrations lower than 2 mg/l (AREA) over the period 1985–95, with little to no data for 1989 (see the Topic 1 report, *Characterization of Hypoxia*). In light of the high variability of fisheries data, this time series is simply too short to establish a credible relationship between the severity of hypoxia and variables relating to fisheries. In an attempt to overcome this problem, the study group used a proxy for hypoxia to extend the analysis over a longer period. However, this proxy, described below, is certainly rough.
- Third, even if the failure to identify clear hypoxic effects in the historical data is taken as evidence of their absence, this does not imply that effects would not occur should conditions worsen. As noted elsewhere in this report, experience with other hypoxic areas shows that ecological effects and fisheries effects become progressively greater as hypoxia worsens (Caddy 1993).

The analysis focused primarily on the two main shrimp species—brown shrimp (*Penaeus aztecus*) and white shrimp (*Penaeus setiferus*)—for three reasons:

- These species are commercially important (Table 1.1).
- As benthic (i.e., bottom-dwelling) species, the potential for experiencing effects due to hypoxia is relatively high.
- The data for these fisheries are relatively good, particularly in terms of geographical resolution. Additional analysis was performed for two other species—Gulf menhaden *(Brevoortia patronus)* and red snapper (*Lutjanus campehanus*)—to address public concerns that have been raised about the effects of hypoxia on them.

TABLE 1.1. Value of landings in selected Gulf fisheries in 1996.

Species	**Value *(in Millions)***
All	$270.8
Brown Shrimp	$61.8
White Shrimp	$60.5
Menhaden	$47.4
Red Snapper	$4.2

Source: National Marine Fisheries Service.

CHAPTER 2

Methods

2.1 ECOLOGICAL DATA SOURCES

Evaluation of ecological effects from the northern Gulf of Mexico hypoxic zone was based primarily on data collected by various investigators and federal programs and secondarily on meetings convened to assess hypoxia in the Gulf (Table 2.1). Most of the data appeared as agency reports or gray literature of limited circulation. In almost all cases these studies were commissioned for reasons other than evaluating the effects of hypoxia, usually for compiling fishery statistics or for information related to oil and gas activities. This particular aspect of the available data made it difficult to single out either ecological or economic effects associated with excess nutrient loading and hypoxia in the Gulf of Mexico.

TABLE 2.1. Meetings held for evaluation of ecological effects of hypoxia on Gulf of Mexico living resources.

Conference	Meeting/Workshop	Location	Date(s)
First Gulf of Mexico Hypoxia Management Conference	Gulf of Mexico Program Meeting	Kenner, LA	December 5–6, 1995
Hypoxia Information Conference	Joint Agricultural and Gulf of Mexico Program Meeting	Davenport, IA	June 1996
Hypoxia Around the World—Causes and Solutions	OECD Workshop	Anaheim, CA	October 30–31, 1997
Effects of Hypoxia on Living Resources in the Northern Gulf of Mexico	Sea Grant Workshop	Baton Rouge, LA	March 11–13, 1998
Ecological and Economic Effects of Hypoxia on the Northern Gulf of Mexico	CENR Workshop	Baton Rouge, LA	March 14, 1998

Excess nutrient loading leading to eutrophication and subsequent hypoxia and anoxia are well studied phenomena in other places around the world (see Rosenberg 1985; Colombo et al. 1992; Nixon 1995; Howarth et al. 1996; Vitousek et al. 1997) and provide information pertinent to the northern Gulf of Mexico. In particular, much of the information dealing with estuarine and marine ecosystem-level effects of these phenomena on fisheries and benthos was recently summarized by Caddy (1993) and Diaz and Rosenberg (1995).

The SEAMAP (Southeast Area Monitoring and Assessment Program) Environmental and Biological Atlas of the Gulf of Mexico database of the Gulf States Marine Fisheries Commission contains large amounts of data on trawlable species that are relevant to the current ecological and economic assessment. SEAMAP is a state, federal, and university program for collection, management, and dissemination of fisheries-independent data in the United States. The Gulf program data collection started in 1982, with many stations located in the hypoxic zone. Details on the sampling strategy used in collecting these data are contained in a series of summary atlases published each year (see Donaldson et al. 1997 as an example). The original data are available at the program's FTP site (ftp://conch.ssc.nmfs.gov/pub/seamap). Our ecological assessment was based on data from 1987 and 1988 (a time when hypoxia was less extensive) and from 1993 and 1994 (a time when hypoxia was more extensive).

2.2 ECONOMIC METHODS

2.2.1 A Conceptual Model for Economic Effects

To focus the analysis on the central issue—namely, the economic impact on fisheries of hypoxia—it was necessary to adopt a conceptual model of how these impacts might arise. Without such a model, the appropriate data analysis would be unclear. The conceptual model adopted here is as follows.

Potential economic effects of hypoxia arise through shifts in either the supply or the demand for fish. The supply model has two components. The first component is the physical production function for fish. A simple model of the production function is:

$$\text{CATCH} = q \text{ EFFORT STOCK} \tag{1}$$

where *q* is the catchability coefficient (e.g., Clark 1985). Under this model, catch per unit effort (CPUE) is proportional to stock size:

$$\text{CPUE} = \text{CATCH/EFFORT} = q \text{ STOCK} \tag{2}$$

As described below, the analysis of shrimp data was performed for three areas for which estimates of STOCK are not available, but for which estimates of CATCH and EFFORT—and, therefore, CPUE—are. Under the assumption that *q* does not depend on the level of hypoxia, an effect of hypoxia on stock can be detected by establishing an empirical relationship between CPUE and a hypoxia measure.

It is important to emphasize that this approach to detecting a hypoxic effect on STOCK does not require that EFFORT be independent of hypoxia. This point is sometimes missed. For example, Zimmermann et al. (1996) found no empirical relationship between CPUE and a measure of the frequency of hypoxia in highly spatially resolved data. As shrimp are known to avoid hypoxic waters, they suggested that this reflected a combination of reduced STOCK and reduced EFFORT in areas of high hypoxia. However, under the model (1), this argument cannot be correct. Specifically, if a reduction in EFFORT leads to a proportional reduction in CATCH, so that CPUE remains constant, then under this model STOCK cannot have changed. The approach outlined above does assume that catchability *q* is independent of hypoxia. If a decline in STOCK due to hypoxia is, in fact, offset by an increase in *q*, then CPUE may remain unchanged, thereby obscuring the STOCK effect. There is anecdotal evidence that shrimp leaving the hypoxic zone congregate in high densities at the border of this zone. By increasing catchability, this may obscure an effect of hypoxia on STOCK. This possibility deserves further attention.

The second component of the supply model is the cost of fishing. If hypoxia causes the cost of a unit of fishing effort to change, then this will result in a shift in supply. In particular, concern has been raised about the possibility that the hypoxia off the Louisiana coast has caused an offshore shift in the distribution of shrimp (and possibly other commercial species). Such a distributional shift could affect the cost of fishing by changing the distance that fishing vessels must travel. Detecting such a distributional shift requires relatively detailed information about the location of fishing activity. Some information along these lines is available for the shrimp fishery. As described below, an attempt was made to detect a distributional shift in that fishery that could be attributed to hypoxia. Incidentally, an increase in catchability q due to hypoxia could reduce the cost of fishing.

Finally, hypoxia could cause the demand for fish to shift if it affects the quality of the landed fish. In particular, the market value per pound is lower for small shrimp than for large shrimp. As a result, if the size of landed shrimp declines as a result of hypoxia (e.g., through an effect on the growth of shrimp or on the location of shrimp harvest), then this would result in a loss in value, even if the total weight of landings remains unchanged.

2.2.2 A Proxy for Hypoxia

The analysis in this part of the study involved identifying empirical relationships between fisheries variables and a measure of hypoxia. One problem with basing the identification of such relationships on the time series of AREA (Figure 2.1) is that this time series is short. Moreover, the correlation between the time series of AREA with time itself is nearly 0.8, so that any other time series exhibiting a secular change over this relatively short period will be correlated with AREA. To overcome this problem, a proxy for hypoxia covering the period 1960–96 was constructed.

Briefly, hypoxia results from the decay of phytoplankton and other kinds of organic material in the bottom waters by oxygen-using bacteria. The amount of phytoplankton in the Gulf depends in part on the amount of nutrients supplied to the Gulf by the Mississippi and Atchafalaya Rivers. The amount of nutrients, in turn, depends on the product of the nutrient concentration in these rivers and their discharge into the Gulf (see the Topic 3 report, *Flux and Sources of Nutrients in the Mississippi–Atchafalaya River Basin*). The hypoxia index (INDEX) for the period 1960–96 is given by:

$$\text{INDEX}(t) = d(t)\exp(0.02\,(t-1960)) \tag{3}$$

where *INDEX(t)* is the hypoxia index in year *t*, *d(t)* is the combined Mississippi–Atchafalaya spring discharge, and the exponential term assumes a 2% growth rate of nutrient concentration over this period (Turner and Rabalais 1991).

The time series of INDEX (Figure 2.1) is in rough qualitative agreement with the time series of AREA (Figure 2.2) over the period 1985–95, with a correlation of 0.60. The correlation between INDEX and time is around 0.7, due mostly to the assumed exponential growth in nutrient concentration. As with AREA, there is a danger of detecting a spurious relationship with a variable that also exhibits a secular change over this period. However, in comparison to AREA, the danger is reduced somewhat by the length of the INDEX time series.

In addition to the problem of secular variation, in interpreting analyses based on this index, it is important to stress that INDEX—and true hypoxic conditions—are expected to be related to climatic conditions, such as temperature and precipitation, and to primary production in the Gulf. These factors can, by themselves, affect coastal fisheries. For example, Griffin et al. (1976) developed a yield model for brown shrimp in which Mississippi River discharge served as a proxy for environmental conditions in estuarine nursery grounds. As a result, the establishment of an empirical relationship between a fisheries variable and INDEX—or even between a fisheries variable and true hypoxic conditions, were they known—does not necessarily imply the existence of an effect due to hypoxia. Instead, the effect may be due to a climatic or other covariates of INDEX. As described below, an attempt was made to avoid this problem in the analysis of the shrimp data by using fisheries data from different parts of the northern Gulf.

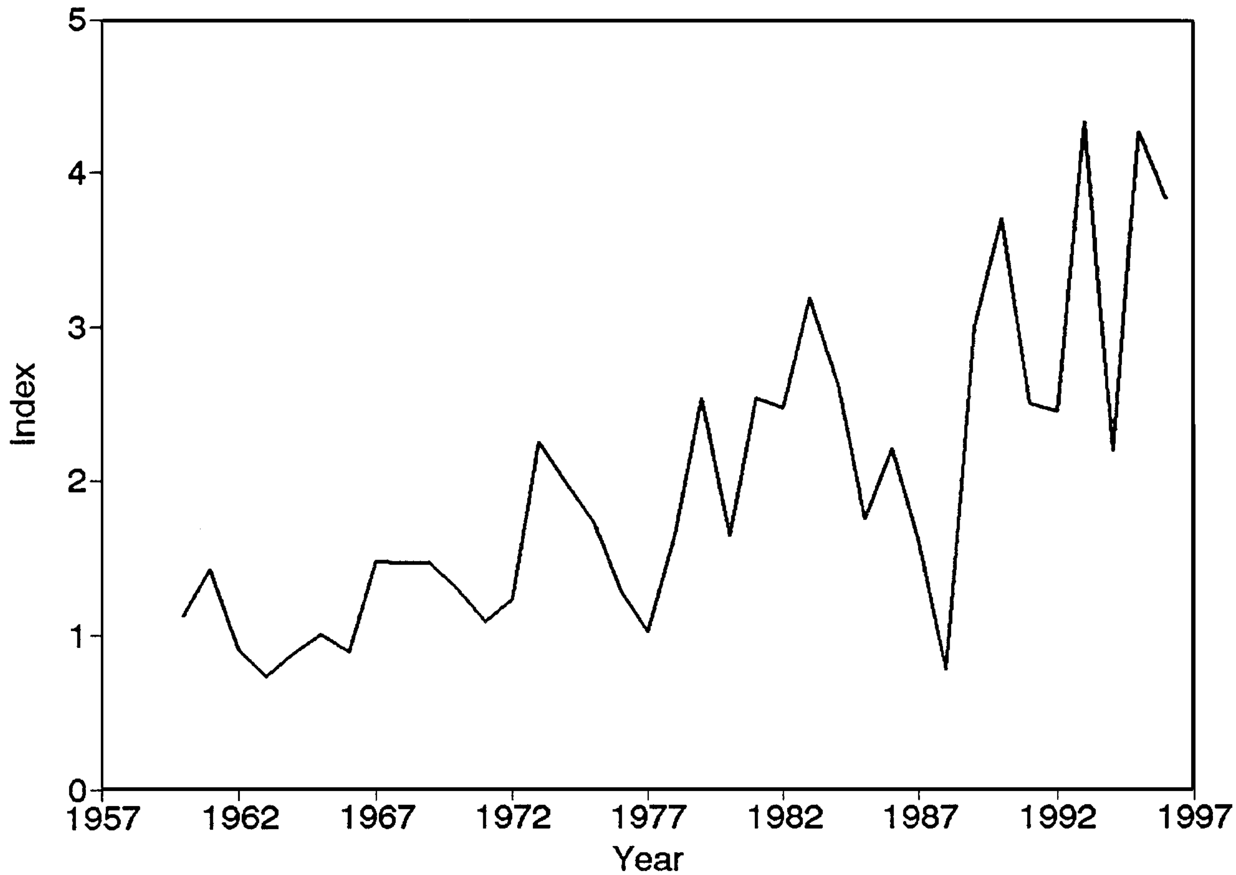

FIGURE 2.1. Hypoxia index used in the economic analysis.

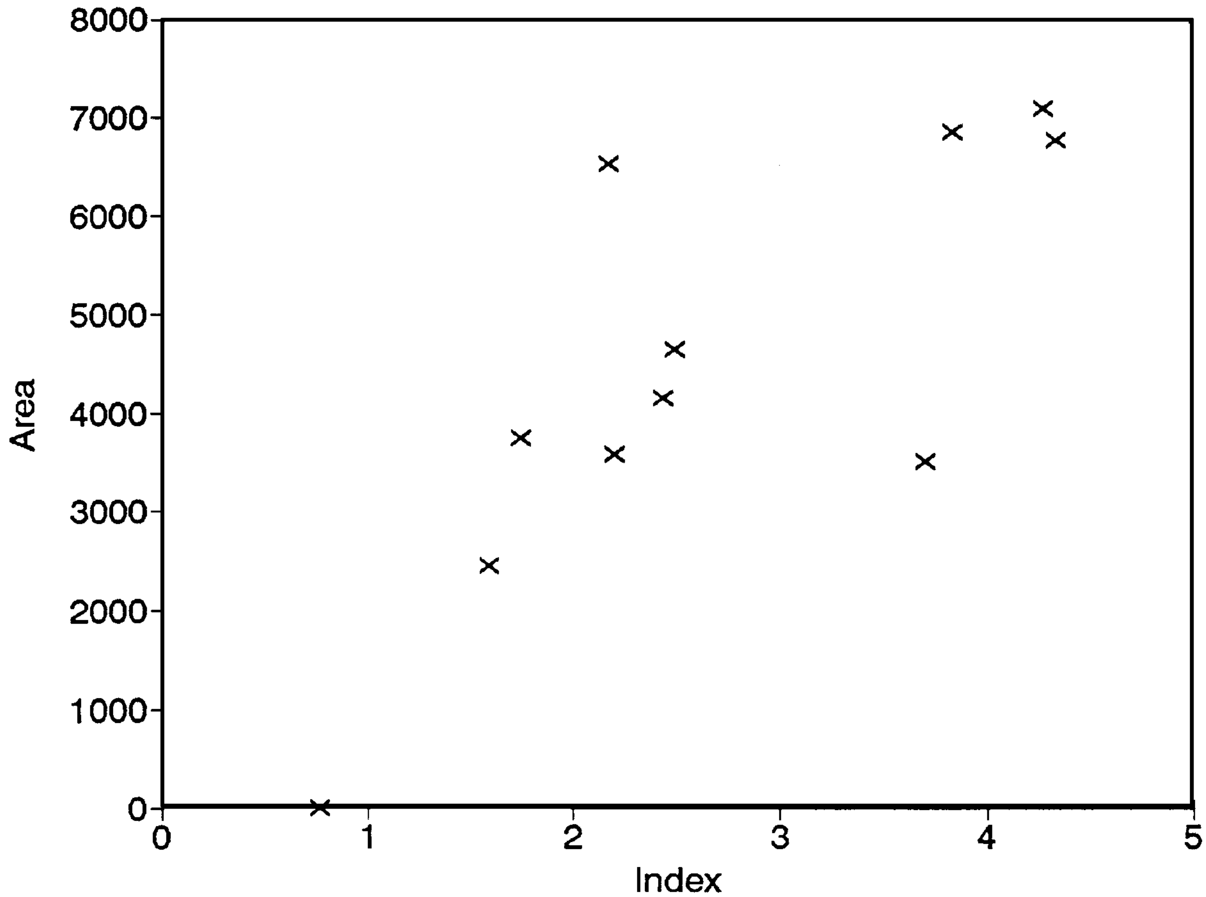

FIGURE 2.2. Plot of measured hypoxic area vs. hypoxia index used in the economic analysis.

2.3 MEETINGS AND WORKSHOPS

A series of meetings and workshops dealing specifically with hypoxia-related issues provided insight and data regarding recent changes to the global picture and the northern Gulf of Mexico. The participants in these meetings were very helpful, and many provided relevant insight into the ecological and economic effects of hypoxia (Table 2.1).

As part of the CENR assessment, we formed two hypoxic effects working teams that specifically provided insight and data on the Gulf of Mexico ecological and economic dynamics. We met and communicated with our teams through the process of developing this assessment. All members are listed in the Acknowledgments section in the beginning of this report.

CHAPTER 3

Results

3.1 BACKGROUND OF HYPOXIA AS A GLOBAL ENVIRONMENTAL PROBLEM

3.1.1 Nutrients, Eutrophication, and Hypoxia

Excess nutrient loading leads to eutrophication of coastal seas, a widespread problem around the globe in general (Nixon 1980, 1995; Howarth et al. 1996). The primary factor driving this marine coastal eutrophication is an imbalance in the nitrogen cycle that can be directly linked to increased population whether through urbanization in coastal river drainages or expanded agricultural activities. In many areas hypoxia follows from eutrophication, which results from the underlying nutrient problem. An examination of the distribution of hypoxic zones around the world showed that they were closely associated with developed watersheds or coastal population centers that deliver large quantities of nutrients to coastal seas, with nitrogen being the most important nutrient. (See the Topic 1 report, *Characterization of Hypoxia*, and the Topic 3 report, *Flux and Sources of Nutrients in the Mississippi–Atchafalaya River Basin.*) Although agriculture and, to a much lesser degree, industry are regarded as the key causes, population growth and rising living standards are in fact driving the need for industry and agriculture to produce.

The scenario linking nutrient additions to the formation of hypoxia and impacts to fisheries via eutrophication can be summarized as follows. Excess nutrients lead to increased primary production, which is new organic matter added to the ecosystem. Because shallow estuarine and coastal systems tend to be tightly coupled (benthic–pelagic coupling), much of this organic matter reaches the bottom. This increased primary productivity may also lead to increased fisheries production (Caddy 1993). At some point, however, the ecosystem's ability to process organic matter in a balanced manner is exceeded, and if physical dynamics permit stratification, water quality is degraded and hypoxic conditions develop. Initially, the increased fisheries production may offset any detrimental effects of hypoxia. But as eutrophication increases and hypoxia expands in duration and area, the fisheries production base is affected and declines. This graded reaction to the combined problems of excess nutrients and hypoxia has been documented for many systems around the globe.

The linkage of the Mississippi River and northern Gulf of Mexico continental shelf has led to a highly productive system that yields significant landings of fish and shellfish to the region. Annual landings have exceeded 1 billion pounds since 1969 (U.S. Department of Commerce Fishery Statistics; see Holliday and O'Bannon 1997 as an example). In the Caddy (1993) model that relates fishery yield to nutrients supplied, the northern Gulf of Mexico is currently somewhere in the eutrophic category (Figure 1.1). To a point, nutrient enrichment may increase fishery yields; but beyond a certain level, it is negative in effect (Caddy 1993).

3.1.2 Oxygen Budgets Around the Globe

The dissolved oxygen conditions of many major coastal ecosystems around the world have been adversely affected through the process of eutrophication. Most of these coastal systems recorded a steady (monotonic) decline in dissolved oxygen through time, in most cases starting from initial oxygen measurements, usually in the 1950s (Rosenberg 1990). For systems that have historical data from the turn of the century, the declines in oxygen levels started in the 1950s and 1960s. However, for the Baltic Sea, declining dissolved oxygen levels were noted as early as the 1930s (Fonselius 1969).

From a historical perspective it is clear that many of the systems that are currently hypoxic were not when they were first studied. The best examples of systems with long-term data come from Europe, where it can be seen that benthic hypoxia was not reported prior to the 1950s in the Baltic Sea (Fonselius 1969), 1960s in the northern Adriatic (Justić 1987), 1970s in the Kategatt (Baden et al. 1990), and 1980s on the Northwest continental shelf of the Black Sea (Mee 1992). Except in areas of natural upwelling, coastal hypoxia is not a natural condition.

By the 1970s ecosystems around the world were becoming saturated with organic matter, and many of them manifested hypoxia for the first time. Once it had occurred, hypoxia quickly became an annual event and a prominent feature that controlled ecosystem energy flow (Diaz and Rosenberg 1995). From the 1980s to the present, the distribution of hypoxia around the world has not appreciably changed. Only in systems that have experienced intensive regulation of nutrient inputs have oxygen conditions improved. There are many examples of small-scale hypoxia reversals associated with improvements in treatment of sewage and pulp mill effluents (Rosenberg 1972, 1976).

In the United States, the improved water quality in Lake Erie is the best example and evidence that large ecosystems do respond positively to nutrient regulation, but that the time interval for achieving noticeable improvements many be long (Boyce et al. 1987; Charlton et al. 1993). The extent of hypoxia in Lake Erie was similar between 1970 and 1990, despite the reduced nutrient loads. The delayed improvement in oxygen conditions may be consistent with mechanisms and processes that contribute to the ecosystem's resilience (Charlton et al. 1993). Improvements in oxygen may not be noticed for decades and could be complicated by climatic changes (DiToro and Blumberg 1990). The Lake Erie example points to the need to have knowledge of a system's response to the complex problems associated with eutrophication before conclusions can be drawn as to the effectiveness of management actions.

3.1.3 System Potential for Hypoxia

Because of their geomorphology and circulation patterns, some marine systems have a greater tendency for hypoxic conditions to develop. The basic features of a system that make it prone to hypoxia are low physical energy (tidal, currents, or wind) and large freshwater input. These features combine to form stratified or stable water masses near the bottom that become hypoxic when they are isolated from reoxygenation with surface waters. The first investigations of bottom water quality in Chesapeake Bay in the 1930s reported hypoxia in deep channel areas of the mainstem (Newcombe and Horne 1938). In Mobile Bay there are accounts of "Jubilees"—likely hypoxia-related then as they are now (Schroeder and Wiseman 1988)—from the 1860s (J. Pennock, personal communication). Better mixed or flushed systems do not have a tendency toward hypoxia. The Baltic Sea and the Kattegat showed no historical tendency toward hypoxia (Pearson et al. 1985; Elmgren 1989). It was not until the 1950s and 1970s, respectively, that oxygen was found to be a problem, even though there were oxygen readings in both systems that go back to the turn of the century (Rosenberg unpublished data). Similarly, the northern Adriatic, with oxygen data from the 1910s, did not exhibit hypoxia until the 1960s (Justić 1987).

A historical picture of oxygen conditions for the northern Gulf of Mexico, derived from reading the geochronology of sediment cores, indicates that hypoxia was most likely not a prominent feature of the shallow continental shelf prior to the 1950s (Rabalais et al. 1996 and Sen Gupta et al. 1996 in the Topic 1 report, *Characterization of Hypoxia*). A longer (2,000-year) geochronology done in Chesapeake Bay pointed to early European settlement of the Bay's watershed as a key feature that led to changes in most paleoenvironmental indicators and set the stage for current oxygen problems as much as 300 years ago (Cooper and Brush 1991).

3.1.4 Type of Hypoxia, Severity, and System Response

Annual summertime hypoxia was the most common form of low dissolved oxygen event recorded around the globe (30 of 47 known anthropogenic hypoxic zones, Diaz and Rosenberg 1995). So in this respect, the northern Gulf of Mexico is not unique. Interestingly, the degree of obvious ecological and economic effects related to the hypoxia varies from system to system. The most serious ecological and economic effects of the combined problems of eutrophication and hypoxia are seen in the Black Sea and Baltic Sea, where demersal trawl fisheries have been either eliminated or severely stressed (Mee 1992; Elmgren 1984). A comparison of effects from three similar coastal hypoxic zones with the Gulf indicates that, at least for now, significant declines in fishery production attributable to hypoxia have not been documented for the Gulf of Mexico (Table 3.1).

In the Kattegat, the sea between Denmark and Sweden, indications of troubled waters were seen by the mid-1970s (increased frequency of algal blooms), with seasonal summertime hypoxia observed since the early 1980s. Initially, hypoxia caused mass mortality of commercial and noncommercial species. Now large-scale migrations and/or mortality among demersal fish and the Norway lobster (*Nephrops*) continue, resulting in a changed species composition and reduced growth and biomass. Hypoxia in this area is believed to be partly responsible for the overall decline in the stock size, recruitment, and landings of commercial fish over the last two decades (Baden et al. 1990, Pihl unpublished data). However, hypoxia is not the only stress factor. Other factors implicated in declining stocks or populations are eutrophication (Caddy 1993), bycatch (Andrew and Pepperell 1992; Chesney et al. in press), trawl disturbance (Currie and Parry 1996), fishing pressure (Turkstra et al. 1991), habitat loss (Chesney et al. in press), and harmful algal blooms (Karup et al. 1993). Given the complexity and potential synergism of stressors, the effects of hypoxia are more clearly expressed in other coastal systems around the world than the northern Gulf of Mexico. Like the Gulf of Mexico, many systems around the world have gradually become eutrophic and hypoxic, but other systems have reached a point were fisheries are clearly negatively affected.

If hypoxia in the Gulf gradually increased in size and duration from its inception—most likely in the 1950s (Sen Gupta et al. 1996)—then the ecosystem's response may also have been gradual and to date not catastrophic. In this scenario the northern Gulf of Mexico ecosystem, while certainly affected by hypoxia and other stressors, has for the last few decades maintained fishery production at a level that we have not been able to distinguish from that experienced previously (Chesney et al. in press). Any scenario that had hypoxia appearing suddenly would have precipitated an ecosystem response similar to the 1976 hypoxic event off the coast of New York/New Jersey, which caused mass mortality of many commercial and noncommercial species (Azarovitz et al. 1979; Boesch and Rabalais 1991). While mass mortality events have been reported in the northern Gulf of Mexico (McEachron et al. 1994), current ecological conditions and lack of any recorded hypoxia-related mass mortality of fishery species, other than "Jubilees," tend to support the scenario of hypoxia developing gradually through time.

TABLE 3.1. Comparison of ecological and economic effects of anthropogenic hypoxic zones from coastal seas around the globe that are similar to the northern Gulf of Mexico hypoxic zone.

System	Area Affected *(km²)*	Benthic Response	Benthic Recovery	Fisheries Response
Louisiana Shelf	15,000	Mortality	Annual	Stressed, but still highly productive. No reports of mortality, except “Jubilees.”
Kattegat, Sweden–Den-	2,000	Mass Mortality	Slow	Collapse of Norway lobster, reduction of demersal

mark				fish. Hypoxia prevents recruitment of lobsters.
Black Sea Northwest Shelf	20,000	Mass Mortality	Annual	Loss of demersal fisheries; shift to planktonic species.
Baltic Sea	100,000	Eliminated	None	Loss of demersal fisheries; shift to planktonic species. Hypoxia is bottleneck for cod recruitment

NOTE: Data are from various sources cited in text.

3.2 NORTHERN GULF OF MEXICO—ECOLOGICAL ANALYSIS OF HYPOXIA

From an ecological standpoint, hypoxia in the northern Gulf of Mexico has become one of the many factors that at present control or influence the population dynamics of the regions of many pelagic and benthic species (Chesney et al. in press). Hypoxia exerts its control at two levels:

- First, and most obvious, is the loss of bottom and near-bottom habitat through the seasonal depletion of oxygen levels. From all indications, few if any, mobile organisms stay on bottoms that are hypoxic (Pavela et al. 1983; Leming and Stuntz 1984). This forced movement could increase population losses due to predation of species dependent on the seabed for their survival. But when hypoxia dissipates, mobile organisms return (SEAMAP database).
- Second, and not so obvious, is the alteration of energy flows. During hypoxia, significant amounts of the system's energy are shunted to microbial decomposition (Rosenberg and Diaz 1993; Grant et al. 1995), the primary biological process that creates and maintains the hypoxia. In the northern Gulf of Mexico the major sources of this energy seem to be organic matter produced in the surface waters and benthic biomass (mostly small worms, snails, and clams) (Harper et al. 1991; Rabalais et al. 1993, 1995). Energy flows between trophic levels (mediated largely by predator/prey interactions) are also altered. In Chesapeake Bay, demersal fish and blue crab abruptly stopped feeding when dissolved oxygen declined below approximately 2.1 mg/l (Nestlerode and Diaz 1998). But they quickly returned to affected areas when hypoxia dissipated, and resumed feeding activity before stressed infauna were able to return to normal living positions in the sediment (Pihl et al. 1992). Breitburg et al. (1997) also found hypoxia altered predator–prey interactions to affect the survival of larval fish.

Considering all the potential sources of stress to the Gulf ecosystem, the most likely contemporary ecological impacts of hypoxia involve altered energy flows and community structure. Annual hypoxia affects energy flows in three primary ways, which unfortunately are not exclusive responses to hypoxia: (1) pelagic species not dependent on direct contact with the bottom take on a more prominent role; (2) energy is diverted from invertebrates to microbes (Pearson and Rosenberg 1992); and (3) the pulsing of energy flow through the ecosystem favors opportunistic species with shorter life cycles, which can take advantage of the shortened time bottom habitats are available. A reduction in the overall biodiversity of the ecosystem is also associated with energy-pulsed systems, since longer-lived species tend to be eliminated (Odum 1981). The first point, enhancement of pelagic species, is a basic ecosystem response to eutrophication and not hypoxia; the third point is a response to the hypoxia; and the second point is a response to both.

3.2.1 Zooplankton and Hypoxia

Zooplankton are an important trophic link between primary production and fisheries species, particularly for larvae, and also contribute to the flux of organic matter to the bottom through the sinking of fecal pellets. Unfortunately, the effects of hypoxia on zooplankton are not very well understood. In addition to mortality, which reduces their population numbers, the documented responses of zooplankton to hypoxia are avoidance for adults, interference with vertical migration, and changes in the composition of smaller species that carry their eggs (Powers 1997; Zaitsev 1992; Qureshi 1995; Stalder and Marcus 1997). Copepods, the dominant zooplankton in the northern Gulf of Mexico, were lower in abundance or absence when dissolved oxygen was <1 mg/l (Qureshi 1995). A similar reaction to hypoxia has been documented in Chesapeake Bay (Roman et al. 1993). While scant data indicate that there may be some avoidance of hypoxia and interference with vertical migration (Powers 1997; Qureshi 1995), the overall abundance and community composition of zooplankton populations appear to be similar to other coastal areas.

3.2.2 Benthic Communities and Hypoxia

The response of northern Gulf of Mexico benthic communities to hypoxia—primarily noncommercial species, which form the base of the food web for shrimp and most demersal fish—has been similar to that of communities from other systems around the globe. In all cases of summertime hypoxia, varying degrees of benthic community mortality were reported, with recolonization of the bottom after hypoxia dissipated. (For Gulf studies, see Gaston 1985; Murrell and Fleeger 1989; Harper et al. 1991; Rabalais et al. 1991, 1993, 1995; Gaston et al. 1998; Vittor & Assoc. 1998. For global studies, see Diaz and Rosenberg 1995.)

There are no historical benthic data sets that can be used for a comparison of pre- and post-hypoxic conditions. The earliest data come from a series of surveys from 1951 to 1957 of the Louisiana–Texas continental shelf by Parker (1960), which mostly described the large fauna (molluscs, echinoderms, crustaceans) associated with shelf regions. Most of the species that Parker (1956, 1960) listed as common were collected by various recent studies (summarized in appendix C of Gaston et al. 1998), but because of gear differences and area sampled, direct quantitative comparison was not possible. The small opportunistic bivalve *Mulinia lateralis* stands out as having been recorded as a dominant component of the fauna in shallow muddy areas in the 1950s and in the 1980s–90s.

Recent data on benthos in the northern Gulf of Mexico come mostly from areas on the eastern side of the hypoxic zone, but showed general signs of hypoxic stress that are most likely found throughout the hypoxic zone. Mortality of benthos was the prominent effect, with the degree of mortality directly related to the severity of hypoxia (Boesch and Rabalais 1991; Rabalais et al. 1993, 1995). Giammona and Darnell (1990) studied the effects of brine discharge on benthos and found that the community around the brine diffuser experienced less mortality due to the mixing effect of the diffuser, which did not allow the dissolved oxygen to decline as much relative to areas away from the diffuser. Areas that experience severe hypoxia, with near-anoxic conditions, experienced greater mortality and had fewer species and lower biomass than areas with intermittent or less severe hypoxia (Table 3.2). Even though mortality from hypoxia was widespread, no study of Gulf benthos has recorded azoic bottom. Recolonization of benthos, while variable from year to year, appeared to occur annually.

TABLE 3.2. Comparison of benthic community structure for areas within the hypoxic zone experiencing different levels of hypoxia.

Season and Severity of Hypoxia	Abundance *(inds. m-^{2})*	Biomass *(g AFDW m-^{2})*	Species *(no. 0.1 m-^{2})*
Hypoxia Intermittent, Not Severe			
Spring 1990	8,600	2.6	22
Fall 1990	1,400	0.4	12
Spring 1991	2,900	0.9	16
Hypoxia Prolonged and Severe			
Spring 1990	18,400	2.9	51
Summer 1990	700	0.2	4

Spring 1991	6,500	1.6	22
Summer 1991	1,300	0.5	8

Source: Rabalais et al. 1995.

In 1980, the Louisiana Department of Wildlife and Fisheries started a long-term benthic monitoring program to investigate the possible effects of oil activities associated with the Louisiana Offshore Oil Port (LOOP). Two study areas located in the Gulf were subjected to hypoxia and provided insight into how benthos respond in the long term. While both study areas were 27 km apart, the shallower nearshore site experienced more frequent and more severe hypoxia than the deeper offshore site on the offshore edge of the hypoxia. Recruitment at the nearshore stations was pronounced and occurred mainly in the spring. Bivalves (mostly *Mulinia lateralis*) dominated the spring pre-hypoxia recruitment, with polychaetes (mostly *Paraprionospio pinnata*) dominating the summer and fall post-hypoxia recruitment. At the offshore stations recruitment was not pronounced and tended to occur in the summer (Table 3.3). While hypoxia was more severe at the nearshore area, it also had higher densities of organisms relative to the offshore area (Table 3.3). However, much of the difference between the nearshore and offshore areas could also be related to timing of recruitment or differences in predation pressure, depth, and/or sediment type. Considering this mix of physical and biological processes that are known to affect community structure, the lack of obvious long-term hypoxic effects on benthic community structure is not surprising. The LOOP study also did not find any benthic effects attributable to oil development activities (Vittor & Assoc. 1998). Most of the dominant species reported are opportunists, which are tolerant of a wide range of environmental stressors, including hypoxia (Diaz and Rosenberg 1995), and adapted to rapidly recolonize disturbed areas (Boesch and Rosenberg 1981).

TABLE 3.3. Long-term average benthic community structure statistics from the 14-year LOOP (Louisiana Offshore Oil Port) study. Quarterly sampling started in November 1980 and ended in 1993.

Station/Season	Hypoxic Seasons[1]	Average Dissolved Oxygen	Average Taxa	Average Inds. (m^{-2})
Nearshore Brine Diffuser Stations[2]				
Winter	0	6.3	56	4,300
Spring	5	2.9	56	6,100
Summer	7	2.6	33	2,400
Fall	0	6.2	46	2,900
Offshore Pumping Station Complex[3]				
Winter	0	5.4	50	700
Spring	0	6.0	62	800
Summer	3	4.0	61	1,400
Fall	7	3.2	53	900

[1]Hypoxic seasons refers to the number of times hypoxia occurred during each of the seasons from 1980 to 1993. There was a maximum of 14 seasons for the nearshore area and 13 seasons for the offshore area.

[2]The Nearshore Brine Diffuser area had four stations, whose averages were based on 53 quarterly collections. The stations were about 6 km from shore, on the inshore edge of the hypoxic zone, for 9 of 14 years, from 1980 to 1993 ('81, '82, '86, '87, '80, '90, '91, '92, '93). Depth: 10 m; sediments: 10–23% sand; interstitial salinity: 29–35 psu.

[3]*The Offshore Pumping Station Complex area had three stations, whose averages were based on 50 quarterly collections. The stations were about 28 km from shore, on the seaward edge of the hypoxic zone, for 8 of 13 years, from 1980 to 1992 (’80, ’83, ’85, ’87, ’88, , ’89, ’90, ’91, ’92). Data for 1993 were not given. Depth: 27–34 m; sediments: 5–32% sand; interstitial salinity: 29–35 psu.*

Source: Vittor & Associates 1998.

Overall, the range of abundance reported for hypoxia-stressed bottoms is well within that reported throughout Louisiana's coastal waters (Table 3.4). Comparison of benthic communities between the area affected by hypoxia with those unaffected in nearby Mississippi Sound indicated that a functional shift has occurred, away from a better-developed, late successional stage, "equilibrium"-type community toward an early successional stage disturbance, adapted community (Pearson and Rosenberg 1978; Rhoads and Germano 1986). Few large, long-lived, deep-burrowing species were present in the areas affected by hypoxia, where there are more small, short-lived species (Rabalais et al. 1993, 1995; Gaston et al. 1998; Vittor & Assoc. 1998). This influences the ability of the benthos to process sediments (D'Andrea et al. 1996) and store energy (Diaz and Schaffner 1990). However, there is evidence that shrimp feed heavily on these short-lived species (Harper et al. 1991) and may even benefit from the shift to a smaller-bodied, shallower-dwelling infauna (McTigue and Zimmerman 1998). This basic difference between the LA and MS shallow continental shelf is at least consistent with stress from hypoxia.

TABLE 3.4. Range of abundance recorded for benthic communities around the Gulf of Mexico.

Area	Affected by Hypoxia	Abundance *(Individuals m^{-2})*	Reference
South TX shelf <45 m	No	500–3,700	Flint 1981
Southwest FL shelf	No	1,300–14,200	Phillips et al. 1990
Mississippi–Alabama–Florida, Offshore	???	<100–9,200	Gaston et al. 1998
Mississippi Sound, Offshore	No	800–17,900	Gaston et al. 1998
Mississippi Sound, Estuaries	???	1,100–35,500	Gaston et al. 1998
Offshore Disposal Sites, LA	???	300–26,600	Gaston et al. 1998
Central Louisiana, Offshore	???	<10–12,600	Gaston et al. 1998
Chandeleur–Breton Sounds	No	126–49,100	Gaston et al. 1998
West Hackberry	Yes	300–8,000	Giammona & Darnell 1990
West Hackberry, Offshore	Yes	700–21,800	Gaston et al. 1998
LOOP, Nearshore	Yes	<100–23,000	Vittor & Assoc. 1998
LOOP, Offshore	Yes	<100-6,400	Vittor & Assoc. 1998
West Delta	Yes	1,400–8,600	Rabalais et al. 1995
South Timbalier	Yes	700–18,400	Rabalais et al. 1993

The reduction in numbers of long-lived, deep-burrowing species has a direct negative effect on the linkage between benthic and pelagic communities within the system. Long-lived species tend to be larger than short-lived species and perform two important ecosystem functions. First, they can store large amounts of energy as biomass, buffering the ecosystem against the pulsing of energy (Odum 1981). Second, they burrow deep into the sediments and aid in the cycling of nutrients and other sediment-bound substances (Rhoads 1974). This "aeration" of sediment in turn helps to prevent the buildup of organic matter (Aller and Aller 1998). Without long-lived species, it is more difficult for the ecosystem to regulate and store the energy that comes to the bottom. Energy is then recycled over shorter time intervals because it is passed on to smaller short-lived species that undergo boom-and-bust cycles (very quickly building large populations that crash to near zero when energy is exhausted or other factors come into play, such as predation or hypoxia). Short-lived species are not good biomass revisions for energy and are of minimal help in oxygenating sediments.

3.2.3 Benthic Secondary Production and Hypoxia

As far as benthic communities are concerned, hypoxia takes the bottom out of production for a period of time—possibly as long as half a year for the northern Gulf of Mexico, depending on the duration of hypoxia. (See the Topic 1 report, *Characterization of Hypoxia.*) Mortality of affected communities is obvious, but the question that remains is: Is the overall secondary productivity of the system affected?

The quality and quantity of secondary production are important, since benthic invertebrates are the major prey base for brown shrimp and other bottom-feeding fish and crabs. Unfortunately, there are no measurements from other systems that are directly comparable. In general, however, bottoms that are exposed to extensive periods of anoxia have low annual production (Rainer and Fitzhardinge 1981). The amount of productivity in these severely stressed habitats is a function of how quickly benthos can recruit and grow during periods of normal oxygen.

In a near-anoxic basin—Port Hacking, Australia—productivity was almost 16 times lower than at a nearby station that only experienced hypoxia (Rainer and Fitzhardinge 1981). In Chesapeake Bay, areas that experience anoxia have about half the annual productivity of areas that are only hypoxic. While some areas affected by seasonal anoxia have lower productivity, the trend is inconsistent across habitat types. This results from a combination of duration of exposure to anoxia and rapid recovery of benthos. Annual secondary production of Chesapeake Bay habitats known to experience only seasonal hypoxia was of the same magnitude as habitats that always had normal oxygen levels, although the qualitative nature of the production differed (Diaz and Schaffner 1990; Neubauer 1993).

3.2.4 Loss of Bottom Habitat: An Example of Hypoxic Effects on Shrimp

Hypoxia clearly disrupts the movement and migration patterns of many species. Trawl data from the fishery-independent SEAMAP database (1987, 1988, 1993, 1994) showed a very consistent pattern that whenever dissolved oxygen declined and approached 3 and 1 mg/l, catch of shrimp and fish, respectively, rapidly declined to zero (Figures 3.1 and 3.2).

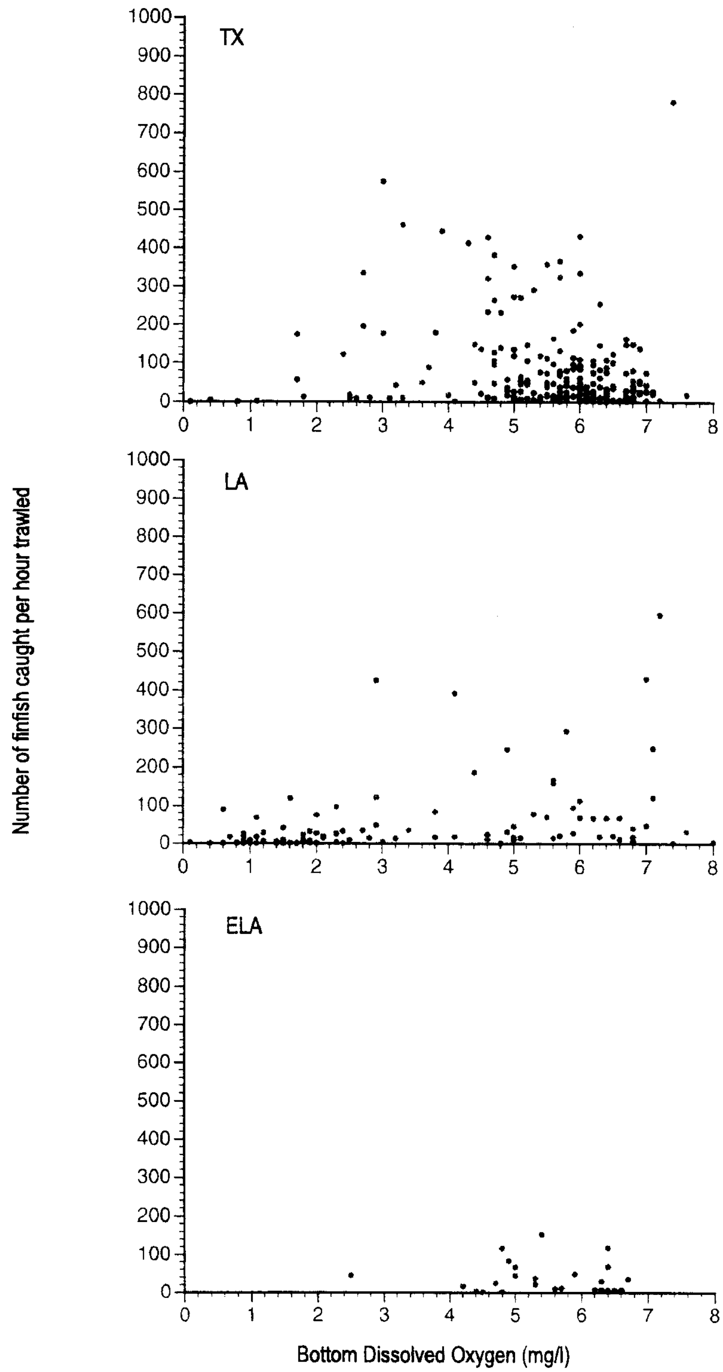

FIGURE 3.1. Total number of finfish caught in summer (July–August) trawls by the SEAMAP program for the years 1987–88 and 1993–94. NOTE: The shelf was divided into three areas: LA = off Louisiana; TX = west of Louisiana, Freeport to Galveston, TX; and ELA = east of Louisiana to Alabama. Data are from the SEAMAP database and have been standardized to numbers trawled per hour.

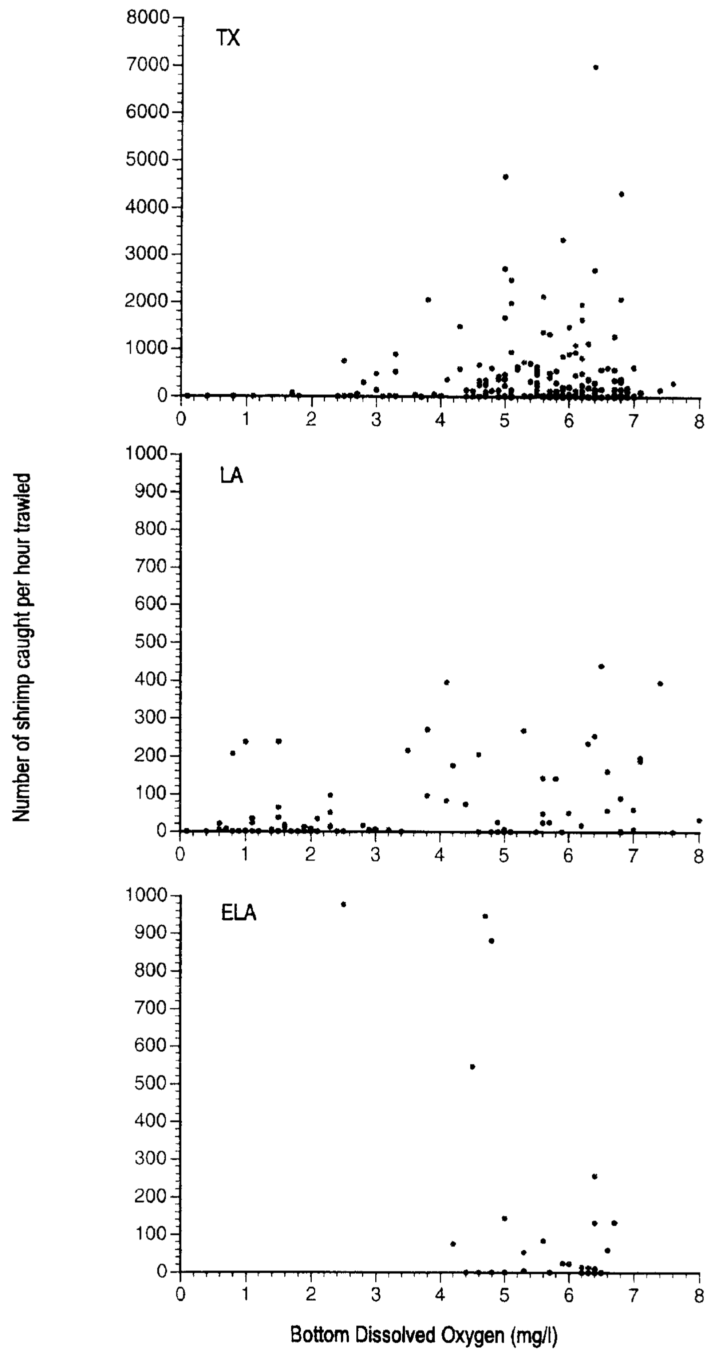

FIGURE 3.2. Total number of penaeid shrimp caught in summer (July–August) trawls by the SEAMAP program for the years 1987–88 and 1993–94. NOTE: The shelf was divided into three areas: LA = off Louisiana; TX = west of Louisiana, Freeport to Galveston, TX; and ELA = east of Louisiana to Alabama. Data are from the SEAMAP database and have been standardized to numbers trawled per hour.

In laboratory experiments, both white and brown shrimp were able to detect and attempted to avoid hypoxic water (<2 mg/l) (Renaud 1986). Because shrimp must move from inshore wetland nurseries to offshore feeding and spawning grounds, hypoxia poses a major problem to their migration. Gazey et al. (1982) found that juvenile brown shrimp leaving marsh nurseries moved farther offshore when hypoxia was not present—an indication that if hypoxia were not present shrimp could exploit more bottom area. Analyses of the distribution of shrimp catch and the localization of catch on the shelf in relation to hypoxia also suggest that hypoxia interferes with shrimp migration (Zimmerman et al. 1996), and where hypoxia was extensive, catch of shrimp was consistently low (Figure 3.3).

The blocking effect of hypoxia on shrimp migration reveals that hypoxia impedes offshore movement, so nearshore abundance of shrimp may be higher. Shrimp are actually capable of moving far distances relative to their small size. Sheridan et al. (1987) reported brown shrimp were capable of moving 1.3–1.6 km/day. The maximum distance traveled was 620 km in 320 days. Hypoxic conditions can easily cause brown shrimp to redistribute hundreds of kilometers to more favorable conditions elsewhere, such as the Texas or Mississippi shelves. A similar blocking effect for bluefish was recorded for the 1976 New York/New Jersey hypoxic event. This event clearly demonstrated that coastal hypoxia cannot only displace demersal fish but can also block the migration of pelagic fish. Northward-migrating bluefish that encountered the hypoxic zone did not pass through or go around it, but stayed to the south, waiting for it to dissipate and then continued their migration north (Azarovitz et al. 1979). If it is important for fish and shrimp to reach critical nursery or feeding areas at certain times in their lives, then hypoxia may have an

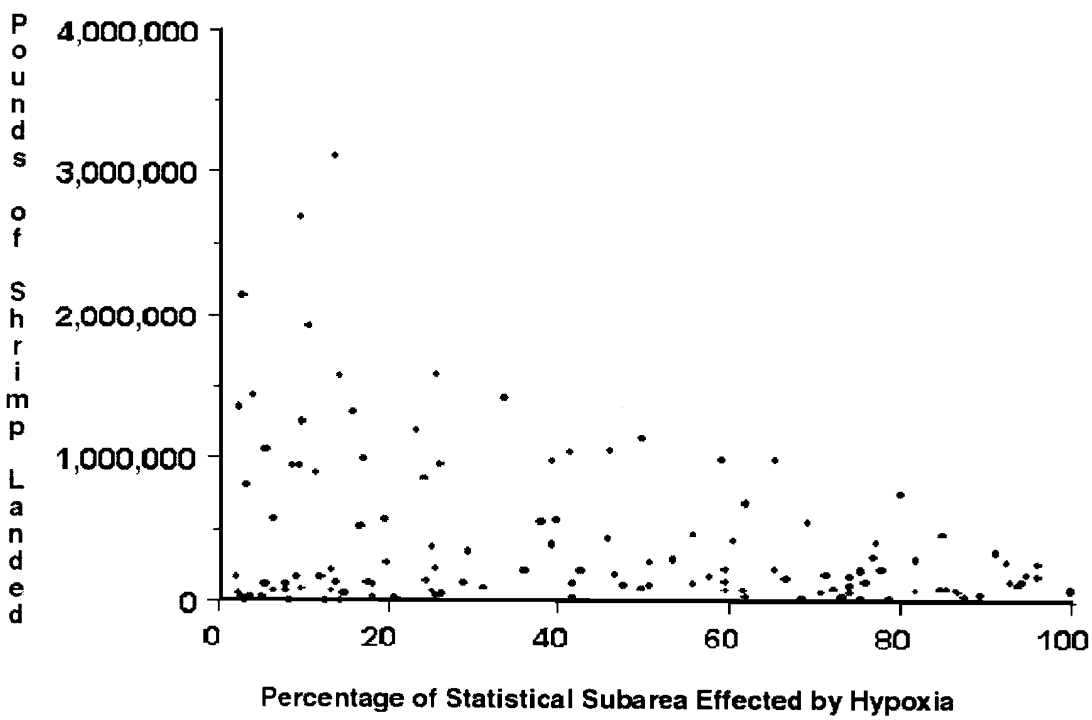

FIGURE 3.3. Pounds of penaeid shrimp landed versus the relative annual occurrence of hypoxia in selected statistical subareas (see Figure 3.4). NOTE: Line is a least-squares regression fit to the data, indicating a significant negative relationship. Data are for the years 1985, 1986, 1990, 1991, 1992, 1993, and 1994. *(From Zimmerman et al. 1996.)*

indirect effect on populations by delaying arrival to spawning or feeding grounds. In such cases, the cost of delayed migration in terms of population mortality and production is unknown.

The brown shrimp catch in the Gulf (mostly caught in Louisiana and Texas) declined from a record high in 1990 to below the historical average during 1992–97. This decline coincides with years of greatly increased hypoxia. By comparison, white shrimp catch within the same area and time period did not exhibit a similar decline. A greater negative effect on adult and large subadult brown shrimp would be expected from enlargement of the hypoxic zone because they require offshore shelf habitat, whereas white shrimp do not (they require nearshore habitat). Thus, the differences in life-cycle requirements are more likely to expose brown shrimp than white shrimp to the offshore effects of hypoxia.

Also, there continues to be the pattern of low shrimp catch and shrimping effort in offshore Louisiana. Geographic comparison of distribution of shrimping effort in Texas and Louisiana shows lower shrimping effort in Louisiana to be coincident with shelf hypoxia. Moreover, although Louisiana's management strategy favors inshore fisheries, it does not preclude offshore shrimping and does not adequately explain the low catch patterns on the Louisiana offshore shelf, where subadult and adult brown shrimp are expected to occur.

3.2.5 Fish Populations

Unfortunately, there have been no studies of how hypoxia affects fish populations in the northern Gulf of Mexico. However, data collected by the SEAMAP program will be instrumental in determining any hypoxic effects. Preliminary analysis of this data set indicates that there may be a herding effect, with higher abundance of fish on the edge of the hypoxic zone (Crowder and Craig, personal communication).

Some effects of hypoxia that have been seen in the Kattegat, Baltic Sea, and Chesapeake Bay are difficult to detect without directed studies, but could occur in the northern Gulf of Mexico. Pelagic eggs of economically and ecologically important species can sink into hypoxic bottom waters and die. For example, oxygen concentrations from 4 to 5 mg/l reduced the survival of cod eggs (Nissling and Vallin 1996). Eggs sinking into hypoxic water is thought to be an important factor that leads to the decline of cod in the Baltic Sea (Nissling et al. 1994) and may be an important source of mortality for Chesapeake Bay anchovy (Kiester et al. unpublished). Habitat restriction can also increase the predation mortality of fish (Breitburg 1992; Breitburg et al. 1997) and can force fish into areas with poor growth potential (Coutant 1985). And hypoxia may increase the incidence of disease and parasitism in exposed fish populations. Mellergaard and Nielsen (1995) found the relative risk of contracting lymphocystis, a viral disease that affects many marine fish worldwide, significantly increased in the Kattegat from 1984 to 1986, compared to 1987 to 1991, years of severe hypoxia.

Also of concern to fisheries populations is the increased incidence of harmful algal blooms in coastal waters resulting from eutrophication (Goldberg 1995). Harmful algal blooms have long been linked to fish kills (Brongersma–Sanders 1957), but recent developments along the Atlantic East Coast indicate how serious they can be (Burkholder et al. 1992). There is also a strong relationship between bloom-related mortality and hypoxia. (See Burkholder et al. 1995 as a recent example. For more details on phytoplankton community changes, see the Topic 1 report, *Characterization of Hypoxia*.)

3.3 NORTHERN GULF OF MEXICO—ECONOMIC ANALYSIS OF HYPOXIA

3.3.1 Economic Analysis of Shrimp Data

As noted, the analysis focused mainly on brown shrimp (*Penaeus aztecus*) and white shrimp (*Penaues setiferus*). The biology and fisheries characteristics of these species are described in detail in the *Fishery Management Plan for the Shrimp Fishery of the Gulf of Mexico, United States Waters* (Gulf of Mexico Fishery Management Council 1981) and in subsequent amendments. The data used in this analysis were extracted from the extensive database of monthly statistics maintained by the National Marine Fisheries Service (NMFS) Laboratory in Galveston, Texas (Poffenberger 1991).

Statistics are maintained for 21 statistical areas (Figure 3.4). The offshore waters of each area are divided into depth zones of 5-fathom increments out to 40 fathoms. In the analysis described here, the statistical areas were grouped into three zones: eastern Louisiana (ELA), covering zones 11 and 12; Louisiana (LA), covering zones 13 through 17; and Texas (TX) covering zones 18 through 21. As the hypoxic zone in the northern Gulf lies within the zone designated as LA, the other two zones serve as a kind of control. It is important to have such a control to distinguish between effects due to hypoxia—which would be confined to LA—and effects due to climatic or other covariates—which could also appear in ELA, TX, or both. The decision to group the statistical areas in this way was based on an extensive analysis of the data for each of the 21 statistical areas. In particular, there is considerable variability between statistical areas, and combining them in this way into zones reduces this considerably, while retaining the value of comparisons between zones.

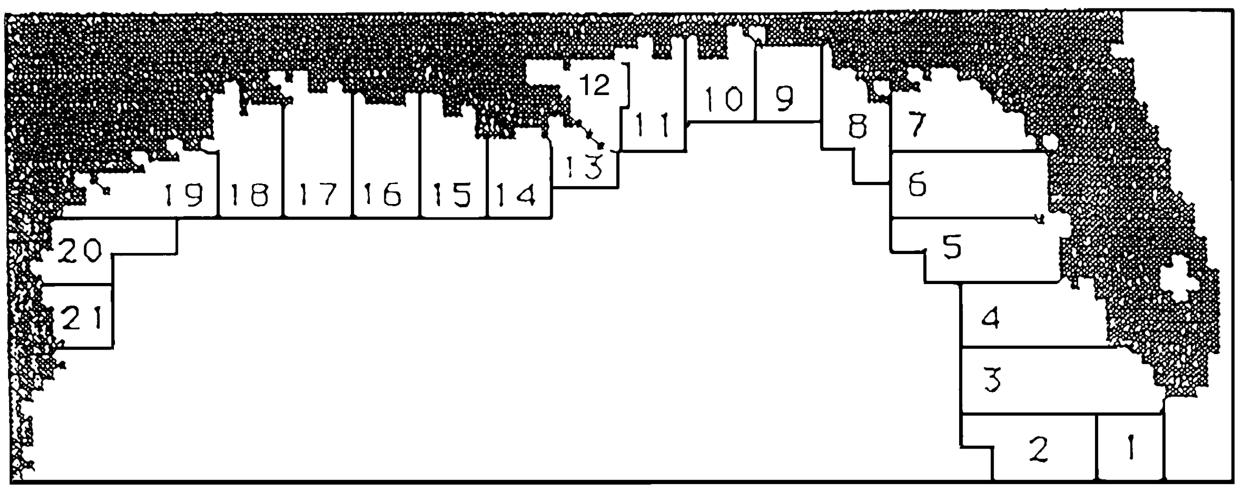

FIGURE 3.4. Boundaries for the 21 statistical subareas established for reporting of fisheries landing in the Gulf of Mexico. NOTE: Data used in the economic assessment came from subareas 11–12 (ELA), 13–17 (LA), and 19–21 (TX).

The analysis involved the calculation of correlations between INDEX and selected fisheries variables for each of the three zones—ELA, LA, and TX. Correlations were based on annual values, although, as with INDEX, the annual values of the fisheries variables were calculated using data for selected months (e.g., brown shrimp CPUE (cost per unit effort) during July–August). As the effect of hypoxia in a particular year may be felt on shrimp in the following year, for certain fisheries variables, both contemporaneous and lagged correlations were calculated, with the largest in magnitude reported below. In the latter case, INDEX lagged the fisheries variable by one year. For completeness, correlations between AREA and the fisheries variables are also presented. However, the time series of AREA was felt to be too short to serve as an adequate basis for empirical analysis, and the analytical effort was directed at the correlations with INDEX.

It is well known that the presence of secular trend can produce spurious correlations or obscure genuine correlations between time series. To avoid this problem, estimated trends were removed from both the INDEX and the fisheries variables by subtracting seven-year moving averages. As noted, this analysis should be viewed as exploratory. The basic idea is that an effect could be attributed to hypoxia if it involved a correlation of reasonably large magnitude that occurred in LA, but not in ELA or TX. To supplement the ordinary correlations, the partial correlation between INDEX and each fisheries variable for LA, with the "effects" of the same fisheries variable in ELA and TX removed, was also calculated. This amounts to treating the time series for ELAand TX as proxies for the effects of climatic and other factors that do not involve hypoxia. This involves the strong assumption that the effects of these factors in LA are linearly related to their effects in ELA and TX.

Although no formal assessment of statistical significance was attempted, as a rough guide, under the unrealistic assumption that each of the individual time series is serially independent, a correlation or partial correlation would have to be around 0.35 in magnitude to achieve significance at the 0.05 level. This critical value would have to be adjusted to account for serial dependence. The assessment of statistical significance would also be complicated by the consideration of so large a number of (not necessarily independent) correlations and by the decision to select (e.g., via the consideration of multiple lags) the largest magnitude correlations.

3.3.1.1 CATCH PER UNIT EFFORT AND HYPOXIA

In Figure 3.5, annual time series of combined July and August catch per unit effort (CPUE) for brown shrimp are shown for the three zones for the period 1960–96. The July–August period covers the most intensive fishing period for this species. Figure 3.6 shows the same time series for white shrimp during the August–September period, which covers the most intensive fishing for this species. In Table 3.5, lag 1 correlations between AREA and log CPUE and between detrended INDEX and detrended log CPUE are reported for each species within each of the three zones. Also reported in Table 3.5 are the partial correlations between detrended INDEX and detrended log CPUE in LA, with the effects of detrended log CPUE in ELA and TX removed. The logarithmic transformation of CPUE reflects the natural assumption of a multiplicative, rather than additive, effect.

The partial correlations (Table 3.5) are the best evidence of a hypoxic effect uncovered in this analysis. While both are rather modest in magnitude, each has the expected sign. However, in this regard, it is important to point out that these estimated partial correlations are not independent of each other and, therefore, cannot be taken as independent pieces of evidence of a hypoxic effect. To illustrate the potential for overinterpretation, the partial correlation between detrended INDEX and detrended log CPUE for brown shrimp in ELA with the effects of LA and TX removed is -0.30. This cannot be attributed to hypoxia, which is absent in ELA.

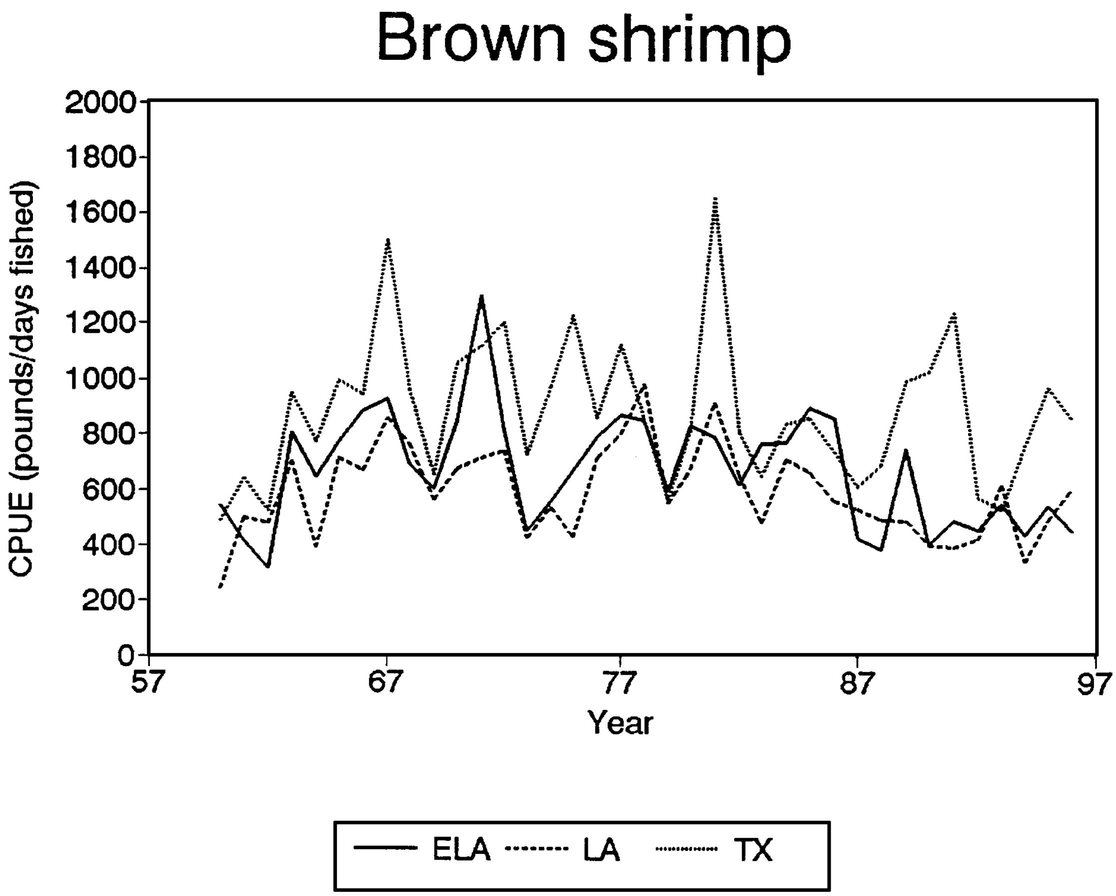

FIGURE 3.5. July–August catch per unit effort (CPUE) for brown shrimp in three fisheries zones.

TABLE 3.5. Lag 1 correlations between July–August log CPUE[1] for brown shrimp and August–September log CPUE for white shrimp and two measures of hypoxia for three zones.

Hypoxia Measure	Zone	Shrimp Species *Brown*	*White*
AREA	ELA	0.18	0.48
	LA	0.14	-0.23
	TX	-0.09	-0.30
INDEX[2]	ELA	-0.35	0.03
	LA	-0.32	0.23
		(-0.23)	(-0.26)
	TX	0.04	0.09

[1]CPUE = catch per unit effort.
[2]In calculating the correlations with INDEX, all time series were detrended by subtracting a 7-year moving average. Also reported in parentheses for each species is the lag 1 partial correlation between

INDEX and log CPUE in LA, with the effects of log CPUE in eastern LA (ELA) and TX removed.

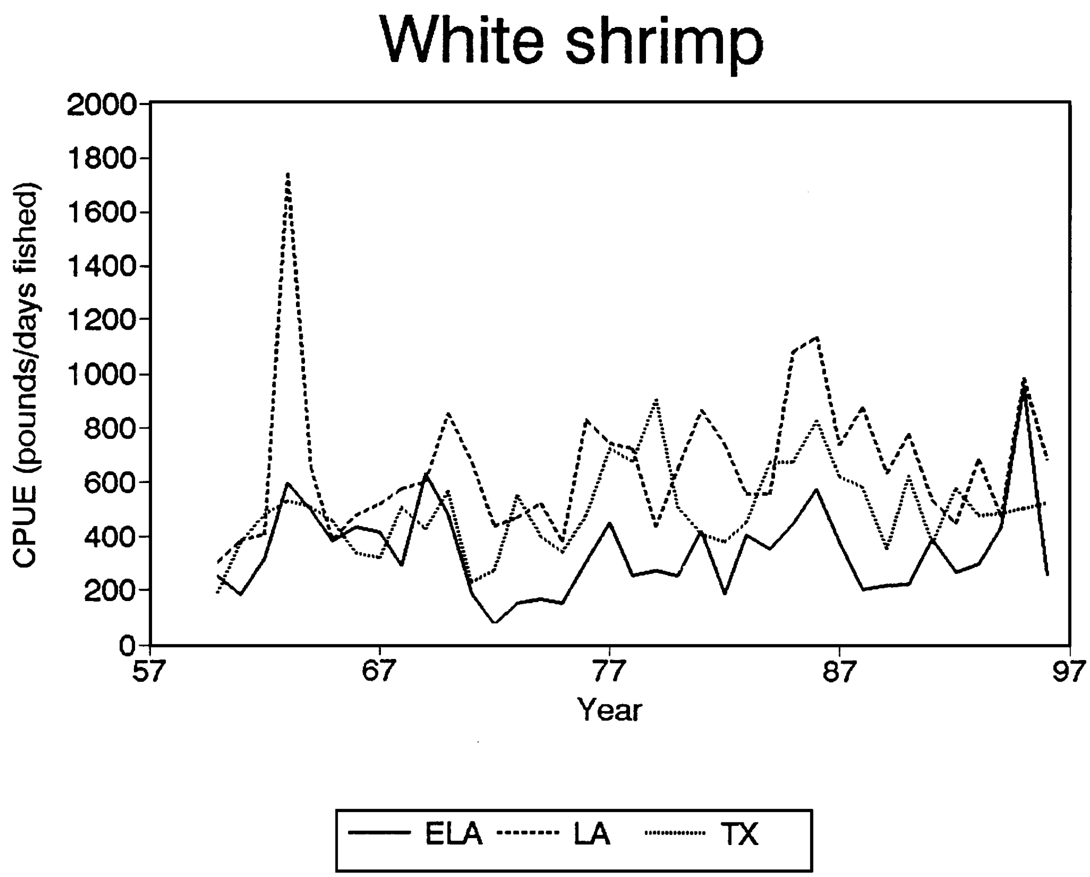

FIGURE 3.6. August–September catch per unit effort (CPUE) for white shrimp in three fisheries zones.

3.3.1.2 DEPTH OF LANDINGS AND HYPOXIA

To address the concern that hypoxia has caused an offshore shift in the distribution of shrimp, thereby increasing the cost of fishing, annual time series of the mean depth of landings (DEPTH) were constructed for brown and white shrimp for ELA, LA, and TX and were correlated with the hypoxia measures. It is worth noting that the assessment of the depth of landings is made separately from the assessment of landings themselves and is, in some ways, rougher. In each year, the value of DEPTH for each species was formed by a weighted sum of the mid-point depths for the eight offshore depth zones. In each year, the weight that each mid-point depth received in this sum is given by the proportion of total landings in that year that were made in the corresponding depth zone. The time series of DEPTH for brown shrimp and white shrimp are shown in Figures 3.7 and 3.8, respectively.

A striking feature of Figure 3.7 is a relatively sharp reduction in DEPTH occurring in 1977 in both ELA and LA. According to information provided by the Louisiana Department of Wildlife and Fisheries, this shift appears to have been due to the closure of inshore waters, resulting in a shift in fishing effort to the shallowest offshore waters. As landings in inshore waters are not included in the calculation of DEPTH, this results in the apparent shift to lower values of DEPTH. This illustrates the importance of removing secular trends: Without it, this shift would almost certainly be attributed to hypoxia.

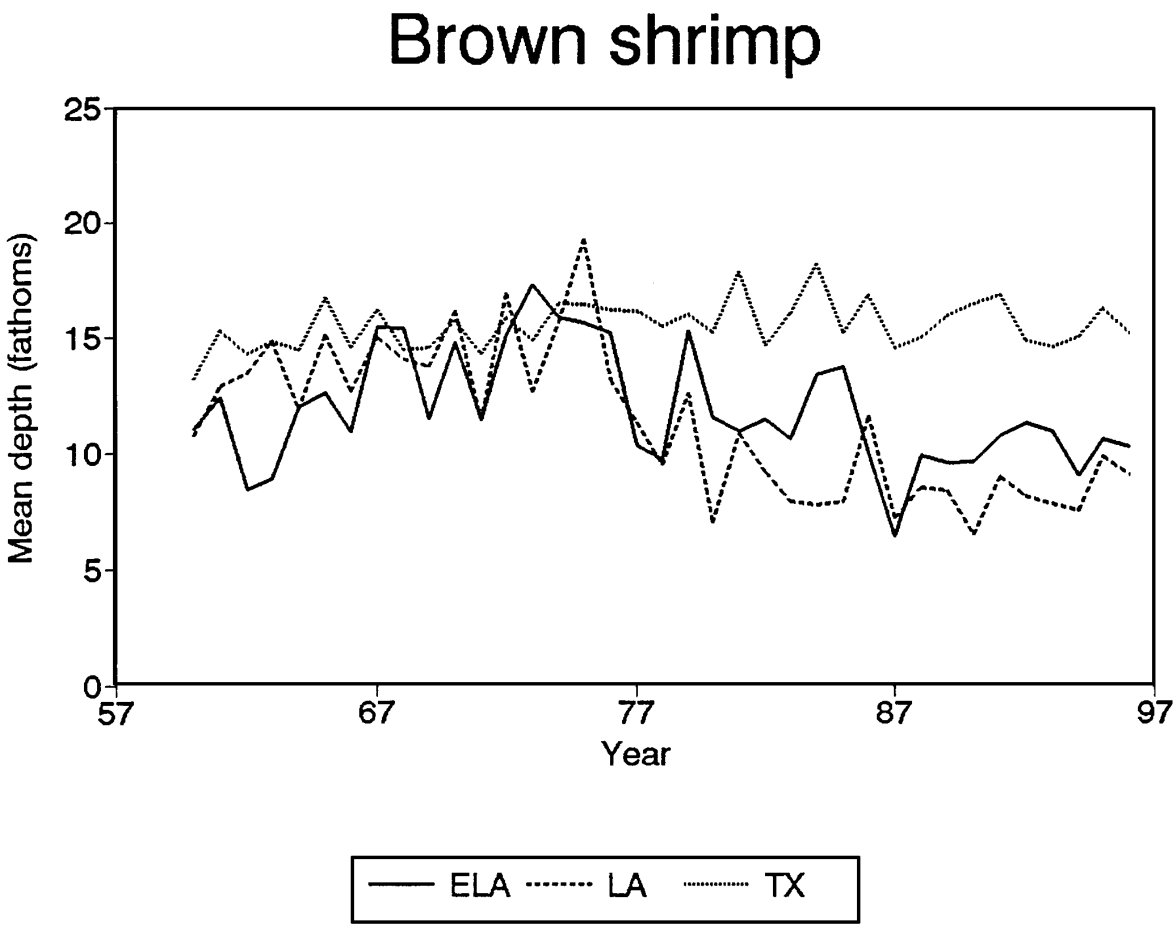

FIGURE 3.7. Average depth of July–August brown shrimp landings in three fisheries zones.

The lag 0 correlations between AREA and DEPTH and between detrended INDEX and detrended DEPTH are reported in Table 3.6, along with the partial correlations between detrended INDEX and detrended DEPTH in LA. The correlations between detrended INDEX and detrended DEPTH are positive in all three zones for brown shrimp and negative for white shrimp. It is notable that for both species this correlation is smallest in LA. As a result, the partial correlations are both negative, suggesting that any hypoxic effect would be to shift harvest toward inshore waters. However, the magnitudes of these partial correlations are small, and it is difficult to attach any significance to them.

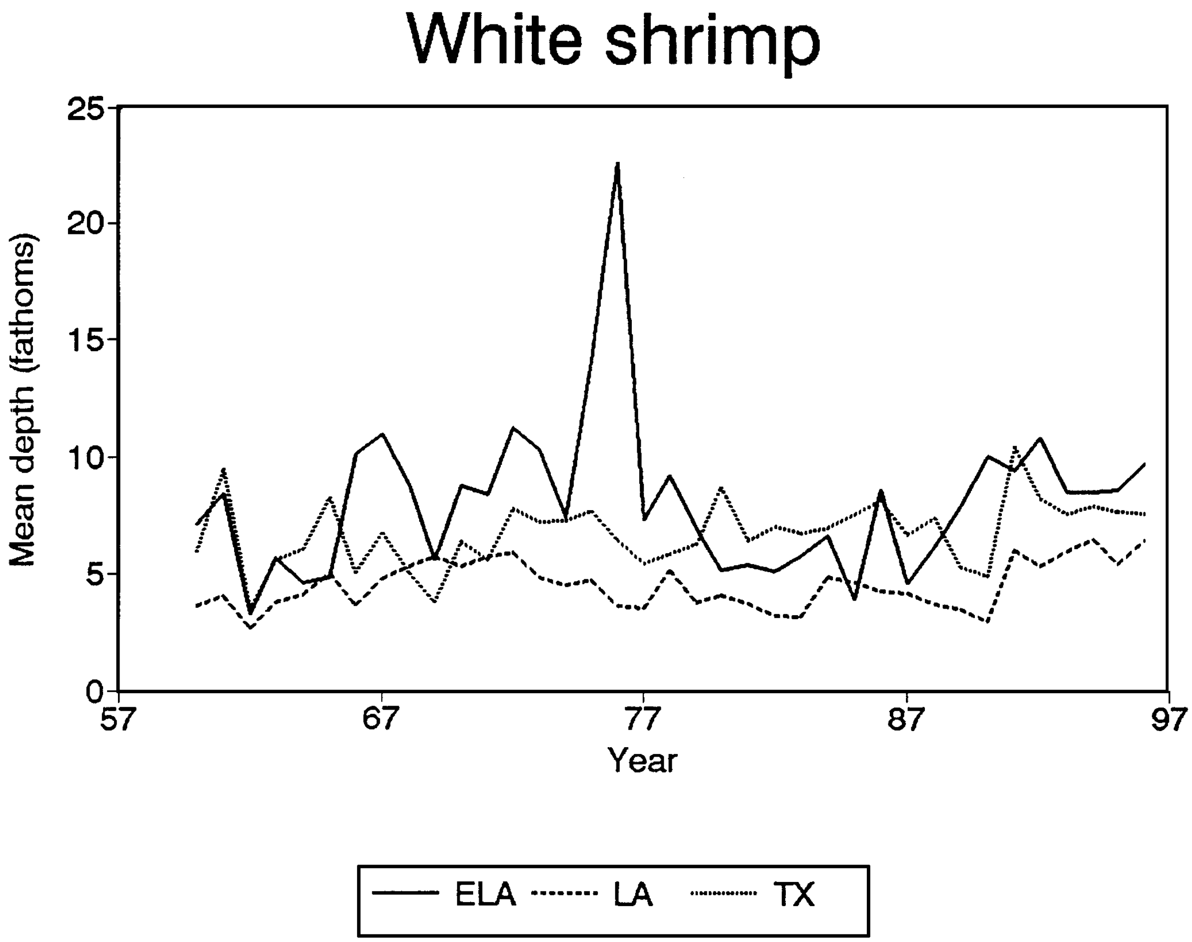

FIGURE 3.8. Average depth of August–September white shrimp landings in three fisheries zones.

TABLE 3.6. Lag 0 correlations between July–August DEPTH for brown shrimp and August–September DEPTH for white shrimp and two measures of hypoxia for three zones.

Hypoxia Measure	Zone	Shrimp Species *Brown*	*White*
AREA	ELA	0.19	0.46
Period: 1985–88,	LA	0.12	0.79
1990–96	TX	0.06	0.21
INDEX [1]	ELA	0.40	-0.05
Period: 1960–96	LA	0.12	-0.17
		(-0.08)	(-0.16)
	TX	0.29	-0.09

[1]In calculating correlations with INDEX, all time series were detrended by subtracting a 7-year moving average. Also reported in parentheses is the lag 0 partial correlation between INDEX and DEPTH in LA, with the effects of DEPTH in eastern LA (ELA) and TX removed.

3.3.1.3 SHRIMP SIZE AND HYPOXIA: SUMMARY

To address the question as to whether hypoxia affects the size of landed shrimp, annual time series of the mean number of shrimp per landed pound (NUMBER), which is inversely related to size, were calculated for July and August landings of brown shrimp and August and September landings of white shrimp in ELA, LA, and TX. These time series are shown in Figures 3.9 and 3.10. It is clear from these figures that there has been an overall tendency for NUMBER to increase for both species in all three zones.

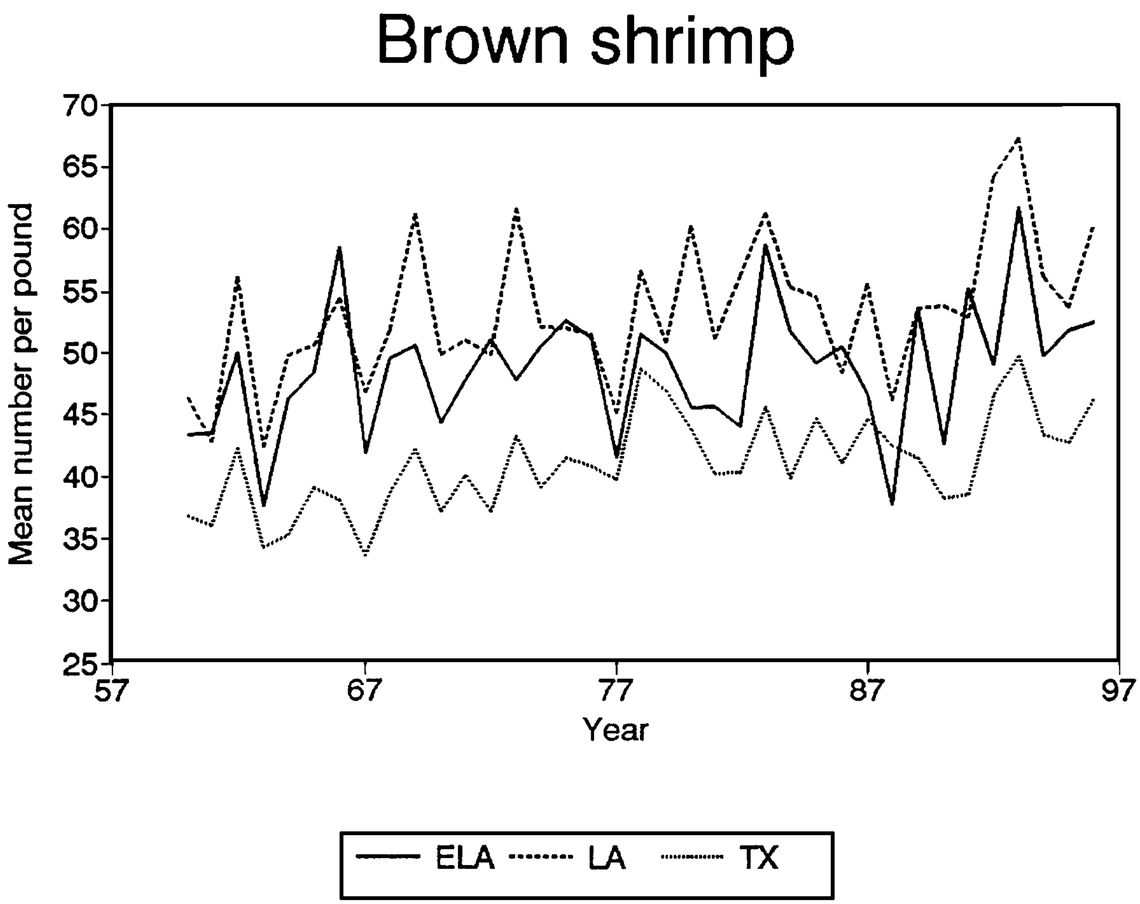

FIGURE 3.9. Average July–August numbers of brown shrimp per landed pound in three fisheries zones.

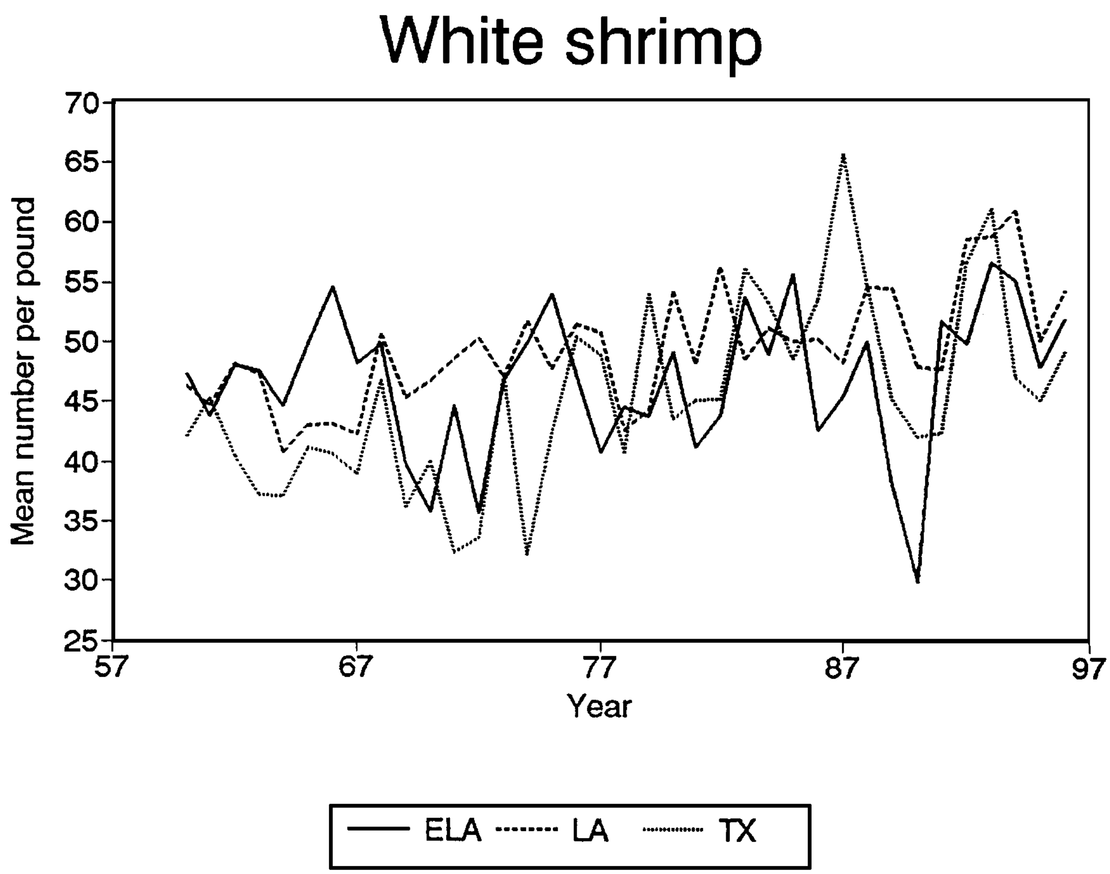

FIGURE 3.10. Average August–September numbers of white shrimp per landed pound in three fisheries zones.

Correlations between AREA and log NUMBER and between detrended INDEX and detrended log NUMBER are given in Table 3.7. For this variable, lag 0 correlations were generally larger in magnitude for brown shrimp, while lag 1 correlations were generally larger in magnitude for white shrimp. The logarithmic transformation reflects the assumption of a multiplicative, rather than additive, effect on growth. Table 3.7 reflects a tendency in both species for the correlation to decline from east to west. The partial correlations between detrended INDEX and detrended log NUMBER for LA, which are also reported in Table 3.7, are small in magnitude and, as with DEPTH, cannot be taken as significant.

3.3.1.4 SHRIMP AND HYPOXIA: SUMMARY

As the analysis of the shrimp data constitutes the bulk of this part of the report, it is worth pausing to summarize the results. However, before doing so, it is also worth briefly restating the underlying logic of the approach.

TABLE 3.7. Correlations between July–August log NUMBER for brown shrimp and August–September log NUMBER for white shrimp and two measures of hypoxia for three zones.

Hypoxia Measure	Zone	Shrimp Species *Brown*	*White*
AREA	ELA	0.80	0.51
Period: 1985–88,	LA	0.62	0.35
1990–96	TX	0.33	0.52
INDEX [1]	ELA	0.35	0.21
Period: 1960–96	LA	0.21	0.10
		(0.15)	(0.10)
	TX	0.06	-0.14

[1]In calculating correlations with INDEX, all time series were detrended by subtracting a 7-point moving average. Also reported in parentheses are partial correlations between INDEX and log NUMBER in LA, with the effects of log NUMBER in eastern LA (ELA) and TX removed.

The goal of the analysis was to relate variations in fisheries data to variations in hypoxia. A fundamental problem is that variation in hypoxic conditions is not the only source of variation in the fisheries data. As a result, it is possible that a hypoxic effect is obscured by variability due to these other sources. While it would be possible, in principle, to control for these other sources of variability, such an analysis would require additional resources. A second serious problem for an empirical analysis is that variation in hypoxic conditions is almost certainly correlated with variation in climatic and other factors that, by themselves, can affect shrimp populations. As a result, even with additional data, it may be extremely difficult to disentangle effects due to hypoxia from effects due to covarying factors.

In an attempt to circumvent these problems, data from zones to the east (ELA) and west (TX) of the main hypoxic zone (LA) were also analyzed. The hope is that these data, which are free of a hypoxic effect, will reflect other sources of variation that are also present in LA. If this hope is well founded, then the time series for ELA and TX serve as a rough control. This notion is formalized in the use of partial correlations, which essentially treat the time series for ELA and TX as proxies for variability not due to hypoxia.

In addition to the problem of multiple, covarying sources of variability, the quality of the data is also open to question. The hypoxia index is certainly far from perfect. There are also problems with the fisheries data. It should be borne in mind that these data were collected for reasons other than the detection of a hypoxic effect.

Unfortunately, the results of this analysis are equivocal. Even in the absence of a formal assessment of significance, from a purely statistical point of view, it is difficult to claim that a significant relationship has been established between the index of hypoxia and the fisheries variables. However, there is a sufficient hint of such a relationship—at least for CPUE—that the possibility cannot be dismissed. Some suggestions for improving this analysis are given below.

3.3.2 Economic Analysis of Menhaden Data

Gulf menhaden (*Brevoortia patronus*) is a pelagic species found in coastal waters throughout the northern Gulf. Adult menhaden feed primarily on phytoplankton. The biological characteristics of this species are described in Nelson and Ahrenholz (1986) and Vaughan et al. (1996). Menhaden are exploited in the northern Gulf through an extensive purse-seine fishery, which is described in detail in Christmas et al. (1988).

During this project, a nonspecific concern was raised about the possible effects of hypoxia on the Gulf menhaden fishery. To address this concern, time series of spawning stock biomass (SSB) (Vaughan, personal communication) and CPUE (Vaughan et al. 1996) were analyzed. The time series for SSB, shown in Figure 3.11, covered the period 1964–89, and the time series for CPUE, shown in Figure 3.12, covered the period 1964–92. Correlations between detrended INDEX and detrended log CPUE and detrended SSB were calculated. As the period of overlap between AREA and these variables is so short, these correlations were not calculated. Both lag 0 and lag 1 correlations were calculated. In no case was the correlation larger than 0.05 in magnitude, and there is clearly no significant relationship between these time series.

It is interesting to note that, despite considerable interannual variability, CPUE for menhaden exhibited no obvious trend during a period in which SSB first increased and then decreased. In other words, CPUE was not proportional to SSB over this period. Vaughan et al. (1996) attributed this to a dynamic aggregation process in schooling species like menhaden (Clark and Mangel 1979), whereby catchability declines with increasing stock level.

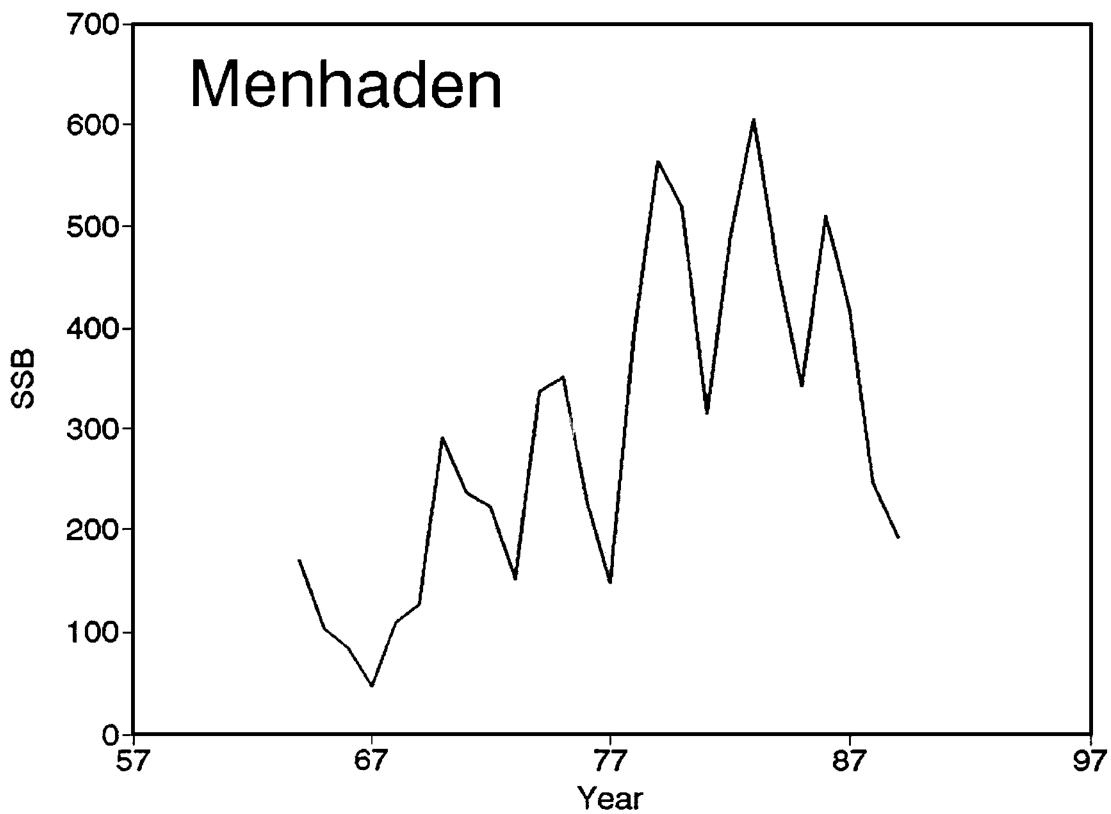

FIGURE 3.11. Spawning stock biomass (SSB) of menhaden in the Gulf of Mexico.

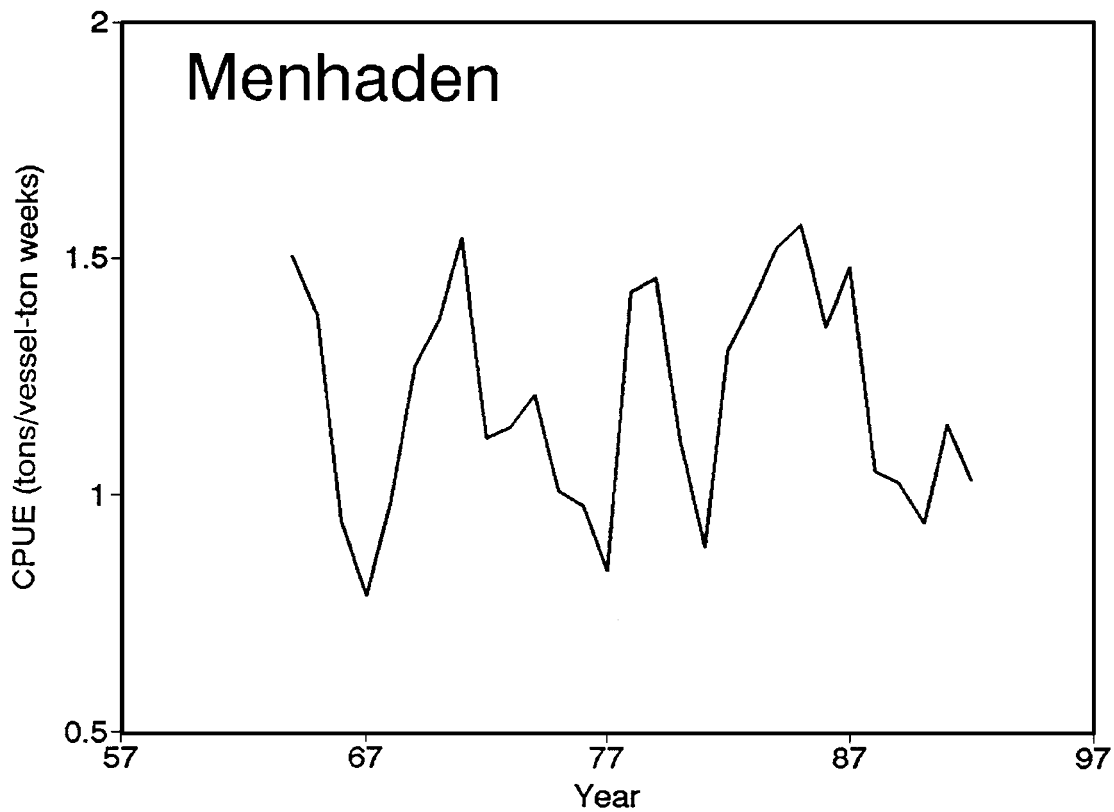

FIGURE 3.12. Catch per unit effort (CPUE) of menhaden in the Gulf of Mexico.

3.3.3 Economic Analysis of Red Snapper Data

Red snapper (*Lutjanus campehanus*) is perhaps the premier food fish in the Gulf of Mexico. The biological and fisheries characteristics of this groundfish are described in Goodyear (1995). During the project, a nonspecific concern was raised about possible hypoxic effects on red snapper. This concern appeared to stem from a dramatic decline in the red snapper stock over the past 50 years. It is important to point out that red snapper have been heavily exploited over that period and the conventional wisdom holds that this decline is due primarily to overfishing. Although it was not possible to undertake as detailed an analysis of data for red snapper as for shrimp and menhaden, the results described here tend to support this conventional wisdom.

Bottom trawl surveys of groundfish have been conducted by NOAA's National Marine Fisheries Service (NMFS) during the fall in the northern Gulf since 1972 (Nichols 1989), and summer surveys have been conducted as part of the SEAMAP program since 1982. The individuals caught in these surveys are typically pre-recruit juveniles, so they should be viewed primarily as measuring recruitment in the following year. These data suggest an overall decline in recruitment during the mid-1980s, with a slight tendency for higher recruitment in the early 1990s. Unfortunately, stock assessment data for red snapper were not available to the project at the time of this writing.

Estimates of commercial landings of red snapper from U.S. waters of the Gulf of Mexico are available for the period 1964–95 (Figure 44 of Goodyear 1995). Commercial landings were stable from 1964 to around 1976, after which they experienced an irregular decline, rebounding slightly in the early 1990s. Gulf-wide estimates of combined commercial and recreational landings of red snapper over the period 1979–94 exhibit a similar trend (Figure 70 of Goodyear 1995). There is also a significant bycatch of juvenile red snapper by shrimp trawls (Nance and Scott–Denton 1997). The rebound in landings after 1990 appears to be due to conservation actions, such as closures (Goodyear 1995). Effort data are only available over the last few years of the record, so it was not possible to perform a time-series analysis of CPUE for red snapper.

The best evidence against a hypoxic effect on red snapper is the spatial distribution of landings (Figure 46 of Goodyear 1995). From 1975 to 1995, landings have been highest in ELA and LA and lower to the east and to the west. Although landings declined generally between 1975 and 1990, the decline was most pronounced in Florida and, to a lesser extent, in Texas. Similarly, the rebound in landings since 1990 has been greatest in Louisiana and particularly in the waters most affected by hypoxia.

CHAPTER 4

Research Needs

4.1 ESTABLISHING A CONCEPTUAL FRAMEWORK

Empirical analysis of the kind attempted here is difficult. Direct, quantitative information about the severity and extent of hypoxia is lacking. For example, the shrimp data, which are certainly among the most amenable to analysis, are still far from perfect. The fisheries—and the shrimp stocks themselves—are subject to a number of factors other than hypoxia, including environmental factors that are almost certainly related to the hypoxia (e.g., climate, temperature). Although the analysis could be improved by the acquisition and use of more data, the problems are, to some extent, fundamental to a purely empirical approach.

In many ways, a more promising approach would involve the use of biological and process-oriented models—for example, Browder (1993) for a biomass model or the Topic 4 report (*Effects of Reducing Nutrient Loads to Surface Waters Within the Mississippi River Basin and the Gulf of Mexico*) for an oxygen budget model. Although the available models were not designed to assess the effects of hypoxia, it may be possible to use them for this purpose. For example, even a relatively simple model may be useful in assessing the effects of hypoxia on the seasonal loss of habitat in the hypoxic region. A more complex model that explicitly incorporates the behavior of shrimp may be useful for assessing the effects of hypoxia on migratory patterns. A model-based approach is almost certainly needed to assess the impact on fisheries of scenarios for future hypoxia. The reason is that certain scenarios may involve effects that have not yet occurred and, therefore, cannot be seen in historical data, however high the quality. Of course, the results of a model-based approach to assessing the impact of hypoxia on fisheries are only as good as the model itself and the data from which it is built.

Finally, in addition to improving the estimation of the actual economic effects of hypoxia, it may be useful to estimate the economic value of potential effects. For example, it may be relatively straightforward to estimate the cost to society of a hypothetical reduction in shrimp stocks. This information could prove useful in formulating a public policy response to hypoxia, even without firm estimates of what a future reduction may be.

4.2 DIRECTED RESEARCH

The northern Gulf of Mexico is a large, open ecosystem whose populations are influenced by many interacting factors. This is clearly seen in both the ecological and the economic analyses, where data were not available to account for the many sources of variability that influence population dynamics and landings, respectively. To understand how any subset of factors—like nutrient enrichment and hypoxia—affect populations, a complete picture is needed of what role each factor plays in regulating the three basic elements of population dynamics: mortality (all forms of loss), recruitment, and growth.

In the case of fisheries populations and hypoxia, an understanding of the importance of each of the following factors is needed:

- Natural sources of mortality, from larvae through adults.
- Losses of essential habitat (natural and anthropogenic), from larvae through adults.

- Commercial landings with catch location and measurement of effort.
- Recreational landings with catch location and measurement of effort.
- Bycatch.
- Trawling effects.

For the ecological processes and populations that support fisheries species, directed studies that examine the interactions between hypoxia and the following are needed:

- Composition of primary producers' populations.
- Population dynamics and secondary productivity.
- Direct and indirect effects on food webs.
- Spatial interaction of organisms, particularly predator–prey interactions.
- Long-term climatic variation.
- Geochemical cycling.
- Eutrophication.

After the models are developed and evaluated, different lines of research should be prioritized to predict basic responses of the system components (from primary producers to fish) to stressors (eutrophication, hypoxia, salinity, etc.).

In addition to the complexity of the interactions among physical, chemical, and biological processes that shape the northern Gulf of Mexico ecosystem, two key elements hindered this assessment of the effects of hypoxia: (1) lack of detail on the actual occurrence and distribution of hypoxia and (2) accessibility of data on various ecosystem components. To resolve these critical issues, a long-term monitoring program needs to be established that would measure dissolved oxygen at proper spatial and temporal scales, and a database management system needs to be developed to facilitate future synthesis of existing data on fishery and nonfishery species.

CHAPTER 5

Conclusions and Recommendations

5.1 ECOLOGICAL EFFECTS

To date, surprisingly few studies are directed at understanding the ecological effects of hypoxia in the northern Gulf of Mexico. It is likely, however, judging from documented responses of other systems to hypoxia, that the northern Gulf of Mexico has already undergone change prior to scientific investigation, and what we now see is a disturbed system.

This is most obvious in the benthos that has responded to seasonal hypoxia with mortality and by becoming a pulsed system (in the sense of Odum 1981) by shifting productivity to nonhypoxic periods of the year. Gulf studies in the late 1970s indicate that the benthos was already responding to hypoxia and that population dynamics, while variable, pulsed from year to year. Unfortunately, these documented changes could also be due to the other sources of stress that disturb sediments, such as trawling.

To date, there are no clear indications of hypoxic effects in fisheries or fish populations in the published literature or data evaluated. It is possible that eutrophication resulting from nutrient enrichment associated with the Mississippi River watershed has offset the negative effects of hypoxia, as has been documented in other systems (Caddy 1993), or that effects are small relative to other sources of variance in the data. Mobile species seem to avoid hypoxia; if any mortality occurs, it is dispersed and, other than "Jubilee" events, not reported. Hypoxia appears to develop in such a way that allows mobile species to escape it by their getting off the bottom or moving ahead of the encroaching hypoxia. Fish populations appear to aggregate or herd on the edge of the hypoxic zone (Crowder and Craig, personal communication).

Lack of identified hypoxic effects in available fisheries and fish population data does not imply that effects would not occur should conditions worsen. Experience with other hypoxic zones around the globe shows that both ecological and fisheries effects become progressively more severe as hypoxia worsens. Several large systems around the globe have suffered serious ecological and economic consequences from seasonal summertime hypoxia—most notably, the Kattegat and Black Sea. The consequences range from localized loss of catch and recruitment failure to complete system-wide loss of fishery species. If experiences in other systems are applicable to the Gulf of Mexico, then in the face of worsening hypoxic conditions, at some point fisheries and other species will decline, perhaps precipitously. Catch per unit effort for brown shrimp, while variable, has trended down since the late 1970s (Figure 3.5). While shrimp and fish can avoid hypoxia, at what cost, for how long, and to what spatial extent are unknown. In fact, a major difference between the northern Gulf of Mexico hypoxic zone and other such zones around the world is that, to date, the Gulf ecosystem for the last few decades has managed to maintain energy flow to productive fisheries (crabs and shrimps) that depend on the bottom.

Any effect of hypoxia in the northern Gulf of Mexico is intertwined with other environmental stressors. To understand how hypoxia affects populations in the Gulf, we first need to determine the contribution of natural and anthropogenic sources of mortality and growth to population dynamics—for example, gas production (Wilson–Ormond et al. 1994)). We also need to understand what functional aspects of the ecosystem are specifically affected by hypoxia. The Caddy (1993) model of ecosystem response to eutrophication, which encompasses hypoxia, may give us insight into the Gulf of Mexico situation. With an increase in nutrient loading, there is an initial increase in fisheries production. As nutrient loading continues to increase, the system approaches a saturation point, and the extra energy coming in can no longer be processed by fishery species. As hypoxia develops, it becomes a predominant force in regulating energy flow (Diaz and Rosenberg 1995), with processes and pathways that are favored by hypoxic conditions (opportunistic species, microbial food web) taking larger portions of the ecosystem's energy. The question is, Where on this curve is the Gulf of Mexico? The lack of obvious detrimental ecological and economic effects does not preclude the possibility of future ecological and economic disaster.

5.2 ECONOMIC EFFECTS

The economic assessment based on fisheries data failed to detect effects attributable to hypoxia. Overall, fisheries landings statistics for at least the last few decades have been relatively constant (Chesney et al. in press). There are several possibilities: (1) hypoxic effects are small relative to the overall variability in the data sets evaluated; (2) the data are not adequate for making an assessment of hypoxic effects; and (3) currently, there are no hypoxic effects.

In interpreting these results, it is important to emphasize three points.

- First, the failure to identify hypoxic effects does not necessarily mean that they are absent, only that the design for monitoring catch and effort failed to identify the reasons for variability in the data. There are many potential sources of variability in the fisheries data. These include: measurement error and other data problems; variation due to climate and weather, coastal development, and economic factors affecting fishers; and variation through time and between localities in fisheries practices and regulations.
- Second, in connection with the first point, the ability to account for different sources of variability in the fisheries data is limited by information about these sources. Most notably, direct information about the severity of hypoxic conditions was limited to estimates of the area experiencing oxygen concentrations of less than 2 mg/l (AREA) over the period 1985–95, with only partial data for 1989 (see the Topic 1 report, *Characterization of Hypoxia*). In light of the high variability of fisheries data, this time series may be too short to establish a relationship between the severity of hypoxia and variables relating to fisheries. To overcome this problem, a proxy for hypoxia was also used to extend the analysis over a longer period.
- Third, the failure to identify hypoxic effects in historical data does not imply that economic effects would not occur should conditions worsen. As noted elsewhere in this report, experience with other hypoxic areas shows that ecological effects and fisheries effects become progressively larger as hypoxia worsens (Caddy 1993) and can cause economic effects (Baden et al. 1990).

5.3 RECOMMENDATIONS

A comprehensive research plan is needed as a focus for efforts directed at assessing the ecological and economic effects of hypoxia in the northern Gulf of Mexico. This plan must include elements for both directing new research and synthesizing existing data.

Our efforts to identify hypoxia-related problems were severely hampered by lack of published data. In the case of fish populations, a large database exists (SEAMAP); however, it has not been analyzed. Although we did find tantalizing bits and pieces of data pointing to differences and responses consistent with hypoxia-related effects, we could not isolate confounding factors that could also produce similar responses.

A total ecosystem approach to the problem will be the only successful one. Consideration of how hypoxia and other stressors interact with all aspects of the Gulf ecosystem is essential prior to planning any restoration efforts.

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