Journal of
Environmental Quality

VOLUME 30 • MARCH–APRIL 2001 • NUMBER 2

SYMPOSIUM PAPERS

Overview of Hypoxia around the World

Robert J. Diaz*

ABSTRACT

No other environmental variable of such ecological importance to estuarine and coastal marine ecosystems around the world has changed so drastically, in such a short period of time, as dissolved oxygen. While hypoxic and anoxic environments have existed through geological time, their occurrence in shallow coastal and estuarine areas appears to be increasing, most likely accelerated by human activities. Several large systems, with historical data, that never reported hypoxia at the turn of the 19th century (e.g., Kattegat, the sea between Sweden and Denmark) now experience severe seasonal hypoxia. Synthesis of literature pertaining to benthic hypoxia and anoxia revealed that the oxygen budgets of many major coastal ecosystems have been adversely affected mainly through the process of eutrophication (the production of excess organic matter). It appears that many ecosystems that are now severely stressed by hypoxia may be near or at a threshold of change or collapse (loss of fisheries, loss of biodiversity, alteration of food webs).

A REVIEW of literature pertaining to ecological effects of hypoxia and anoxia revealed that the oxygen budgets for major coastal ecosystems around the world have been adversely affected mainly through the process of eutrophication. Eutrophication produces excess organic matter that fuels the development of hypoxia and anoxia when combined with water column stratification. Many ecosystems have reported some type of monotonic decline in dissolved oxygen levels through time with a strong correlation between human activities and declining dissolved oxygen (for example: Gulf of Mexico, Texas–Louisiana; Northern Adriatic Sea, Italy–Croatia; Kattegat, Sweden–Denmark). In some, the linkage of human activity to hypoxia is less obvious (for example: Chesapeake Bay, Maryland–Virginia; Saanich Inlet, British Columbia; Port Hacking, Australia).

The northern Gulf of Mexico may be typical of these severely stressed ecosystems that are currently burdened with severe seasonal hypoxia. Over the last several decades hypoxia, popularly know as the *dead zone*, has affected benthic invertebrate communities, but there is no clear signal of hypoxia in fisheries landings statistics (Diaz and Solow, 1999). The shallow northwest continental shelf of the Black Sea (which is not part of the deep central basin anoxia) is typical of ecosystems that have experienced drastic reductions in bottom fisheries due to hypoxia. Since the 1960s, increasing hypoxia and anoxia have been blamed for the replacement of the highly valued demersal fish species with less desirable planktonic omnivores. Of the 26 commercial species fished in the 1960s only six still support a fishery (Mee, 1992).

In this article I will present an overview of the effects of hypoxia on large coastal ecosystems around the world.

HYPOXIA—WHAT IS IT?

Oxygen is necessary to sustain the life of all fishes and invertebrates. In aquatic environments, oxygen from the atmosphere or from phytoplankton dissolves in the water and helps to meet the respiration needs of all animals, including those that swim or move about the bottom and those that have a sedentary life. Once dissolved into surface waters, the normal condition is for dissolved

---

School of Marine Science, Virginia Institute of Marine Science, College of William and Mary, Gloucester Pt., VA 23062. Received 14 July 2000. *Corresponding author (diaz@vims.edu).

Published in J. Environ. Qual. 30:275–281 (2001).

oxygen to be mixed down into bottom waters. When the supply of oxygen to the bottom is cut off or the consumption rate exceeds resupply, oxygen concentrations decline beyond the point that sustains most animal life. This condition of low dissolved oxygen is known as hypoxia. The point at which various animals suffocate varies, but generally effects start to appear when oxygen drops below 2 mg O_2 L^{-1}. For sea water, this is only about 18% of air saturation. As a point of reference, air is about 280 mg O_2 L^{-1}. Anoxia is the complete absence of oxygen. The two principal factors that lead to the development of hypoxia, sometimes leading to anoxia, are water column stratification, which isolates the bottom water from exchange with oxygen-rich surface water, and decomposition of organic matter in the bottom water, which reduces oxygen levels. Both conditions must occur for hypoxia to develop and persist.

THE LINK BETWEEN HYPOXIA, NUTRIENTS, AND EUTROPHICATION

Excess nutrient loading leads to eutrophication of coastal seas, a widespread problem around the globe in general (Nixon, 1995; Howarth et al., 1996). The primary factor driving marine coastal eutrophication is an imbalance in the nitrogen cycle that can be directly linked to increased population, whether through urbanization in coastal river drainage 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, the most important of which is nitrogen, to coastal seas (Howarth et al., 1996). Agriculture and, to a lesser degree, industry are regarded as the key generators of nitrogen, but in fact it is the increased population and rising living standards that drive the need for industry and agriculture to produce.

The scenario linking nutrient additions to the formation of hypoxia and effects on 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. If physical dynamics permit stratification, 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 (Table 1).

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 model of Caddy (1993) that relates fishery yield to nutrients supplied, the northern Gulf of Mexico is currently somewhere in the eutrophic category (Fig. 1). To a point, nutrient enrichment may increase fishery yields, but beyond a certain level, it is negative in effect (Caddy, 1993).

The increasing input of anthropogenic nutrients to many coastal areas over the last several decades has been suggested as the main contributor to more recently declining trends in bottom water oxygen concentrations around the world. Many studies have demonstrated a correlation through time between population growth, increased nutrient discharges, increased primary production in coastal areas, and increased occurrence of hypoxia and anoxia. The Gulf of Trieste (Northern Adriatic Sea) is a good example of this connection. Oxygen measurements from early in this century indicated that oxygen concentrations in bottom waters were always high. The current state of severe annual hypoxia in this region has been reached gradually over a period of about 25 years as a direct result of increased sedimentation of organic matter from phytoplankton blooms fueled by excess nutrients coming out of the Po River, Italy.

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 aeons 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 USA with more than one-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 organic matter production increases, changes occur in the food web that lead to different endpoints. These changes are very predictable and have followed the same path in many marine ecosystems (Fig. 1). For example, the relationship between nutrient loads delivered to the northern Gulf of Mexico and basic ecological responses (i.e., increased primary productivity in the water column, increased flux of organic matter to the bottom, bottom water hypoxia, al-

Table 1. Summary of benthic effects for hypoxic systems around the world. Several of these systems also experience anoxia. In the case of many fjords there is an anoxic zone within which no macrofauna occur. The absence of fauna from these anoxic zones is not considered a community response but a consequence of stable anoxia.

System	Hypoxia type†	Hypoxia level‡	Time trends§	Fauna response¶	Fauna recovery#	Fisheries response
New York Bight, New Jersey	aperiodic	severe	.	mass mort.	slow	surf clam losses
Shallow Texas Shelf	aperiodic	severe	+	mass mort.	slow	stressed
Deep Texas Shelf	aperiodic	moderate	0?	mortality	annual	stressed
German Bight, North Sea	aperiodic	mod./severe	+	mass mort.	annual	.
Sommone Bay, France	aperiodic	severe	+?	mass mort.	slow	collapse of Cockle fishery
North Sea, W. Denmark	aperiodic	severe	+	mortality	annual	stressed
New Zealand	aperiodic	severe	.	mass mort.	.	stressed
York River, Virginia	periodic	mod./severe	0	none	no change	stressed
Rappahannock River, Virginia	periodic	severe	+	mortality	annual	stressed
Long Island Sound, New York	seasonal	severe	+	?	?	lobsters displaced
Main Chesapeake Bay, Maryland	seasonal	severe	+	mortality	annual	stressed
Pamlico River, North Carolina	seasonal	severe	.	mass mort.	annual	.
Mobile Bay, Alabama	seasonal	severe	0	mass mort.	?	stressed
Hillsborough Bay, Florida	seasonal	severe	.	mass mort.	annual	.
Louisiana Shelf	seasonal	mod./severe	+	mortality	annual	stressed
Seto Inland Sea, Japan	seasonal	moderate	.	mortality	annual	.
Saanich Inlet, British Columbia	seasonal	mod./severe	0	mortality	annual	.
Bornholm Basin, S. Baltic	seasonal	mod./severe	+††	mass mort.	slow	.
Oslofjord, Norway	seasonal	mod./severe	+	mortality	annual	reduced
Kattegat, Sweden–Denmark	seasonal	mod./severe	++	mass mort.	slow	collapse of Norway lobster
German Bight, North Sea	seasonal	severe	+?	mortality	annual	stressed
Port Hacking, Australia	seasonal	severe	.	mortality	annual	.
Tolo Harbor, Hong Kong	seasonal	severe	.	mass mort.	annual	.
Japan, all major harbors	seasonal	severe	++	mass mort.	?	reduced
Tome Cove, Japan	seasonal	severe	.	mortality	annual	.
Laholm Bay, Sweden	seasonal	severe	++	mortality	annual	stressed
Gullmarsfjord, Sweden	seasonal	severe	+	mass mort.	annual	stressed
Swedish west coast fjords	seasonal	severe	++	mortality	some	stressed
Limfjord, Denmark	seasonal	severe	+	mass mort.	annual	none
Kiel Bay, Germany	seasonal	severe	+	mass mort.	annual	stressed
Lough Ine, Scotland	seasonal	severe	0	mass mort.	annual	.
Gulf of Trieste, Adriatic	seasonal	severe	++	mass mort.	slow	stressed
Elefsis Bay, Aegean Sea	seasonal	severe	.	mass mort.	annual	.
Black Sea NW Shelf	seasonal	severe	++	mass mort.	annual	reduced
Århus Bay, Denmark	seasonal	severe	+	mass mort.	slow	.
Loch Creran, Scotland	persistent	severe	0	mass mort.	no change	.
Byfjord, Sweden	persistent	severe	0	mortality	some	pelagic only
Black Sea (except NW shelf)	persistent	severe	+	no benthos	no change	pelagic only
Idefjord, Sweden–Norway	persistent	severe	+‡‡	mortality	some	.
Baltic Sea, Central	persistent	severe	++	mortality	some	stressed
Fosa de Cariaco, Venezuela	persistent	severe	.	reduced	no change	.
Caspian Sea	persistent	mod./severe	0	mortality	some?	.
Gulf of Finland, Deep	persistent	mod./severe	–	reduced	slow	.

† Aperiodic, events that are known to occur at irregular intervals greater than a year; periodic, events occurring at regular intervals shorter than a year; seasonal, yearly events related to summer or autumnal stratification; persistent, year-round hypoxia.

‡ Moderate, oxygen decline to about 0.5 mL L^{-1}; severe, decline to near anoxic levels, could also become anoxic.

§ – = improving conditions; + = gradually increasing; ++ = rapidly increasing; 0 = stable; . = no temporal data; ? = uncertain.

¶ None, communities appear similar before and after hypoxic event; mortality, moderate reductions of populations, many species survive; mass mort., drastic reduction or elimination of the benthos.

No change, dynamics appear unrelated to hypoxia; some, recolonization occurs but community does not return to prehypoxic structure; slow, gradual return of community structure taking more than a year; annual, recolonization and return of community structure within a year.

†† These systems are currently in a persistent hypoxic state.

‡‡ Recent improvements in oxygen concentrations due to pollution abatement.

tered energy flow, and stressed fisheries) are typical of other system responses around the world (see reviews by Brongersma-Sanders, 1957; Caddy, 1993; Diaz and Rosenberg, 1995). Basically, a hypoxic zone is a secondary manifestation of the larger problem of excess nutrients, which leads to increased production of organic matter or eutrophication (Nixon, 1995). When combined with water column stratification, hypoxia results.

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 19th 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, p. 1–97).

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 benthic hypoxia was not reported prior to the 1950s in the Baltic Sea (Fonselius, 1969, p. 1–97), 1960s in the northern Adriatic (Justić, 1987), 1970s in the Kattegat (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 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 changed appreciably. Only in systems that have experienced intensive regulation of nutrient inputs have oxygen conditions improved. There are many examples

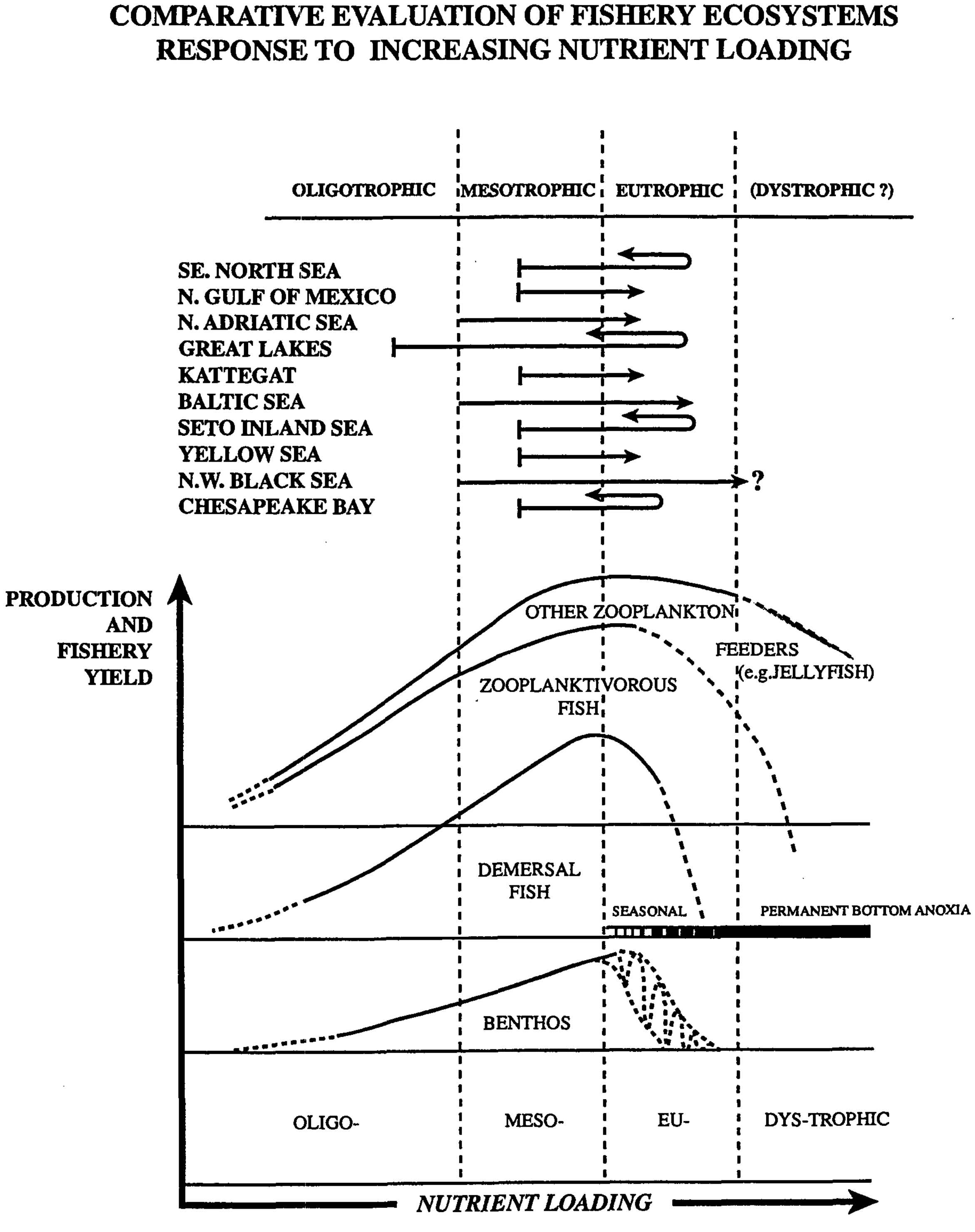

Fig. 1. Comparative evaluation of fishery response to nutrients based on data from around the world (modified and redrawn from Caddy, 1993). Each curve represents a general guild of species and their reaction to increasing nutrient supplies. The top part of the figure lists recent trends for various systems around the world. Vertical dashed lines separate general categories of organic production that result from different levels of nutrients.

of small-scale hypoxia reversals associated with improvements in treatment of sewage and pulp mill effluents (Rosenberg, 1972, 1976).

In the USA, the improved water quality in Lake Erie is the best example and evidence that large ecosystems do respond positively to nutrient regulation, even though 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 (Di Toro 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.

SYSTEM POTENTIAL FOR HYPOXIA

Because of their geomorphology and circulation patterns, some marine systems have a greater tendency to develop hypoxic conditions. 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, Alabama, there are accounts of "Jubilees" (the herding of fish and shellfish against a shoreline by hypoxic water) from the 1860s (J. Pennock, personal communication, 1997). These "Jubilees" were probably hypoxia-related then as they are now (Schroeder and Wiseman, 1988). Better-mixed or flushed systems do not have a tendency toward hypoxia. The Baltic Sea and the Kattegat exhibit no natural tendency to 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 measurements in both systems that go back to the turn of the 19th century (R. Rosenberg, unpublished data, 1989). 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 probably not a prominent feature of the shallow continental shelf prior to the 1920s to 1950s (Rabalais et al., 1996, 1999; Sen Gupta et al., 1996). A longer (2000-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).

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 either been eliminated or severely stressed (Mee, 1992; Elmgren, 1984). A comparison of effects from four similar coastal hypoxic zones indicates that, to date, only the Gulf of Mexico has not suffered documented declines in fishery production due to hypoxia-related mortality (Table 2).

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 lobster 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 stock size, recruitment, and landings of commercial fish over the last two decades (Baden et al., 1990; L. Pihl, unpublished data, 1990). 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., 2001), trawl disturbance (Currie and Parry, 1996), fishing pressure (Turkstra et al., 1991),

Table 2. 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. Data from various sources cited in text.

System	Area affected	Benthic response	Benthic recovery	Response fisheries
	km^2			
Louisiana Shelf	15 000	mortality	annual	Stressed but still highly productive. Mortality reported in shallow water related to "Jubilees".
Kattegat, Sweden–Denmark	2 000	mass mort.	slow	Collapse of Norway lobster, reduction of demersal fish. Hypoxia prevents recruitment of lobsters.
Black Sea Northwest Shelf	20 000	mass mort.	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 bottle-neck for cod recruitment.

habitat loss (Chesney et al., 2001), and harmful algal blooms (Rosenberg et al., 1988). 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 of Mexico gradually increased in size and duration from its inception, probably 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 adjusted to hypoxia and other stressors, and for at least the last few decades has maintained fishery production (Chesney et al., 2001). 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.

CONCLUSIONS

It is clear that no other environmental variable of such ecological importance to estuarine and coastal marine ecosystems around the world has changed so drastically, in such a short period of time, as dissolved oxygen. While hypoxic and anoxic environments have existed through geological time, their occurrence in estuarine and coastal areas clearly is rapidly increasing, most likely accelerated by human activities. The importance of oxygen as an ecological factor for maintaining populations of fisheries-related species cannot be overemphasized. The seriousness of hypoxia and anoxia as environmental issues that must be effectively dealt with now is best expressed by the motto of the American Lung Association: "If you can not breath, nothing else matters."

Up to the 1950s, reports of mass mortality of marine animals caused by lack of oxygen were limited to systems that already had histories of oxygen stress, such as Mobile Bay, AL. Starting in the 1960s, the number of systems reporting hypoxia-related problems increased. See Table 1 for a summary of coastal bays and seas that are experiencing excess nutrient-related hypoxia.

Oxygen deficiency (hypoxia and anoxia) may very well be the most widespread anthropogenically induced deleterious effect in estuarine and marine environments around the world. Over the last 15 to 20 years the number of coastal areas with seasonal hypoxia in the bottom water is spreading rapidly and the main cause for this is suggested to be delivery of excess nutrients to the system. Global warming may accelerate these effects and enlarge the areas that are affected.

REFERENCES

Andrew, N.L., and J.G. Pepperell. 1992. The by-catch of shrimp trawl fisheries. Oceanogr. Mar. Biol. Ann. Rev. 30:527–565.

Azarovitz, T.R., C.J. Byrne, M.J. Silverman, B.L. Freeman, W.G. Smith, S.C. Turner, B.A. Halgren, and P.J. Festa. 1979. Effects on finfish and lobster. p. 295–314. *In* R.L. Swanson and C.J. Sindermann (ed.) Oxygen depletion and associated benthic mortalities in New York Bight, 1976. Prof. Paper 11. NOAA, Washington, DC.

Baden, S.P., L.O. Loo, L. Pihl, and R. Rosenberg. 1990. Effects of eutrophication on benthic communities including fish—Swedish west coast. Ambio 19:113–122.

Boesch, D.F., and N.N. Rabalais. 1991. Effects of hypoxia on continental shelf benthos: Comparisons between the New York Bight and the northern Gulf of Mexico. p. 27–34. *In* R.V. Tyson and T.H. Pearson (ed.) Modern and ancient continental shelf anoxia. Spec. Publ. no. 58. Geol. Soc., London.

Boyce, F.M., M.N. Charlton, D. Rathke, C.H. Mortimer, and J. Bennett. 1987. Lake Erie research: Recent results, remaining gaps. J. Great Lakes Res. 13:826–840.

Brongersma-Sanders, M. 1957. Mass mortality in the sea. p. 941–1010. *In* J.W. Hedgpeth (ed.) Treatise on marine ecology and paleoecology. Vol. 1. Waverly Press, Baltimore, MD.

Caddy, J. 1993. Toward a comparative evaluation of human impacts on fishery ecosystems of enclosed and semi-enclosed seas. Rev. Fish. Sci. 1:57–96.

Charlton, M.N., J.E. Milne, W.G. Booth, and F. Chiocchio. 1993. Lake Erie offshore in 1990: Restoration and resilience in the central basin. J. Great Lakes Res. 19:291–309.

Chesney, E.J., D.M. Baltz, and R.G. Thomas. 2001. Louisiana estuarine and coastal fisheries and habitats: Perspectives from a fish's eye view. Ecol. Applic. (in press).

Cooper, S.R., and G.S. Brush. 1991. Long-term history of Chesapeake Bay anoxia. Science 254:992–996.

Currie, D.R., and G.D. Parry. 1996. Effects of scallop dredging on a soft sediment community: A large-scale experimental study. Mar. Ecol. Prog. Ser. 134:131–150.

Diaz, R.J., and R. Rosenberg. 1995. Marine benthic hypoxia: A review of its ecological effects and the behavioural responses of benthic macrofauna. Oceanogr. Mar. Biol. Ann. Rev. 33:245–303.

Diaz, R.J., and A. Solow. 1999. Ecological and economic consequences of hypoxia. Topic 2. Gulf of Mexico hypoxia assessment. NOAA Coastal Ocean Program Decision Analysis Series. NOAA COP, Silver Springs, MD.

Di Toro, D.M., and A.F. Blumberg. 1990. Effects of climate warming on dissolved oxygen concentrations in Lake Erie. Trans. Am. Fish. Soc. 119:210–223.

Elmgren, R. 1984. Trophic dynamics in the enclosed, brackish Baltic Sea. Rapp. P-V. Réun. 183:152–169.

Elmgren, R. 1989. Man's impact on the ecosystem of the Baltic Sea: Energy flows today and at the turn of the century. Ambio 18:326–332.

Fonselius, S.H. 1969. Hydrography of the Baltic deep basins III. Ser. Hydrogr. Rep. no. 23. Fishery Board of Sweden, Stockholm.

Holliday, M.C., and B.K. O'Bannon. 1997. Fisheries of the United States, 1997. Current Fishery Statistics no. 9700. U.S. Dep. of Commerce, Washington, DC.

Howarth, R.W., G. Billen, D. Swaney, A. Townsend, N. Jaworski, K. Lajtha, J.A. Downing, R. Elmgren, N Caraco, T. Jordan, F. Berendse, J. Freney, V. Kudeyarov, P. Murdoch, and Z. Zhao-Liang. 1996. Regional nitrogen budgets and reverine N & P fluxes for the drainage to the North Atlantic Ocean: Natural and human influences. Biogeochemistry 35:75–139.

Justić, D. 1987. Long-term eutrophication of the northern Adriatic Sea. Mar. Pollut. Bull. 18:281–284.

McEachron, J.W., G.C. Matlock, C.E. Bryan, P. Unger, T.J. Cody, and J.H. Martin. 1994. Winter mass mortality of animals in Texas bays. Northeast Gulf Sci. 13:121–138.

Mee, L.D. 1992. The Black Sea in crisis: A need for concerted international action. Ambio 21:278–286.

Newcombe, C.L., and W.A. Horne. 1938. Oxygen poor waters of the Chesapeake Bay. Science 88:80–81.

Nixon, S.W. 1995. Coastal marine eutrophication: A definition, social causes, and future concerns. Ophelia 41:199–219.

Pearson, T.H., A.B. Josefson, and R. Rosenberg. 1985. Petersen's benthic stations revisited. I. Is the Kattegat becoming eutrophic? J. Exper. Mar. Biol. Ecol. 92:157–206.

Rabalais, N.N., R.E. Turner, D. Justić, Q. Dortch, and W.J. Wiseman. 1999. Characterization of hypoxia. Topic 1. Gulf of Mexico Hypoxia Assessment. NOAA Coastal Ocean Program Decision Analysis Series. NOAA COP, Silver Springs, MD.

Rabalais, N.N., W.J. Wiseman, Jr., R.E. Turner, D. Justić, B.K. Sen Gupta, and Q. Dortch. 1996. Nutrient changes in the Mississippi River and system responses on the adjacent continental shelf. Estuaries 19:386–407.

Rosenberg, R. 1972. Benthic faunal recovery in a Swedish fjord following the closure of a sulphite pulp mill. Oikos 23:92–108.

Rosenberg, R. 1976. Benthic faunal dynamics during succession following pollution abatement in a Swedish estuary. Oikos 27:414–427.

Rosenberg, R. 1990. Negative oxygen trends in Swedish coastal bottom waters. Mar. Pollut. Bull. 21:335–339.

Rosenberg, R., O. Lindahl, and H. Blanck. 1988. Silent spring in the sea. Ambio 17:289–290.

Schroeder, W.W., and W.J. Wiseman. 1988. Mobile Bay estuary: Stratification, oxygen depletion, and jubilees. p. 41–52. *In* Hydrodynamics of estuaries. Vol. II. Estuarine case studies. CRC Press, Boca Raton, FL.

Sen Gupta, B.K., R.E. Turner, and N.N. Rabalais. 1996. Seasonal oxygen depletion in continental-shelf waters of Louisiana: Historical record of benthic foraminifers. Geology 24:227–230.

Turkstra, E., M.C.Th. Scholten, C.T. Bowmer, and H.P.M. Schobben. 1991. A comparison of the ecological risks from fisheries and pollution to the North Sea biota. Water Sci. Technol. 24:147–153.