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# A Global Perspective On The Effects Of Eutrophication And Hypoxia On Aquatic Biota And Water Quality

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# FISH PHYSIOLOGY, TOXICOLOGY, AND WATER QUALITY

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# A GLOBAL PERSPECTIVE ON THE EFFECTS OF EUTROPHICATION AND HYPOXIA ON AQUATIC BIOTA

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## ABSTRACT

Development associated with human populations has led to the globalization of many environmental problems. In marine systems, the most serious of these problems are directly related to the process of eutrophication. The increased production of organic matter in these marine systems associated with eutrophication is the primary factor impacting species abundance and composition and dissolved oxygen budgets. Oxygen, which is essential to maintaining balance in ecosystem processes through its role in mediating microbial and metazoan activities, has declined to critically low levels in many systems, which has led to the development of hypoxia (<2 ml $O_2$/l) and anoxia (0 ml $O_2$/l). Currently, most oxygen depletion events are seasonal, but trends toward longer periods that could eventually lead to persistent hypoxic or anoxic conditions are emerging. Over the last 50 years, there has been an increase in the number of systems reporting problems associated with low dissolved oxygen. Currently there are over 100 hypoxic/anoxic areas around the globe, ranging in size from <1 $km^2$ to 70000 $km^2$, that exhibit a graded series of responses to oxygen depletion, ranging from no obvious change to mass mortality of bottom fauna. Ecosystems currently severely stressed by eutrophication-induced hypoxia continue to be threatened with the loss of fisheries, loss of biodiversity, alteration of food webs, and simplification of energy flows.

## INTRODUCTION

Cloern (2001) succinctly summarized current understanding of coastal eutrophication, indicating that the long-term records of nutrient discharges over the past 50 years provide compelling evidence of a rapid increase in the fertility of many temperate coastal ecosystems (for example, Baltic and adjoining seas – Karlson *et al.* 2002; Northwest Black Sea – Mee 1992; Northern Adriatic Sea – Solic *et al.* 1997; North Sea rivers – Howarth *et al.* 2002; United States bays and estuaries - Jaworski *et al.* 1997, Howarth *et al.* 1996; Northern Gulf of Mexico – Rabalais *et al*. 1996, Rabalais and Turner 2001; Japan – Suzuki 2001). In each of these systems, the fertilization is directly related to an expanding human population, which recently passed 6 billion and will likely exceed 8 to 10 billion by the year 2050 (Wilson 2002). Seitzinger *et al.* (2002) found that at scales of regions and continents, human population was a good predictor of

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dissolved inorganic nitrogen (DIN) exported to coastal systems. By 2050, projections indicate that a 2.4 to 2.7-fold increase in nitrogen and phosphorus driven eutrophication will result from this population expansion (Tilman *et al.* 2001), with serious consequences for coastal ecosystems.

Fertilization of marine systems, mainly from excess nitrogen, has been linked in a complicated way to many ecosystem-level changes associated with eutrophication, or more precisely, cultural eutrophication. Cultural eutrophication is specific to impacts related to human populations on the environment and separates the conditions in these coastal systems from natural processes that can also lead to eutrophic-like conditions, such as those associated with coastal upwelling zones and oxygen minimum zones (OMZ) where oxygen consumption exceeds resupply. Oxygen depletion associated with upwelling events tends to be episodic, severe, short-lived (less than a year), and associated with the western boundaries of continental landmasses (Brongersma-Sanders 1957, Rosenberg *et al.* 1983). OMZs are unusual oxygen-depleted areas that are widespread and stable oceanic features occurring at intermediate depths (typically 400 to 1000 m), persisting for long periods of time (at greater than decadal scales), and are completely controlled by natural processes and cycles (Wyrtki 1966, Kamykowski and Zentara 1990, Olson *et al.* 1993, Childress and Seibel 1998).

While eutrophication can be defined simply as the production of organic matter in excess of what an ecosystem is normally adapted to processing (Nixon 1995), it is actually only part of a complex web of stressors that interact to shape and direct ecosystem-level processes (Breitburg *et al.* 1998, Cloern 2001) (Figure 1). From Figure 1, the most visible ecosystem response to this set of multiple stressors is the greening of the water column as primary production increases in direct response to nutrient enrichment. However, the unseen is most dangerous. For nutrient enrichment, which leads to increased organic matter production (eutrophication), the unseen decrease in dissolved oxygen in bottom waters created by the increased flux of particulate organic matter to the bottom is most threatening. The degree to which an ecosystem responds to any of the multiple stressors is dependent upon physical, chemical, and biological characteristics that act to filter and modulate the response (Cloern 2001).

Human impacts are accelerating the rate and magnitude of change within an ecosystem as more and more ecosystem level processes are affected (Jackson *et al.* 2001). The history and pattern of human disturbance in terrestrial, aquatic, coastal, and oceanic ecosystems have brought us to a point at which oxygen depletion is likely to become the keystone impact for the 21$^{st}$ century, replacing the 20$^{th}$ century keystone of overfishing (Jackson *et al.* 2001). A mounting volume of literature documenting change in marine ecosystems indicates oxygen depletion as a major phenomenon that is a tertiary manifestation of the severe levels of stress experienced by many ecosystems. The primary stress is nutrient enrichment, which regulates the secondary response of eutrophication. See reviews and summaries by Gray (1992), Nixon (1995), Diaz and Rosenberg (1995), Cloern (2001), Turner (2001), and Karlson *et al.* (2002) for examples of ecosystem responses. The correlation between human activities and declining dissolved oxygen is strong, with the oxygen budgets of many marine ecosystems around the world adversely affected by eutrophication.

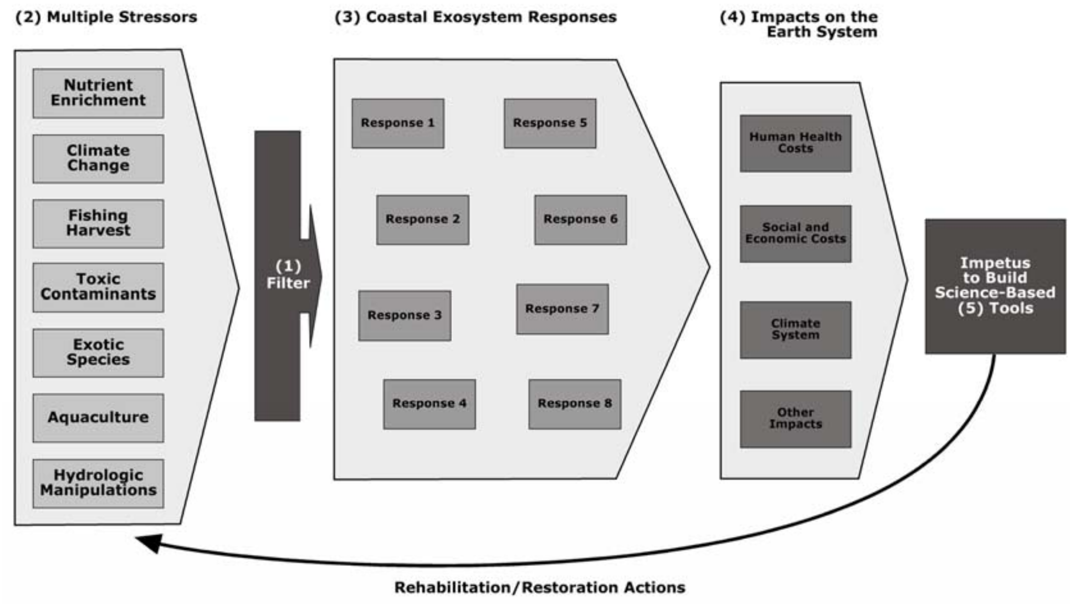


Figure 1. Conceptual model of coastal eutrophication modified from Cloern (2001). (1) system attributes that determine responses to nutrient enrichment; (2) nutrient enrichment as one of many stressors; (3) complex linkage between responses to multiple stressors; (4) change in coastal ecosystems; (5) application of scientific understanding of eutrophication with the goal of building rational management strategies for ecosystem rehabilitation/restoration.

The emphasis of this paper is ecosystem response to oxygen depletion resulting directly from eutrophication. The emphasis on dissolved oxygen is warranted given the importance of oxygen for sustaining life for all fishes and invertebrates. Metaphorically speaking, the American Lung Association motto could be adopted for this situation. "When you can't breathe, nothing else matters." When the supply of dissolved oxygen in aquatic environments is cut off or the consumption rate exceeds resupply, oxygen concentrations quickly decline beyond the point that sustains most animal life. Two factors are required for the development of hypoxia, and at times anoxia; one is water column stratification that isolates the bottom water from oxygen-rich surface water, and the second is decomposition of organic matter that reduces oxygen levels in the isolated bottom water. The first factor is generated primarily by salinity stratification and the second by microbial metabolism. Both factors must be at work for hypoxia to develop and persist. In fact, the reaction of microbial populations to eutrophication has been explosive, particularly in systems with the greatest oxygen depletion problems (Jackson *et al.* 2001).

The terms used to describe low dissolved oxygen or oxygen depletion are hypoxia and anoxia. Hypoxia is defined by dissolved oxygen concentrations <2 ml $O_2$/l or <2.8 mg $O_2$/l; for seawater this is about 18% of air saturation (Tyson and Pearson 1991). Anoxia is the complete absence of dissolved oxygen (0 ml $O_2$/l). The point at which various animals suffocate varies, but effects generally appear when oxygen drops below 2 ml $O_2$/l (Diaz and Rosenberg 1995, Breitburg *et al.* 2001, Karlson *et al.* 2002). The relationship between declining oxygen and animal response are graded and follow a predictable path, good examples of which are given by Diaz and Rosenberg (1995) and Rabalais *et al.* (2001b). This paper presents a brief overview and update of hypoxic conditions in estuarine and marine systems around the world.

## OXYGEN DEPLETION AROUND THE WORLD

On a geological time scale, low-dissolved-oxygen environments (hypoxia and anoxia) have been major factors in shaping the evolution of life (Caplan and Bustin 1999). Today, the vestiges of naturally occurring oxygen depletion are the oceanic OMZs, the largest pools of hypoxic water in world oceans, particularly in the Pacific and Indian Oceans and the Arabian Sea (Olsen *et al.* 1993). The largest pool of naturally occurring anoxic water is the Black Sea (Kideys 2002). The Black Sea anoxic zone does not support any eukaryotic life, which is typical of all areas experiencing extended periods of anoxia, whether natural or anthropogenic. However, the temporal and spatial stability of OMZs has allowed the development of species aerobically adapted to dissolved oxygen concentrations from 0.5 ml $O_2$/l to about 0.1 ml $O_2$/l (Levin *et al.*1991, Childress and Seibel 1998). This is in stark contrast to the faunal response to cultural-eutrophication-induced hypoxia in shallow coastal and estuarine areas, where oxygen concentrations of <0.5 ml $O_2$/l lead to mass mortality of individuals and major change in community structure.

The worldwide distribution of coastal oxygen depletion is either centered on major population concentrations, or closely associated with developed watersheds that deliver large quantities of nutrients (Figure 2, Table 1). The historical perspective indicates that many of these currently hypoxic systems were not so when they were first studied. Since at least the 1950s and 1960s, dissolved oxygen concentrations of many major coastal ecosystems around the world have been adversely affected by eutrophication. Most of these coastal systems have documented declines in dissolved oxygen through time, starting in most cases from their initial oxygen measurements (Rosenberg 1990). The declining trend in dissolved oxygen seems to have lagged about 10 to 20 years behind the increased use of chemical fertilizer that began in the 1940s (Howarth *et al.*2002). For systems with historical data from the first half of the $20^{th}$ century, declines in oxygen concentrations started in the 1950s and 1960s for the northern Adriatic Sea (Justic 1987), between the 1940s and 1960s for the northwest continental shelf of the Black Sea (Mee 1992, Kideys 2002), and in the 1970s for the Kattegat (Baden *et al.*1990a). Declining dissolved oxygen levels were noted in the Baltic Sea as early as the 1930s (Fonselius 1969), but it was in the 1950s that hypoxia became widespread (Karlson *et al.* 2002). Other systems have experienced hypoxia since the beginning of oxygen data collection, for example, in the 1930s for the Chesapeake Bay (Officer *et al.* 1984), and the 1970s for the northern Gulf of Mexico (Rabalais and Turner 2001) and many Scandinavian fjord systems (Karlson *et al.* 2002). However, the longer-term geochronological records indicate that hypoxia was not always present in these particular ecosystems (Sen Gupta *et al.* 1996; Karlson *et al.* 2002; Zimmerman and Canuel 2002). Not all nutrient-enriched systems have developed eutrophic conditions and related oxygen depletion problems. San Francisco Bay receives higher levels of nutrients than the Chesapeake Bay, but has lower primary production and oxygen depletion due to strong tidal mixing and turbid water (Cloern 2001).

Table 1. Eutrophication-associated hypoxic areas around the world with an emphasis on benthic and fisheries responses. Several of these systems also experience anoxia. Hypoxia is characterized as Episodic: events occurring at irregular intervals greater than one year; Periodic: events occurring at regular intervals shorter than one year; Annual: yearly events related to summer or autumnal stratification; Persistent: year-round hypoxia. Benthic faunal response is categorized as None: communities appear similar before and after hypoxic event; Mortality: moderate reductions of populations, many species survive; Mass Mortality: drastic reduction or elimination of the benthos. Benthic recovery is described by No Change: dynamics appear unrelated to hypoxia; Reduced: recolonization occurs but community does not return to prehypoxic structure; Multi-year: gradual return of community structure; Annual: return of similar community structure in a year. First observed is usually first documentation in literature and in most cases not the first occurrence of oxygen depletion.

| System | Country/State | First Observations | Recent Observations | Area ($km^2$) | Fisheries Response | Benthic Response | Benthic Recovery | Reference |
|---|---|---|---|---|---|---|---|---|
| **Annual Oxygen Depletion** | | | | | | | | |
| Åland archipelago | Finland | 1990 | | 10 | | Mortality | Reduced | Norkko and Bonsdorff 1996 |
| Aquaculture | Taiwan | 2000 | | | Mortality of prawns | Mortality | | Cheng *et al*. 2002 |
| Århus Bay | Denmark | 1980 | | 1300 | | Mass Mortality | Multi-year | Fallesen and Jorgensen 1991 |
| Barnegatt Inlet | New Jersey | 1990 | | | | Mass Mortality | Annual | Moser 1998 |
| Belt Sea | Denmark | 1970 | | 2150 | | | | Karlson *et al*. 2002 |
| Bilbao Estuary | Spain | 1990 | | | | Mortality | | Gonzales-Oreja and Saiz-Salinas 1998; Saiz-Salinas and Frances-Zubillaga 1997 |
| Bornholm Basin | Baltic Sea | 1950 | | 2500 | | Mass Mortality | Multi-year | Tulkki 1965; Leppakoski 1969 |
| Cabbage Tree Basin | Australia | 1980 | | | | Mortality | Annual | Rainer and Fitzhardinge 1981 |
| Chesapeake Bay Mainstem | Maryland | 1930 | | 2750 | Avoidance, some mortality | Mortality | Annual | Holland *et al.* 1987; Boesch *et al*. 2001; Seliger and Boggs 1988 |
| Corpus Christi Bay | Texas | 1980 | | 15 | | Reduced | Reduced | Ritter and Montagna 1999 |
| Dead-end canals | Maryland, Delaware | 1990 | | 5 | | | | Maxted *et al*. 1997 |
| Delaware River, Lower | Delaware | 1910 | Improved | | Recovery American shad/striped bass fishery | Mass Mortality | Increasing | Weisberg *et al.* 1996 |
| Delaware River, Upper | Delaware | 1910 | Improved | | | | | Patrick 1988 |
| Eckernforde Bay | Germany | 1990 | | | | Mortality | Annual | D'Andrea *et al.* 1996 |
| Elbe Estuary | Germany | 1980 | Improved | | Stressed | | | Thiel *et al.* 1995 |
| Elefsis Bay, Aegean Sea | Greece | 1980 | | | | Mass Mortality | Annual | Friligos and Zenetos 1988; Theodorou 1996 |
| Fjords of Skagerrak coast | Sweden | 1950 | | | | | | Rosenberg 1990 |
| Flushing Bay | New York | 1990 | | | | Mortality | | Diaz, unpublished data |
| German Bight | Germany | 1980 | | | Mortality | Mortality | Reduced | Brockmann *et al.* 1988; Niermann *et al.* 1990 |
| Gialova Lagoon | Ionian Sea, Greece | 1990 | | 2500 | | Mortality | Annual | Arvanitidis *et al.* 1999 |
| Goro Lagoon | Italy | 1990 | | | | Mortality | Annual | Reizopoulou *et al.* 1996 |
| Great Egg Harbor River | New Jersey | 1990 | | | | | | Glenn *et al.* 1996 |
| Guanabara Bay | Brazil | 1990 | | | Tropical | Mortality | | Valentin *et al.* 1999 |
| Gulf of Mexico | Louisiana | 1970 | | 17000 | Avoidance | Mortality/avoidance | Reduced | Rabalais and Turner 2001 |
| Gulf of Trieste | Adriatic Sea | 1960 | | | Stressed | Mass Mortality | Multi-year | Stachowitsch 1984, 1991; Simunovic *et al.* 1999; Justic *et al.* 1987 |
| Gullmarsfjord | Sweden | 1980 | | | Stressed | Mass Mortality | Reduced | Nilsson and Rosenberg 2000; Josefson and Widbom 1988 |
| Hakata Bay | Japan | 1970 | | 120 | | Mortality | Annual | Karim *et al*. 2002 |
| Havstens Fjord | Sweden | 1990 | | | | | | Gustafsson and Nordberg 2000 |
| Herring River | Massachusetts | 1980 | | | Fish kills, decline of alewife fishery | | | Portnoy 1991 |
| Hillsborough Bay | Florida | 1980 | | | | Mass Mortality | Annual | Santos and Simon 1980 |

| System | Country/State | Observations | | ($km^2$) | Fisheries Response | Response | Recovery | Reference |
|---|---|---|---|---|---|---|---|---|
| Hiuchi Sound | Japan | 1970 | | | | Mass Mortality | | Sanukida *et al.* 1984 |
| Hood Canal | Washington | 1980 | | | | | | Paulson *et al.* 1993 |
| Horseshoe Lagoon | Australia | 1990 | | | | | | Donnelly *et al*. 1999 |
| Hudson River | New York | 1960 | Improved | | | | | Bronsnan and O'Shea 1996 |
| Inre Verkviken | Finland | 1970 | | 0.5 | | | | Lindholm 1996 |
| Ise Bay | Japan | 1990 | | | Stressed | Mortality | | Nakata *et al.* 1997 |
| Kattegat | Sweden, Denmark | 1980 | | 3850 | Collapse of Norway lobster | Mass Mortality | Multi-year | Baden *et al.* 1990a; Josefson and Jensen 1992; Rosenberg *et al.* 1992 |
| Kiel Bay | Germany | 1960 | | 890 | Stressed | Mass Mortality | Annual | Arntz 1981; Rumohr 1986; Weigelt 1990, 1991; Oeschger and Storey 1990 |
| La Coruna Bay | Spain | 1990 | | | | | | Lopez-Jamar *et al*. 1995 |
| | | First | Recent | Area | | Benthic | Benthic | |
| Laholm Bay | Sweden | 1980 | | | Mortality | Mortality | Annual | Baden *et al.* 1990b; Rosenberg and Loo 1988 |
| Lake Nakaumi | Japan | 1990 | | | Mortality/avoidance | | | Ishitobi *et al*. 2000 |
| Lake Shinji | Japan | 1990 | | | | Mass Mortality | | Yamamuro *et al*. 1998 |
| Limfjord | Denmark | 1980 | | 440 | Demersal fisheries gone | Mass Mortality | Annual | Jorgensen 1980; Hylleberg 1993 |
| Loire Estrary | France | 1990 | | | Mortality of migratory species | | | Thouvenin *et al*. 1994 |
| Long Island Sound | New York | 1980 | | 232 | Avoidance, some mortality | Mortality | | Howell and Simpson 1994; Welsh *et al.* 1994; Schimmel *et al.* 1999; NOAA 1997 |
| Los Angeles Harbor | California | 1950 | Improved | | | Mass Mortality | Reduced | Reish 1955, 2000 |
| Lough Ine | Ireland | 1970 | | | | Mass Mortality | Annual | Kitching *et al.* 1976 |
| Mecklenburg Bay | Germany | 1980 | | 1860 | | | | Weigelt and Rumohr 1986 |
| Mikawa & Ise Bays | Japan | 1980 | | | | Mortality/avoidance | | Suzuki and Matsukawa 1987 |
| Mobile Bay | Alabama | 1880 | | 1060 | Mortality | Mass Mortality | | May 1973; Engle and Summers 1999; Pennock *et al.* 1994 |
| Mullica River Estuary | New Jersey | 1990 | | | | | | Glenn *et al*. 1996 |
| Neuse River Estuary | North Carolina | 1990 | | | Fish kills, mortality of oyster | Mortality/avoidance | Annual | Paerl *et al.* 1995, 1998; Lenihan and Peterson 1998; Lenihan 1999 |
| New York City Harbor | New York | 1990 | | | | Mass Mortality | Annual | Diaz, unpublished data |
| Nichupti Lagoon | Mexico | 1980 | | | | | | Diaz, unpublished data |
| Northern Adriatic Sea | Italy | 1970 | | 3750 | | | | Barmawidjaja *et al*. 1995; Justic *et al.* 1987, 1993 |
| NW Gulf of Mexico | Louisiana | 1980 | | | | Mortality | Annual | Gaston 1985 |
| NW Shelf Black Sea | Ukraine, Romania | 1960 | | 40000 | Reduced | Mass Mortality | Annual | Zaitsev 1993; Bakan and Buyukgungor 2000 |
| Oder Lagoon | Germany | 1990 | | | | | | Pohl *et al.* 1998 |
| Omura Bay | Japan | 1980 | | | | | | Iizuka and Min 1989 |
| Osaka Bay | Japan | 1980 | | | | | | Tanimoto and Hoshika 1997 |
| Oslofjord | Norway | 1910 | | 150 | Reduced | Mortality | Annual | Petersen 1915; Mirza and Gray 1981; Rosenberg *et al*. 1987 |
| Palude della Rosa | Italy | 1990 | | | | Mortality | Annual | Tagliapietra *et al.* 1998 |
| Pamlico River | North Carolina | 1960 | | | Mortality | Mass Mortality | Annual | Tenore 1972; Hobbie *et al.* 1975; Stanley and Nixon, 1992 |
| Patuxent Piver | Maryland | 1990 | | | Avoidance, low egg hatching/larval mortality | Avoidance/mortality | Annual | Keister *et al*. 2000, Breitburg *et al*. 1997 |
| Perdido Bay | Florida | 1990 | | | | | | Flemer *et al.* 1999 |
| Pomeranian Bay | Germany | 1990 | | 170 | | Mass Mortality | Reduced | Powilleit and Kube 1999 |
| Potomac River | Maryland | 1990 | | 264 | | Mortality | Annual | NOAA 1997 |
| Raritan Bay | New York, New Jersey | 1970 | | | | | | Christensen and Packard 1976 |
| SE Kattegat | Sweden | 1980 | | | Reduced demersal fishes | Avoidance/mortality | Multi-year | Peterson and Pihl 1995 |
| Seine Estuary | France | 1990 | | | | | | Michel *et al.* 2000 |
| Seto Inland Sea | Japan | 1980 | | | | Mortality | Annual | Imabayashi 1986 |
| St. Johns River | Florida | 1990 | | | | Mortality | Annual | Mason 1998 |
| Swedish West Coast Fjords | Sweden | 1980 | | | Stressed | Mortality | Reduced | Josefsen and Rosenberg 1988 |

| System | Country/State | First Observations | Recent | Area ($km^2$) | Fisheries Response | Benthic Response | Benthic Recovery | Reference |
|---|---|---|---|---|---|---|---|---|
| Thau | France | 1990 | | | Mortality/Reduced shellfish production | Mass Mortality | | Souchu *et al*. 1998; Mazouni *et al*. 1996; Chapelle *et al*. 2000 |
| Tolo Harbor | Hong Kong | 1980 | | | | Mass Mortality | Annual | Wu 1982 |
| Tome Cove | Japan | 1980 | | | | Mortality | Annual | Tsutsumi 1987 |
| Townsend-Hereford Inlet | New Jersey | 1990 | | | | | | Glenn *et al.* 1996 |
| Western Gulf of St. Lawrence | Canada | 1990 | | | | No response | | Comeau *et al* 2002 |
| **Episodic Oxygen Depletion** | | | | | | | | |
| Baie de Somme | France | 1990 | | | Collapse of cockle industry | Mass Mortality | | Rybarczyk *et al*. 1996 |
| Beacon Key, Biscane Bay | Florida | 1990 | | | | | | Leverone 1995 |
| Bude Bay | SW England | 1990 | | 12 | | Mortality | | Gibbs *et al.* 1999 |
| Buzzard Bay | Massachusetts | 1990 | | 2 | | | | NOAA 1997 |
| Cape Fear River | North Carolina | 1990 | | | Fish kills | Reduced | Annual | Mallin *et al.* 1999; Posey *et al.* 1999 |
| Chester River | Maryland | 1990 | | 24 | | | | NOAA 1997 |
| Choptank River | Maryland | 1990 | | 48 | | | | NOAA 1997 |
| Connecticut River | Connecticut | 1990 | | 9 | | | | NOAA 1997 |
| East Frisian, Wadden Sea | Netherlands | 1990 | | | | | | Kaiser and Lutter 1998 |
| Finnish Archipelago | Finland | 1970 | | | | | | Karlson *et a*l. 2002 |
| German Bight | Germany | 1980 | | 15000 | | Mass Mortality | Annual | Dethlefsen and Westernhagen 1983 Brockmann *et al.* 1988 |
| Gulf of Mexico, off Freeport | Texas | 1970 | | 50 | Mortality | Avoidance/mortality | 2 years | Harper and Rabalais 1995 |
| Krka, Adriatic Sea | Yugoslavia | 1980 | | | | Mortality | Annual | Legovic *et al*. 1991 |
| Lake Pontchartrain | Louisiana | 1990 | | | Loss of large clams | Reduced | | Abadie and Poirrier 2000 |
| Loch Ailort | Scotland | 1990 | | | Salmon farms in the system | Reduced | | Gillibrand *et al.* 1996 |
| New York Bight | New York, New Jersey | 1970 | | 987 | Surf clam/finfish mortality, Avoidance | Mass Mortality | Multi-year | Garlo *et al.* 1979; Sindermann and Swanson 1980 |
| North Sea coast | Germany | 1980 | | 25 | | Mortality | Reduced | Koenig 1996 |
| Off Cape Rodney | New Zealand | 1980 | | | Mortality | | | Taylor *et al.* 1985 |
| Pamlico Sound | North Carolina | 1990 | | | Mortality | Mortality | | Paerl *et al.* 2000 |
| Salts Hole | United Kingdom | 1990 | | 6 | | Mortality | | McArthur 1998 |
| SE North Sea | Denmark | 1980 | | | Stressed | Mortality | Annual | Dyer *et al.* 1983; Westernhagen and Dethlefson 1983 |
| Sommone Bay | France | 1980 | | 3 | Collapse of cockle fishery | Mass Mortality | Multi-year | Desprez *et al.* 1992 |
| Texas Shelf, Deep | Texas | 1980 | | | Stressed | Mortality | Annual | Harper *et al.* 1981, 1991 |
| Texas Shelf, Shallow | Texas | 1980 | | | Stressed | Mass Mortality | Multi-year | Harper *et al.* 1981, 1991 |
| Wadden Sea | Wadden Sea | 1990 | | 3000 | Stressed | Mortality | | deJonge *et a*l. 1994 |
| Wismar Bay | Baltic Sea | 1980 | | | Stressed | Mortality | Reduced | Prena 1995a, 1995b |
| Vestfjord | | 1970 | | | | | | Karlson *et a*l. 2002 |
| **Periodic Oxygen Depletion** (>1 event per year) | | | | | | | | |
| Bon Secour Bay | Alabama | 2000 | | | Loss of oyster | Mortality | | Rikard *et al*. 2000 |
| Florida Keys | Florida | 1990 | | | | Mortality | | Lapointe and Matzie 1996 |
| Gironde Estuary | France | 1990 | | | | | | Abril *et al.* 1999 |
| Great South Bay | New York | 1990 | | 15 | | | | NOAA 1997 |
| Gullmarsfjord, Alsback Deep | Sweden | 1990 | | | | Mortality | | Gustafsson and Nordberg 2001 |
| Jamaica Bay | New York | 1990 | | 26 | | | | NOAA 1997 |
| James Island Creek | South Carolina | 1990 | | | Avoidance | Avoidance | | Cochran and Burnett 1995 |
| Koljo Fjord | Sweden | 1990 | | | | Mortality | Annual | Gustafsson and Nordberg 1999; Rosenberg *et al*. 2001 |
| Narragansett Bay | Rhode Island | 1990 | | 11 | | | | NOAA 1997 |
| Prevost Lagoon | France | 1990 | | | Reduced aquaculture production | Mass Mortality | Annual | Guyoneaud *et al*. 1998 |

| System | Country/State | Observations | | (km$^2$) | Fisheries Response | Response | Recovery | Reference |
|---|---|---|---|---|---|---|---|---|
| Rappahannock River | Virginia | 1990 | | 55 | Avoidance | Mortality | Annual | Llanso 1992; NOAA 1997 |
| St. Joseph Bay | Florida | 1990 | | | Avoidance | | | Leonard and McClintock 1999 |
| St. Lucie River | Florida | 1990 | | | | | | Chamberlain and Hayward 1996 |
| York River | Virginia | 1980 | | 30 | Avoidance | No response | No Change | Pihl *et al.* 1991; Diaz *et a*l. 1992; Sagasti *et al*. 2001 |
| **Persistent Oxygen Depletion** | | | | | | | | |
| Arkona Basin | Sweden | 1980 | | 1000 | | | | Karlson *et al* 2002 |
| Baltic proper | Baltic Sea | 1960 | | 70000 | Avoidance, mortality/low hatch cod eggs | Mortality/avoidance | | deJonge *et al.* 1994 |
| Big Glory Bay | New Zealand | 2000 | | | Caused by salmon farming | Mass Mortality | | Morrisey 2000 |
| Byfjord | Sweden | 1970 | | | Pelagic only | Mortality | Reduced | Rosenberg 1990, Rosenberg *et al.* 1977 |
| Caspian Sea | Caspian Sea | 1990 | | | | Mortality | Some? | Dumont 1998 |
| Gdansk Basin | Poland | 1960 | | 1200 | | | | Karlson *et a*l. 2002 |
| Gotland Basin | Sweden | 1960 | | | Avoidance, mortality/low hatch cod eggs | Mortality | Reduced | Laine *et al.* 1997 |
| Gulf of Finland, Deep | Gulf of Finland, Deep | 1960 | Improved | 2330 | | Reduced | Increasing | Laine *et al.* 1997; Andersin and Sandler 1991 |
| Himmerfjord | Sweden | 1970 | Improved | 11 | | | | Karlson *et al.* 2002 |
| Idefjord | Sweden, Norway | 1960 | Improved | 80 | | Mortality | Reduced | Rosenberg 1980 |
| Loch Carron | Scotland | 1970 | | | | Mass Mortality | No Change | |
| Scheldt Estuary | Belgium | 1990 | | | | | | Verlaan *et al.* 1998 |
| Sea of Azov | Russia-Ukraine | 1990 | | | Lower production | Mortality | Reduced | Balkas *et al.* 1991; Chechum 1998 |
| | | First | Recent | Area | | Benthic | Benthic | |
| Skagerrak Coast Fjords | Sweden, Norway | 1920 | | 54 | Stressed | Mortality | | AnnualJohannessen and Dahl 1996a,b |
| St. Anna Archipelago | Sweden | 1970 | | 25 | | | | Karlson *et al.* 2002 |
| Stockholm Inner Archipelago | Sweden | 1970 | | 60 | | No Benthos | No Change | Rosenberg and Diaz 1993 |
| Sullom Voe | Shetland | 1980 | | | | Mass Mortality | No Change | Pearson and Eleftheriou 1981 |
| Tan Shui Estuary | Taiwan | 1990 | | | | | | Jeng and Han 1996 |
| **Unknown Oxygen Depletion Cause** | | | | | | | | |
| Etang de Berre | France | 1970 | | 132 | | | | Stora and Arnoux 1983 |
| Kilviken Fjord | Sweden | 1970 | | | | Reduced | | Hendelberg and Jensen 1993 |
| Marmara Sea | Marmara Sea | 1990 | | | Mass Mortality | Mass Mortality | | Orhon and Yuksek, unpublished data |
| Mauritius Island | Mauritius Island | 1990 | | | Coral reef affected | | | Thomassin *et al*. 1998 |
| Mondego River | Portugal | 1990 | | | | | | Kamp-Nielsen *et al.* 1997 |
| Pettaquamscutt River | Rhode Island | 1990 | | | | | | Wilkin and Barnes 1997 |
| Roskilde Fjord | Denmark | 1990 | | | | | | Kamp-Nielsen *et al.* 1998 |
| Waquoit Bay | Massachusetts | 1990 | | | | | | Fritz *et al*. 1996 |

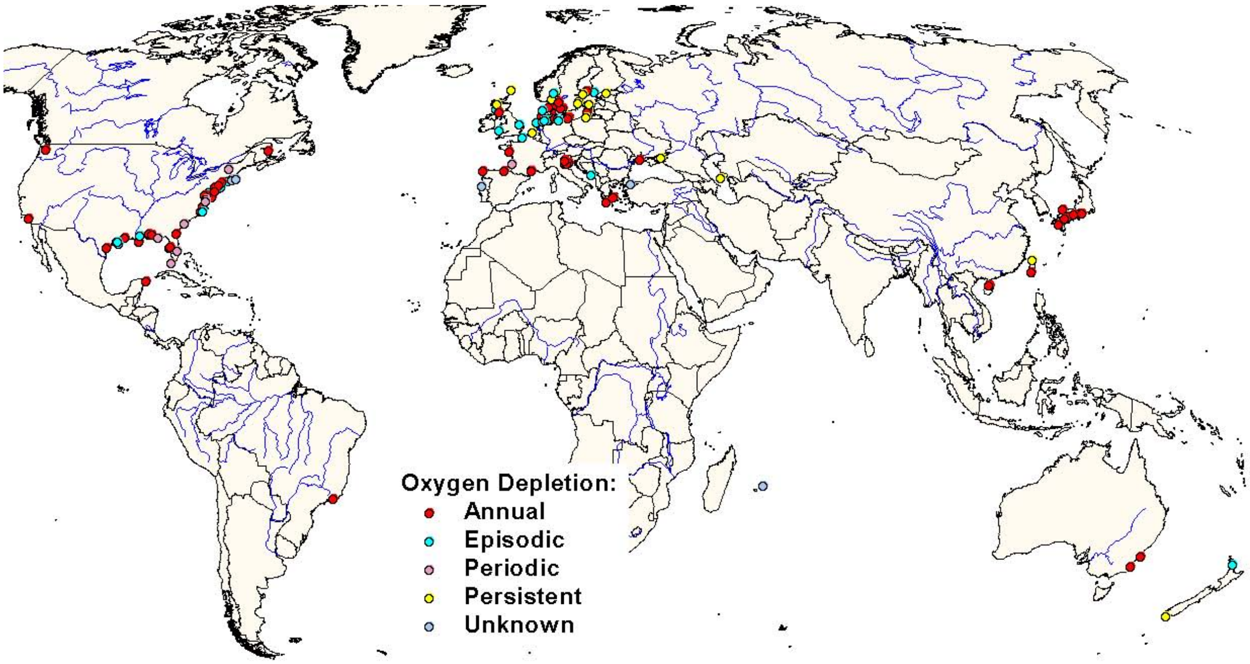


Figure 2. Global distribution of the 146 oxygen depletion zones related to cultural eutrophication listed in Table 1. Systems are categorized by type of hypoxia (see Table 1 for details).

The most common form of hypoxia is one annual event, occurring at 54% of the 146 oxygen-depleted systems. The most common response to annual oxygen depletion was mortality of benthos followed by some level of recolonization with the return of normal oxygen conditions (Table 1). In essence, annual hypoxia forces an annual pulsing of energy over the shortened interval of normal dissolved oxygen conditions (Diaz and Rosenberg 1995). The second most common form of oxygen depletion is episodic, occurring 18% of the time in the 146 systems. It appeared that episodic oxygen depletion was the first signal that a system had reached a critical point. Many systems, such as the Kattegat, first experienced episodic events that initially caused mass mortality of benthic organisms, but now experience annual oxygen depletion (Karlson *et al.* 2002).

Since the 1960s, the number of oxygen-depleted ecosystems has doubled every ten years (Figure 3). Prior to 1960, we found nine systems with cultural eutrophication-related oxygen depletion. During the 1960s, another ten systems were added, but by the 1970s estuarine and coastal ecosystems around the world were becoming over enriched with organic matter (Nixon 1995) and the number of oxygen-depleted ecosystems had doubled (Figure 3). After this point, hypoxia quickly became an annual event and a prominent feature affecting energy flow processes in marine ecosystems (Elmgren 1989, Pearson and Rosenberg 1992). During the 1980s, 37 systems were added, and in the 1990s 68 more were added (Table 1). By the end of the 20$^{th}$ century, oxygen depletion had become a major, worldwide environmental problem with only a small fraction of systems (6%) showing signs of improvement.

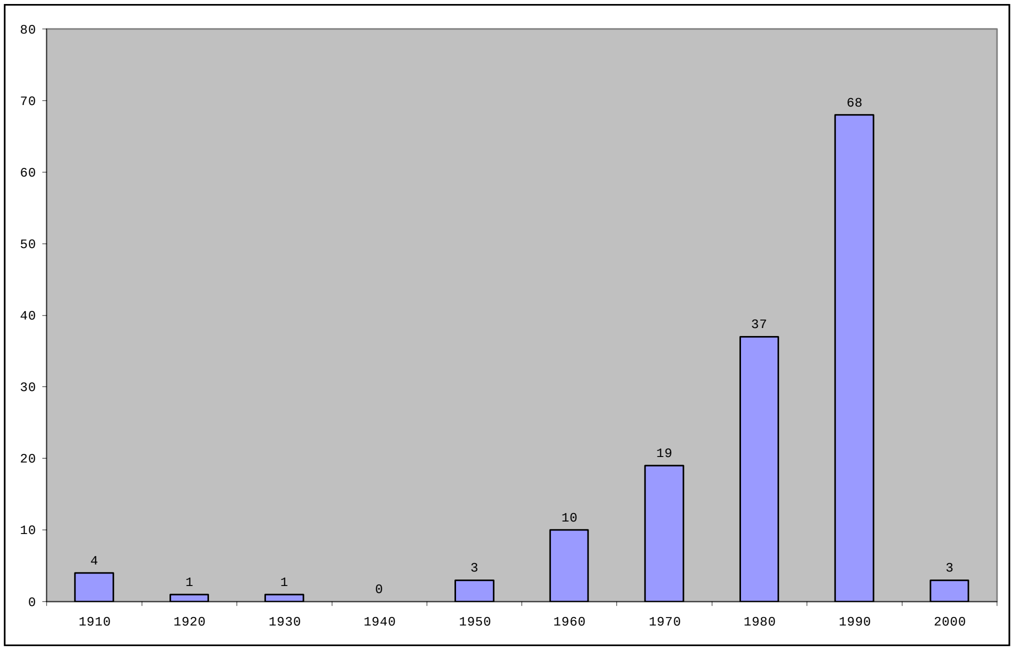


Figure 3. Histogram of the number of ecosystems reporting oxygen depletion by decade. The decade was determined either from the first time hypoxia was seen in historical data or the first year a published account appeared in the literature. Data from Table 1.

The largest systems with improved dissolved oxygen conditions were the northwest Black Sea and the Gulf of Finland. In the Black Sea, a reduction in nutrients and possibly a balancing of exotic species led to an improvement in ecosystem function and reduction in hypoxia (Kidey 2002). In the Gulf of Finland, a decrease in water column stratification led to improved dissolved-oxygen conditions and the return of benthic fauna (Karlson *et al.* 2002). Conditions have also improved in some systems that have experienced intensive regulation of nutrient or carbon inputs, such as the Hudson River, New York, and the Delaware River in Pennsylvania and New Jersey. In others, such as the Chesapeake Bay, improvements in dissolved oxygen await the 'burn off' of nitrogen that has accumulated within the system's sediments. Many examples of small-scale reversals in hypoxia associated with improvements in treatment of sewage and pulp mill effluents as early as the 1970s (Rosenberg 1972, 1976) also exist. In the northern Gulf of Mexico, the hypoxic zone is very tightly coupled with runoff from the Mississippi River. During low flow years, the area of hypoxia is greatly reduced, only to increase when river flow increases (Rabalais *et al.* 2001a, unpublished data). Similarly, the Baltic Sea can experience temporary dissolved oxygen increases associated with episodic water exchanges across the belt seas. Even though the exchange of deep water in the Baltic is episodic, there is convincing evidence that eutrophication accelerates oxygen consumption in its bottom waters (Karlson *et al.* 2002).

In general, coastal hypoxia is not a natural condition. Only hypoxia and anoxia associated with naturally-occurring events have a historical context dating back 100 to 150 years.

This includes: areas of natural upwelling, such as those off Peru and Central America (Tarazona *et al.* 1988) or West Africa's Namibian shelf (Hamukuaya *et al.* 1998); oceanic OMZ, such as in the Arabian Sea (Gooday *et al.* 2000); and stagnant basins, such as Santa Barbara Basin off California (Bernhard and Reimers 1991). Methodologies for measuring dissolved oxygen were not developed until the 1880s (Winkler 1888). Accounts in the historical literature do imply the occurrence of oxygen depletion prior to development of Winkler's method, and were generally in water bodies associated with human development. For example, in 1884 the Mobile Register (Alabama, USA) described what was very likely a hypoxic/anoxic event in Mobile Bay, with fishes congregating in shallow water where they were easily caught by hand (J. Pennock, University of Alabama, personal communication). Mobile Bay has a well-documented history of oxygen depletion that extends back to at least the 1960s, with descriptions of similar attempts by fish to escape oxygen-depleted waters (May 1973). A detailed review of the historical literature will likely find hundreds of such accounts, and we predict that most of them can be associated with some sort of human development.

The most serious effects of the combined problems associated with eutrophication and hypoxia are seen in the Black Sea and Baltic Sea, where demersal trawl fisheries have either been eliminated or severely stressed (Elmgren 1989, Mee 1992). Karlson *et al.* (2002) provide a detailed summary of the development of oxygen depletion in the Baltic and surrounding seas. The Black Sea, in particular, provides an excellent example of how multiple stressors conspired to alter an entire system. In the 1980s and early 1990s, the northwest coastal shelf of the Black Sea was in a severe state of deterioration from stress exerted by multiple factors, including over-fishing, exotic species introduction (the ctenophore *Mnemiopsis* spp.), pollution, altered hydrology and nutrient enrichment that led to eutrophication-induced hypoxia (Mee 1992, Kideys 1994, 2002). Historical data show that in the 1940s, the northwest Black Sea was considered to be oligotrophic. However, by the 1970s nutrient enrichment had led to a highly eutrophic condition that, in turn, led to alterations in the composition and quality of phytoplankton production, including harmful algal blooms (HAB). In the 1970s prior to the introduction of the ctenophore, and in the 1980s before ctenophore populations exploded, eutrophication resulted in increased anchovy (*Engraulis encrasicolus*) production and widespread hypoxia. Through the 1970s and 1980s hypoxia and anoxia became more prevalent and were the primary cause of mass mortality of the benthos, including demersal fish. Other complex changes that occurred and were likely a response to the multiple stressors included increased turbidity, decrease in nongelatinous zooplankton, decline in biodiversity, and replacement of highly-valued demersal fish species with less desirable planktonic omnivores (Mee 1992, Kideys 2002). Of the 26 commercial species fished in the 1960s, only six still supported a fishery in the early 1990s (Mee 1992). In 1989, the ctenophore populations exploded and caused a crash in the pelagic anchovy and nongelatinous zooplankton communities that was not oxygen-related. This event indicates that the combination of stressors affecting the Black Sea needs to be examined in order to understand ecosystem response. The resilience of the Black Sea ecosystem was observed in the 1990s when nutrient loads declined between 1991 and 1997. Primary production declined, there was a species shift back to diatoms, harmful algal blooms decreased, nongelatinous zooplankton increased, and pelagic fish reappeared (Kideys 2002). The introduction of the ctenophore *Beroe* spp., a predator of *Mnemiopsis* spp., further improved the Black Sea ecosystem.

The eutrophication-related oxygen depletion zone in the northwest Black Sea is not related to the central Black Sea anoxic zone, which over the last 5000 years has evolved an oxic/anoxic ecosystem in a precise redox balance (Konovalov and Murray 2001). However, there is now evidence that even the central Black Sea anoxic zone is showing the signs of eutrophication due to an increased flux of organic matter. This, in turn, has increased the rate of sulfate reduction and created an imbalance in the sulfide budget. As a result, sulfide concentrations have increased in the anoxic zone over the past 20 to 25 years (Konovalov and Murray 2001).

As early as the 1980s, the occurrence of hypoxia in coastal systems was closely linked to eutrophication. In the German Bight, van Pagee *et al*. (1983) found that from 1930 to 1983 an increase in nutrients corresponded with an increase in the duration and severity of hypoxia. In all recent cases, (listed in Table 1), hypoxia appears to be a result of general ecosystem eutrophication, with other stressors acting to complicate ecosystem response. It is difficult or impossible to separate the response of an ecosystem to eutrophication-induced hypoxia from the other multiple stressors on ecosystem functioning; the Black Sea provides a good example. However, some level of eutrophication appears to be a positive force in enhancing a system's secondary productivity (Nixon and Buckley 2002), and to a point enhances fisheries yield (Caddy 1993, 2001). The critical point in the ecosystem response trajectory to eutrophication is the appearance of severe hypoxia or anoxia, either of which can potentially cause mass mortality of both benthic and pelagic species. The general effect of eutrophication and hypoxia to favor benthic macrofaunal communities and species with opportunistic life histories, shorter life spans, and smaller body size is well characterized by the Pearson and Rosenberg (1978) organic gradient response model. However, eutrophication has a preconditioning effect on benthic fauna by eliminating sensitive species, which tends to lessen the acute response of the system to hypoxia when it does occur. This is the reason some systems that experience mild hypoxia show no acute effect, such as the York River, in Virginia (Neubauer 1993, Sagastie *et al.* 2001).

Climate change, whether from global warming or from microclimate variation, will have direct consequences for eutrophication-related oxygen depletion. The form of climate change effect will depend primarily upon how the strength of water column stratification is affected, and secondarily on factors that affect organic matter production such as nutrient supplies. At a global scale, general circulation models predict large changes in rainfall patterns under a $CO_2$ doubling scenario. If these changes in rainfall lead to increased discharges of freshwater to coastal ecosystems, stratification is likely to increase and oxygen depletion will expand in those systems already affected, and may begin in other systems. Conversely, if stratification decreases, oxygen depletion or the chances for depletion will decrease. For that part of the Mississippi River basin associated with the northern Gulf of Mexico annual oxygen depletion, a doubling of $CO_2$ would increase river discharge by 20% and temperature by $2^{o}C$ to $4^{o}C$ (Miller and Russell 1992). Justic *et al.* (1996) predicted that these changes would lead to a 50% increase in primary production, a 30% to 60% decrease in subpycnocline dissolved oxygen, and expansion of the oxygen-depleted area. Smaller-scale climate variation, such as the North Atlantic Oscillation (NAO) index, may have similar effects on dissolved oxygen budgets. Nordberg *et al.* (2000, 2001) found that the NAO index was correlated to hydrographic conditions in Swedish west coast fords, and may in part be responsible for changes in dissolved oxygen budgets, particularly in fjords not subjected to significant human pollution.

## SUMMARY

Hypoxia related to anthropogenic activities appears to develop within a system as a result of the cumulative effects of eutrophication in combination with other stressors. Many times hypoxia is not noticed until higher-level ecosystem effects are manifested. For example, hypoxia did not become a prominent environmental issue in the Kattegat until the collapse of a Norway lobster fishery several years after hypoxic bottom waters were first reported (Baden *et al.* 1990b). The northern Gulf of Mexico is representative of severely stressed coastal ecosystems that currently experience seasonal hypoxia, but have not experienced hypoxia-related loss of fisheries. Although hypoxia in the northern Gulf of Mexico has affected benthic invertebrate communities over the last several decades, there is no clear signal of hypoxia in fisheries landings statistics (Rabalais *et al.* 2001a, Chesney and Baltz 2001). However, ecosystem level change is rarely the result of a single factor, and several forms of stress typically act in concert to cause change within an ecosystem. The critical point for fisheries losses in the northern Gulf of Mexico may be potential effects from global warming. The shallow, northwest continental shelf of the Black Sea (not part of the deep central basin anoxia) is another example of a system that was stressed by eutrophication-driven hypoxia in combination with other stressors that led to drastic reductions in bottom fisheries (Mee 1992, Kideys 1994, 2002).

Until the 1950s, reports of mass mortality of marine animals caused by lack of oxygen were limited to small systems that had histories of oxygen stress (Brongersma-Sanders 1957). In the 1960s, the number of systems with reports of hypoxia-related problems started to increase, but it was in the 1970s and 1980s when most initial reports of hypoxia occurred. By the 1990s, most estuarine and marine systems in close proximity to population centers had reports of hypoxia or anoxia. It does not appear that reports of oxygen depletion have leveled off, and the number of systems affected by hypoxia/anoxia continues to rise. There is encouraging news since 2000 that some large systems such as the Black Sea and Gulf of Finland have responded positively to a decrease in stressors.

Coastal and estuarine hypoxia does not appear to be a natural condition, except in areas influenced by OMZs, upwelling, or some enclosed fjord systems. The main factor in development of hypoxia in coastal and estuarine systems has been the input of excess nutrients leading to eutrophication. The determination of population or ecosystem level effects from hypoxia is complicated by many factors, including inadequate data on historic trends of species populations and dissolved oxygen concentrations and the interaction and synergistic effects of multiple stressors such as fishing pressure, habitat loss, etc. (Figure 1). Hypoxia and anoxia are among the most widespread deleterious anthropogenic effects in estuarine and marine environments. The effects of hypoxia may be reversed by the reduction of nutrient or organic inputs to a system that lead to a reduction or elimination of the hypoxia.

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## REFERENCES

Abadie, S.W. and M.A. Poirrier. 2000. Increased density of large *Rangia* clams in Lake Pontchartrain after the cessation of shell dredging. Journal of Shellfish Research 19:481-485.

Abril, G., H. Etcheber, P.L. Hir, P. Bassoullet, B. Boutier, and M. Frankignoulle. 1999. Oxic/anoxic oscillations and organic carbon mineralization in an estuarine maximum turbidity zone (The Gironde, France). Limnology and Oceanography 44:1304-1315.

Andersin, A.B., J. Lassig, L. Parkkonen, and H. Sandler. 1978. The decline of macrofauna in the deeper parts of the Baltic proper and the Gulf of Finland. Kieler Meeresforschungen, Sonderheft 4:23-52.

Andersin, A.-B. and H. Sandler. 1991. Macrobenthic fauna and oxygen deficiency in the Gulf of Finland. Memoranda Soc Fauna Flora Fennica 67:3-10.

Arntz, W. 1981. Zonation and dynamics of macrobenthos biomass in an area stressed by oxygen deficiency. *In:* Stress effects on natural ecosystems, G.W. Barrett and R. Rosenberg (eds.), John Wiley and Sons, Chichester. pp. 215-225.

Arvanitidis C., D. Koutsoubas, C. Dounas, and A. Eleftheriou. 1999. Annelid fauna of a Mediterranean Lagoon (Gialova Lagoon, south-west Greece): community structure in a severely fluctuating environment. Journal of Marine Biology Association UK 1999: 849-856.

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

Baden, S.P., L. Pihl, and R. Rosenberg. 1990b. Effects of oxygen depletion on the ecology, blood physiology and fishery of the Norway lobster *Nephrops norvegicus*. Marine Ecology Progress Series 67:141-155.

Bakan, G. and H. Buyukgungor. 2000. The Black Sea. Marine Pollution Bulletin 41:24-43.

Barmawidjaja, D. M., G. J. Van Der Zwaan, F.J.Jorissen, and S. Puskaric. 1995. 150 years of eutrophication in the northern Adriatic Sea: Evidence from a benthic formaminiferal record. Marine Geology. 122: 367–384.

Bentley, S.J. and C.A. Nittrouer. 1999. Physical and Biological Influences on the Formation of Sedimentary Fabric in an Oxygen-restricted Depositional Environment: Eckernfoerde Bay, Southwestern Baltic Sea. Palaios 14.

Bernhard, J.M. and C.E. Reimers. 1991. Benthic foraminiferal population fluctuations related to anoxia: Santa Barbara basin. Biogeochemistry 15:127-149.

Boesch, D.F., R.B. Brinsfield, and R.E. Magnien. 2001. Chesapeake Bay Eutrophication: Scientific understanding, ecosystem restoration, and challenges for agriculture. Journal of Environmental Quality 30:303-320.

Breitburg, D.L, T. Loher, C.A. Pacey, and A. Gerstein. 1997. Varying effects of low dissolved oxygen on trophic interactions in an estuarine food web. Ecological Monographs 67:489-507.

Breitburg, D.L., J. Baxter, C. Hatfield, R.W. Howarth, C.G. Jones, G.M. Lovett, and C. Wigand. 1998. Understanding effects of multiple stresses: ideas and challenges. *In*: Successes, Limitations and Frontiers in Ecosystem Science, M. Pace and P. Groffman (eds.), Springer, New York, pp. 416-431.

Breitburg, D.L., L. Pihl, and S.E. Kolesar. 2001. Effects of low dissolved oxygen on the behavior, ecology and harvest of fishes: a comparison of the Chesapeake and Baltic systems. *In:* Coastal Hypoxia Consequences for Living Resources and Ecosystems, N.N. Rabalais and R.E. Turner (eds.), American Geophysical Union, Washington, D.C. pp. 241-267.

Brockmann, U., G. Billen, and W. Gieskes. 1988. North Sea Nutrients and Eutrophication. *In:* Pollution of the North Sea: An Assessment, W. Salomons, B. Bayne, E. Duursma, and U. Förstner (eds.), Springer-Verlag, New York, pp. 348-389.

Brongersma-Sanders, M. 1957. Mass mortality in the sea. *In*: Treatise on Marine Ecology and Paleoecology, Volume 1, J.W. Hedgpeth (ed.), Waverly Press, Baltimore, pp. 941-1010.

Brosnan, T.M. and M.L. O'Shea. 1996. Long-term improvements in water quality due to sewage abatement in the lower Hudson River. Estuaries 19:890-900.

Caddy, J. 1993. Toward a comparative evaluation of human impacts on fishery ecosystems of enclosed and semi-enclosed seas. Review of Fishery Science 1:57-96.

Caddy, J. 2001. A brief overview of catchment basin effects on marine fisheries. *In:* Coastal Hypoxia Consequences for Living Resources and Ecosystems, N.N. Rabalais and R.E. Turner (eds.), American Geophysical Union, Washington, D.C. pp. 355-370.

Caplan, M.L. and R.M. Bustin. 1999. Devonian-Carboniferous Hangenberg mass extinction event, widespread organic-rich mudrock and anoxia: causes and consequences. Palaeogeography, Palaeoclimatology, Palaeoecology 148:187-208.

Chamberlain, R. and D. Hayward. 1996. Evaluation of water quality and monitoring in the St. Lucie Estuary, Florida. Water Resources Bulletin 32:681-696.

Chapelle, A., A. Menesguen, J.-M. Deslous-Paoli., P. Souchu, N. Mazouni, A. Vaquer, and B. Millet. 2000. Modelling nitrogen, primary production and oxygen in a Mediterranean lagoon. Impact of oysters farming and inputs from the watershed. Ecological Modelling 127: 161–181.

Chechun, T.Y. 1998. Nutrition of the Acipenseridae of the Sea of Azov under present conditions. Journal of Ichthyology 38:147-154.

Cheng, W., C.-H. Liu, J.-P. Hsu, and J.-C. Chen. 2002. Effect of hypoxia on the immune response of giant freshwater prawn *Macrobrachium rosenbergii* and its susceptibility to pathogen Enterococcus. Fish and Shellfish Immunology 13:351-365.

Chesney, E.J. and D.M. Baltz. 2001. The effects of hypoxia on the northern Gulf. *In:* Coastal Hypoxia Consequences for Living Resources and Ecosystems, N.N. Rabalais and R.E. Turner (eds.), American Geophysical Union, Washington, D.C. pp. 321-354.

Childress, J.J. and B.A. Seibel. 1998. Live at stable low oxygen levels: adaptations of animals to oceanic oxygen minimum layers. Journal of Experimental Biology 201:1223-1232.

Christensen, J. and T. Packard. 1976. Oxygen utilization and plankton metabolism in a Washington fjord. Estuarine and Costal Marine Science 4:339-347.

Cloern, J.E. 2001. Our evolving conceptual model of the coastal eutrophication problem. Marine Ecology and Progress Series 210:223-253.

Cochran, R.E. and L.E. Burnett. 1995. Respiratory responses of the salt marsh animals *Fundulus heteroclitus*, *Leiostomus xanthurus*, and *Palaeominetes pugio* to environmental hypoxia and hypercapnia, and to the organophosphate pesticide, azinphosmethyl. Journal of Experimental Marine Biology and Ecology 195:125-144.

Comeau, L.A., S.E. Campana, and G.A. Chouinard. 2002. Timing of cod (*Gadus morhua* L.) seasonal migrations in the southern Gulf of St. Lawrence: interannual variability and proximate control. ICES Journal of Marine Science 59: 333-351.

D'Andrea, A.F., N.I. Craig, and G.R. Lopez. 1996. Benthic macrofauna and depth of bioturbation in Eckernfoerde Bay, southwestern Baltic Sea. Geo-Marine 16:155-159.

deJonge, V.N., W. Boynton, C.F. D'Elia, R. Elmgren, and B.L. Welsh. 1994. Responses to developments in eutrophication in four different North Atlantic estuarine systems. *In*: Changes in Fluxes in Estuaries: Implications from Science to Management, K. Dyer and R. Orth (eds.), Olsen and Olsen, Fredensborg, Denmark, pp. 179-196.

Desprez, M., H. Rybarczyk, J.G. Wilson, J.P Ducrotoy, F. Sueur, R. Olivesi, and B. Elkaim. 1992. Biological impact of eutrophication in the Bay of Somme and the induction and impact of anoxia. Netherlands Journal of Sea Research 30:149-159.

Dethlefsen, V. and H.V. Westernhagen. 1983. Oxygen deficiency and effects on bottom fauna in the eastern German Bight 1982. Meeresforschung 60:42-53.

Diaz, R.J. and R. Rosenberg. 1995. Marine benthic hypoxia - review of ecological effects and behavioural responses on macrofauna. Oceanography and Marine Biology: an Annual Review 33:245-303.

Diaz, R.J. and R. Rosenberg. 2001. Overview of anthropogenically-induced hypoxia effects on marine benthic fauna. *In:* Coastal Hypoxia Consequences for Living Resources and Ecosystems, N.N. Rabalais and R.E. Turner (eds.), American Geophysical Union, Washington, D.C. pp. 129-146.

Diaz, R.J., R.J. Neubauer, L.C. Schaffner, L. Pihl, and S.P. Baden. 1992. Continuous monitoring of dissolved oxygen in an estuary experiencing periodic hypoxia and the effect of hypoxia on macrobenthos and fish. Science of the Total Environment, Supplement 1992, pp. 1055-1068.

Donnelly, T.H., P.W. Ford, D. McGregor, and D. Allen. 1999. Anthropogenic changes to a billabong in New South Wales. 1. Lagoon evolution and phosphorus dynamics. Marine and Freshwater Research 50:689-698.

Dumont, H.J. 1998. The Caspian Lake: History, biota, structure, and function. Limnology and Oceanography 43:44-52.

Dyer, M.F., J.G. Pope, P.D. Fry, R.J. Law, and J.E. Portmann. 1983. Changes in fish and benthos catches off the Danish coast in September 1981. Journal of the Marine Biological Association of the United Kingdom 63:767-775.

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.

Engle, V.D., J.K. Summers, and J.M. Macauley. 1999. Dissolved oxygen conditions in northern Gulf of Mexico estuaries. Environmental Monitoring and Assessment 57:1-20.

Engle, V.D. and J.K. Summers. 1999. Refinement, validation, and application of a benthic condition index for northern Gulf of Mexico estuaries. Estuaries 22(3A):624-635.

Fallesen, G. and H.M. Jørgensen. 1991. Distribution of *Nephtys hombergii* and *N. ciliata* (Polychaeta: Nephtyidae) in Århus Bay, Dennmark, with emphasis on the effect of sewage oxygen deficiency. Ophelia Supplement 5:443-450.

Flemer, D.A., W.L. Kruczynski, B.F. Ruth, and C.M. Bundrick. 1999. The relative influence of hypoxia, anoxia, and associated environmental factors as determinants of macrobenthic community structure in a northern Gulf of Mexico estuary. Journal of Aquatic Ecosystem Stress and Recovery 6:311-328.

Fonselius, S.H. 1969. Hydrography of the Baltic deep basins III. Fishery Board of Sweden, Series Hydrography report No.23. pp. 1-97.

Friedrich, J., C. Dinkel, G. Friedl, N. Pimenov, J. Wijsman, M.-T. Gomoiu, A. Cociasu, L. Popa, and B. Wehrli. 2002. Benthic nutrient cycling and diagenetic pathways in the north-western Black Sea. Estuarine, Coastal and Shelf Science 54: 369–383.

Friligos, N. and A. Zenetos. 1988. Elefsis Bay anoxia: nutrient conditions and benthic community structure. Marine Ecology 9:273-290.

Fritz, C., E. LaBrecque, J. Tober, P.J. Behr, and I. Valiela. 1996. Shrimp in Waquoit Bay: Effects of nitrogen loading on size and abundance. General Scientific Meetings of the Marine Biological Laboratory, Woods Hole, MA. 191:326-327.

Garlo, E.V., C.B. Milstein, and A.E. Jahn. 1979. Impact of hypoxic conditions in the vicinity of Little Egg Inlet, New Jersey in summer 1976. Estuarine and Coastal Marine Science 8:421-432.

Gaston, G. 1985. Effects of hypoxia on macrobenthos of the inner shelf off Cameron, Louisiana. Estuarine, Coastal and Shelf Science 20: 603-613.

Gibbs, P.E., J.C. Green, and P.L. Pascoe. 1999. A massive summer-kill of the dog whelk, Nucella lapillus, on the north Cornwall coast in 1995: freak or forerunner? Journal of Marine Biology Association UK 1999: 103-109.

Gillibrand, P.A., W.R. Turrell, D.C. Moore, and R.D. Adams. 1996. Bottom water stagnation and oxygen depletion in a Scottish sea loch. Estuarine, Coastal and Shelf Science 43:217-235.

Glenn, S., M. Crowley, D. Haidvogel, and Y. Song. 1996. Underwater observatory captures coastal upwelling event off New Jersey. EOS Transaction, American Geophysical Union, 77:223-236.

Gonzales-Oreja, J., and J. Saiz-Salinas. 1998. Loss of herterotrophic biomass structure in an extreme estuarine environment. Estuarine, Coastal and Shelf Science 48:391-399.

Gooday, A.J., J.M. Bernhard, L.A. Levin, and S.B. Suhr. 2000. Foraminifera in the Arabian Sea oxygen minimum zone and other oxygen-deficient settings: taxonomic composition, diversity, and relation to metazoan faunas. Deep-Sea Research Part II 47:25-54.

Gray, J.S. 1992. Eutrophication in the sea. *In*: Marine Eutrophication and Population Dynamics, G. Colombo, I. Ferrari, V.U. Ceccherelli and R. Rossi (eds.), Proceedings 25th European Marine Biology Symposium. Olsen and Olsen, Fredensporg, pp. 3-15.

Gustafsson, M. and K. Nordberg. 1999. Benthic foraminifera and their response to hydrography, periodic hypoxic conditions and primary production in the Koljo fjord on the Swedish west coast. Journal of Sea Research 41: 163-178.

Gustafsson, M., and K. Nordberg. 2000. Living (stained) benthic foraminifera and their response to the seasonal hydrographic cycle, periodic hypoxia and to primary production in Havstens Fjord on the Swedish west coast. Estuarine, Coastal and Shelf Science 51: 743-761.

Gustafsson, M. and K. Nordberg. 2001. Living (stained) benthic foraminiferal response to primary production and hydrography in the deepest part of the Gullmar Fjord, Swedish west coast, with comparisons to Hoglund's 1927 material. Journal of Foraminiferal Research 31: 2-11.

Guyoneaud, R., R. De Wit, R. Matheron, and P. Caumette. 1998. Impact of macroalgal dredging on dystrophic crises and phototrophic bacterial blooms (red waters) in a brackish coastal lagoon. Oceanologica Acta 21:551-561.

Hagerman, L., A. B. Josefson and J.N. Jensen. 1996. Benthic macrofauna and demersal fish. *In*: Eutrophication in Coastal Marine Ecosystems, B.B. Jørgensen and K. Richardson (eds.), Coastal and Estuarine Studies, Volume 52. American Geophysical Union, Washington, D.C. pp. 155-178.

Hamukuaya, H., M.J. O'Toole, and P.M.J. Woodhead. 1998. Observations of severe hypoxia and offshore displacement of Cape hake over the Namibian shelf in 1994. South African Journal of Marine Science 19:57-59.

Harper, D.E., Jr., and N.N. Rabalais. 1995. Responses of Benthonic and Nektonic Organisms, and communities, to severe hypoxia on the inner continental shelf of Louisiana and Texas. *In*: Proceedings of the First Gulf of Mexico Hypoxia Management Conference, Dec 5-6, 1995, Kenner, Louisiana, USEPA-55-R-97-002, pp. 41-56.

Harper, D.E., L.D. McKinney, J.M. Nance, and R.B. Salzer. 1991. Recovery responses of two benthic assemblages following an acute hypoxic event on the Texas continental shelf, northwestern Gulf of Mexico. *In*: Modern and Ancient Continental Shelf Anoxia, R.V. Tyson and T.H. Pearson (eds.), Geological Society Special Publication No. 58, London, pp. 49-64.

Harper, D.E., L.D. McKinney, R.B. Salzer, and R.J. Case. 1981. The occurrence of hypoxic bottom water off the upper Texas coast and its effects on the benthic biota. Contributions in Marine Science 24:53-79.

Hendelberg, M. and P. Jensen. 1993. Vertical distribution of the nematode fauna in a coastal sediment influenced by seasonal hypoxia in the bottom water. OPHELIA 37: 83-94.

Hobbie, J. E., B. J. Copeland, and W. G. Harrison. 1975. Sources and fates of nutrients in the Pamlico River estuary of North Carolina. *In:* Estuarine Research. Vol.1, L. E. Cronin (ed.), Academic Press, New York, pp. 287-302.

Holland, A.F., A.T. Shaughnessy, and M.H. Hiegel. 1987. Long-term variation in Mesohaline Chesapeake Bay macrobenthos: spatial and temporal patterns. Estuaries 10:370-378.

Howell, P. and D. Simpson. 1994. Abundance of marine resources in relation to dissolved oxygen in Long Island Sound. Estuaries 17:394-402.

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 riverine N & P fluxes for the drainage to the North Atlantic Ocean: natural and human influences. Biogeochemistry 35:75-139.

Howarth, R.W., A. Sharpley, and D. Walker. 2002. Sources of nutrient pollution to coastal waters in the United States: implications for achieving coastal water quality goals. Estuaries 40:656-676.

Hylleberg, J. 1993. Extinction and immigration of benthic fauna, the value of historical data from Limfjorden, Denmark. *In:* Symposium Mediterranean Seas 2000, Santa Margherita Ligure, September 23-27, 1991, Instituto di Scienze Ambientali Marine, Santa Margherita Ligure, Italy, pp. 43-70, N. Della Croce (ed.).

Iizuka, S. and S. Min. 1989. Formation of anoxic bottom waters in Omura Bay. Engan Kaiyo Kenkyu. 2:75-86.

Imabayashi, H. 1986. Effect of oxygen-deficient water on the settled abundance and size composition of the bivalve *Theora lubrica*. Bulletin of the Japanese Society of Scientific Fisheries. 5:391-397.

Ishitobi, Y., J. Hiratsuka, H. Kuwabara, and M. Yamamuro. 2000. Comparison of fish fauna in three areas of adjacent eutrophic estuarine lagoons with different salinities. Journal of Marine Systems 26:171–181.

Jackson, J.B.C., M.X. Kirby, W.H. Berger, K.A. Bjorndal, L.W. Botsford, B.J. Bourque, R.H. Bradbury, R. Cooke, J. Erlandson, J.A. Estes, T.P. Hughes, S. Kidwell, C.B. Lange, H.S. Lenihan, J.M. Pandolfi, C.H. Peterson, R.S. Steneck, M.J. Tegner, and R.R. Warner.

2001. Historical overfishing and the recent collapse of coastal ecosystems. Science 293:629–638.

Jaworski, N.A., R.W. Howarth, and L. J. Hetling. 1997. Atmospheric deposition of nitrogen oxides onto landscape contributes to coastal eutrophication in the northeast United States. Environmental Science and Technology 31:1995-2004.

Jeng, W-L. and B-C. Han. 1996. Coprostanol in a sediment core from the anoxic Tan-Shui Estuary, Taiwan. Estuarine, Coastal and Shelf Science 42:727-735.

Johannessen, T. and E. Dahl. 1996a. Declines in oxygen concentrations along the Norwegian Skagerrak coast, 1927-1993: A signal of ecosystem changes due to eutrophication? Limnology and Oceanography 41: 766-778.

Johannessen, T. and E. Dahl. 1996b. Historical changes in oxygen concentraions along the Norwegion Skagerrak coast: Reply to the comment by Gray and Abdullah. Limnology and Oceanography 41: 1847-1852.

Jørgensen, B.B. 1980. Seasonal oxygen depletion in the bottom waters of a Danish fjord and its effect on the benthic community. Oikos 34:68-76.

Jørgensen, B.B. and K. Richardson. 1996. Eutrophication in Coastal Marine Ecosystems. Coastal and Estuarine Studies, Volume 52. American Geophysical Union, Washington, D.C., pp. 273.

Josefson, A.B. and J. N. Jensen. 1992. Effects of hypoxia on soft-sediment macrobenthos in southern Kattegat. *In*: Marine Eutrophication and Population Dynamics, G. Colombo, I. Ferrari, V. U. Ceccherelli and R. Rossi (eds.), Olsen and Olsen, Fredensborg, pp. 21-28.

Josefson, A.B. and R. Rosenberg. 1988. Long-term soft-bottom faunal changes in three shallow fjords, west Sweden. Netherlands Journal of Sea Research 22, 149-159.

Josefson, A.B. and B. Widbom. 1988. Differential response of benthic macrofauna and meiofauna to hypoxia in the Gullmar Fjord basin. Marine Biology 100:31-40.

Justic, D. 1987. Long-term eutrophication of the northern Adriatic Sea. Marine Pollution Bulletin. 18:281-284.

Justic, D., T. Legovic, and L. Rottini-Sandrini. 1987. Trends in oxygen content 1911-1984 and occurrence of benthic mortality in the northern Adriatic Sea. Estuarine Coastal Shelf Science 25:435-445.

Justic, D., N.N. Rabalais, and R.E. Turner. 1996. Effects of climate change on hypoxia in coastal waters: a doubled $CO_2$ scenario for the northern Gulf of Mexico. Limnology and Oceanography 41: 992 - 1003.

Justic, D., N.N. Rabalais, R.E. Turner, and W.J. Wiseman, Jr. 1993. Seasonal coupling between riverborne nutrients, net productivity and hypoxia. Marine Pollution Bulletin 26: 184-189.

Kaiser, J. and S. Lutter. 1998. Do we have the right strategies to combat eutrophication in the Wadden Sea? A critical review of current policies. Ecosystem Research in the Wadden Sea Area. 9. International Scientific Wadden Sea Symposium, Norderney, Germany, 5-8 Nov 1996. Senckenbergiana maritima 29:17-24.

Kamykowski, D. and S-J. Zentara. 1990. Hypoxia in the world oceans as recorded in the historical data set. Deep Sea Research 37:1861-1874.

Karim, M.R., S. Masahiko, and U. Masao. 2002. Simulation of eutrophication and associated occurrence of hypoxic and anoxic condition in a coastal bay in Japan. Marine Pollution Bulletin 45: 280–285.

Karlson, K., R. Rosenberg, and E. Bonsdorff. 2002. Temporal and spatial large-scale effects of eutrophication and oxygen deficiency on benthic fauna in Scandinavian and Baltic waters – a review. Oceanography and Marine Biology: an Annual Review 40:427-489.

Keister, J.E., E.D. Houde, and D.L. Breitburg. 2000. Effects of bottom-layer hypoxia on abundances and depth distributions of organisms in Patuxent River, Chesapeake Bay. Marine Ecology Progress Series 205:43-59.

Kideys, A.E. 1994. Recent dramatic changes in the Black Sea ecosystem: the reason for the sharp decline in Turkish anchovy fisheries. Journal of Marine Systems 5:171-181.

Kideys, A.E. 2002. Fall and rise of the Black Sea ecosystem. Science 297:1482-1484.

Kitching, J.A., F.J. Ebling, J.C. Gable, R. Hoare, A.A.Q.R. McLeod, and T.A. Norton. 1976. The ecology of Lough Ine. XIX. Seasonal changes in the western trough. Journal of Animal Ecology 45:731-758.

Koenig, R. 1996. Black spots blot German coastal flats. Science 273: 25.

Konovalov, S.K. and J.W. Murray. 2001. Variations in the basic chemical properties of the Black Sea on a scale of decades (1960-1995). Journal of Marine Systems 31: 217-243.

Laine, A.O., H. Sandler, A-B. Andersin, and J. Stigzelius. 1997. Long-term changes of macrozoobenthos in the eastern Gotland Basin and the Gulf of Finland (Baltic Sea) in relation to the hydrographical regime. Netherlands Journal of Sea Research 38:135-159.

Lapointe, B.E. and W.R. Matzie. 1996. Effects of stormwater nutrient discharges on eutrophication processes in nearshore waters of the Florida Keys. Estuaries 19:422-435.

Legović, T., D. Petricioli, and V. Zutic. 1991. Hypoxia in a pristine stratified estuary (Krka, Adriatic Sea). Marine Chemistry 32: 347-359.

Lenihan, H.S. 1999. Physical-biological coupling on oyster reefs: how habitat structure influences individual performance. Ecological Monographs 69: 251-275.

Lenihan, H.S. and C.H. Peterson. 1998. How habitat degradation through fishery disturbance enhances impacts of hypoxia on oyster reefs. Ecological Applications 8:128-140.

Leonard, C.L. and J.B. McClintock. 1999. The population dynamics of the brittlestar *Ophioderma brevispinum* in near- and farshore seagrass habitats of Port Saint Joseph Bay, Florida. Gulf of Mexico Science 17:87-94.

Leppäkoski, E. 1969. Transitory return of the benthic fauna of the Bornholm Basin, after extermination by oxygen insufficiency. Cahiers de Biologie Marine 10:163-172.

Leverone, J.R. 1995. Diurnal Dissolved Oxygen in two Tampa Bay seagrass meadows: Ramifications for the survival of adult bay scallops (*Argopectin irradians concentricus*). Florida Scientist 58: 141-152.

Levin, L.A., C.L. Huggett, and K.F. Wishner. 1991. Control of deep-sea benthic community structure by oxygen and organic-matter gradients in the eastern Pacific Ocean. Journal of Marine Research 49:763-800.

Lindholm, T. 1996. Periodic anoxia in an emerging coastline lake basin in SW Finland. Hydrobiologia 325: 223-230.

Llansó, R.J. 1992. Effects of hypoxia on estuarine benthos: the lower Rappahannock River (Chesapeake Bay), a case study. Estuarine, Coastal and Shelf Science 35:491-515.

Lopez-Jamar, E., O. Francesch, A.V. Dorrio, and S. Parra. 1995. Long-term variation of the infaunal benthos of La Coruna Bay (NW Spain): results from a 12-year study (1982-1993). Scientia marina 59:49-61.

Mallin, M.A., M.H. Posey, G.C. Shank, M.R. McIver, S.H. Ensign, and T.D. Alphin. 1999. Hurricane effects on water quality and benthos in the Cape Fear watershed: Natural and anthropogenic impacts. Ecological Applications 9:350-362.

Mason, W.T., Jr. 1998. Macrobenthic monitoring in the Lower St. Johns River, Florida. Environmental Monitoring and Assessment 50:101-130.

Maxted, J.R., R.A. Eskin, S.B. Weisberg, J.C. Chaillou, and F.W. Kutz. 1997. The ecological condition of dead-end canals of the Delaware and Maryland coastal bays. Estuaries 20: 319-327.

May, E. 1973. Extensive oxygen depletion in Mobile Bay, Alabama. Limnology and Oceanography 18:353-366.

Mazouni, N., J.-C. Gaertner, J.M. Deslous-Paoli, S. Landrein, and M. Geringer d'Oedenberg. 1996. Nutrient and oxygen exchanges at the water–sediment interface in a shellfish farming lagoon (Thau, France). Journal of Experimental Marine Biology and Ecology 205: 91–113.

McArthur, V.E. 1998. Predation and the survival of juvenile *Cerastoderma glaucum* Bruguiere (Mollusca: Bivalvia) in a coastal lagoon. Journal of Experimental Marine Biology And Ecology 225: 79-97.

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

Michel, M., B. Averty, J.-F. Chiffoleau, and L.-A. Roman. 2000. Biogeochemical Behavior of Arsenic Species in the Seine Estuary in Relation to Successive High-Amplitude Primary Production, Anoxia, Turbidity, and Salinity Events. Estuaries 24: 1066–1073.

Mirza, F.B. and J.S. Gray. 1981. The fauna of benthic sediments from the organically enriched Oslofjord, Norway. Journal of Experimental Marine Biology and Ecology 54:181-207.

Morrisey, D.J. 2000. Predicting impacts and recovery of marine-farm sites in Stewart Island, New Zealand, from the Findlay-Watling model. Aquaculture 185:257-271.

Moser, F.C. 1998. Sources and Sinks of Nitrogen and Trace Metals, and Benthic Macrofauna Assemblages in Barnegat Bay, New Jersey. Dissertation Abstracts International Part B: Science and Engineering, University Microfilms International 58:5849.

Nakata, K., S-I. Sugioka, and T. Hosaka. 1997. Hindcast of a Japan Sea Oil Spill. Spill Science and Technology Bulletin 4:219-229.

National Oceanographic and Atmospheric Administration (NOAA) 1997. NOAA's Estuarine Eutrophication Survey. Volume 2: Mid-Atlantic Region. Silver Spring, MD: Office of Ocean Resources Conservation and Assessment. p. 51.

Neubauer, R.J. 1993. The relationship between dominant macrobenthos and cyclical hypoxia in the lower York River. Masters Thesis, College of William and Mary, Williamsburg, Virginia.

Niermann, U., E. Bauerfeind, W. Hickel, and H .V. Westernhagen. 1990. The recovery of benthos following the impact of low oxygen content in the German Bight. Netherlands Journal of Sea Research 25:215-226.

Nilsson, H. and R. Rosenberg. 2000. Succession in marine benthic habitats and fauna in response to oxygen deficiency: analysed by sediment profile-imaging and by grab samples. Marine Ecology Progress Series 197: 139-149.

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

Nixon, S.W. and B.A. Buckley. 2002. "A strikingly rich zone" - nutrient enrichment and secondary production in coastal marine ecosystems. Estuaries 25:782-296.

Norkko, A. and E. Bonsdorff. 1996. Rapid zoobenthic community responses to accumulations of drifting algae. Marine Ecology Progress Series 131:143-157.

Nordberg, K., M. Gustafsson, and A-L. Krantz. 2000. Decreasing oxygen concentration in the Gullmar Fjord, Sweden, as confirmed by benthic foraminifera, and the possible association with NAO. Journal of Marine Systems 23: 303-316.

Nordberg, K., H. L. Filipsson, M. Gustafsson, R. Harland, and P. Roos. 2001. Climate, hydrographic variations and marine benthic hypoxia in Koljö Fjord, Sweden. Journal of Sea Research 46: 187-200.

Oeschger, A. and K.B. Storey. 1990. Regulation of glycolytic enzymes in the marine invertebrate *Halicryptus spinulosus* (Priapulida) during environmental anoxia and exposure to hydrogen sulfide. Marine Biology 106: 261-266.

Officer, C.B., Biggs, R.B., Taft, J.L., Cronin, L.E., Tyler, M.A, and W.R. Boynton. 1984. Chesapeake Bay anoxia: origin, development, and significance. Science 223:22-27.

Olsen, D.B., G.L. Hitchcock, R.A. Fine and B.A. Warren. 1993. Maintenance of the low-oxygen layer in the central Arabian Sea. Deep-Sea Research II 40:673-685.

Paerl, H.W., J.L. Pinkney, and S.A. Kucera. 1995. Clarification of the structural and functional roles of heterocysts and anoxic microzones in the control of pelagic nitrogen fixation. Limnology and Oceanography 40:634-638.

Paerl, H.W., J.L. Pinckney, J.M. Fear, and B.L. Peierls. 1998. Ecosystem responses to internal and watershed organic matter loading: Consequences for hypoxia in the eutrophying Neuse River Estuary, North Carolina, USA. Marine Ecology Progress Series 166:17-25.

Paerl, H.W., J.D. Bales, L.W. Ausley, C.P. Buzzelli, L.B. Crowder, L.A. Eby, M. Go, B.L. Peierls, T.L. Richardson, and J.S. Ramus. 2000. Hurricanes' hydrological and ecological effects linger in major US estuary. EOS Transaction, American Geophysical Union, 81: 457-462.

Patrick, R. 1988. Changes in the chemical and biological characteristics of the Upper Delaware River estuary in response to environmental laws. *In:* Majumdar, E., W. Miller and L.E. Sage (eds.), Unnamed publication of the Pennsylvania Academy of Science, Philadelphia, PA, pp. 332-359.

Paulson, A.J., H.C. Curl, Jr., and R.A. Freely. 1992. The biogeochemistry of nutrients and trace metals in Hood Canal, a Puget Sound fjord. Marine Chemistry 43: 157-173.

Pearson, T.H. and A. Eleftheriou. 1981. The benthic ecology of Sollom Voe. Proceedings of the Royal Society of Edinburgh 80B:241-269.

Pearson, T.H. and R. Rosenberg. 1992. Energy flow through the SE Kattegat: a comparative examination of the eutrophication of a coastal marine ecosystem. Netherlands Journal of Sea Research 28:317-334.

Pennock, J.R., J.H. Sharp, and W.W. Schroeder. 1994. What Controls the Expression of Estuarine Eutrophication? Case Studies of Nutrient Enrichment in the Delaware Bay and Mobile Bay Estuaries, USA. *In:* Changes in Fluxes in Estuaries: Implications from Science to Management, K.R. Dyer and R.J. Orth (eds.), Olsen and Olsen. Fredensborg. pp. 139-146.

Petersen, C.G.J. 1915. On the animal communities of the sea bottom in the Skagerak, the Christiania Fjord and the Danish waters. Report from the Danish Biological Station 23:1-28.

Petersen, J.K. and L. Pihl. 1995. Responses to hypoxia of plaice, *Pleuronectes platessa* and dab, *Limanda limanda*, in the south-east Kattegat: distribution and growth. Environmental Biology of Fishes. 43: 311-321.

Pihl, L., S.P. Baden, and R.J. Diaz. 1991. Effects of periodic hypoxia on distribution of demersal fish and crustaceans. Marine Biology 108:349-360.

Pohl, C., U. Hennings, I. Petersohn, and H. Siegel. 1998. Trace metal budget, transport, modification and sinks in the transition area between the Oder and Peene rivers and the southern Pomeranian Bight. Marine Pollution Bulletin 36:598-616.

Portnoy, J.W. 1991. Summer Oxygen Depletion in a Diked New England Estuary. Estuaries 14:122-129.

Posey, M.H., T.D. Alphin, L. Cahoon, D. Lindquist, and M.E. Becker. 1999. Interactive effects of nutrient additions and predation on infaunal communities. Estuaries 22: 785-792

Powilleit, M. and J. Kube. 1999. Effects of severe oxygen depletion on macrobenthos in the Pomeranian Bay (southern Baltic Sea): a case study in a shallow, sublittoral habitat characterised by low species richness. Netherlands Journal of Sea Research 42:221-234.

Prena, J. 1995a. Effects of eutrophication on macrobenthos zonation in Wismar Bay (western Baltic Sea). Archiv fur Hydrobiologie. Stuttgart 133:245-257

Prena, J. 1995b. Temporal irregularities in the macrobenthic community and deep-water advection in Wismar Bay (western Baltic Sea). Estuarine, Coastal and Shelf Science 41:705-717.

Rabalais, N.N. and R.E. Turner. 2001. Hypoxia in the northern Gulf of Mexico: description, causes and change. *In:* Coastal Hypoxia Consequences for Living Resources and Ecosystems. N.N. Rabalais and R.E. Turner (eds.). American Geophysical Union, Washington, D.C. pp. 1- 36.

Rabalais, N.N., R.E. Turner, and W.J. Wiseman, Jr. 1996. Nutrient changes in the Mississippi River and system responses on the adjacent continental shelf. Estuaries 19:386-407.

Rabalais, N.R., L.E. Smith, and D.E. Harper, Jr. 2001a. Effects of seasonal hypoxia on continental shelf benthos. *In:* Coastal hypoxia consequences for living resources and ecosystems. N.N. Rabalais and R.E. Turner (eds.). American Geophysical Union, Washington, D.C. pp. 185-210.

Rabalais, N.N., R.E. Turner, and W.J. Wiseman, Jr. 2001b. Hypoxia in the Gulf of Mexico. Journal of Environmental Quality 30: 320-329.

Rainer, S.F. and R.C. Fitzhardinge. 1981. Benthic communities in an estuary with periodic deoxygenation. Australian Journal of Marine and Freshwater Research 32:227-243.

Reish, D.J. 1955. The relation of polychaetous annelids to harbor pollution. Public Health Report 70:1168-1174.

Reish, D.J. 2000. The seasonal settlement of polychaete larvae before and after pollution abatement in Los Angeles-Long Beach Harbors, California. Bulletin of Marine Science 67:672.

Reizopoulou, S, Thessalou-Legaki, M, and A. Nicolaidou. 1996. Assessment of disturbance in Mediterranean lagoons: An evaluation of methods. Marine Biology. Berlin, Heidelberg 125:189-197.

Richardson, K. and B.B. Jørgensen. 1996. Eutrophication: Definition, history, and effects. *In*: Eutrophication in Coastal Marine Ecosystems, B.B. Jørgensen and K. Richardson (eds.), Coastal and Estuarine Studies, Volume 52. American Geophysical Union, Washington, D.C. pp. 1-19.

Rikard, F.S., R.K. Wallace, D. Rouse, and I. Saoud. 2000. The effect of low oxygen on oyster survival during reef restoration efforts in Bon Secour Bay, Alabama. Journal of Shellfish Research 19:640.

Ritter, C. and P.A. Montagna. 1999. Seasonal hypoxia and models of benthic response in a Texas bay. Estuaries 22:7-20.

Rosenberg, R. 1980. Effects of oxygen deficiency on benthic macrofauna in fjords. *In*: Fjord Oceanography, H.J. Freeland, D.M. Farmer, and C.D. Levings (eds.), Plenum Publishing Corp., New York. pp. 499-514.

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. Marine Pollution Bulletin 21: 335-339.

Rosenberg, R. and R.J. Diaz. 1993. Sulphur bacteria (*Beggiatoa spp.)* mats indicate hypoxic conditions in the Inner Stockholm Archipelago. Ambio 22:32-36.

Rosenberg, R. and L.O. Loo. 1988. Marine eutrophication induced oxygen deficiency: effects on soft bottom fauna, western Sweden. Ophelia 29:213-225.

Rosenberg, R., I. Olsson, and E. Olundh. 1977. Energy flow model of an oxygen-deficient estuary on the Swedish west coast. Marine Biology 42: 99-107.

Rosenberg, R., W.E. Arntz, E. Chumán de Flores, L.A. Flores, G. Carbajal, I. Finger, and J. Tarazona. 1983. Benthos biomass and oxygen deficiency in the upwelling system off Peru. Journal of Marine Research 41: 263-279.

Rosenberg, R., L.O. Loo, and P. Möller. 1992. Hypoxia, salinity and temperature as structuring factors for marine bethic communities in a eutrophic area. Netherlands Journal of Sea Research 30:121-129.

Rosenberg, R., H.C. Nilsson, and R.J. Diaz. 2001. Response of benthic fauna and changing sediment redox profiles over a hypoxic gradient. Estuarine, Coastal and Shelf Science 53: 343-350.

Rosenberg, R., J.S. Gray, A.B. Josefson, and T.H. Pearson. 1987. Petersen's benthic stations revisited. II. Is the Oslofjord and eastern Skagerrak enriched? Journal of Experimental Marine Biology and Ecology 105:219-251.

Rumohr, H. 1986. Historical evidence for eutrophication processes in the Kieler Bucht (western Baltic). Meeresforschung 31:115-123.

Rybarczyk, H., B. Elkaim, J.G. Wilson, and N. Loquet. 1996. Eutrophication in the Baie de Somme: Consequences and impacts on the benthic population. Oceanologica Acta 19:131-140.

Sagasti, A., L.C. Schaffner, and J.E. Duffy. 2001. Effects of periodic hypoxia on mortality, feeding and predation in an estuarine epifaunal community. Journal of Experimental Marine Biology and Ecology 258: 257-283.

Saiz-Salinas, J.I. and G. Frances-Zubillaga. 1997. Tidal zonation on mud flats in a polluted estuary caused by oxygen-depleted water. Journal of Experimental Marine Biology and Ecology 209: 157-170.

Santos, S.L. and J.L. Simon. 1980. Marine soft-bottom community establishment following annual defaunation: larval or adult recruitment. Marine Ecology Progress Series 2:235-241.

Sanukida, S., H. Okamato, and M. Hitomi. 1984. Alteration of pollution indicator species of macrobenthos during stagnant periods in eastern Hiuchi Sound. Bulletin Japanese Society of Scientific Fisheries 50:727.

Schimmel, S.C., S.J. Benyi, and C.J. Strobel. 1999. An assessment of the ecological condition of Long Island Sound, 1990-1993. Environmental Monitoring and Assessment 56:27-49.

Seitzinger, S.P., C. Kroeze, A.F. Bouwman, N. Caraco, F. Dentener, and R.V. Styles. 2002. Global patterns of dissolved inorganic and particulate nitrogen inputs to coastal systems: recent conditions and future projections. Estuaries 25:640-655.

Seliger, H.H. and J.A. Boggs. 1988. Long term pattern of anoxia in the Chesapeake Bay. *In:* Understanding the estuary: Advances in Chesapeake Bay research: Proceedings of conference. 29-31 March 1988, Baltimore, MD. Chesapeake Research Consortium Publication 129. CBP/TRS 24/88, pp. 570-583.

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

Sindermann, C. and R. Swanson. 1980. Chapter 1. Historical and Regional Perspective. *In:* Oxygen Depletion and Associated Benthic Mortalities in New York Bight, 1976. R.L. Swanson and C.J. Sindermann (eds.), Rockville. U.S. Department of Commerce National Oceanic and Atmospheric Administration. pp. 1-16.

Simunovic, A., C. Piccinetti, and M. Zore-Armanda. 1999. Kill of benthic organisms as a response to an anoxic state in the northern Adriatic (a critical review). Acta Adriatica 40:37-64.

Solic, M., N. Krstulovic, L. Marasovic, A. Baranovic, T. Pucher-Petkovic, and T. Vucetic. 1997. Analysis of time series of planktonic communities in the Adriatic Sea: distinguishing between natural and man-induced changes. Oceanologica Acta 20:131-143.

Souchu, P., A. Gasc, Y. Collos, A. Vaquer, H. Tournier, B. Bibent, and J-M. eslous-Paoli. 1998. Biogeochemical aspects of bottom anoxia in a Mediterranean lagoon (Thau, France). Marine Ecology Progress Series 164:135-146.

Stachowitsch, M. 1984. Mass mortality in the Gulf of Trieste: The course of community destruction. Marine Ecology 5: 243-264.

Stachowitsch, M. 1991. Anoxia in the Northern Adriatic Sea: rapid death, slow recovery. *In*: Modern and ancient continental shelf anoxia R.V. Tyson and T.H. Pearson (eds.), London: Geological Society Special Publication No. 58. pp. 119-129.

Stanley, D.W. and S.W. Nixon. 1992. Stratification and bottom-water hypoxia in the Pamlico River Estuary. Estuaries 15:270-281.

Stora, G. and A. Arnoux. 1983. Effects of large freshwater diversions on benthos of a Mediterranean lagoon. Estuaries 6: 115-125.

Suzuki, T. 2001. Oxygen-deficient waters along the Japanese coast and their effects upon the estuarine ecosystem. Journal of Environmental Quality 30:291-302.

Suzuki, T. and Y. Matsukawa. 1987. Hydrography and budget of dissolved total nitrogen and dissolved oxygen in the stratified Mikawa Bay, Japan. Journal of the Oceanographic Society of Japan 43:37-48.

Tagliapietra, D., M. Pavan, and C. Wagner. 1998. Macrobenthic community changes related to eutrophication in Palude della Rosa (Venetian Lagoon, Italy). Estuarine, Coastal and Shelf Science 47:217-226.

Tanimoto, T. and A. Hoshika. 1997. Transport of total suspended matter, paticulate organic carbon, organic nitrogen and phosphorus in the inner part of Osaka Bay. Journal of Oceanography., 53, 365-371.

Tarazona, J., H. Salzwedel, and W. Arntz. 1988. Positive effect of "El Nino" on macrozoobenthos inhabiting hypoxic areas of the Peruvian upwelling system. Oecologia 76:184-190.

Taylor, F.J., N.J. Taylor, and J.R. Walsby. 1985. A bloom of the planktonic diatom, *Cerataulina pelagica*, off the coast of northeastern New Zealand in 1983, and its contribution to an associated mortality of fish and benthic fauna. Internationl Revue ges Hydrobiol. 70: 773-795.

Tenore, K.R. 1972. Macrobenthos of the Pamlico River estuary, North Carolina. Ecological Monographs 42:51-69.

Thiel, R., A. Sepulveda, R. Kafemann, and W. Nellen. 1995. Environmental factors structuring the fish community of the Elbe estuary. Journal of Fisheries Biology 46:47-69.

Theodorou, A.J. 1996. Long-term environmental effects of raw sewage sea disposal in Elefsis Bay (Saronikos Gulf, Greece). Partnership in coastal zone management, Samara Publishing ltd., Cardigan, UK. pp. 547-556.

Thomassin, B.A., P. Gourbesville, B. Gout, and A. Arnoux. 1998. Impact of an industrial and urban sewage off a coral fringing reef at Mauritius (Indian Ocean): modeling of plumes, distribution of trace metals in sediments and effects of the eutrophication on coral reef communities. Oceans 98 - Engineering for sustainable use of the oceans: conference proceedings, Nice, IEEE/OES, Piscataway, New Jersey. 1:301-305

Thouvenin, B., P. Le Hir, and L.A. Romana. 1994. Dissolved oxygen model in the Loire Estuary. Changes in fluxes in estuaries: implications from science to management. Olsen and Olsen, Fredensborg, Denmark. pp. 169-178.

Tilman, D., J. Fargione, B. Wolff, C. D'Antonio, A. Dobson, R. Howarth, D. Schindler, W.H. Schlesinger, D. Simberloff and D. Swackhamer. 2001. Forecasting agriculturally driven global environmental change. Science 292:281-284.

Tsutsumi, H. 1987. Population dynamics of *Capitella capitata* (Polychaeta, Capitellidae) in an organically polluted cove. Marine Ecology Progress Series 36:139-149.

Tulkki, P. 1965. Disappearance of the benthic fauna from the basin of the Bornholm (southern Baltic) due to oxygen deficiency. Cahiers de Biologie Marine 6:455-463.

Turner, R.E. 2001. Some effects of eutrophication on pelagic and demersal marine food webs. *In:* Coastal Hypoxia Consequences for Living Resources and Ecosystems. N. N. Rabalais and R.E. Turner (eds.), American Geophysical Union, Washington, D.C. pp. 371-398.

Tyson, R.V. and T.H. Pearson (eds.) 1991. Modern and ancient continental shelf anoxia: an overview. London: Geological Society Special Publication No. 58, pp. 1-24.

Valentin, J., D. Tenenbaum, A. Bonecker, S. Bonecker, C. Nogueira, R. Paranhos, and M.C. Villac. 1999. Hydrobiological characteristics of the Guanabara Bay (Brazil). Journal de recherche Oceanographique 24:33-41.

van Pagee, J.A., P.C.G. Glas, A.A. Markus, and L. Postma. 1988. Mathematical modeling as a tool for assessment of North Sea pollution. *In:* Pollution of the North Sea: An Assessment, W. Salomons, B. Bayne, E. Duursma, and U. Förstner (eds.), Springer-Verlag, New York. pp. 400-422.

Verlaan, P.A.J., M. Donze, and P. Kuik. 1998. Marine vs. fluvial suspended matter in the Scheldt Estuary. Estuarine, Coastal and Shelf Science 46:873-883.

Weigelt, M. 1990. Oxygen conditions in the deep water of Keil Bay and the impact of inflowing salt-rich water from the Kattegatt. Meeresforschung 33:1-22.

Weigelt, M. 1991. Short- and long-term changes in the benthic community of the deeper parts of Kiel Bay (Western Baltic) due to oxygen depletion and eutrophication. Meeresforsch 33: 197-224.

Weigelt, M. and H. Rumohr. 1986. Effects of wide-range oxygen depletion on benthic fauna and demersal fish in Kiel Bay 1981-1983. Meeresforsch 31: 124-136.

Weisberg, S.B., H.T. Wilson, P. Himchak, T. Baum, and R. Allen. 1996. Temporal trends in abundance of fish in the tidal Delaware River. Estuaries 19:723-729.

Welsh, B., R. Welsh, and M. DiGiacomo-Cohen. 1994. Quantifying hypoxia and anoxia in Long Island Sound. *In:* Changes in fluxes in estuaries: Implications from science to management, K. Dyer and R. Orth (eds.), Fredensborg: Olsen and Olsen. pp. 131-137.

Westernhagen, H. V. and V. Dethlefsen. 1983. North Sea oxygen deficiency 1982 and its effects on the bottom fauna. Ambio 12:264-266.

Wilkin, R. and H.L. Barnes. 1997. Pyrite formation in an anoxic estuarine basin. American Journal of Science 297:620-650.

Wilson, E.O. 2002. The future of life. Alfred A. Knopf, New York. p. 229.

Winkler, L. 1888. The determination of dissolved oxygen in water. Berichte der Deutschen chemicer Gesellschaft 21:28-43.

Wu, R.S.S. 1982. Periodic defaunation and recovery in a subtropical epibenthic community, in relation to organic pollution. Journal of Experimental Marine Biology and Ecology 64:253-269.

Wyrtki, K. 1966. Oceanography of the eastern equatorial Pacific Ocean. Oceanography and Marine Biology: an Annual Review 4:33-68.

Yamamuro, M., N. Oka, and J. Hiratsuka. 1998. Predation by diving ducks on the biofouling mussel *Musculista senhousia* in a eutrophic estuarine lagoon. Marine Ecology Progress Series 174:101-106.

Zaitsev, Y.P. 1993. Impacts of eutrophication on the Black Sea fauna. *In:* Fisheries and Environment Studies in the Black Sea System, Food and Agricultural Organization of the United Nations, Rome, Italy. pp. 64-86.

Zimmerman, A.R. and E.A. Canuel. 2000. A geochemical record of eutrophication and anoxia in Chesapeake Bay sediments: anthropogenic influence on organic matter composition. Marine Chemistry 69: 117-137.