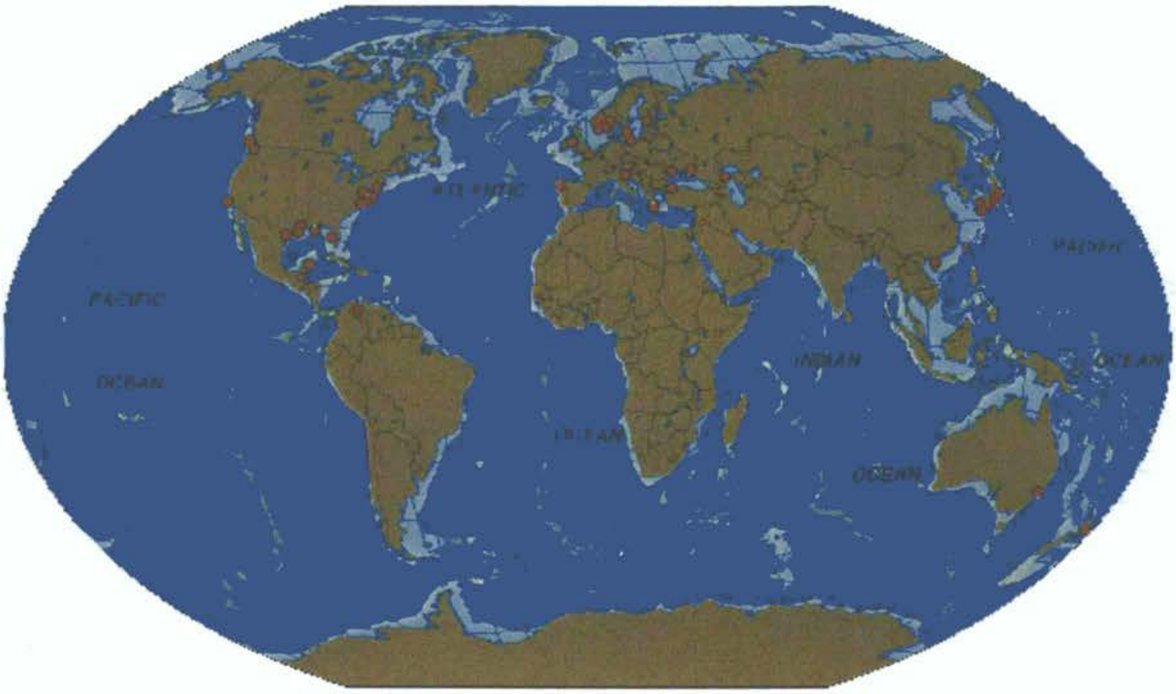
A global assessment of hypoxia: causes, impacts and recommendations



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by Tim Abercrombie
Division of Early Warning and Assessment (DEWA)
United Nations Environment Programme (UNEP)

UNEP

Map: Diaz and Rosenberg, 1995 o
http://daac.gsfc.nasa.gov/

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NOTE

The following report is submitted as consultancy report for UNEP/DEWA. It reflects the views and opinions of the author and not necessarily that of UNEP.

The author would like to inform the reader that this report has not had extensive editing or review and remains a work in progress.

The author would appreciate comments and can be contacted at: tharperabercrombie@yahoo.ca

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1. Abstract

Eutrophication is one of the most serious threats to coastal waters around the world. Human activities such as agricultural fertiliser use, the burning of fossil fuels and sewage effluents are dramatically increasing nutrient inputs into rivers, lakes, coastlines and oceans. An over abundance of nutrients eventually deprives the water of oxygen and it becomes void of life. These 'dead zones' are expanding and not only threaten marine ecosystems but also impact goods and services provided by these water bodies. Tourism and recreation, agriculture, fisheries and aquaculture will invariably be affected and economic losses are imminent. There is currently insufficient understanding of how marine nutrient cycles, marine ecosystems and human socioeconomics are interlinked in the eutrophication process. This report aims toward a better understanding of these links to enable marine and coastal managers and policy makers to make informed decisions to lessen the impacts of hypoxia. Eutrophication is a global problem and thus this report focuses on a global scale. However case studies of serious concern are also examined, as nutrient input must be addressed at an ecosystem level. This report will help explain the ecosystem impacts, the natural and anthropocentric causes and human socio-economic consequences of eutrophication. This report will also identify gaps in the present state of knowledge and it will provide a review of regulations and policies and options for mitigative action.

2. Introduction

2.1. Phytoplankon

Phytoplankton are fundamental to the productivity of the world's oceans. All marine animals ultimately depend on phytoplankton for survival. Representing the first level in the marine trophic system, phytoplankton are photosynthetic, converting light energy, nutrients, water and carbon dioxide into orgainc carbon that is essential to zooplankton, invertebrates, fish and mammals in higher trophic levels. It is for this reason that phytoplankton are known as primary producers. Phytoplankton account for approximately half of the photosynthesis on the planet and are responsible for 95 percent of all marine primary production. They also play an important role in regulating the amount of carbon in the atmosphere.

The ocean generally has ample water, light and carbon dioxide but the limiting factor in phytoplankton growth is the availablity of nutrients. The three nutrients most important for controlling phytoplankton growth and production in marine ecosystems are nitrates and phosphates (NO_3 and PO_4) and silicon, where nitrogen is the most critical. Nutrients are found in more abundance in the deeper, colder depths of the ocean where the animals that produce the nutrients live. When mixing occurs and these nutrient rich waters are brought up near the surface, the phytoplanton are enriched and they 'bloom'. In temperate zones waters are seasonally thermally stratified. In winter the surface water is cool and thus less stratified which allows sufficient mixing of layers to occur bringing nutrients up to the surface. Then in the spring and summer when runoff and light intensity increases plankton blooms occur. Coastal areas have much higher primary production than open seas because high run-off, continous mixing and coastal upwelling all deliver nutrients to the surface waters. Global distributions and productivity of phytoplankton in the ocean are closely related to locations where nutrients are being supplied to the surface waters.

However, in addition to natrual nutrient sources, humans are also a great source of nutrient input to the ocean. It is even misleading to label domestic and idustrial sewage, runoff of agricultural fertilizers and fossil fuels as ‘nutrients’ however phytoplankton do not discrimenate between natural and anthropocentric nutrient sources and blooms result. Because marine animals are so dependent on phytoplankton any change in their patterns of distribution and abundance can have significant impacts on the entire ecosystem. While some plankton blooms can enhance ocean productivty, some can bloom in such large numbers to physically inhibit orther marnie life. Dense blooms of phytoplankton can essentially block sunlight from reaching the bottom in shallow areas of coastal waters or estuaries and can cause declines in aquatic vegetaion that are vital nursery grounds for many species of fish and invertebrates having drastic consequences to the ecosystem. Some phytoplankton known as dinoflagellates are the source of red tides and produce toxins that can be quite harmful to marine animals and to humans as well.

2.2. What is hypoxia?

Hypoxic zones are coastal areas where the bottom water is hypoxic or anoxic (jointly termed hypoxic or hypoxia), that is having very low to zero concentration of dissolved oxygen, respectively. Although hypoxia is more common off industrialised coastlines, they are now occurring in many coastal areas globally. Hypoxic areas are popularly known as ‘dead zones’ (Rabalis et al., 2002) because few organisms are able to tolerate hypoxic conditions and thus they destroy marine habitats; and now ‘creeping dead zones’ (NASA, http://daac.gsfc.nasa.gov/ and UNEP/DEWA, personal communication, 2003) because they are spreading away from the coast over larger areas of the continental shelf.

The hypoxic conditions are caused by the build up of excess organic matter in the benthos which causes high oxygen demands. Phytoplankton photosynthesise at the surface of the ocean, in the euphotic zone where growth is influenced by nutrients. The spatial and temporal interactions of nutrients strongly influence phytoplankton species composition. At normal nutrient levels, much of the phytoplankton is consumed by higher organisms. However, when nutrients are abundant, populations are very dense and much phytoplankton goes unconsumed. They eventually die and sink to the bottom or benthic zone where they are subject to breakdown by the action of bacteria, in a process known as bacterial respiration. In fact, 25-50 percent of organic matter produced by phytoplankton sinks to the benthos where it is mineralised by aerobic and anaerobic processes (Jørgensen, 1996). Like other marine organisms, bacteria use oxygen and produce carbon dioxide during respiration. The excess of organic matter with accompanying bacteria causes a greater than normal demand for the dissolved oxygen. Because fish, shellfish and other invertebrates and most marine animals require oxygen to survive, these great demands for dissolved oxygen lead to hypoxic conditions causing animals to die or move elsewhere. The area soon becomes void of life and thus 'dead'. Once hypoxia has developed dissolved oxygen levels become lower and the oxygen demand will decrease because respiration becomes oxygen limited. As well as bacterial decomposition, other sources of high oxygen demand can be the direct input of organics such as those found in sewage effluent. For hypoxic zones to persist the water column most be stratified such that the bottom water is isolated from exchange with oxygen enriched surface water.

Hypoxia is caused by eutrophication which has been defined as an increase of carbon supply to the water mass (Nixon, 1995). The 'normal' states are oligotrophic and mesotrophic but increased nutrients and primary production can lead to a eutrophic state and possibly dystrophic (Table 2.1.). Nixon (1995) stresses that while 'eutrophic' is a state, 'eutrophication' is a process and a eutrophic system does not necessarily infer further eutrophication.

Table 2.1. Trophic states (Source: modified from US Environmental Protection Agency (EPA)[1] and Nixon, 1995)

Trophic States	**Description**	**Organic Carbon Supply ($gCm^{-2}y^{-1}$)**
Oligotrophic	Clear waters with little organic matter or sediment and minimum biological activity.	<100
Mesotrophic	Waters with more nutrients, and therefore, more biological productivity.	100-300
Eutrophic	Waters extremely rich in nutrients, with high biological productivity. Some/many species may be choked out.	301-500
Dystrophic	Low in nutrients, highly coloured with dissolved humic organic material. (Not necessarily a part of the natural trophic progression.)	>500

'Normal' (normoxic) marine oxygen levels are about $7mll^{-1}$. Hypoxia begins $2mll^{-1}$ of oxygen and extends to 0 mg/l, the point of anoxia. The point at which various animals suffocate varies, but generally effects start to appear when oxygen drops below $2mll^{-1}$ or $3mll^{-1}$ in some systems. When oxygen levels fall below critical values, those organisms capable of swimming such as demersal fish, crabs, and shrimp evacuate the area. The stress on less motile fauna caused by declining oxygen levels varies according to the oxygen requirements of the organism. Benthic animals are usually more resistant to low oxygen concentrations. Mortality is initiated at oxygen concentrations close to $1mll^{-1}$ (about 15 percent saturation) and that mass mortality is initiated at about $0.5mll^{-1}$ (about 7 percent saturation) (Diaz and Rosenberg, 1995).

Most cases of hypoxic events follow the natural seasonal increase in primary production seen in the spring and summer months when runoff brings a surge of nutrients to coastal waters. Annual summertime hypoxia is the most common form of low dissolved oxygen event recorded around the globe. In a global assessment of anthropogenic hypoxic zones, 64 percent were seasonal (Diaz and Rosenberg, 1995). Hypoxic zones dissipates later in the autumn when the vertical temperature-induced stratification breaks up, allowing mixing of oxygen-rich surface waters with deeper, oxygen-poor waters.

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[1] http://www.epa.gov/maia/html/esutroph.html

The Black and Baltic Seas and the Gulf of Mexico are among the oldest and most well documented water bodies suffering from hypoxia. In an influential paper Robert Diaz (Diaz and Rosenberg, 1995) documented the impacts and mapped the world's hypoxic zones (version of map seen on cover). In 1995 the number of published accounts of hypoxic zones was 40. Now about 100 cases around the globe are documented (personal communication, Robert Diaz, 2003). Some of these areas are newly developed hypoxic zones from the time of the last report while some of them are just zones that have recently received greater attention from the scientific community from this growing environmental issue. However, hypoxic environments are not recent phenomena, they have occurred naturally through geological time.

The initial understanding of the process of hypoxia emphasised changing nutrient input as a signal and responses of increased phytoplankton biomass increased primary production, increased decomposition of phytoplankton-derived organic matter, and enhanced depletion of oxygen from bottom waters. This initial understanding was based on responses of lakes to eutrophication. Coastal research now identifies differences in the systems toward a better understanding of hypoxia. While science is improving oxygen deprived waters are worsening and a greater focus on the problem is needed.

3. Principle causes

There seem to be two principle causes of hypoxic zones in coastal areas:

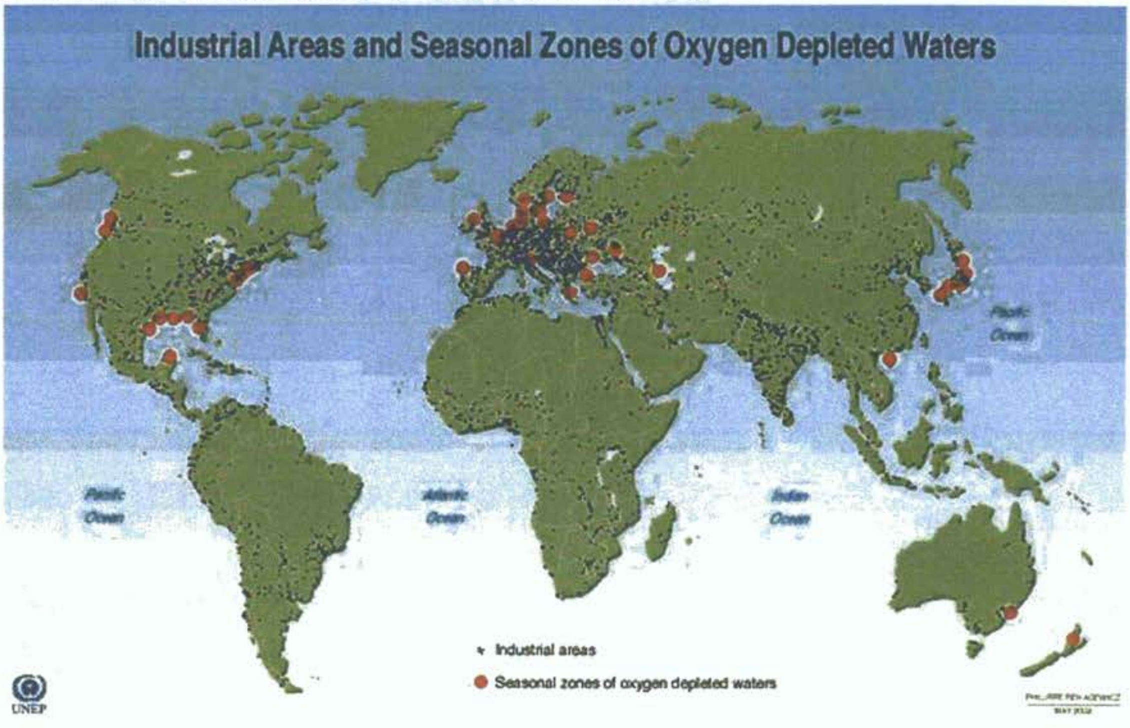
- If phytoplankton productivity is enhanced, more organic matter is produced, more falls to the benthic layer, more bacteria respire and thus more oxygen is demanded and consumed.
- If natural water flow is restricted, the replenishing flow of oxygenated water is reduced and dissolved oxygen concentrations are less and the remaining oxygen is depleted faster.

The reduction in the natural flow of water results in less mixing between the layers or a greater stratification, which isolates the bottom water from exchange with oxygen rich surface water. Mixing is largely a natural factor that cannot be controlled, and the principle cause is the decomposition of organic matter in the bottom water, which reduces the oxygen levels. However, for hypoxia to develop, both these conditions must be met. Although other factors contribute, it is probably useful to think of hypoxia formation as a balance between nutrient loading and mixing. Many areas exist that receive high nutrient inputs but have good mixing and no hypoxia develops. Oppositely, many areas receive comparatively less nutrient inputs but have poor circulation that results in hypoxia. This particularly highlights what is meant by 'sensitivity of receiving waters.'

The forcing functions of hypoxia are nitrate inputs and mixing. However anything that contributes to reduced oxygen contributes to hypoxia such as respiration or reduced photosynthesis. Increased primary production increases the accumulation rate of sediments however this does not necessarily accelerate bottom oxygen demand compared to less oxygen stressed areas. If sedimentation happens quickly, organic carbon will be buried which does not consume oxygen; rather, it prevents it (Rowe et al., 1995. Thus, it has been suggested if bottom water and bottom sediment oxygen consumption are not enhanced by particulate carbon fluxes that are the result of high nitrate loading, perhaps the high nitrate loading does not have as great an influence as previously thought and that density stratification (mixing) is a more important factor (Gilbert, 2001).

Never the less, the principle human induced and controllable cause of hypoxia is eutrophication due to excess nitrogen loading. This is now a well-documented occurrence globally (Diaz, 2001). From the front cover map (Diaz and Rosenberg, 1995) it is evident that cases are largely isolated to North America, Europe and Japan. A similar map with the same oxygen depleted zones including industrial areas (Figure. 3.0.) shows a strong link between areas with high densities of industrial activity and zones of seasonally oxygen depleted waters.

Figure 3.0. Industrial areas and seasonal zones of oxygen depleted waters
(Source: UNEP, 2002b adapted from Diaz and Rosenberg, 1995)



While the links will soon seem obvious, it is important to make a distinction between eutrophication and hypoxia. While other factors may contribute to hypoxia, eutrophication is the primary cause. And while there are a number of factors that can increase primary production, the most important factor in causing eutrophication is nitrogen enrichment. Thus the greatest cause of hypoxia is nutrient loading from different sources. The core of this section will discuss the causes of hypoxia and the principle causes of eutrophication.

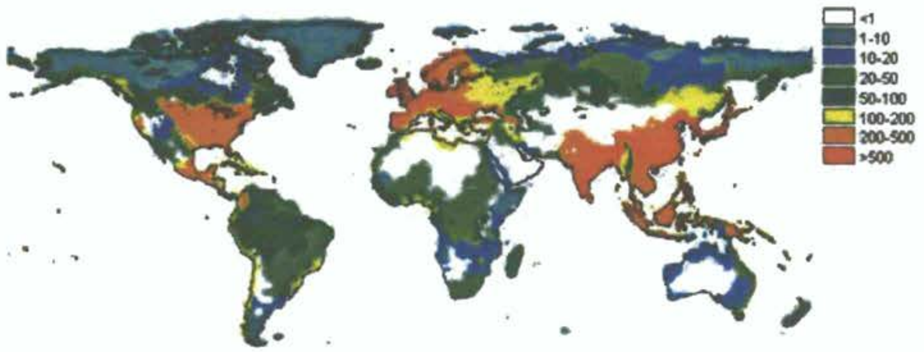
While other nutrients play a role, the driving force of coastal eutrophication is an imbalance in the nitrogen cycle of the marine environment due to anthropogenic inputs where the principle sources of nutrients to coastal systems are the following:

- Runoff (surface, subsurface or groundwater) including inputs from industry, municipal discharge, and agriculture;
- Direct inputs of municipal discharge and industrial waste;
- Atmospheric emissions from agriculture, fuel combustion, including traffic; and
- Marine activities such as fish farming.

3.1. Nutrient input

A global view of nitrogen flux intensity arising directly and indirectly from various sources currently show uneven spatial distribution of human population, agriculture, and industrial activity leading to spatial differences in nutrient inputs to coastal ecosystems (Figure 3.1.). While hypoxic areas are consistent with areas of high nitrogen influx, areas of high nitrogen influx are not necessarily consistent with hypoxic areas. This indicates a vast array of nutrient sources and contributing factors.

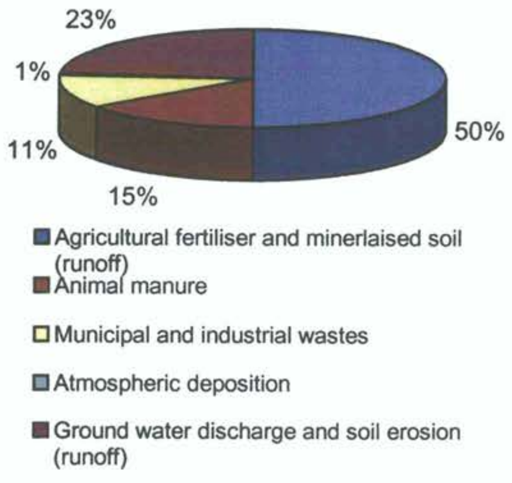
Figure 3.1. Nitrogen (inorganic N) export from watersheds to coastal systems.
units: kg N km-2 watershed y-1 (Source: Seitzinger and Kroeze, 1998)



3.2. Agriculture runoff

Many studies now exist that link the frequency and volume of hypoxic conditions to increased nutrient inputs (most notably, Diaz and Rosenberg, 1995; Rabalais et al., 1996). Most but not all of the coastal areas experiencing eutrophication and dead zones are in industrialised countries where there is a positive correlation between increased population, urbanisation in river watersheds and coastal areas and increased agricultural activity that deliver large quantities of nutrients to the coastal seas (Howarth et al., 1996). Agriculture is the largest user worldwide of freshwater (UNEP, 2002a). With the widespread use of fertilisers, pesticides and herbicides, it should come as no surprise that agricultural wastewater is making a great contribution to coastal eutrophication.

Figure 3.2.1. Nitrogen flux to the Gulf of Mexico (Source: Goolsby et al., 2001)



In a soil system nitrates are continually supplied naturally through the processes of nitrification and mineralisation of soil organic matter. Anthropogenic nitrogen inputs can be converted to nitrates in the same process. Nutrients reach waterways through subsurface drainage or groundwater but very little is transport via surface runoff (Jackson et al., 1973). None-the-less, it is estimated that nitrogen concentrations are almost nine times greater downstream from agricultural lands than down stream from forested areas with the greatest concentration near intensive regions (Omernik, 1977).

Probably the best example of the link of hypoxia with agriculture is that of the Mississippi River basin and the Gulf of Mexico. Here, in the world's second largest hypoxic zone, the principal source areas of nitrogen are basins in southern Minnesota, Iowa, Illinois, Indiana, and Ohio, USA that drain intensive agricultural land. Basins in this region yield 1500 to more than 3100 kg N km^2 /yr to streams several times the nitrogen yield of basins outside this region and the flux of nitrates to the Gulf has approximately tripled in the last 30 years (Goolsby et al., 2001). The majority of Mississippi River nitrogen originates from agricultural practice, while smaller fractions arise from human sewage, non-agricultural fertiliser use, and precipitation (Howarth et al., 1996; Goolsby et al., 1999; Downing et al., 1999). Figure 3.2.1. shows that 65 percent of nitrogen flux has agricultural origins (50 percent from fertiliser and mineralised soil and 15 percent from animal manure). The increased nutrient loading is consistent with population increases and subsequent increases in agricultural activity in the area. An increase in agricultural acreage, increases in fertiliser use and animal husbandry have resulted in two- to tenfold increases in the level of nutrient inputs during this century, with particularly dramatic increases since the 1950s (Howarth et al., 1996; Nixon, 1997; Goolsby et al., 1999). Retrospective analysis indicates that the nitrate flux could have been reduced by 33 percent over the time period 1960-1998, if the use of nitrogen-containing fertilisers in the Mississippi River basin had been cut by 12 percent (Gregory et al., 2001).

Satellite image of the Mississippi River delta and northern Gulf of Mexico showing phytoplankton blooms (Source: NASA SeaWiFS: http://daac.gsfc.nasa.gov/).

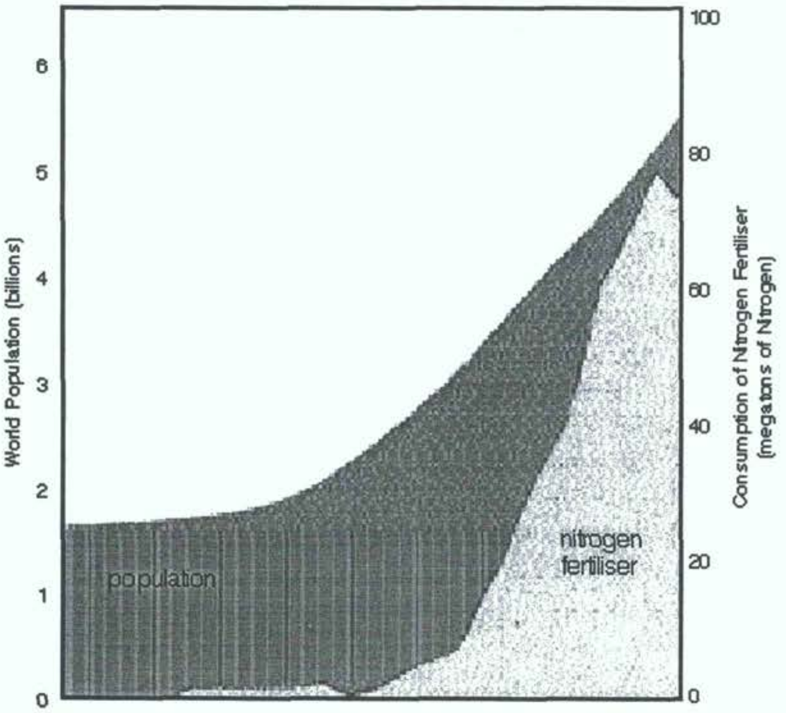
Globally, increases in nutrient loading, which result from higher rates of fertiliser application (Vitousek et al., 1997) has been implicated in increased nutrient loading. Increases in world population and consequent global fertiliser demand coincide with increasing concerns of eutrophication over the last two decades. World consumption of nitrogen fertilisers increased from 10 million tonnes in 1960 to 85 million tonnes in

1990. In Asia it increased from 1 to 48 million tonnes, principally in China, India, Java and in Egypt as well (Figure 3.2.2.). The potential for increased eutrophication and hypoxic events is enormous.

The implications of high fertiliser use go beyond greater subsurface runoff. An increasing fraction of fertiliser is lost with increased intensity of application. Nitrogen fertiliser is thought of be only 50-60 percent efficient (Smil, 1990) and with heavier application efficiency drops. In addition, greater fertiliser use towards greater food production will result in greater waste production from livestock and humans that is released into the environment and ultimately has the potential to lead to eutrophication (Nixon, 1995).

The impact of livestock waste to nutrient loading should not be underestimated. In some areas livestock are a greater source of nitrogen than fertiliser. While in Europe and North America, fertiliser makes the majority of agricultural nitrogen emissions, livestock waste contributes the greatest portion in Africa, Asia, Oceania and South America (Nixon, 1995). In the Gulf of Mexico 15 percent of nitrogen input is attributed to animal manure (Figure 3.2.1.).

Figure 3.2.2. World population and nitrogen fertiliser use (1900-1990) (Source: Smil, 1997)



The same nitrogen fertilisers and livestock waste (and other contaminants) that runoff the land as surface or subsurface water also effect the groundwater. The movement of contaminants from the surface through the unsaturated zone to deep aquifers is very slow and can take years. However, groundwater should be taken into account, in the Southern Atlantic Bight groundwater may be equivalent to riverine discharge (Moore, 1996). While coastal agricultural activities grow so will nitrogen inputs to groundwater.

Subsurface tiles are drainage systems used on poorly drained soils. They increase agricultural capacity but also increase nutrient leeching to subsurface waters.

The natural process of mineralisation should also be considered carefully. In some agricultural areas in the U.S.A., it is thought that intensive agricultural practices that enhance mineralisation of soil nitrogen with subsurface drainage are the major contributors of nitrate rather than fertilisers (Keeney and DeLuca, 1993; David et al., 1997). Agriculture also results in atmospheric emissions, which will be discussed in the next section.

3.3. Sewage

The link between sewage inputs and eutrophication is well documented where worldwide cases of eutrophication are often principally related to nitrogen from sewage discharges. Increases in coastal nutrient loading have much to do with population growth and urbanisation, the combined development of city water supplies, flush toilets and associated point source discharges from city sewage systems (Nixon et al., 1986a). However, (when compared to agricultural and atmospheric inputs) these point source discharges are easy to identify and manage and treatment schemes can quickly yield dramatic improvements. Among the limitless pollutants supplied by sewage to waterways and coastal zones, organic matter that increases the biochemical oxygen demand (BOD) of waters and nutrient-stimulated phytoplankton blooms are the most influential to eutrophication and hypoxia. Both scenarios can equally result in hypoxia and widespread mortality of resident fin-and shellfish (Paerl et al., 1998).

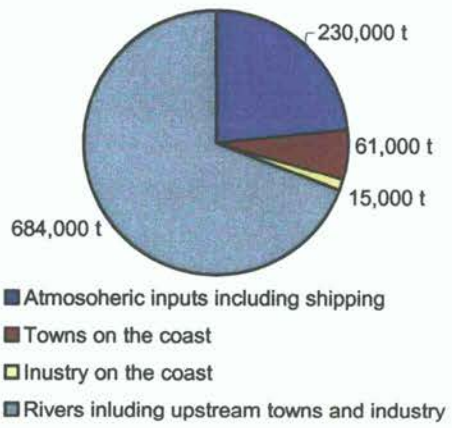
Sewage is probably better defined as waste water. This can be in the form domestic or municipal wastewater or industrial wastewater or storm water contaminants including runoff from roads, lawns and atmospheric deposition. In developed countries domestic and industrial sewage likely undergoes some treatment before discharge to waterways or the coastal ocean and the quality and quantity will vary with the size and diversity of the community and the types of industry present. Storm water quantity will vary with the storm length and severity, the season and the terrain. Storm run-off is usually less contaminated than the other sources and receives little or no treatment before release. Septic systems are also common in rural areas where sewerage systems are not in place. Here wastewater is absorbed into the ground and nutrients migrate into the hydrological system.

Hypoxia exists on various Japanese coasts. The breakdown of nutrients from Tokyo Bay, Osaka Bay, Ise Bay, and Mikawa Bay show that domestic sewage accounts for 66, 46, 37, and 41 percent nutrient load, respectively (Suzuki, 2001). Domestic sources account for the largest portion of nutrient inputs, where agricultural (and livestock) inputs are secondary in importance. A well-known study of sewage in Kaneohe Bay, Oahu in the Hawaiian Islands (Smith et al., 1981) provides a different viewpoint. Historically, the bay was receiving large amounts of domestic sewage input. The planned diversion of sewage for engineering purposes was followed by significant declines in the concentrations of nutrients, phytoplankton biomass and production, zooplankton biomass, macroalgal blooms, benthic animals, detritus and nitrogen released by sediments (Smith et al., 1981). Analysis shows an association between higher organisms and phytoplankton productivity in this system where the greatest biomass of benthic animals was found in the most eutrophic area (Nixon et al., 1986). Interestingly, Kaneohe Bay had even after the diversion of sewage, much higher nutrient loading than the North Sea or Baltic but that concentrations were relatively low due to a rapid flushing time (Nixon et al., 1986) (8 days for the Bay as a whole: Smith et al., 1981). Why this case saw only positive impacts and hypoxia was not identified is probably due to low nutrient tropical waters and high mixing and rapid flush time of the bay.

3.4. Atmosphere

Atmospheric deposition of nitrogen may originate from natural sources such as decomposition of organic matter, dust and aerosols generated from storms and atmospheric photolysis. When total global atmospheric emissions from natural and anthropogenic sources of nitrogen are compared, man-made emissions are the vast majority in the total however non point sources are difficult to measure and uncertainties can be quite large (Olivier et al., 1999). Anthropogenic emissions arise from fossil fuel combustion and biomass burning and agricultural emissions. These are a significant and growing source of nitrogen input, which may be implicated in eutrophication of estuarine and coastal waters. GESAMP (2001b) believes that between 10 and 70 percent of the fixed nitrogen input in many coastal regions is delivered by rain and the fallout of nitrogen compounds from the atmosphere. Other estimates put the range at <10 to >40 percent of North American and European coastal waters (Paerl et al., 2000). While estimates vary and ranges are very large, it seems that atmospheric nitrogen deposition may be having a greater impact than it is given credit for.

Figure 3.4. Nitrogen inputs into the Baltic (1995) (Source: HELCOM, 2003)



In the Baltic, although runoff accounts for 69 percent (684,000t), atmospheric inputs account for 23 percent (230,000t) of all water and airborne nitrogen inputs to the Baltic Sea (Figure 3.4.). However contributions vary, atmospheric deposition of nitrogen in the Gulf of Mexico is estimated to be less than 1 percent of total nitrogen input (Goolsby et al., 1999).

One of the most rapidly growing (both in terms of amount and geographical scale) sources of anthropogenic nitrogen loading is atmospheric deposition (Paerl et al., 2000). It is suggested that much of this is attributed to growing agricultural, urban and industrial emissions from fossil fuel combustion from automobiles, industry and forest and crop burning (Martin et al., 1989, Loye-Pilot, et al., 1990, Prado-Fiedler 1990, Duce et al, 1991, Paerl 1993, 1995, Valigura et al., 1996). In developed areas atmospheric nitrogen deposition may be the single most important source of new nitrogen entering the coastal zone (Valigura et al., 1996; Paerl, 1997) however, this source has most rapidly increased in developing countries (Paerl, 1999).

While agriculture and livestock contribute to terrestrial inputs they also contribute to atmospheric inputs. It is estimated that 40-70 percent of the nitrogen in waste is volatised as ammonia emissions resulting from animal operations which is regionally deposited as ammonium (Pearl, 1997). In Western Europe, this is now recognised as one of the most important sources of nitrogen enrichment to estuaries and coastal waters (Asman et al., 1994). Ammonium has also been found to accumulate in rainwater associated with agricultural regions (Paerl et al., 1995).

The relative contribution of atmospheric deposition of nitrogen to total nitrogen loading depends on land use, watershed and airshed size, and hydrological and morphological characteristics such as water retention time of the receiving waters. Atmospheric nitrogen deposition enters coastal waters either by direct input to the water surface, or indirectly where nitrogen is first deposited in the watershed prior to discharge to coastal waters. Nitrogen deposition in watersheds affects the nitrogen cycle. As nitrogen is a plant nutrient temperate forests initially respond to increased nitrogen availability with a gradual increase in productivity however, in the final stages of saturation productivity declines. Once soils become saturated leaching to the groundwater results (Aber et al., 1989).

3.5 Aquaculture

Aquaculture is a developing industry that is rapidly growing due to depleting wild fish stocks. Although some aquaculture is conducted inland most takes places in coastal waters. It is also having detrimental, long-term environmental impacts to the environment. Coastal fish farms are resulting in increased releases of nutrients, pathogens and potentially hazardous chemicals into coastal waters. Inland operations are resulting in salinisation of groundwater and nutrient pollution of waterways. In both cases, the end result is nutrient enrichment of coastal waters.

Organic wastes from aquaculture may include uneaten food, faeces, urine, mucus, and dead fish. Farmed species are supplied feed so this activity acts as a new source of nutrients. As much as 70 percent of total phosphorus and 80 percent of total nitrogen fed to fish may be released into the water column through organic wastes (Beveridge, 1996), and approximately 80 percent of those nutrients are available to plants and may contribute to eutrophication (Troell et al., 1997). Aquaculture has a relatively small role in global nutrient loading (compared to agriculture), however it does contribute to eutrophication. In the US, aquaculture contributes nutrients and other pathogens to, among other water bodies, Gulf of Mexico, the Chesapeake Bay which are already plagued with eutrophication and hypoxia (EPA, 2000). Fish farming can have great impacts in localised areas. It is estimated that a salmon farm of 200,000 fish releases an amount of nitrogen, phosphorus, and faecal matter roughly equivalent to the nutrient waste in the untreated sewage from 20,000, 25,000, and 65,000 people, respectively (Hardy, 2000). More over, in some areas with intensive cage farming, such as L'Etang Inlet in New Brunswick, Canada, nitrogen and phosphorus inputs from aquaculture are the largest anthropogenic source of nutrients to the inlet (Strain et al., 1995). Inland farming has fewer impacts than coastal operations because the water is contained. However it is faced effluents problems and eutrophication contributions depend on the type and volume of discharge, and the characteristics of the receiving waters.

Coastal farming can also alter the oxygen levels in the benthos. Raised levels of organic matter underneath cage operations change the chemical and biological structure of the sediment (Beveridge, 1996). Reported impacts include a dead zone under coastal salmon farms in severe cases, surrounded by a ring of decreased animal diversity. These impacts can extend up to 150m from the site (Beveridge, 1996). However not all forms of aquaculture contribute to nutrient loading. Molluscs are filter-feeding organisms that can improve water quality by consuming plankton. Mussel farms near fish farms can remove nitrogen from water at a 70 percent higher rate than occurs in surrounding waters (Kaspar et al., 1985). As plants take up nutrients, seaweed biofilters can also reduce nutrient loads around coastal operations (Chopin et al., 1999; Troell et al., 1997). Seaweeds can improve water quality by removing nutrients, and oxygenating the water. For this reason seaweeds have a mitigative role in eutrophication management. The level of nutrients will also be affected by the mixing or flushing rate of the water.

3.6. Land use and alteration

Although the use of coastal land is not a direct source of nutrients contributing to hypoxic waters, land alteration and use will have a significant impact on the amount and type of runoff entering coastal waters. The uses of land for agricultural purposes will likely result in increased runoff of fertilisers just as the uses of land for industrial activities may result in effluents reaching coastal waters. General removal of forests and vegetation will drastically increase the rates of runoff. For example, in Finland, Russia, Sweden and Estonia, forests, wetlands and lakes make up between 65 and 90 percent of the Baltic catchment area in. However, in Germany, Denmark and Poland as much as 60-70 percent of the Baltic's catchment area consists of farmland. This is consistent with differences in nutrient loading. Justic et al., (1995a, 1995b) report on changes in land cover and its implications in increased runoff and nutrient loading in the Baltic.

Chesapeake Bay, U.S.A. is another well-documented hypoxic zone. The basin was formerly surrounded by forest and wetlands, which serve as sinks for nutrients so little nitrogen and phosphorus ran off the land into the water. Farms, cities, and suburbs, which serve as sources, have replaced much of the forests and wetlands. As the use of the land has changed and the watershed's population has grown and the amount of nutrients entering the bay's waters has increased. As development increases the problem will only worsen. As is being seen now in Gulf of Mexico, the development and protection of coastal wetlands are being used to combat eutrophication and hypoxia. While oxygen deficiency is prevalent off most Japanese coasts south of Tokyo, Mikawa Bay is the most serious hypoxic area. However Mikawa Bay receives less much less nutrient loads than comparative hypoxic zones in the area. The reason for its extensive hypoxia has been attributed to the reclamation of shallow water area and tidal mudflats that have impaired the water purification functions. This (and increasing irrigation needs) has resulted in the reduction of freshwater inflow to the sea area resulting in lower rates of exchange and reoxygenation (Suzuki, 2001).

3.7. Natural barriers to mixing

Although hypoxic bottom water, in most cases results from eutrophication, it would not occur without appropriate physical conditions. Under 'normal' conditions, oxygen rich surface water is mixed with oxygen poor bottom water through wind, wave and current actions. If the water column is highly stratified little mixing occurs and bottom

Satellite image of the Black Sea and Bosporus Straits (Source: NASA SeaWiFS: http://daac.gsfc.nasa.gov/)

water does not become reoxygenated. Although most hypoxic zones have anthropocentric root causes, there are naturally occurring hypoxic zones. Most low-oxygen zones are merely hypoxic and seasonal however, the Black Sea is the world's largest hypoxic zone (Tolmazin, 1985) and is permanently anoxic below a depth of 150-200 meters. The Bosporus Straits is the narrow channel that connects the semi-enclosed Black Sea with the Mediterranean Sea. Through this channel, saline water from the Mediterranean ventilates the Black Sea basin, however the channel is narrow and prevents extensive mixing between the two water bodies. High freshwater runoff creates a density gradient, divided by a pycnocline at 150m. Mixing takes place in the upper 150 meters below which, the water column is entirely anoxic to the bottom. The strong stratification of the water column and slow renewal times for deep waters contribute to the permanent anoxia. It has been theorised that the Black Sea was a freshwater lake at one time, and it became an anoxic marine basin fairly recently, around 5600 BC when and a flood of seawater broke through the Bosporus Straits and submerged the lake. The influx of Mediterranean seawater raised the level of the lake about 150 meters, and created the density difference that prevented mixing quickly developing anoxic conditions. Dated freshwater mussels that died as oxygen concentrations fell are used as an indicator of the occurrence (Pitman and Ryan, 1999). It should be noted however, that while natural factors may cause hypoxia anthropogenic nutrient loading is worsening the problem (Mee, 1992).

The North Sea is a heavily studied area and while estimates vary there is little doubt that anthropogenic nutrient inputs have increased drastically in the last 50 years although there is now some indication that phosphorus inputs are declining due to management techniques (Frid et al., 2002). The highly populated and industrial areas surrounding the North Sea are contributing greatly to nutrient input but even up until the late 1980's fish stocks remained strong (Nixon et al., 1986a). Now the same could not be said, and while fishing pressure is likely the major culprit, eutrophication which is widely described around the North Sea (Frid et al., 2002) may be partly responsible. In comparison, the Baltic (which probably receives more nutrient fertilisation) has had a total collapse of fisheries, eutrophication is a serious problem throughout and has in contributed to growing hypoxia. While there have been episodes of hypoxia (Gieskes and Kraay, 1986), why has the North Sea not seen the same extensive hypoxic effects as the Baltic? The answer may lie in natural physical characteristics of the seas. The North Sea is well mixed from currents of the Northern

Satellite image of the Baltic Sea, including a visible plankton bloom in the Skagerrak just north of Denmark (Source: NASA SeaWiFS: http://daac.gsfc.nasa.gov/)

Atlantic that oxygenate the water and dilute any negative effects of eutrophication. It is the same dispersal effect that keeps the North Sea relatively safe from minor oil spills from the extensive oil industry activities in its waters. If the North Sea had similar restrictive water flow and lack of circulation and re-oxygenation as the Baltic, it would likely have similar hypoxia. A similar parallel can be drawn between freshwater. Lake eutrophication has a much longer history than marine eutrophication which is probably due to the fact that lakes are smaller, isolated water bodies with comparatively less mixing. It should be noted however, that while natural causes enable hypoxia to persist, the Baltic Sea exhibits no natural tendency toward hypoxia (Pearson et al., 1985; Elmgren, 1989). It was not until the 1950's and 1970's, respectively, that oxygen was found to be a problem even though there were oxygen measurements that go back to the turn of the 19th century (Rosenberg, unpublished data, 1989).

The Saanich Inlet on Vancouver Island, Canada has a sill near the mouth of the inlet, about 70m deep, which restricts the exchange of water from the Pacific Ocean and the bottom of the inlet. Lack of sufficient mixing has created hypoxic bottom waters below 100m. Sediments from the inlet have annual layers which have been studied to provide information about changing environmental conditions on this coast and can be compared to tree rings (McQuoid and Hobson, 1997). The Cariaco Basin, near the coast of Venezuela is another naturally occurring anoxic basin.

Some hypoxic areas occur naturally and some are merely more prone than others to developing hypoxia due to natural factors and thus exhibit varying degrees of severity. In the study of Kaneohe Bay (Smith et al., 1981) nutrient loading was much higher than the North Sea or the Baltic but nutrient concentrations were relatively low and hypoxia was absent due to a rapid flushing time. None-the-less, hypoxic waters are being intensified in area and severity by anthropogenic factors.

3.8. Oceanic circulation

Mixing also occurs during tidal cycles. As currents accelerate the production of turbulent kinetic energy grows and can become the largest source of mixing energy in shallow coastal waters. This explains why the impacts of nutrient enrichment are most extreme in regions with a small tidal energy such as the Baltic, the northern Gulf of Mexico and the Black Sea. Horizontal transport of nutrients and phytoplankton are also important. These movements are controlled by physical attributes of the water column (e.g. currents, wind, tides, and basin geography) and play an important role in algal blooms. Wind stress can also be an important mechanism in mixing and climatic changes in wind frequency and intensity can result in changes in phytoplankton growth.

3.9. Climatic influences

Particularly wet years or flooding can drastically change the amount of runoff reaching the coastal waters, which will greatly affect the nutrients input. The difference in hypoxia following a drought period versus a flood period reinforces the relationship between river discharge and the extent of hypoxia. The 1993 flood in the Mississippi region and northern Gulf of Mexico is a good example of this where prior to 1993, the hypoxic zone averaged 8,000 to 9,000 km^2 (1985-1992). After which the hypoxic zone doubled in size to 18,000 km^2 (Rabalais et al., 1998, 1999). In the summer of 2002, the largest hypoxic zone ever recorded was measured at 22,000 km^2. In the Gulf, large year-to-year variations in nitrogen flux occur because of variations in precipitation. During wet years the nitrogen flux can increase by 50 percent or more due to flushing of nitrate that has accumulated in the soils and unsaturated zones in the basin. (Goolsby et al., 2001). Phytoplankton blooms follow periods of elevated nitrogen loading brought with high precipitation, except however during extremely high runoff periods (e.g. hurricanes), when high rates of flushing and reduced water residence times do not allow sufficient time for bloom development. During these periods, hypoxia may be absent or it may be dominated by watershed-derived organic matter loading (Paerl et al., 1998). Storm related events of high river flow also establish strong vertical salinity gradients and can develop into hypoxic bottom waters (Paerl et al., 1998). Oppositely, low flow times increase resident times and reduced mixing can result in algal blooms.

Drainage is also influenced by soil moisture. In the spring, when evapotranspiration (ET) rates are low and the soil is saturated, storage capacity is minimal and drainage water carrying nitrates is more plentiful. However in the summer when ET rates are high and soil moisture is low, a significant storage reservoir can exist in the soil and drainage may be less. Year to year changes in precipitation can greatly affect drainage. Soil naturally converts organic matter into nitrates via mineralisation, which is susceptible to loss in subsurface drainage. As seen above agricultural nitrates can increase mineralisation however high concentrations of nitrates can easily be lost to drainage from high organic matter soils even if little or no nitrogen is applied externally (Randall and Mulla, 2001).

As temperature increases the severity of hypoxia tends to increase (Diaz and Rosenberg, 1995). Hypoxia is seasonal and this is partially based on seasonal differences in water temperature. For example in the Mississippi delta the water temperature rises about 5°C between May and September the same period as seasonal hypoxia. This may be partly because of increased primary production and also because sediment oxygen consumption is higher at warmer water temperatures (Gilbert, 2001). The ENSO weather phenomena event in 1998 bringing warmer ocean temperatures caused many algal blooms (and harmful algal blooms) globally. In the future, global warming may accelerate the effects of hypoxia and enlarge the areas that are affected (Kennedy, 1990; Beukema, 1992).

3.10. Other contributors

Exceptional phytoplankton blooms, with associated deoxygenation and fish kills in the North Sea (1980-1981) have been linked to discharges from a hydroelectric power plant (Reid, 1997). Large freshwater discharge to the sea causes shallow and stable stratification, which are ideal conditions for rapid phytoplankton growth. This is similar to the result of increased runoff. Human manipulation of coastal hydrology such as that which results from dams and human control of water flow can have implications for eutrophication, although Cloern, (2001) notes this is a virtually unexplored interaction that does not yet operate in highly engineered physical systems.

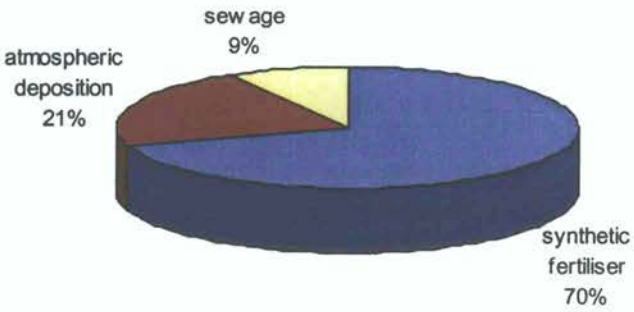
The human induced introduction of nonindigenous species can have great impacts on marine ecosystems. How these new species can interact with nutrient enrichment and impact primary production is not entirely known. Boats carrying micro-organisms in ballast water can release new species to unsuspecting environments. In Australia, a series of toxic algal blooms was the result a dinoflagellate directly introduced from ship ballast (Hallegraeff, 1993). A similar scenario is playing out in the Black Sea, where nutrient enrichment has caused a decline in native species while the non-native ctenophore (*Mnemiopsis leidyi*) has exploded in growth causing great threat to the anchovy fishery (Mee, 1992).

Another possible contributor is the interactions of nutrient enrichment with other toxic contaminants, however these have not been extensively investigated. Heavy metals like silver and copper chlorinated hydrocarbons such as DDT and PCB's and various herbicides can selectively inhibit some classes of algae and thus promote the growth of other species. It is viable that some algal blooms, which are caused by the explosive growth of one or two species, may be the result of interactions with nutrient enrichment and other toxic pollutants. There are a variety of possible relationships including, changes in efficiency of trophic transfer and amplifying effects of toxic contaminants (Cloern, 2001).

3.11. Summary

While there can be many factors in the development of eutrophication and hypoxia, anthropogenic nutrient inputs are the principal contributors and every region has different sources of nitrogen inputs. Globally, coastal watersheds receive 73.6 Tg (70 percent) of nitrogen form synthetic fertiliser, 22.5 Tg (21 percent) from atmospheric deposition of oxidised nitrogen and 9.1 Tg (9 percent) from human sewage (Figure 3.11.)

Figure 3.11. Global nitrogen inputs to coastal watersheds (Source: Seitzinger and Kroeze, 1998)



Perhaps following Malthusian tradition population growth with related effluents and industries has fuelled the causes of eutrophication and hypoxia. Growth in population density within coastal watersheds has been implicated in increasing nutrients inputs (Peierls et al., 1991; Howarth et al., 1996).

Most hypoxia cases are from developed industrialised areas where point source discharges such as sewage can be controlled and most inputs are coming from agricultural runoff and atmospheric inputs that are difficult to regulate. The developing world is experiencing eutrophication most often from sewage outfalls but not yet extensive hypoxia. This suggests that it is the non-point sources discharges associated with industrialism are the major causes of hypoxia. This is consistent with global nitrogen inputs to coastal waters (Figure 3.11.).

Although different hypoxic zones will naturally have different sources of nitrogen it is generally agreed that land runoff contributes the greatest amount of nutrient loading to coastal waters. The link between nutrient loading and eutrophication is strong but it is not easily defined in large marine ecosystem globally with many identified (flushing time) and unidentified interacting stressors. While coastal nutrient loading is a vital and natural process, anthropogenic changes have resulted in complex and fragile ecosystem balances. A study of the Nile makes an interesting point that different human-induced stressors can create an artificial balance. Construction of the Aswan High Dam stopped nutrient input to the Mediterranean coastal waters off Egypt. Flow from the Nile was reduced by over 90 percent, and a formerly productive fishery collapsed. It remained unproductive for about 15 years until a dramatic recovery began during the 1980s, coincident with increasing fertiliser use, expanded agricultural drainage, increasing human population, and dramatic extensions of urban water supplies and sewage collection systems. It is suggested that these inputs now support the fertility once provided by the Nile, however not surprisingly the nature of the productive ecosystem now supporting the fishery appears to be quite different from the natural one (Nixon, 2003).

While hypoxic zones appear largely off industrial coastlines, it doesn't mean they do not exist in other parts of the world. In fact the cause of hypoxic zones, eutrophication is being seen globally for example the toxic algal bloom in January 2002 that washed rays, puffer fish, sharks, red snapper, parrot fish, octopus and turtles along the coast of Kenya and Somalia[2]. Perhaps is it just a matter of time before coastal hypoxia will truly be a global issue. The intensity of nitrogen emissions from fertiliser, livestock waste, and fossil fuel combustion varies widely however, it is strongest in Europe, the northeastern U.S.A, India/Pakistan, Japan/Korea, and the Caribbean (Nixon, 1995). This geographical distribution corresponds with many areas where coastal marine eutrophication and hypoxia have being documented. Demographic and social trends suggest that past practices leading to coastal nutrient enrichment are likely to be repeated in the coming decades in the developing countries of Asia, Africa and Latin America.

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[2] http://eces.org/ Consulted September 10, 2003

4. Ecosystems impacts

Among those who study it, it is generally agreed that there is no other environmental variable of such ecological importance to coastal marine ecosystems that has changed so drastically in such a short period as dissolved oxygen (Diaz and Rosenberg, 1995). Hypoxia affects living resources, biological diversity, and the capacity of aquatic systems to support biological populations. Ecosystem impacts of hypoxia and some contributing impacts of eutrophication will be discussed. Ecosystem impacts and fisheries impacts will be discussed separately. Hypoxic impacts on ecosystems and fisheries are tightly coupled, as fish are an integral part of the overall ecosystem. The separation was arbitrarily made only because fisheries impacts have greater socio-economic implications.

4.1. Community structure

The indirect effects of low dissolved oxygen variably affect marine species including important commercial species. Direct mortality, forced migration, reduction in suitable habitat, increased susceptibility to mortality from natural predation and fisheries, physiological stress, changes in food resources, growth and disruption of life cycles are all likely to have population and community-level consequences. When oxygen levels fall below critical values (usually 2 mg/l), those organisms capable of swimming such as demersal fish, crabs, and shrimp evacuate the area to avoid death (Leming and Stuntz, 1984). However many organisms are caught and hypoxia has a direct mortality effect on mobile species resulting in fish kills. The migration of species away from hypoxia can cause the herding of fish and shellfish at the edge of hypoxic water. This is commonplace in low oxygen zones and known as the boundary or edge effect (Mullins et al., 1985). A similar circumstance is seen in Mobile Bay, U.S.A. and the Gulf of Mexico where fish flock toward the shoreline known as jubilees (Schroeder and Wiseman, 1988; Diaz, 2001)

The ecological impacts on less motile and sessile fauna caused by declining oxygen levels vary according to the oxygen requirements of the particular organism and the frequency and severity of the hypoxia. Benthic animals are often more resistant to low oxygen levels, but they also experience stress or die as oxygen concentrations decline from 1 mg/l to anoxia. Gray (1992) suggests a sequence of responses to developing hypoxia that includes: escape of sensitive demersal fishers (cod, whiting) when oxygen concentrations fall to 25 to 40 percent of saturation; escape of other benthic fishes (dabs, flounders) at 15 percent saturation; mortality of bivalves, echinoderms and crustaceans at 10 percent saturation; and extreme lose of benthic diversity at <5 percent oxygen saturation when only the most resistant species of invertebrates (*Capitella, Polydora*) persist. Generally, polychaetes are the most tolerant taxa, followed by bivalves and crustaceans (Diaz and Rosenberg, 1995). Studies from the Gulf of Mexico hypoxic zone show that the benthos consists of short-lived, smaller surface deposit-feeding polychaete worms while marine invertebrates such as pericaridean crustaceans, bivalves, gastropods, and ophiuroids are absent (Rabalais et al., 2002). This community structure is characteristic of an oxygen stressed zone. Oxygen-deficient zones are also characteristic of a positive feedback loop. Hypoxia leads to a reduction of macrobenthic suspension feeders resulting in lower removal of organic particulates from the water, deposit-feeder activity also drops. Lower transparency then hinders nutrient uptake by plants and photosynthetic activity and oxygen levels drop accelerating hypoxia development (Suzuki, 2001).

In seasonally hypoxic areas, benthic fauna experience pulses of mass mortality and winter recolonisation is common but this depends on the severity of the episode. Aperiodic episodes of hypoxia can lead to hypoxia-resistant communities, however mass moralities still result (Diaz and Rosenberg, 1995). 'When exposed to long term or severe hypoxia, macrofaunal communities experience mass mortality. Temporal variability of communities increases and energy flow through the community becomes more pulsed. Large individuals and long-lived equilibrium species are eliminated and the population shifts toward younger individuals, and smaller and more short-lived species that possess opportunist life histories' (Diaz and Rosenberg, 1995). These opportunist species are anaerobic taxa, which replace the aerobic taxa. This shift is typical of hypoxic areas and results in alterations of community composition and function (Hessen et al., 1997). No macrofauna occur in persistent severe hypoxic environments and there appear to be no long-term mechanisms for survival. While some species show some tolerance, they cannot survive to complete their lifecycles (Diaz and Rosenberg, 1995). Long term or persistent severe hypoxia induces retarded growth and poor reproductive success resulting in failures in recolonisation and in habitats that are devoid of macrofauna or possibly all metazoan life, except where a high volume of organic matter is present with efficient energy transfer (Diaz and Rosenberg, 1995). In addition repeated stress from hypoxia may have influences on normal predator prey relationships. Hypoxia favours small-sized prey species with a short life cycle, which would in turn favour small-sized fishes. Thus, altered food resources and the direct effects of hypoxia might result in a shit in dominance among demersal fish species (Pihl, 1994). Reoccurring hypoxia stress not only halts successional development of a community but also keeps the communities in a constant pioneering state that could have consequences for ecosystem energy flow. These changes in marine communities, along with the low dissolved oxygen, over time will result in altered energy flow, sediment structure and sediment biogeochemical cycles.

While effects of hypoxia vary between species and from ecosystem to ecosystem the effects on shrimp in the Gulf of Mexico show reduced food resources in hypoxic waters (Rabalais et al., 1995), reduced abundance in hypoxic waters (Pavela et al., 1983; Leming and Stuntz, 1994; Renaud, 1986), loss of production potential due to the blocked migration offshore by the presence of the hypoxic zone (Nance et al., 1994; Zimmerman et al., 1997; Downing et al., 1999), are all resulting in decline in catch and catch efficiency since hypoxia expanded (Zimmerman et al., 1997; Downing et al., 1999). In studies of carp, oxygen-starved fish had lower hormone levels, and significantly smaller sexual organs than the fish raised under 'normal' oxygen conditions. Under hypoxic conditions the survival rate was less than 5 percent of the hatched larvae, as compared with approximately 90 percent under 'normal' conditions (Wu et al., 2003). While carp are freshwater fish endocrine disruption and drastic reduction of reproductive success could contribute to major population declines in fish and other marine organisms. The collapse of the Baltic Sea cod fishery in the early 1990's is blamed on oxygen loss in deep waters due to eutrophication, which interfered with egg development.

In the Black Sea a long history of eutrophication has caused the euphotic zone (the surface water that receives sufficient light for photosynthesis) to become shallower due to reduced water transparency resulting in loss of benthic shallow water macrophytes, blooms of phytoplankton, zooplankton, jelly fish and ctenophores and widening hypoxia that are further contributing to declines in species richness (Mee, 1992). Historically the Black Sea was one of the most productive marine fisheries regions in the world. Since the 1970's however, the number and quality of fish catches has declined. Whereas 30 years ago economical valuable mackerels and bonito were caught, in the 1980's catches consisted only of anchovies (Tolmazin, 1985). Now there is evidence that introduced ctenophores are out-competing the anchovies and are responsible for catastrophic decreases in catches of Azov-Black Sea anchovies (Caddy, 1993; Zaitsev, 1993). Similarly in Makawa Bay, Japan, over the last 30 year period, nutrients and hypoxia have increased and water transparency and fisheries have declined (Suzuki, 2001).

The Chesapeake Bay is a well-studied seasonal hypoxic area. Here, macrobenthic communities are characterised by lower species diversity, lower biomass, a lower proportion of deep-dwelling biomass (deeper than 5 cm in the sediment), and changes in the community composition. Hypoxia also correlates to higher dominance in density and biomass of opportunistic species such as euryhaline annelids and lower dominance of equilibrium species such as long-lived bivalves and maldanid polychaetes (Dauer et al., 1992), again characteristic community structure of oxygen stressed zones. But in less severe areas of Chesapeake it is thought that hypoxia may be a mechanism for regulating benthic population dynamics (Dauer et al., 1992). In Chesapeake Bay, nutrient loading is also creating dense plankton blooms that reduce the amount of sunlight available to freshwater rooted submerged macrophytes, collectively called submerged aquatic vegetation (SAV). Lack of sufficient light limits photosynthesis and this is killing the grasses, which are an important habitat for fish, shellfish and other and invertebrates. Moreover, reduced photosynthesis reduces oxygen production contributing to hypoxia. Seagrasses, along with other SAV's underwent serious declines in population abundance in the 1970's with increased eutrophication and have not as yet rebounded to previous levels.

4.2. Phytoplankton: primary and higher production

It is difficult to separate the impacts of eutrophication from hypoxia. Hypoxia is a result of eutrophication and in most cases a system has to be eutrophic to be hypoxic. Thus impacts of eutrophication and hypoxia occur concurrently. While there are no observable benefits to hypoxia, hypoxic systems will likely see increased primary production (and possibly higher trophic level production) from the eutrophication. The extent to which an ecosystem can assimilate and process nutrients and organic matter and exhibit varying degrees of eutrophication and/or hypoxia is dependent on integrated physical features (such as those discussed in causes) and biological factors. For example, when nutrient enrichment causes increased primary production, particularly opportunistic species may take advantage and transfer the organic carbon to higher trophic levels. Little carbon is left to bring negative impacts of eutrophication such as hypoxia. This is often the case in the early stages of eutrophication where ecosystems can accommodate and even benefit from nutrient loading. In fact lower productivity is initially seen in estuaries and coastal areas that have been cleaned up (Smith et al., 1981). However, much energy is lost in transfers to higher trophic levels. Experiments of nutrient enrichment show a lack of dramatic increase in animal production, particularly in higher trophic levels. Although interestingly, hypoxia resulted from the nutrient inputs which was thought to prevent increased primary production from reaching higher trophic levels (Nixon et al., 1986a).

Phytoplankton is the first community to be impacted by eutrophication. Nutrient acquisition is a major factor determining the outcome of competitive interaction and phytoplankton community structure (Titman, 1976; Huisman and Weissing, 1995). Phytoplankton and bacteria utilise different forms of nitrogen from different inputs (NH_4, NO_x) and can thus result in community compositional changes. A specific nitrogen input may enhance primary production by favouring growth of specific phytoplankton functional groups (Paerl et al., 2001). The effects of this are most evident in the growth of harmful algal blooms, which can harm fish and shellfish, as well as the people who consume them. Phytoplankton change and resulting trophic changes may also increase hypoxia via enhanced sedimentation of ungrazed phytoplankton. It should also be noted however, that there are examples of areas that show no trend of increasing phytoplankton biomass, even during decades of increasing nutrient concentrations (Cloern, 2001). While the signal of nutrient increase and the response of increased phytoplankton biomass is probable it is not definite.

The large volume of phytoplankton leads to organic accumulation on the benthic layer that consumes oxygen in decomposition. The material formed can fill up a shallow area, decreasing the depth and organisms that require a broad depth will begin to disappear. If this process continues, the area may eventually totally fill up with mud. In addition, anything that mixes up the nutrient- rich benthos means the process of eutrophication and hypoxia is continued.

4.3. Nutrient cycles

While nutrient loading obviously affects the nitrogen cycle, hypoxia can also impact the nitrogen cycle. During 'normal' bacterial decomposition of organic matter bacteria reduce nitrate to give atmospheric nitrogen (N_2) in a process called dentrification. This is the only significant natural process converting fixed nitrogen to atmospheric N_2, however it has be shown that dentrification is controlled by nitrate supply (Seitzinger and Gilbin, 1996). The nitrates can come from anthropogenic sources or naturally through nitrification where sediment produces nitrate, supporting dentrification. But nitrification is an oxygen-requiring process and is inhibited by hypoxia. Thus nitrogen is retained in the system and contributes towards hypoxia.

There is also evidence that hypoxia is causing large-scale releases of previously stored nitrogen (and phosphorus and iron) from sediment, altering nutrient forms and availability, and inducing microbial community change (Fenchel, 1998). Once hypoxia has be come large enough this release of nutrients transforms the water from its role in purification capacity to a nutrient source further intensifying the dissolved the dissolved oxygen deficiency. It has also recently been shown that anaerobic oxidation of ammonium coupled to nitrate reduction performed by anoxic zone bacteria contributes substantially to N_2 production in marine sediments (Thamdrup and Dalsgaard, 2002). This process, while secondary to dentrification, may play an important role in the marine nitrogen budget and it is important in the removal of fixed nitrogen (nutrients) in the oceans.

There may also be secondary nutrient interactions in eutrophic and hypoxic areas. Pristine rivers export silicon, nitrogen and phosphorus in excess to coastal waters, however anthropogenically altered rivers load nitrogen and phosphorus and can result in silicon limitation. The availability of dissolved silicon and its ratio to total inorganic nitrogen are important in controlling diatom community production and composition. Coastal areas with deficient silicon (and high nitrogen) may see a limitation in diatom productivity and increasing production of non-siliceous taxa with implications for eutrophication, harmful algal blooms and oxygen depletion (Dortch and Whitledge, 1992). Similarly, if nitrate loading is not accompanied by iron enrichment, iron-nitrogen co-limitation can occur (Paerl, 1997), where iron may act to stimulate primary production by synergistic effects with nitrogen (Paerl, et al., 1999).

Due to bacterial decomposition, hypoxic waters are strongly reducing and stimulate sulphate reduction thus they are characterised by the absence of dissolved nitrate and the presence of hydrogen sulphide (H_2S) (Bullister and Lee, 1995). The gas is trapped in benthos and builds up, until it is eventually released when the area is disturbed. The poisoning effects of hydrogen sulphide restrict benthic life and its release by sediments of hypoxic benthos intensifies hypoxia (Harper et al., 1981, 1991). The combined impacts of H_2S and hypoxia are often difficult to distinguish. H_2S is however restricted to the water mass below the halocline and does not normally contaminate overlying water. Sulphur bacteria (*Beggiatoa spp*) also inhabit these zones. Research also indicates interactions with the reducing hydrogen sulphide of anoxic waters and CFC's (Lee et al., 1999; 2002).

4.4. Fisheries impacts

In a coastal ecosystem not influenced by man, the land has a very positive effect on ocean productivity. The most productive zones around the world are characterised by nutrient enrichment either from upwelling regions or land runoff. This is a vital process that can be demonstrated by major declines in fisheries followed by controlled or eliminated river flow. While the Aswân High Dam on the Nile River was being constructed, river flow and associated nutrient inputs decreased and valuable fisheries declined. After the dam was finished discharges resumed and fisheries largely recovered (however under a different community structure) (Lasserre et al., 1997). Many parallels in thinking and management have been historically drawn between agriculture and ocean production partly because this 'fertilisation' is so vital to fisheries (Nixon et al., 1986a). Man has been curious about this relationship. The most dramatic example of which is an experiment involving the application of commercial fertiliser to two sea lochs on the coast of Scotland during WWII in the hopes of increasing the yield of fish for local food sources. Increased growth of fish was met but yields were disappointing due to the complements of increased predation and competition and hydrogen sulfide poisoning from bacterial decomposition (hypoxia) (Gross, 1946).

Table 4.4.1. 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 (Source: Diaz, 2001).

System	**Hypoxia typeΣ**	**Hypoxia levelΦ**	**Time trendsΩ**	**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	+ΣΣ	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	+ΦΦ	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	.

ΣAperiodic, 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.

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

Ω– = 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, recolonisation occurs but community does not return to prehypoxic structure; slow, gradual return of community structure taking more than a year; annual, recolonisation and return of community structure within a year. ΣΣThese systems are currently in a persistent hypoxic state.

ΦΦRecent improvements in oxygen concentrations due to pollution abatement.

COMPARATIVE EVALUATION OF FISHERY ECOSYSTEMS RESPONSE TO INCREASING NUTRIENT LOADING

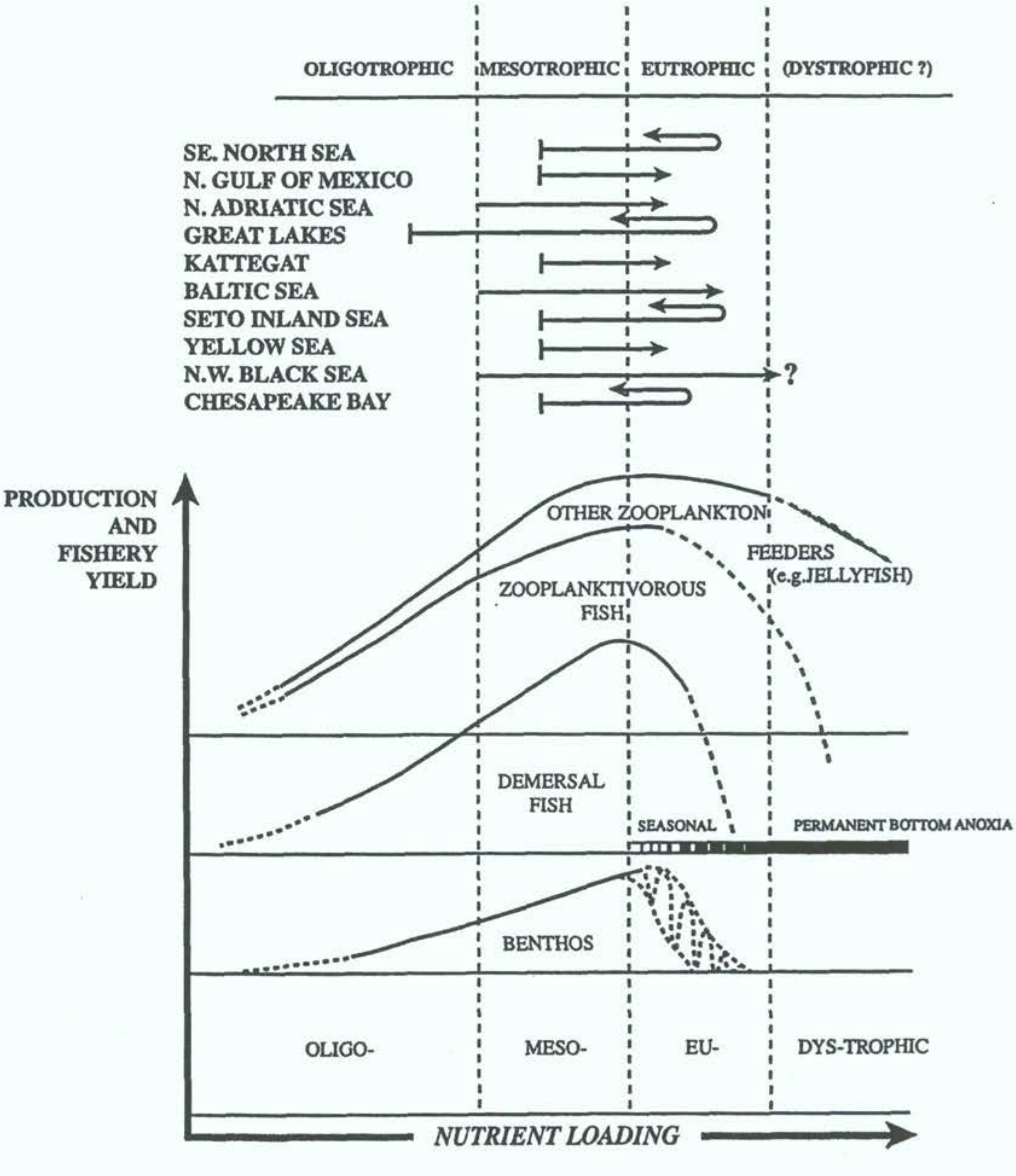


Fig. 4.4. Comparative evaluation of fishery response to nutrients based on data from around the world (Source: Diaz, 2001, modified and redrawn from Caddy, 1993). Each curve represents a general guild of species and their reaction to increasing nutrient supplies. The top part of the figure lists recent trends for various systems around the world. Vertical dashed lines separate general categories of organic production that result from different levels of nutrients

Excess nutrients lead to increased primary production which adds new organic matter to the ecosystem. Because benthic and pelagic environments tend to be tightly coupled in coastal and estuarine systems between, meaning a high degree of organic carbon transfer, much of the organic matter reaches the benthos. Increased primary production can transfer greater amounts of carbon to higher trophic levels, which has been documented in cases of increased fisheries production (Caddy, 1993; DeVries et al., 1990). However, at some point carbon production exceeds that which can be managed by the ecosystem, the organic matter ends up as benthos and if stratification prevents mixing, hypoxic conditions will result. As eutrophication increases and hypoxia expands in duration and area, the fisheries production base is affected and declines (Diaz, 2001). Table 4.4.1. shows this graded relationship between nutrients, hypoxia and fisheries.

Diaz (2001; based on Caddy, 1993) reports that ecosystem changes are very predictable and have followed the same path in many ecosystems. Ecological responses seen in the Gulf of Mexico i.e. increased nutrient input, increased primary productivity in the water column, increased flux of organic matter to the bottom, bottom water hypoxia, altered energy flow and stressed fisheries, could be expected anywhere. Figure 4.4. shows this trend. The top of the diagram presents 10 global problem areas and the stage of nutrient input. Most are in the eutrophic stage however some areas are improving. The bottom of the diagram shows the response of different trophic groups through increasing nutrient stages. It is evident that the highest production occurs between mesotrophic and eutrophic stages, after which productivity drops.

Fish killed by hypoxia on Grand Isle barrier beach, Louisiana coast, northern Gulf of Mexico (Photo: Kerry St. Pé)

The Mississippi River and northern Gulf of Mexico, is one of the best-documented and second worst hypoxic zones on the planet. Fish kills results however to date, there is still a highly productive fisheries industry. For the last few decades, the Gulf ecosystem has managed to maintain productive fisheries of crab and shrimp that depend on a healthy benthic environment (Diaz and Solow, 1999). Equally U.S. Department of Commerce Fisheries statistics support theses high catches in a very economically productive zone (Holiday and O'Bannon, 2000). How are productive fisheries being maintained? The exact mechanisms are not clear however, it is proposed that nutrients from river discharge enhance fishery production principally by enhancing recruitment of fish larvae. Recruitment is the natural process that makes the largest contribution to changes in fish stock production. Larvae concentrated in the vicinity of the plume (extent of nutrient enrichment into coastal waters from river runoff) take advantage of abundant food resources and consume a superior diet, grow faster and thus experience shorter larval stage duration and survive better (Grimes and Finucane, 1991). While the area is hypoxic, it is also eutrophic and may be able to transfer some energy to higher pelagic fisheries in spite of the dead zone. While feeding and growth of some species of fish larvae are enhanced, in other species they are not, and larval survival may be lower in the vicinity of river discharge (Allman and Grimes, 1998; DeVries et al., 1990). This is perhaps because the advantage of higher growth from concentrated prey is outweighed by increased predation from concentrated predators (Grimes and Kingsford, 1996). While different fish species are variably affected, studies of the shrimp fishery show a decline in catch and catch efficiency since hypoxia expanded (Zimmerman et al., 1997; Downing et al., 1999). The edge effect may also be contributing to sustained fisheries. When fish cluster to the edge of hypoxic zones it makes fishing easier and reduces catch effort. Alternatively, any lack of hypoxic effects on fisheries does not mean they are absent. Never-the-less, whether some species remain productive while others do not, according to Caddy's model, any enhanced fisheries productivity in the Gulf of Mexico will inevitably shift to a less productive stage (Caddy, 1993).

If hypoxia in the Gulf of Mexico gradually increased in size and duration from its beginning, presumably beginning in the 1950s (Sen Gupta et al., 1996), then it is supposed that the ecosystem's response may also have been gradual adjusting to hypoxia and other stressors over time, and for at least the last few decades has maintained fishery production and avoided a disastrous crash (Chesney et al., 2001). Oppositely in the circumstances that hypoxia appeared suddenly this may result in 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 non-commercial species (Azarovitz et al., 1979; Boesch and Rabalais, 1991). Minor mass mortality events have been reported in the northern Gulf of Mexico (McEachron et al., 1994), however, generally fisheries are productive (Diaz and Solow, 1999). The lack of any reported hypoxia-related mass mortality of fishery species tends to support the idea of the ecosystem gradually adapting to hypoxia over time.

The degree of ecological and economic impacts related to hypoxia obviously varies from system to system. However, the most severe 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 (Zaitsev, 1991, 1993; Elmgren, 1984). In the case of the Black and Azov Sea, eutrophication has resulted in coastal countries losing valuable fisheries resources, which have suffered an almost total collapse, and of an enormous potential for recreation and tourism (Mee, 1992). A comparison of effects from four similar coastal hypoxic zones (Diaz, 2001) indicates that, to date, only the Gulf of Mexico has not suffered documented declines in fishery production due to hypoxia-related mortality (Table 4.4.2.). However, as discussed, this may be about to change. The severe impacts reported in the Baltic are supported by an affected area five times greater than the other areas, elimination of benthic life and no benthic recovery (Table 4.4.2.).

In the Kattegat Sea, off the Swedish west coast, there has been increased frequency of algal blooms since the mid-1970's and seasonal hypoxia has been observed since the early 1980's. When initially documented, hypoxia caused mass mortality of marine life including commercial fish species. Now, large-scale migration and mortality among demersal fish and lobster have continued, 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). Hypoxic waters are a cause of mortality not only to benthic organisms and pelagic fisheries, but also to several aquaculture species. Hypoxic water can upwell in coastal areas and totally destroy fishery resources such as bivalves (Suzuki, 2001).

Table 4.4.2. 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 (Source: Diaz, 2001)

System	**Area affected km²**	**Benthic response**	**Benthic recovery**	**Response fisheries**
Louisiana Shelf	15000	mortality	annual	Stressed but still highly productive. Mortality reported in shallow water related to "jubilees".
Kattegat, Sweden–Denmark	2000	mass mort.	slow	Collapse of Norway lobster, reduction of demersal fish. Hypoxia prevents recruitment of lobsters.
Black Sea Northwest Shelf	20000	mass mort.	annual	Loss of demersal fisheries, shift to planktonic species.
Baltic Sea	100000	eliminated	none	Loss of demersal fisheries, shift to planktonic species. Hypoxia is bottle-neck for cod recruitment.

The impacts of eutrophication and hypoxia on fisheries are as many as the species and water bodies that are affected however, they may follow a predictable path. Hypoxia results primarily from eutrophication and while eutrophication increases primary production, it may or may not increase the productivity of a particular higher species. There is no evidence that hypoxia increases fisheries or any productivity, in fact quite that contrary. So while in some cases fisheries may be maintained or even enhanced and others see a total collapse depends highly on the specific attributes of that system.

Eutrophication and hypoxia is just one of many factors that has been implicated in declining global fish stocks including the likes of, harmful algal blooms, bycatch, benthic disturbance by trawlers, fishing pressure and habitat loss. Stressors such as bottom trawling may act synergistically as eutrophic processes make demersal ecosystems particularly sensitive to disturbance of bottom habitats (Caddy, 2000). Massive fisheries losses have already been attributed to other effects of eutrophication such as toxic algal blooms. This has great impacts on human health, where it is estimated that 300 human fatalities each year are caused by the consumption of shellfish contaminated with toxic algae (Hallegraeff, 1993).

4.5. Summary

The impacts of hypoxia and eutrophication are complicated by the varying intensities and interlinks with varying causes. Ecosystem responses include interlinked changes in water transparency, distribution of vascular plants and biomass of macroalgae, sediment biogeochemistry and nutrient cycling, nutrient ratios and their regulation of phytoplankton community composition, frequency of harmful algal blooms, habitat quality, reproduction, growth, and survival of pelagic and organisms.

The principle socio-economic impact of hypoxia is on fisheries. It has been suggested that all fisheries of affected systems are inevitably heading for collapse without mitigative measures. However eutrophication impacts could be much greater with the proliferation of harmful algal blooms, water toxicity and general degradation of water quality. Results include; in increasing operating expenses of public water supplies including taste and odour problems, loss of recreational use of water due to slime, weed infestation and noxious odour from decaying algae, impediments to navigation due to dense weed growth and general recreational and aesthetic values for tourism may be compromised. In addition, nonusers may be discouraged by perceived pollution. Commercial fisheries can also have taste and odour problems (Paerl and Millie, 1996). These are serious threats, which may compromise their economic importance. This importance of coastal waters should not be underestimated as they provide extremely valuable ecosystem services.

With all of the interlinked ecosystem functions and increasing anthropogenic stressors on ecosystems and fisheries, the ecosystem approach to sustainable management is becoming more and more important. Arising from the Earth Summit in Rio in 1992, a fully comprehensive ecosystem-based approach would require taking into account all possible interactions of the target fish stock with predation, competition and prey species; the effects of climate variation; the effects of fishing on species and habitat; the interactions between fish and habitat; anthropogenic nutrient and others. However science is unlikely to achieve perfect understanding and a precautionary management approach is needed.

5. Recommendations

The role of nutrient reductions and other preventative measures as solutions to reducing eutrophication and hypoxia will be discussed. An evaluation of legislation and management strategies at the national, regional and global levels will be considered as well as a discussion of the current state of the science and a direction for the future.

5.1. Reducing nutrient inputs

Restoring ecosystem balance and reversing the trend of increasing hypoxia will require dealing with the global problem of coastal eutrophication and determining how to reduce the production of organic matter in sensitive coastal areas. Most but not all of the coastal areas experiencing eutrophication and dead zones are in industrialised countries where there is a positive correlation between increased population, urbanisation in river watersheds and coastal areas and increased agricultural activity that deliver large quantities of nutrients to the coastal seas (Howarth et al., 1996). Management actions to reduce nutrient loading in response to legislative mandates or enforcement of regulatory standards such as US Federal Clean Water Act, EU Urban Waste Water Treatment Directive, Danish National Parliament decision to reduce nitrogen loading to Danish coasts by 50 percent, have shown successful. Ecosystem recoveries from Tampa Bay, USA a formerly highly eutrophic system have been dramatic where a 10-fold reduction in nitrogen loading from municipal effluent resulted in a reduction in algal blooms and recolonisation of seagrasses (Johansson and Lewis, 1992). Severe problems of hypoxia have been eliminated with advanced waste treatment in the Forth Estuary, Scotland and Thames Estuary followed by recovery in the diversity of fishes previously decimated by anoxia (Griffiths, 1987; Attrill, 1998). An important lesson is that responses to anthropogenic nutrient enrichment can be reversed with mitigative actions to reduce nutrient loading. However these improvements to small, localised areas represent point source discharges. To date there is no large system characterised by non-point source discharges that has recovered after development of persistent hypoxia (Diaz and Rosenberg, 1995). It is not known at what point permanent damage will be done but everything possible must be done to keep hypoxic areas from expanding in area and severity.

Where point sources of nutrients are more easily identified, monitored and managed, non point sources are plagued by the 'out of sight out of mind' dilemma. Agricultural activity is most often the principle cause of eutrophication and hypoxia. In recent years this relationship is becoming better documented and there has been an increasing focus on trying to reduce nitrogen levels in agricultural runoff. Considerate nitrogen fertiliser management is essential to reducing nitrate loss where the time and rate of application play a dominant role in the loss of nitrate to surface waters. Consideration of alternative cropping systems that contain perennial and legume crops and rotations would also likely reduce nitrate losses. It has been shown that row crops (continuos corn and corn soybean rotation) have substantially higher nitrogen concentrations when compared to a perennial crop that have a longer period of greater nutrient and water uptake by roots and nitrogen cycling is optimised (Randall and Mulla, 2001). Improving the efficiency of fertiliser use is the challenge for the future and science and technology is well enough advanced to provide no shortage of options. Techniques include matching the supply of fertiliser to the demands of specific crops, ensuring the appropriate timing of nutrient applications, using efficient irrigation practices, converting to nitrogen-fixing plants as cover crops during crop rotation, and employing advanced fertilisation techniques such as controlled-release fertilisers and nitrification inhibitors, which slow the conversion of ammonium to nitrate nitrogen. Proper management of livestock waste and use as manure can also lower nitrate losses. Another promising area for research is soil biology. Increased runoff drains the soil of nutrients, which must be replaced by fertilisers if the land is to remain productive. However, this is a cyclical degradation process. Often, particularly in tropical areas, erosion causes the increasing use of fertiliser application and the loss of soil productivity results. Preventing soil erosion and degradation will lessen the need for fertilisers and their environmental impacts. Apart from less nutrient runoff and improved water quality additional environmental benefits include reduced emissions of nitrous oxide and reduced emissions of carbon dioxide associated with fertiliser manufacturing. More needs to done on a global scale to educate about the impacts of fertilisation not just on the environment but on agriculture itself.

Initially fertiliser reduction would be difficult because the economic losses from reduced yields will be severe. However, economic incentives of improving nitrogen fertiliser efficiency exist. These include reduced fertiliser costs for farmers and a potential for increased yield and profitability in some crops. This may convince them of the need to buy non-nitrogen fertiliser and adopt much more balanced fertiliser applications. However farmers generally are most motivated to use fertilisers efficiently when crop prices are low and/or fertiliser prices are high. Either way, there are economic and environmental costs and benefits related to fertiliser application.

Fertiliser regulation at the regional or international level does not exist it merely comes in the form as recommendations or suggestions. However some efforts are being made nationally. In the USA fish kills in Chesapeake Bay in 1998 resulted in the first mandatory fertiliser management plans in the state of Maryland. Now EPA has adapted these plans nationally with some incentives. The agricultural community is taking steps to deal with this problem now, even though it is attributed to many different sources, by: applying best management practices, implementing soil erosion controls, planting winter cover crops, using precision agriculture, creating new animal food formulas. For almost two decades nitrogen pollution from Danish agriculture has been considered a problem and as a consequence a number of mitigating policy initiatives have been implemented. A common feature of these regulations has been the a heavy emphasis on rule-based quantitative instruments putting restrictions on animal density, land location, minimum storage capacity and standards for nitrogen applications, although an excess tax on nitrogen use was introduced in recent regulations.

Agriculture has a major role to play but should not be unfairly targeted as the only source of nutrient runoff. While agricultural sources have been easier to identify as a direct source, the reduction of atmospheric nitrogen emissions (at least in industrialised countries) remain the greatest challenge to fighting coastal eutrophication and hypoxia. GESAMP (2001b) recommends that atmospheric nitrogen must be included among the nutrient sources assessed as part of the management of coastal water quality. However, it notes political factors are also of major significance, as the primary causes of atmospheric anthropogenic nitrogen result from energy generation and transportation, and thus from society's core economic and social activities. In this way coastal water quality is tightly coupled to, perhaps the greatest global environmental effort and concern of the 20th century: the reduction of atmospheric emissions to minimise human-induced global climate change.

5.2. Tradeable emissions permits

Emissions trading is a proposed economic solution to air pollution from the traditional command-and-control approach in reducing pollution. Command-and-control pollution regulation generally requires that different emission sources meet the same pollution standards, whatever the cost. Yet controlling pollution from one source may be far more costly than controlling it from another. By trading the right to emit a specific amount of pollution, industries can take the least costly route whether it is abatement or purchase of the permits. If corporations upgrade to cleaner equipment this generally results in lowered operating costs, but the cost/benefit ratio of many new technologies has not yet made such upgrades worthwhile. However the addition of taxes related to emissions could make the cost/benefit ratio change enough that many companies would elect to install such equipment, rather than pay ongoing taxes.

In emission trading schemes, government agencies set limits or caps on particular pollutants by auctioning a fixed number of permits. Corporations that intend to exceed the limits may buy emissions credits on the open market from entities that are not likely to exceed the limits. This results in a free market. The U.S.A. began emissions trading after passage of the 1990 Clean Air Act, which authorised the EPA to limit sulphur dioxide emissions from the operations of fossil-fuelled plants. Internationally, the Kyoto Protocol will bind ratifying nations to a similar system, with the United Nations Framework Convention on Climate Change (UNFCCC) setting caps that differ between nations. Under the proposed treaty, nations that emit less than their quota of greenhouse gases will be able to sell emissions credits to polluting nations.

The premise behind emissions trading is purely economic because it allows corporations to conserve resources. In fact, emission trading does little to solve pollution problems as groups that do not pollute are granted emissions credits, which they then sell. Some environmental NGO's are attempting to solve this problem by buying credits and refusing to use or sell them in hopes that reduced supply of permits will raise the price until it is more economical to take abatement measures. Likewise emissions caps could be set lower and fewer permits auctioned.

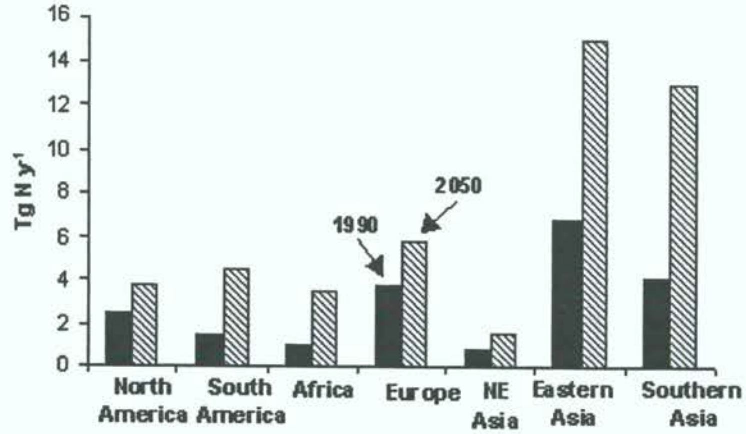
5.3. Short term expectations

Conclusions from a Gulf of Mexico study (Goolsby et al., 2001) may provide some foresight. In the future, the flow of nitrate to coastal waters will likely be dictated by variations in precipitation and runoff. Because the soil and ground water system and the extensive drainage network contain a large pool of nitrate, fluxes will be high in wet years and low in dry years. However, the nitrogen levels in the soil and ground water system will adjust slowly to changes in nitrogen inputs and outputs. As a result the flux of nitrate will likely change slowly in response to changes in nitrogen inputs. While the response time of the basin to changes in inputs and out puts is unknown, it could take several years or longer for the effects of significant reduction in nitrogen inputs to produce a noticeable reduction in nitrogen flux to the coastal water. In the short term any major changes in nitrogen inputs will be a result of changes in precipitation and runoff not changes from the sources. This has implications for expected results from efforts to reduce nitrogen loading.

5.4. Demographics

World population will grow by 50 percent, from 6.1 billion in mid-2001 to 9.3 billion by 2050. All of the projected growth will take place in today's developing countries, which by 2050 will account for over 85 percent of world population. World population is now growing by 1.3 percent, or 77 million people per year. Six countries account for half of this growth: India (with 21 per cent of the total increase), China, Pakistan, Nigeria, Bangladesh and Indonesia. While total population in developed countries will remain at around 1.2 billion and population declines are expected in Europe (UN, 2001).

Figure 5.4. Predicted increases in N export to coastal systems by the year 2050. Model predictions from (Source: Kroeze and Seitzinger, 1998).



Population is key to the eutrophication problem. Nitrate discharge from 42 rivers around the world with various watershed differences showed human population density accounted for 53 percent the variation in nitrate exported to coastal waters. While area and flow showed no significant relationship to either nitrate concentrations or nitrate export (Peirels et al., 1991).

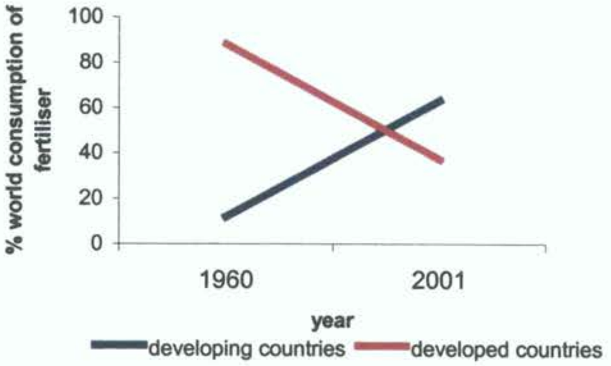
Future nutrient export to the coastal zone is likely to be spatially diverse. Relative and absolute increases are predicted in all regions however large increase will be concentrated in developing regions such as Africa, South America, and Eastern and Southern Asia (Figure 5.4.).

5.5. Challenges for developing nations

The potential for increased eutrophication and hypoxic events is enormous, particularly in developing nations. In fact FAO (2000) projects world crop production to increase 57 percent by 2030 with developing countries accounting for 72 percent of world crop production in 2030 compared with 53 percent in 1961/63. Like production, fertiliser use in developed countries is falling and it is rising in developing nations

(Figure 5.5.). In 2001 North America, Western Europe and China and South Asia used 16, 12 and 43 percent of world fertiliser respectively, while most of the future increase will be in South and East Asia and in North and South America. While past and present eutrophication and hypoxic events have been largely isolated to Europe and North America, if fertiliser use is any indication, China and South Asia will be areas of concern in the future. Demographic and social trends suggest that past practices leading to coastal nutrient enrichment are likely to be repeated in the coming decades in the developing countries of Asia, Africa, and Latin America (Nixon, 1995.)

Figure 5.5. World consumption of fertiliser. (Source: IFA: www.fertilizer.org)



Nixon (1995) presents an important point relating to sewage discharges and eutrophication. 'Once human metabolic wastes are emitted, they must be transmitted directly or indirectly to coastal water if they are to me of a concern as a potential cause of marine eutrophication. The effectiveness of that transmission is governed to a large degree by the technology used for human waste disposal. In the absence of a supply of running water, human wasters are disposed of in individual privies or on the surface of the groundwater. Such dry, diffuse disposal does not favour the efficient transport of phosphorus and nitrogen to stream, rivers and coastal marine wasters. However, once running water become available, either from an urban supply system or from electric pumps and individual or community wells, flush toilets are soon installed and a system of sewage disposal is required. The water carriage system of waste disposal provides for a highly efficient transmission of nutrient from many points of emission to one or a few points of direct discharge into streams, rivers, or coastal waters.'

Major efforts are being made globally to improve access to safe drinking water and sanitation. In a quote from UNEP's World Water Day (March 22, 2003) UN secretary general, Kofi Annan sates "no single measure would do more to reduce disease and save lives in the developing world than bringing safe water and adequate sanitation to all.[3]" While this need for water is essential for a better quality of life in developing nations, together with urbanisation, it will result in the expansion of water and sewage systems. The eutrophic conditions in the Baltic Sea developed during the same period in which 75 percent of the municipal sewers in Sweden were constructed (Hagerstrand and Lohm, 1990). A similar situation resulted in northeastern U.S. where eutrophication coincided with the installation of water and sewer systems (Tarr and Ayres, 1990). These examples of historical eutrophication in Europe and the U.S. are now exhibiting hypoxia. Indicating that hypoxia may develop over time in areas of

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[3] http://www.waterday2003.org/un-system-prog.htm consulted on August 17, 2003

prolonged eutrophication. If this is the case, as water access and sewage systems develops in Africa, Asia and Latin America their coastal water will see similar eutrophication as U.S.A. and European waters and a great potential for hypoxia in the coming decades. Opportunities exist for the application of the precautionary principle in developing nations.

5.6. Preventative measures

5.6.1 Protection or creation of artificial wetlands

Coastal wetlands have invaluable ecological functions. These include: water storage; storm protection and flood mitigation; shoreline stabilisation and erosion control; groundwater recharge; groundwater discharge; retention of nutrients, sediments and pollutants; and stabilisation of local climatic conditions, particularly rainfall and temperature. They also provide valuable habitat for birds and marine invertebrates.
These functions are the result of the interactions between the biological, chemical and physical components of a wetland, such as soils, water, plants and animals. Most important to eutrophication, coastal wetlands are a nutrient sink and an important site of dentrification (the process by which bacteria reduce nitrates (NO_3) to molecular N_2, which is then volatilised into the atmosphere). They also moderate the impacts of rainfall and temperature. Their protection and restoration are a critical element to fighting eutrophication in coastal waters. Another option is creating artificial wetlands or dentriying ponds where drainage water could be routed and treated to remove excess nitrogen before discharge to waterways. If well designed and managed properly, they can remove substantial nitrogen from runoff. However it is at best, a partial solution that can be incorporated into the overall nitrogen control strategy, complementing natural wetland protection and restoration efforts.

The Baltic region has many differences in land use and nutrient sources. Wetlands have been drained or totally eliminated due to intensive agriculture in some regions changing the retention capacity in the catchments. As well as to decrease nutrients inputs, preventative measures being examined are the possible use of wetlands as building blocks as a contribution to the management of Baltic Sea eutrophication (Paludan et al., 2002). The wetlands generally have a positive effect and large potential to reduce non-point nutrient pollution to aquatic and marine environments. Conservation and restoration initiatives for wetlands is an integral part of the BERNET project (Baltic Eutrophication Regional Network).

Large areas of wetlands are required to have measurable benefits. Thus the protection and creation of wetlands creates a development conflict as in many other environmental protection issues. However the designations of protected areas can provide public access to the coast and bird life while having an educational value in the role of land based habitat in coastal water quality. The UK is well established in coastal wetland protection, although principally for bird habitat, it is also likely reducing nutrient loading to coastal waters.

5.6.2. Sewage treatment and outfall relocation

If sewage is not treated, some level of treatment would be a first solution to reducing nutrient loading. In developed countries sewage is not greatly contributing to nutrient input. This is largely due to the sewage systems and treatment levels. In the most sophisticated systems there is a separate sewage system for urban runoff, domestic wastes, and industrial wastes each with their own treatment process. Sewage treatment consists of several stages: primary, secondary and tertiary. Primary treatment filters most of the solids from the sewage through several methods and separates wastewater from sludge. Secondary treatment removes the bacteria, nutrients and organic compounds and renders the outfall biologically safe. Secondary treatment also handles wastewater and sludge separately. Tertiary treatment removes salts and chemicals from sewage including nitrates and phosphates. Sewage treatment is costly and is not normally pursued unless mandatory by regulation. In developed countries secondary treatment is most common. Tertiary treatment can be used for highly sensitive receiving waters. Developing countries often have no treatment.

Relocation of outfalls is an alternative that involves redirecting sewage outfalls away from highly sensitive or priority areas. This alternative can improve dissolved oxygen in key locations. However, new locations must be carefully assessed, as adverse water quality and coastline impacts at new discharge locations should be anticipated. It must also be determined if relocation of outfalls is cost-effective. Removing a nutrient source may also disturb a habitat that has become accustomed to it and introduce a nutrient source to a habitat that is not accustomed to it. This may create more adverse effects than leaving the outfall in its original location.

5.6.3. Seaweed farms

Benthic macroalgae (seaweed) are nutrient absorbing, photosynthetic plants. Seaweed farms can thus help alleviate hypoxia by intercepting nitrogen from the water column. In addition, seaweed's help lessen oxygen deficiency by creating dissolved oxygen through the photosynthetic process. In addition to nutrient management, there is an existing and growing market for seaweed and its products that can be exploited. Seaweed farms in Japan have proven to be successful. Japanese nori (*Porphyra yezoensis*) has a huge market in Asia where it has been cultivated since the 1960's. The north-eastern U.S.A are now breeding nori to tap into this market as well as to fight coastal eutrophication. This dual purpose with an economic incentive can present an attractive management option. In seaweed aquaculture however, consideration needs to be taken in identification of seaweed species that would be feasible. Water and other conditions should permit species should to be successful and also limit ecosystem impacts. Also the floating structures required may be an inconvenience. Seaweed farms in conjunction with coastal fish farm can be a pollution-control method that can pay for itself if the use of pesticides and other chemicals is limited (Goldburg et al., 2001).

All of these alternatives have limited effectiveness as a single solution to the hypoxia problem. It is only when combined with nutrient reductions and incorporated into overall nitrogen management plans that improvements will be made. All options and solutions to hypoxia require a cost benefit evaluation.

5.6.4. Other alternatives

One extreme alternative is installing tide gates that can prevent tidal currents from entering hypoxic areas. Tide gates may increase the overall circulation in the coastal area and block nutrients and other pollutants from entering the hypoxic area. Also coliform bacteria concentrations may be reduced and the gates may act to flush the affected area with cleaner oxygenated water. This option has serious disadvantages. The gates may; affects tidal heights and currents; may cause potential changes in flora, fauna and fish migration patterns; may alter salinity and temperature patterns; increases pollutant loading to other areas; and restrict navigation. Ecosystem consequences may be unintended, unpredictable and possibly irreversible. In addition construction costs would be very high. This option was considered in Long Island, New York[4].

Another, perhaps impractical option for shallow bays is altering the basin morphology by dredging to increase water circulation and reoxygenation. The ecosystem changes of dredging are threatening. Deeper water increases tidal velocities and reduces flow across intertidal mudflats while increasing sediment accumulation. Dredging changes the tidal profile and causes increased erosion of some areas while increasing deposition in other areas. Dredged areas may also cause changes in salinity and associated ecological effects, and disrupt benthic communities. Dredging can be done in portions to evaluate the impacts however, altering the coastal or estuarine system make it unstable and it will try to re-stabilise it self by increasing sedimentation. It is thus often the case that dredging leads to an increased need to dredge. Another major problem is what to do with the removed material. In some cases, around industrial ports, the contamination of the dredged material is so high that it must treated as contaminated waste. It can be dumped at sea or if it is a suitable quality, used in coastal defence or for the creation of coastal habitats such as beaches or mudflats. While dredging is technologically simple it is also expensive.

One more severe solution is using mechanical aerators to introduce oxygen to hypoxic waters. Aerators would also disrupt vertical density stratification in the water column, allowing mixing of oxygen-rich surface waters with oxygen-depleted bottom waters. Although it could be effective in small areas, aeration is impractical for large areas, however could be considered after reduced nitrogen inputs have reduced the area of hypoxic waters. The negative effects of aeration would likely out weigh the benefits. Resuspension of sediments and contaminants, disruption of marine organisms, intensive long-term use of mechanical equipment and high costs make aeration impractical in most circumstances.

5.7. Research including satellite technology

Because of the link between hypoxia and primary production, complementing technologies have a role in linking specific nitrogen inputs to coastal biogeochemical and trophic changes. When phytoplankton bloom in large quantities they can change the colour of the ocean to such a degree that it can be measured from space using remote sensing satellite photography. The more phytoplankton in the water, the

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[4] http://www.epa.gov/ consulted September 12, 2003

greener it is and the less phytoplankton, the bluer it is. National Aeronautics and Space Administration (NASA) is using its Sea-viewing Wide Field-of-view Sensor (SeaWiFS) to make satellite images of coastal and estuarine surface waters of identified and potential hotspots. The satellite photographs seen throughout the text are from this source. While these images are superficial they do show the level of organic matter on the surface which can give an indication of the oxygen demand and the possible presence of hypoxic waters. The images can also observe areas where water flow is restricted, such as the Baltic and Black Sea, which may also suggest oxygen depleted waters. Researchers are using SeaWiFS data to observe the productivity cycles in the surface water, which can be correlated with the scientific record preserved in the organic-rich, anoxic bottom sediments. Snapshots are not of much use as it is the change in distribution and abundance of phytoplankton in time and space that matters. Thus time series photographs are used.

Geographic information systems (GIS) are also a powerful tool in land use characterisation that can be used to characterise and identify nutrient sources. The computer model uses spatially related data sets to provide information used to develop a better understanding of environmental relationships for making resource management decisions.

Another advantage to hypoxia research is that study is facilitated because oxygen deprivation in anoxic basins prevents bacteria from breaking down organic matter and it is preserved. Thus, these zones naturally trap and preserve sediments, recording the annual production of organic matter from overlying waters.

5.8. Common management at the regional level

While some causes and impacts may be local in scale, pollutants know no boundaries and regional approaches are needed. UNEP's Regional Seas Programme has been active in marine protection through common management regimes. The first Action Plan was adopted in the Mediterranean in 1975, and the most recent for the North-East Pacific in 2002. The Regional Seas have expanded and now cover the marine environment of more than 140 of the world's coastal countries and the programme is widely considered a success (Hass, 1991).

Many seas globally are now covered by conventions and commissions toward integrated management; The Barcelona Convention in the protection of the Mediterranean, The Kuwait Convention for the Kuwait region, The Abidjan Convention for West and Central Africa, The Lima Convention for the South-East Pacific, The Jeddah Convention for the Red Sea and Gulf of Aden, The Cartagena Convention for Wider Caribbean, The Nairobi Convention for Eastern Africa, The Noumea Convention for South Pacific, The Bucharest Convention for the Black Sea, The Helsinki Convention for the Baltic, OSPAR (Oslo and Paris) for the North East Atlantic and the North East Pacific Convention (Guatemala Convention) and all of the associated protocols. However, no conventions have yet been developed for East Asian Seas, South Asian Seas, Upper South-West Atlantic, North West Pacific, North-East Pacific, or the Arctic.

Among these areas and associated management strategies the Helsinki Convention and Helsinki Commission (HELCOM), the governing body of the convention can provide lessons in approach toward a eutrophic and hypoxic water body such as the Baltic. The Helsinki Convention was established in 1974 and revised in 1992 to cover the whole of the Baltic Sea area, including inland waters as well as the water of the sea itself and the seabed. As well as the overall protection from pollution, specific efforts to control eutrophication in the Baltic include the Marine Research on Eutrophication (MARE) programme, which aims to help decision-makers develop cost-effective measures to alleviate eutrophication in the Baltic Sea. Also the Baltic Eutrophication Regional Network (BERNET) which involves cooperation between 7 regions with coastal eutrophication problems around the Baltic Sea. Conservation and restoration initiatives for wetlands are an essential part of the work in the project[5]. The Black Sea has also been heavily impacted by hypoxia, with extensive loss of keystone species, mass mortality of fish and benthos, damage to habitats, pronounced changes to the composition of the phytoplankton, and major reductions in fish stocks (Mee, 1992). However conversely the Bucharest Convention for the Black Sea is newly developed convention which was adopted 1992, and went into force in 1994. A major international recovery programme has been initiated by the Black Sea Commission to address these problems, entitled the Black Sea Ecosystem Recovery Project (BSERP)[6] but it is still immature in managing a heavily eutrophied water body and be able to draw experience from HELCOM.

Areas of special concern in Europe such as the Baltic Sea includes Denmark, Estonia, the European Community, Finland, Germany, Latvia, Lithuania, Poland, Russia and Sweden with in its catchment area. The Black Sea includes Bulgaria, Georgia, Romania, Russian Federation, Turkey and Ukraine on its coasts. These regions have a high density of countries and with different political and management methods that bring a need for intergovernmental cooperation between states toward the protection of these seas. Regional Seas conventions and commissions serve this role. In contrast the northern Gulf of Mexico is one of the world's worst eutrophic and hypoxic areas. The problem area falls within the territorial sea of just one country; the USA. While also part of the wider Caribbean under the Cartagena Convention, management of the northern Gulf of Mexico is largely conducted by U.S.A national organisations and institutes most principally, the U.S. Environmental Protection Agency (EPA) and the National Oceanic and Atmospheric Administration (NOAA). Efforts were even written into US congressional law. While seas that are shared by more than one country may fall to the tragedy of the commons and require a cooperative, intergovernmental management approach, the U.S.A. likely has a greater vested interest in protecting its coastal environments. This may explain counter initiatives but may or may not explain actual improvements.

5.9. Regional and international actions

It has been estimated that about 80 percent of all marine pollution originates from land-based activities through direct input, via rivers, or through atmospheric depositions. As such, there is an urgent action for controlling land-based activities. At the technical, management and policy levels, the most vital actions for controlling

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[5] For more information see: http://www.helcom.fi/ consulted September 11, 2003

[6] For more information see: http://www.blacksea-environment.org/ consulted September 11, 2003

land-based activities, in order to improve the quality of the marine environment are, according to GESAMP (2001b):

(a) Preventing habitat destruction and the loss of biodiversity through education, combined with the development and enforcement of legal, institutional and economic measures appropriate to local circumstances
(b) Establishing protected areas for habitats and sites of exceptional scenic beauty or cultural value
(c) Devoting primary management attention to the control of pollution from sewage, nutrients (especially nitrogen) and sediment mobilisation
(d) Designing national policies that take account of the economic value of environmental goods and services, and provide for the internalisation of environmental costs
(e) Integrating the management of coastal areas and associated watersheds.

Another global effort is UNEP's Global Programme of Action for the Protection of the Marine Environment from Land Based Activities (GPA). Although completely non-binding, nutrient reductions are one of GPA's focus areas[7]. GPA recommends that states within a *region* should cooperate in the following actions to reduce eutrophication:

(a) Establishment of common criteria for the identification of existing and potential problem areas including possible solutions with regard to eutrophication;

(b) Identification of marine areas in the region where nutrient inputs are causing or are likely to cause pollution, directly or indirectly;

(c) Identification of areas for priority actions;

(d) Establishment of uniform approaches to the calculation of anthropogenic nutrient inputs to the aquatic environment from agriculture and other sources, as appropriate, with the aim of improving the estimation of these inputs;

(e) Development and implementation of programmes and measures for reducing nutrient inputs from anthropogenic activities to areas where these inputs are causing or are likely to cause pollution directly or indirectly and, where the agricultural sector is a predominant source, to pay particular attention to that sector and the implementation of measures identified for it;

(f) Establishment of mechanisms for assessing the effectiveness of the measures taken to reduce nutrient inputs to the aquatic environment from both point and diffuse sources;

(g) Development of strategies for reducing eutrophication in areas already affected and those susceptible to being affected.

GPA recommends that *international* responses should include the following actions to reduce eutrophication:

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[7] For more information see: http://www.gpa.unep.org/ consulted September 9, 2003

(a) Participation in a clearing-house for providing information about best environmental practice and access to best available techniques to reduce and/or eliminate causes of anthropogenic eutrophication;

(b) Strengthening of international programmes for enhancing capacity for: Identification of areas where inputs of nutrients are causing or are likely to cause pollution, directly or indirectly; nutrient control and removal techniques; application of best environmental practice in aquaculture and agriculture;

(c) Cooperation with countries in need of assistance, through financial, technological and scientific support, in developing and implementing practices which minimise releases of nutrients to the environment, including environmentally sound land-use techniques, planning and practices;

(d) Provision of forums for establishing criteria for determining the circumstances in which nutrients are likely to cause pollution, directly or indirectly and;

(e) Maintaining existing international quality assurance and quality control procedures relevant to eutrophication

5.10. Gaps in knowledge and a model for the future

It remains undisputed that anthropogenic nutrient loading is worsening eutrophication and associated hypoxia, however the issue is not a simple cause and effect reaction from nutrient enrichment (see Annex 1 for a graphic of nutrients sources and impacts or eutrophication). The relationship of nutrients and eutrophication is well documented and well understood yet there are many other stressors that may be influencing this relationship in some way. The importance of water column mixing and the various causes of this are a major influence on eutrophication and hypoxia but there are many other factors that have yet to be fully explored. Multiple stressors cause impacts to marine environments that translate into coastal production and food web alterations so a broader view of coastal eutrophication will consider how anthropogenic nutrient enrichment interacts with other stressors such as translocation of species, habitat loss, fishing, inputs of toxic contaminants, manipulation of freshwater flows, aquaculture, and climate change. In addition, system-specific attributes such as mixing ability, horizontal transport, and light penetration require a deeper understanding (Cloern, 2001). We also need to determine to what extent nutrient impacts and it's various stressors and contributors are local, regional or global in scale.

Cloern (2001) highlights the limitations to our current understanding of the eutrophication problem.

- It is a young and developing scientific discipline.
- Focus on nutrient enrichment as a single stressor that does not include ecosystem wide stressors that can cause change.
- Most knowledge comes from site-specific assessments.

- Much information is from a few highly impacted regions of the developed world at temperate latitudes (e.g. Baltic Sea, North Sea, Black Sea, Chesapeake Bay and northern Gulf of Mexico).

Because of the many interlinkages and different stressors, the ecosystem approach is the only way forward for this science. The ecosystem approach will integrate management of land, water and living resources and promote conservation and sustainable use in an equitable way, while also recognising that humans, with their cultural diversity, are an integral component of coastal, and all ecosystems. To meet this objective, ecosystem level physical –chemical-biological modelling will prove valuable in parameterising and predicting eutrophication potential based on externally supplied and internally regenerated nutrient input and cycling dynamics. This is a critical element for effective management of nutrient and biomass assimilative capacity in the ecosystem and resultant water quality.

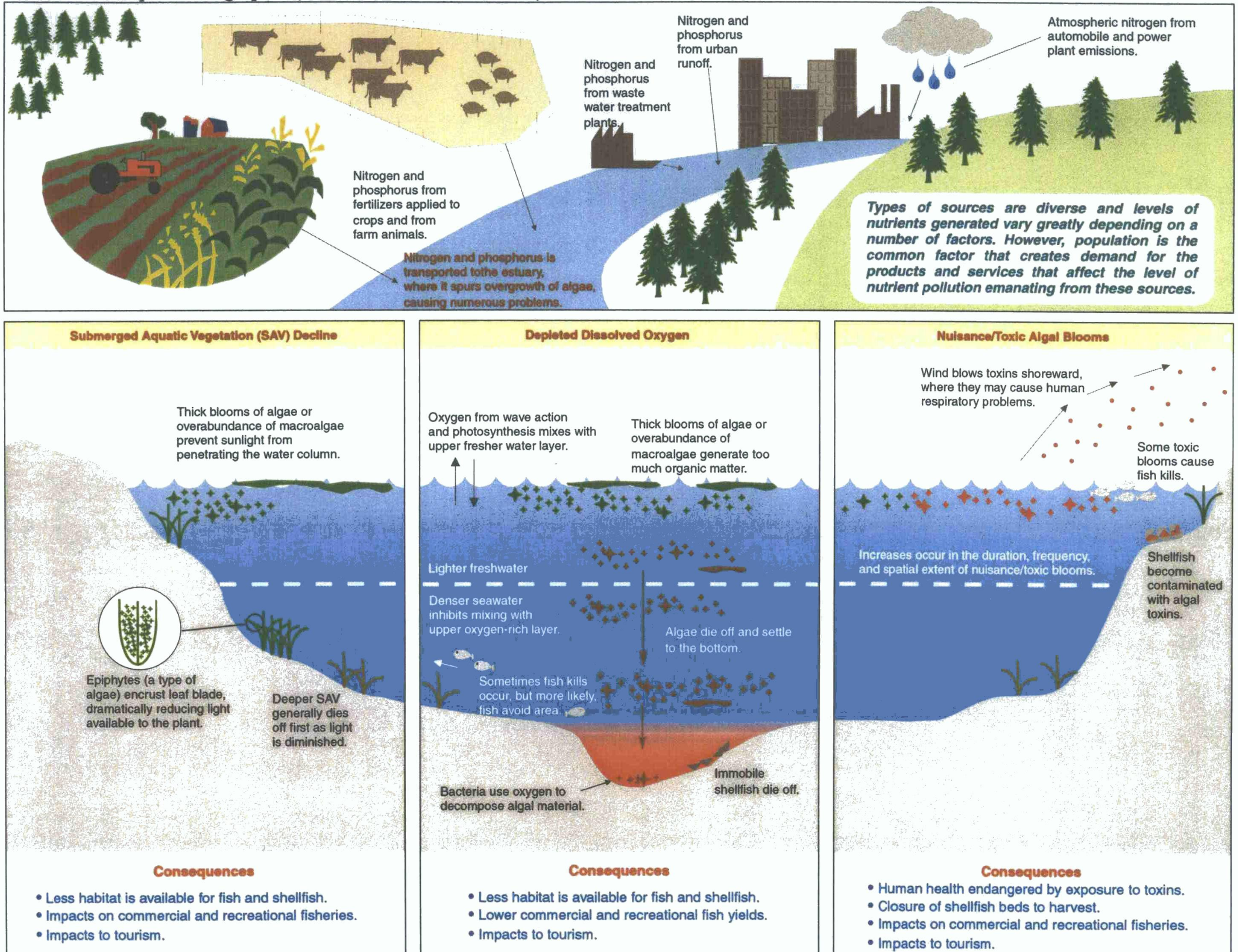
Given this, Cloern, (2001) conceptualises a new model towards this broader perspective of eutrophication that will be guided by 5 questions:
(1) *How do system specific attributes constrain or amplify the responses to coastal ecosystems to nutrient enrichment?* (This explores how the different components work together.)
(2) *How does nutrient enrichment interact with other stressors?* (mentioned above)
(3) *How are responses to multiple stressors linked?* (These (2 and 3) leave behind the notion of nutrient enrichment as an isolated stressor and replace it with a more challenging notion that coastal ecosystems are subjected to multiple interactive stressors and responses are intimately connected.)
(4) *How does human-induced change in the coastal zone impact the Earth system as habitat for humanity and other species?* (This will have a perspective that considers the social, economic and human-health costs of coastal eutrophication and the impacts of nutrient enrichment of the Earth system at the planetary scale.)
(5) *How can a deeper scientific understanding of the coastal eutrophication problem be applied to develop tools for building strategies at ecosystem restoration or rehabilitation?*

5.11. Conclusions

Like most human impacts on the environmental, coastal eutrophication and hypoxia are not without solutions. Due to the remarkable resilience of the earth system most anthropogenically encouraged deterioration is reversible. There are ample examples of recovered ecosystems. I would tend to agree with Cloern (2001) who states that 'this science has not yet evolved to the point where we have made a major investment in comparative analyses to synthesise the lessons form site-specific investigations into a comprehensive understanding of how nutrient enrichment promotes change in coastal waters at a global scale.' More sustained programmes of integrated research and monitoring are needed. However it does not and should not take advanced science or a perfectly complete model of every ecosystem to make positive mitigative actions to reduce coastal eutrophication and hypoxia. Principle nutrient sources and associated reductions, land uses and water dynamics are largely understood. National programmes, regional and international agreements are in place. There is adequate understanding of the problem to make improvements and more importantly, to prevent hypoxia from spreading to a global scale. Science will never be perfect; one could wait forever for flawless knowledge and standby while degradation continues. Uncertainty inherent in the scientific process demands a precautionary approach that is now being recognised internationally. Article 15 of the Rio Declaration on Environment and Development (1992) states that: "In order to protect the environment, the precautionary approach shall be widely applied by States according to their capabilities. Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation"

The economic pressures will unfortunately, always be present. Atmospheric emissions are the result of the key economic drivers of industrialised countries making regulations and reductions difficult. Agriculture and fisheries- both industries that feed the world are in direct conflict. While fertilisers are in the best interests of agriculture, healthy coastal waters are in the best interest of fisheries. As population pressures rise the conflicts will only worsen. However, coasts and estuaries provide more valuable ecosystem services per unit surface area than any other biome on the planet (Costanza et al., 1997). Thus their protection and sustainable use will be in the best interests of future economic stability. Economic forces and environmental forces seem to be coming closer together in recent years. People want a clean environment, but they also want economic growth. But there will always be economic and social costs and tradeoffs of water quality management, or any environmental management strategies. Real improvements will be made when consumers demand and will be willing to pay additional costs for products and services coming from environmentally sound practices. We can only hope that as hypoxia and its impacts worsen, the issue will receive greater scientific attention and political and financial support.

Annex 1. Eutrophication graphic (Source: Bricker et al., 1999)



References

Aber, J. D., K.N. Nadelhoffer, P. Steudler, J.M. Melillo, and R. Boone, 1989. Nitrogen saturation in northern forest ecosystems. BioScience 39: 378-386.

Allman, R. J. and C. B. Grimes, 1998. Growth and mortality of little tunny, *Euthynnus alletteratus*, from the Mississippi River discharge plume and Panama City, Florida. Bulletin of Marine Science 62(1): 189-197.

Aman, W.A.H., Harrison, R.M. and Ottley, C.J., 1994. Estimation of net air-sea flux of ammonia one the southern bight of the North Sea. Atmosph. Environ. 28: 3647-3652.

Attrill., M.J., (ed) 1998. A rehabilitated estuarine ecosystem. The environment and ecology of the Thames Estuary. Kluwer Academin Publishers, Dordrecht.

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.

Beveridge, M.C.M., 1996. Cage Aquaculture, 2nd ed. Edinburgh, Scotland: Fishing News Books: 346.

Beukema, J.J., 1992. Expected changes in the Wadden Sea benthos in a warmer world: lessons from periods with mild winters. Netherlands Journal of Sea Research 30: 37-79.

Bricker S. B., Clement C. G., Pirhalla D. E., Orlando S. P., Farrow D. R.G., 1999. National Estuarine Eutrophication Assessment. Effects of Nutrient Enrichment in the Nation's Estuaries, NOAA – NOS Special Projects Office, 1999. 71 pp.

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.

Bullister, J.L., Lee, B.S., 1995. Chlorofluorocarbon-11 Removal in Anoxic Marine Waters. Geophysical Research Letters, 22, 1893-1896.

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.

Caddy, J.F., 2000. Marine catchment basin effects versus impacts of fisheries on semi-enclosed seas. ICES Journal of Marine Science 57 (3): 628-640.

Chen N.H., Bianchi T.S., McKee B.A., Bland J.M., 2001. Historical trends of hypoxia on the Louisiana shelf: application of pigments as biomarkers. Organic Geochemistry 32 (4): 543-561.

Chesney, E. J., D. M. Baltz and R. G. Thomas, 2000. Louisiana estuarine and coastal fisheries and habitats: Perspectives from a fish's eye view. Ecological Applications, 10(2):350-366.

Chopin, T., C. Yarish, R.Wilkes, E. Belyea, S. Lu, and A.Mathieson, 1999. Developing Porphyra/salmon integrated aquaculture for bioremediation and diversification of the aquaculture industry. Journal of Applied Phycology 11:463–472.

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

Costanza, R. and 12 others, 1997. The value of the world's ecosystem services and natural capital. Nature 387: 253-260.

Dauer, D.M., Rodi, A.J., Ranasinghe, J.A., 1992. Effects of low dissolved- oxygen events on the macrobenthos of the lower Chesapeake Bay. Estuaries 15 (3): 384-391.

David, M.B., L.E. Gentry, D.A. Kovacic, and K.M. Smith. 1997. Nitrogen balance in and export from an agricultural watershed. Journal of Environmental Quality 26:1038–1048.

DeVries, D. A., C. B. Grimes, et al., 1990. Age and growth of king and Spanish mackerel larvae and juveniles from the Gulf of Mexico and U.S. south Atlantic. Environmental Biology of Fishes 29: 135-143.

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, Robert J., and Andrew Solow, 1999. Ecological and Economic Consequences of Hypoxia: Topic 2 Report for the Integrated Assessment on Hypoxia in the Gulf of Mexico. NOAA Coastal Ocean Program Decision Analysis Series No. 16. NOAA Coastal Ocean Program, Silver Spring, MD. 45 pp.

Diaz R.J., 2001. Overview of Hypoxia around the World. Article Symposium Paper. Journal of Environmental Quality 30:275-281.

Dortch, Q., and T.E., Whitledge, 1992. Does nitrogen or silicon limit phytoplankton production in the Mississippi River plume and nearby regions? Continental Shelf Research 12: 1293-1309.

Downing, J. A., James L. Baker, Robert J. Diaz, Tony Prato, Nancy N. Rabalais and Roger J. Zimmerman, 1999. Gulf of Mexico Hypoxia: Land-Sea Interactions, Council for Agricultural Science and Technology, Task Force Report, No. 134.

Duce, R et al., 1991. The atmospheric input of trace species to the world ocean. Global Biogeochemical Cycles 5: 193- 259.

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

EPA, 2000. Proposed Effluent Guidelines Plan Federal Register Notice (June 16, 2000) (http://www.epa.gov/fedrgstr/EPA-WATER/2000/June/Day-16/w15298.htm) consulted, August 11, 2003.

FAO, 2000. Fertilizer Requirements in 2015 and 2030. Rome, Food and Agriculture Organization

Fenchel, T., 1998. Bacterial Biogeochemistry: The Ecophysiology of Mineral Cycling. San Diego: Academic Press.

Frid, Chris, Cornelius Hammer, Robin Law, Harald Loeng, Janet F. Pawlak, Philip C. Reid, Mark Tasker, 2003. Environmental Status of the European Seas, International Council of the Exploration of the Sea (ICES).

GESAMP (IMO/FAO/UNESCO-IOC/WMO/WHO/IAEA/UN /UNEP Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection) and Advisory Committee on Protection of the Sea, 2001a, A Sea of Troubles. Rep. Stud. GESAMP No. 70.

GESAMP and Advisory Committee on Protection of the Sea, 2001b, Protecting the Oceans from Land-Based Activities - Land-Based Sources and Activities Affecting the Quality and Uses of the Marine, Coastal and Associated Freshwater Environment. Rep. Stud. GESAMP No. 71.

Gieskes, W.W., Kraay, G.W., 1986. Analysis of phytoplankton pigment by HPLC before, during and after mass occurrence of the microflagellate Corymbellus-Aureeus during the spring bloom in the open northern North Sea in 1983. Marine Biology 92 (1): 45-52.

Global Environment Facility (GEF) Unit/UNEP, Global International Water Assessment Project Document, UNEP, November 1998. The GEF Secretariat, Washington DC.

Goldburg, Rebecca J., Matthew S. Elliott, Rosamond L. Naylor, 2001. Marine Aquaculture in the United States: Environmental Impacts and Policy Options. The Pew Oceans Commission (http://www.pewoceans.org/reports/137PEWAquacultureF.pdf) consulted August 14, 2003.

Goolsby, D. A., W. A. Battaglin, G. B. Lawrence, R. S. Artz, B. T. Aulenbach and R.P. Hooper, 1999. Flux and Sources of Nutrients in the Mississippi-Atchafalaya River Basin: Topic 3 Report for the Integrated Assessment of Hypoxia in the Gulf of Mexico. NOAA Coastal Ocean Program Decision Analysis Series No. 17. NOAA Coastal Ocean Program, Silver Spring, MD, 130 pp.

Goolsby, Donald A., William A. Battaglina, Brent T. Aulenbachb and Richard P. Hooperc, 2001. Nitrogen Input to the Gulf of Mexico Article Symposium Paper
Journal of Environmental Quality 30:329-336.

Gray, J.S., 1992. Eutrophication in the sea In: Colombo, G., Ferrari, I., Ceccherelli, V.U., Rossi, R. (eds) Marine eutrophication and population dynamics. Proc 25th Eur Mar Biol Symp, Olsen & Olsen, Fredensborg, pp3-15.

Gregory F. Mcisaac, Mark B. David, Georgre Z., Gertner and Donald A., Goolsby, 2001. Eutrophication: Nitrate flux in the Mississippi River. Nature 414, 166 – 167.

Griffiths, A.H., 1987. Water quality of the estuary and Firth of Forth Estuary, Scotland. Proceedings of the Royal Society Edinburgh 93:303-314.

Grimes, C. B. and J. H. Finucane, 1991. Spatial distribution and abundance of larval and juvenile fish, chlorophyll and macrozooplankton around the Mississippi River discharge plume, and the role of the plume in fish recruitment. Marine Ecology Progress Series 75: 109-119.

Grimes, C. B. and M. J. Kingsford, 1996. How do riverine plumes of different sizes influence fish larvae: Do they enhance recruitment? Marine Freshwater Research 47: 191-208.

Gross, F., 1947. An experiment in marine fish cultivation: I. Introduction. Proceedings of the Royal Society of Edinburgh. 63 (B), 1-2.

Hagerstrand, T. and V. Lohm, 1990. Sweden. In: B.L. Turner, II, W.C. Clark, R, W. Kates, J.F. Richards, J. T. Mathews and W.B. Meyer (eds.): The Earth as Transformed by Human Action: Global and Regional Changes in the Biosphere over the Past 300 years, pp. 605-622. Cambridge University Press. 713 pp.

Hallegraeff, G.M., 1993. A review of harmful algal blooms and their apparent global increase. Phycologia 32: 79-99.

Hardy, R.W, 2000. Urban legends and fish nutrition. Aquaculture Magazine 26(6): 47–50.

Harper, Jr., D. E., L. D. McKinney, et al., 1991. Recovery responses of two benthic assemblages following an acute hypoxic event on the Texas continental shelf, northwestern Gulf of Mexico. Pages 49-64 in R.V. Tyson and T. H. Pearson (eds.), Modern and Ancient Continental Shelf Anoxia. Geological Society Special Publication No. 58, The Geological Society, London, 470 pp.

Harper, D. E., R. R. Salzer, et al., 1981. The occurrence of hypoxic bottom water off the upper Texas coast and its effect on the benthic biota. Contributions in Marine Science 24: 53-79.

Harrison P. and Pearce F., AAAS Atlas of Population and Environment, 2001. Victoria Dompka Markham (ed.). American Association for the Advancement of Science and the University of California Press.

Hass, P.M., 1991. “Save the Seas: UNEP’s Regional Seas Programme and the Coordination of Regional Pollution Control Efforts.” In: Ocean Yearbook Vol. 9 (eds) E.M. Borgese, N. Ginsburg, and J.R. Morgan. Chicago: University of Chicago Press.

HELCOM, 2003. Fourth Periodic Assessment of the Marine Environment of the Baltic Sea Area, 1994-1998 (BSEP 82B, 2003). Helsinki Commission.

Hessen, D.O., A. Henriksen, A. Hindar, J. Mulder, K. Tørseth and N. Vagstad, 1997.
Human impacts on the nitrogen cycle: a global problem judged from a local perspective. Ambio (26) 32221-325.

Holiday, M.C., and B.K. O’Bannon, 2000. Fisheries of the United States, 1999. Current Fisheries Statistics No. 9900. Silver Spring, Md.: National Marine Fisheries Service.

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.

Huisman, J. and J. Weissing, 1995. Competition for nutrients and light in a mixed water column: A theoretical analysis. Am. Nat. 146: 536-564.

Jackson, W.A., L.E. Asmussen, E.W. Hauser, and A.W. White. 1973. Nitrate in surface and subsurface flow from a small agricultural watershed. Journal Environmental Quality 2:480–482.

Jørgensen, B.B., 1996. Material flux in the sediment. In: Jørgensen, B.B., Richardson K. (eds) Eutrophication in coastal marine ecosystems. American Geophysical Union, Washington, DC, pp 115-135.

Johansson, J.O.R., Lewis, R.R. III, 1992. Recent improvements of water quality and biological indicators in Hillsborough Bay, a highly impacted subdivision of Tampa Bay, Florida, USA. Sci Total Environ (Suppl) 1992: 1190-1215.

Justic, D., N. N. Rabalais, et al., 1995a. Stoichiometric nutrient balance and origin of coastal eutrophication. Marine Pollution Bulletin 30: 41-46.

Justic, D., N. N. Rabalais, et al., 1995b. Changes in nutrient structure of river-dominated coastal waters: Stoichiometric nutrient balance and its consequences. Estuarine, Coastal and Shelf Science 40: 339-356.

Kaspar, H. F., P. A. Gillespie, I. C. Boyer, and A. L.MacKenzie, 1985. Effects of mussel aquaculture on the nitrogen cycle and benthic communities in Kenepuru Sound, Marlborough Sounds, New Zealand. Marine Biology 85:127–136.

Keeney, D.R., and T.H. DeLuca. 1993. Des Moines River nitrate in relation to watershed agricultural practices: 1945 versus 1980s. Journal of Environmental Quality 22:267–272.

Kennedy, V.S., 1990. Anticipated effects of climate change on estuarine and coastal fisheries. Fisheries 14: 16-25.

Kroeze, C. and S. P., Seitzinger, 1998. Nitrogen inputs to rivers, estuaries and continental shelves and related nitrous oxide emissions in 1990 and 2050: A global model. Nutrient Cycling in Agroecosystems 52: 195-212.

Lasserre, G., M. I. Bebars, et al., 1997. Analysis of Egyptian marine and lagoon fishery landings in relation to the construction of the Aswân Dam. Oceanologica Acta 20(2): 421-436.

Lee, B.S., Bullister JL, Whitney FA, 1999.Chlorofluorocarbon CFC-11 and carbon tetrachloride removal in Saanich Inlet, an intermittently anoxic basin. Marine Chemistry 66 (3-4): 171-185.

Lee, B.S., J.L. Bullister, J.W. Murray and R. Sonnerup., 2002. Anthropogenic chlorofluorocarbons in the Black Sea and the Sea of Marmara. Deep-Sea Research Pt. I 49 (5): 895-913.

Leming, T. D. and W. E. Stuntz, 1984. Zones of coastal hypoxia revealed by satellite scanning have implications for strategic fishing. Nature 310: 136-138.

Loye-Pilot, M.D., J.M. Martin and J. Morelli, 1990. Atmospheric input of inorganic nitrogen to the western Mediterranean. Biogeochemistry 9:117-134.

Martin, J.M., F.Elbaz-Poulichet, C. Gwue, M.D. Loye-Pilot and G. Han, 1989. River versus atmospheric input of material to the Mediterranean Sea: an overview. Marine Chemistry. 28: 159-182.

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.

McQuoid, M.R. and Hobson, L.A., 1997. Diatoms and silicoflagellates as indicators of Holocene climate trends in Saanich Inlet, British Columbia, Canada. 30th Annual Meeting of the American Association of Stratigraphic Palynologists, Program and Abstracts. Edited by: R.Wicander; S. Damassa; and P.K. Strother.. Swope Center, Marine Biological Laboratories, Woods Hole, Massachusetts September 14 - 19, 1997.

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

Moore, W.S., 1996. Large groundwater input to coastal waters revealed by ^{226}Ra enrichments. Nature 380: 612-614.

Mullins, H.T., Thompson, J.B., McDougall, K. and Vercoutere, T.L., 1985. Oxygen-minimum zone edge effects: evidence from the central California coastal upwelling system. Geology 13: 491-494.

Nance, J. M., E. X. Martinez, et al., 1994. Feasibility of improving the economic return from the Gulf of Mexico brown shrimp fishery. North American Journal of Fisheries Management 14: 522-536.

Nixon, S.W., C.A. Oviatt, J. Frithsen and B. Sullivan, 1986a. Nutrients and the productivity of estuarine and coastal marine systems. Journal of the Limnological Society of South Africa 12 (1/2): 43-71.

Nixon, S.W., C.D. Hunt and B.L. Nowicki, 1986b.The retention of nutrients (C, N, P), heavy metals (Mn, Cd, Pb, Cu), and petroleum hydrocarbons in Narragansett Bay.
Pp. 99-122 in: P. Lasserre and J. M. Martin, eds. Biogeochemical Processes at the Land-Sea Boundary. Elsevier, N.Y.

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

Nixon, S. W., 1997. Prehistoric nutrient inputs and productivity in Narragansett Bay. Estuaries 20: 253-261.

Nixon, S.W., 2003. Replacing the Nile: Are Anthropogenic Nutrients Providing the Fertility Once Brought to the Mediterranean by a Great River? Ambio (32):

Olivier, J.G.J., A.F. Bouwman, K.W. van der Hoek, and J.J.M. Berdowski, 1999. Global air emission inventories for anthropogenic sources of NO_X, NH_3 and N_2O in 1990, Environ. Poll. 102: 135-148.

Omernik, J.M. 1977. Nonpoint source-stream nutrient level relationships—A nationwide study. EPA-600/3-P77-105. USEPA, Corvallis, OR.

Paerl, H. 1993. Emerging role of atmospheric nitrogen deposition in coastal eutrophication: biogeochemical and trophic perspectives. Canadian Journal of Aquatic Science 2254-2269.

Paerl, H., 1995. Coastal eutrophication in relation to atmospheric nitrogen deposition: current perspectives. Ophelia 41: 237-259.

Paerl, H.W., Mallin, M.A., Donmahue, C.A., Go, M. and Peierls, B.L., 1995. Nitrogen loading sources and eutrophication of the Neuse River estuary, NC: Direct and indirect roles of atmospheric deposition. Report No. 291. University of North Carolina Water Resources Research Institute, Raleigh, NC, 119p.

Paerl, H.W. and D.F. Millie., 1996. Physiological ecology of toxic cyanobacteria. Phycologia 35(6): 160-167.

Paerl H., 1997. Coastal eutrophication and harmful algal blooms: Importance of atmospheric deposition and groundwater as "new" nitrogen and other nutrient sources. Limnol. Oceanogr. 42: 1154-1165.

Paerl HW, Pinckney JL, Fear JM, Peierls BL, 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., 1999. Cultural eutrophication of shallow coastal waters: Coupling changing anthropogenic nutrient inputs to regional management approaches. Limnologica 29: 249-254.

Paerl, H. W., Boynton, W. R., Dennis, R. L., Driscoll, C. T., Greening, H. S., Kremer, J. N., Rabalais, N. N., Seitzinger, S. P., 2000. Atmospheric Deposition of Nitrogen in Coastal Waters: Biogeochemical and Ecological Implications. In, R. Valigura et al., Nitrogen Deposition in Coastal Waters, AGU Press, Washington, DC.

Paludan C, Alexeyev FE, Drews H, Fleischer S, Fuglsang A, Kindt T, Kowalski P, Moos M, Radlowki A, Stromfors G, Westberg V, Wolter K, 2002. Wetland management to reduce Baltic Sea eutrophication. Water Science and Technology, 45 (9): 87-94.

Pavela, J. S., J. L. Ross, et al., 1983. Sharp reductions in abundance of fishes and benthic macroinvertebrates in the Gulf of Mexico off Texas associated with hypoxia. Northeast Gulf Science 6: 167-173.

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.

Peierls, B. L., N. F. Caraco, M. L. Pace, and J.J. Cole, 1991. Human influence on river nitrogen. Nature 350:386-387.

Pihl, L., 1994. Changes in the diet of demersal fish due to eutrophication-induced hypoxia in the Kattegat, Sweden. Canadian Journal of Aquatic Science 51: 321-336.

Pitman, Walter C. and William B. F. Ryan. Noah's Flood: The New Scientific Discoveries About the Event That Changed History. Simon & Schuster, 1999.

Pokryfki L, Randall R.E., 1987. Nearshore hypoxia in the bottom water of the Northwestern Gulf of Mexico from 1981 to 1984. Marine Environmental Research 22 (1): 75-90.

Prado-Fiedler, R.R., 1990. Atmospheric input of inorganic nitrogen species to the Kiel Bight. Helgolander Meeresunt 44: 21-30.

Rabalais, N. N., L. E. Smith, et al., 1995. The effects of bottom water hypoxia on benthic communities of the southeastern Louisiana continental shelf. New Orleans, Louisiana, U.S. Minerals Management Service, Gulf of Mexico OCS Region: 105.

Rabalais N.N., Wiseman, W.J., Turner, R.E., SenGupta, B.K., Dortch Q, 1996. Nutrient changes in the Mississippi River and system responses on the adjacent continental shelf. Estuaries 19 (2B): 386-407.

Rabalais, N. N., R. E. Turner, et al., 1998. Consequences of the 1993 Mississippi River flood in the Gulf of Mexico. Regulated Rivers: Research & Management 14: 161-177.

Rabalais, N.N., R.E. Turner, D. Justi, 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 Coastal Ocean Program, Silver Springs, MD, 167 pp.

Rabalais N.N., Turner, R.E., Wiseman, W.J., 2002. Gulf of Mexico hypoxia, aka "The dead zone" Annual Review of Ecology and Systematics 33: 235-263.

Ragan, J.G., A.H. Harris, and J.H. Green. 1978. Temperature, salinity and oxygen measurements of surface and bottom waters on the continental shelf off Louisiana during portions of 1975 and 1976. Prof. Papers Ser. (Biology) 3:1–29. Nicholls State Univ., Thibodaux, LA.

Randall, G.W. and D.J. Mulla, 2001. Nitrate nitrogen in surface waters as influenced by climatic conditions and agricultural practices. Journal of Environmental Quality 30 (2): 337-344.

Renaud, M, 1986. Hypoxia in Louisiana coastal waters during 1983: implications for fisheries. Fishery Bulletin 84: 19-26.

Reid, P.C., 1997. Discharges from hydroelectric power schemes as a trigger for marine algal blooms. Marine Pollution Bulletin 34 (9): 730-733.

Rowe, G., J. Morse, G. Boland, and M.L. Cruz-Kaegi., 1995. Sediment metabolism and heterotrophic biomass associated with the Mississippi River plume. p. 102–105. In Nutrient-enhanced coastal ocean productivity. Proceedings of the Synthesis Workshop, Baton Rouge, LA. Apr. 1994. Louisiana Sea Grant College Program, Baton Rouge.

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.

Seitzinger, S.P. and A.E. Gilbin, 1996. Estimating dentrification in North Atlantic continental shelf sediments. Biogeochemistry (35): 235-260.

Seitzinger, S.P. and C. Kroeze, 1998. Global distribution of nitrous oxide production and N inputs on freshwater and coastal marine ecosystems. Global Biogeochem. Cycles, 12(1) 93-113.

Smetacek, V. S., 1986. Impact of freshwater discharge on production and transfer of materials in the marine environment. The role of freshwater outflow in coastal marine ecosystems. S. Skeslet. Berlin, Springer: 85-106. (may or may not be used)

Smil, V. 1990. Nitrogen and Phosphorus. In: B.L. Turner, II, W.C. Clark, R, W. Kates, J.F. Richards, J. T. Mathews and W.B. Meyer (eds.): The Earth as Transformed by Human Action: Global and Regional Changes in the Biosphere over the Past 300 years, pp. 423-436. Cambridge University Press. 713 pp.

Smil, V., 1997. Global Population and the Nitrogen Cycle, Scientific American, July.

Smith, S. V., W. J. Kimmerer, E. A. Laws, R. E. Brock and T. W. Walsh., 1981. Kaneohe Bay sewage diversion experiment: perspectives on ecosystem responses to nutritional perturbation. Pacific Science. 35: 279-395.

Strain, P.M., D. J.Wildish, and P.A. Yeats. 1995. The application of simple models of nutrient loading and oxygen demand to the management of a marine tidal inlet. Marine Pollution Bulletin 30(4): 253–261.

Suzuki, Teruaki, 2001. Oxygen-Deficient Waters along the Japanese Coast and Their Effects upon the Estuarine Ecosystem. Journal of Environmental Quality (30): 291-302.

Tarr, J. and R. Ayres, 1990. The Hudson-Raritan Bain. In: B.L. Turner, II, W.C. Clark, R, W. Kates, J.F. Richards, J. T. Mathews and W.B. Meyer (eds.): The Earth as Transformed by Human Action: Global and Regional Changes in the Biosphere over the Past 300 years, pp. 623-639. Cambridge University Press. 713 pp.

Thamdrup B., Dalsgaard T., 2002. Production of N-2 through anaerobic ammonium oxidation coupled to nitrate reduction in marine sediments. Applied and Environmental Microbiology 68 (3): 1312-1318.

Titman, D., 1976. Ecological competition between algae: experimental confirmation of resource-base competition theory. Science 42: 1171-1177.

Tolmazin, D., 1985. Changing coastal oceanography of the Black Sea. 1: Northwestern shelf. Prog. Oceanog. 15: 217-276.

Troell, M., C. Halling, A. Nilsson, A. H. Buschmann, N. Kautsky, and L. Kautsky, 1997. Integrated marine cultivation of *Gracilaria chilensis* (*Gracilariales, Rhodophyta*) and salmon cages for reduced environmental impact and increased economic output. Aquaculture 156:45–61.

Turner, R. E. and N. N. Rabalais, 1991. Changes in Mississippi River water quality this century. Implications for coastal food webs. BioScience 41: 140-148.

Turner, R. E. and N. N. Rabalais, 1994. Coastal eutrophication near the Mississippi delta. Nature 386: 619-621

Turner, R.E., 1997. Wetland loss in the northern Gulf of Mexico: Multiple working hypotheses. Estuaries 20 (1): 1-13.

United Nations, 2001. World Population Prospects, The 2000 Revision: Highlights. Population Division, Department of Economic and Social Affairs.

UNEP, 2002a. Global Environment Outlook - Past, present and future perspectives. Earthscan, UK, USA.

UNEP, 2002b. Vital water graphics: An overview of the state of the world's fresh and marine waters.

Valigura, R., W. Luke, R. Artz and B. Hicks, 1996. Atmospheric Nutrient Inputs to Coastal Area: Reducing the uncertainties. US-NOAA Coastal Ocean Program Decision Analysis Series No. 9 Washington DC.

Vitousek, P.M., H.A. Mooney, J. Lubchenko and J.M. Mellilo, 1997. Human domination of Earth's ecosystems. Science 277: 494-499.

Wu, Rudolf S. S., Bing Sheng Zhou, David J. Randall, Norman Y. S. Woo, and Paul K. S. Lam, 2003. Aquatic Hypoxia Is an Endocrine Disruptor and Impairs Fish Reproduction. Journal of Environmental Science and Technology 37: 1137 – 1141.

Zaitsev, Y. P., 1991. Cultural eutrophication of the Black Sea and other European seas. La Mer 29: 1-7.

Zaitsev, Y. P., 1993. Impacts of eutrophication on the Black Sea Fauna. Fisheries and environment studies in the Black Sea System. Rome, United Nations, Food and Agricultural Organization: 64-86.

Zimmerman, R.J., J.M. Nance, and J. Williams, 1997. Trends in shrimp catch in the hypoxic area of the northern Gulf of Mexico. In Proceedings of theFirst Gulf of Mexico Hypoxia Management Conference. EPA-55-R-97-001. Washington, D.C.: EPA Gulf of Mexico Program Office, pp. 64–75.