productive and essential task there is a danger that it leads to a form of scientific nihilism where everything is reduced to a simple testable null hypothesis that if rejected leads us nowhere. What pollution research needs is a far better understanding of the basic biology of species that show changes in response to pollution. Here there can be no dispute.

REPORTS

Vlaams Instituut voor de Zee
Flanders Marine Institute

18842

Marine Pollution Bulletin, Vol. 16, No. 6, pp. 227–231, 1985
Printed in Great Britain

0025-326X/85 $3.00+0.00

Eutrophication—the Future Marine Coastal Nuisance?

RUTGER ROSENBERG
Institute of Marine Research, Lysekil, Sweden

Increased inputs of nutrients to marine coastal areas over the last decades have created a basis for eutrophication of the waters surrounding Sweden. In combination with relatively low water exchange in these vertically stratified and almost non-tidal waters, local and regional effects of increased macro-algal biomass, and decreased oxygen concentrations in bottom water leading to mortalities of benthic animals and decreased fish catches have at times been observed. The effects were first noted in the Baltic, but are now obvious also in Swedish and Danish coastal areas in the Kattegat and the Belt Sea. Similar symptoms have recently also been recorded off the Danish North Sea coast. Other shallow coastal and shelf areas, where stratification occurs, can be regarded as potentially eutrophic risk areas.

During the past few decades marine coastal areas all over the world have been exposed to many environmental hazards. The most potentially threatening have probably been the wide spread disemination of various persistant and poisonous chlorinated compounds (e.g. DDT, PCB, etc), heavy metals (e.g. Hg, Cd, etc.) and residual nuclear wastes. Oil spill accidents, although their effects are usually less persistent, are immediately spectacular and have been given much publicity.

Although it has for long been a recognized problem in fresh water environments, eutrophication of marine waters has not attracted much attention. Eutrophication is here defined as an increase in nutrients leading to increased growth of algae and plants. The consequences of this process are in most cases an increased biological oxygen demand in the bottom waters, as planktonic production sediments out, which may initially have a stimulatory effect on benthic communities. Ultimately, however, it results in increasing anoxia of the bottom water bringing about the eventual elimination of aerobic organisms.

Eutrophication may be triggered by a variety of natural causes which result in organic enrichment in isolated water bodies, but generally becomes a widespread phenomenon only under anthropogenic influences. Thus, before the curtailment of indiscriminate flows of untreated sewage to local waters, most fresh water lakes and rivers in heavily populated areas suffered from temporary or permanent eutrophic effects. It is now increasingly apparent that nutrient enrichment is about to cause, or indeed has already brought about, eutrophication as an almost permanent effect in some local coastal waters and even in entire sea areas (Rosenberg *et al.*, 1984; Cederwall & Elmgren, 1980; Larsson *et al.*, 1985). There are good reasons to believe that eutrophication will, in the near future become a common hazard in marine coastal areas in many parts of the world, with consequent potentially damaging effects on both inshore fisheries and recreational facilities. The support for this belief has developed from recent investigations in marine waters surrounding Sweden, which have provided suggestive evidence of wide spread nutrient enrichment of the Baltic Sea and Kattegat areas (Fig. 1) stemming principally from increased atmospheric deposition and river outflow. With an increasing trend world-wide in the use of fertilizers, and the continued venting of nitrogen oxides from the burning of fossil fuels it is most likely that the general phenomena observed in Swedish waters are also occurring, or will appear later, in other regions.

Limiting nutrients

In fresh water phosphorus (P) is the limiting nutrient for growth of algae and plants. In order to reduce the import of P to receiving waters from municipalities and industries, purification plants have been installed in many countries during the last decades. In some countries, including Sweden, similar purification methods have also been used for discharges to marine coastal

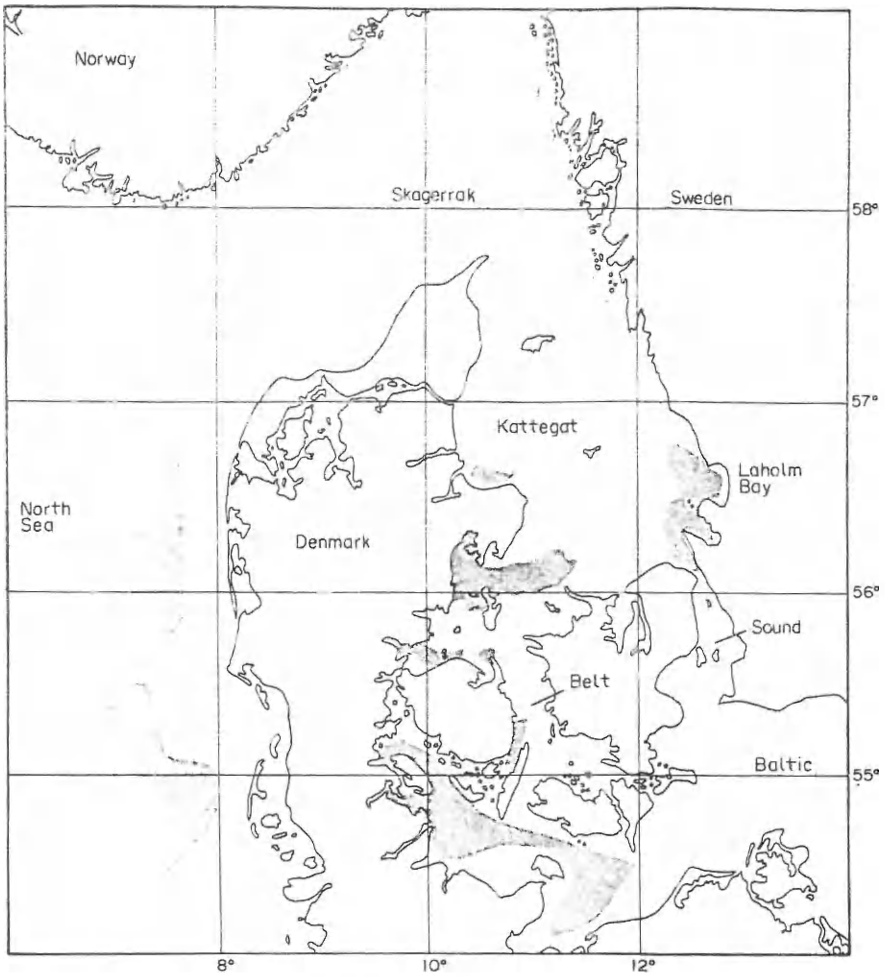

Fig. 1 Areas affected by periodically low oxygen concentrations in the bottom water (grey). The Kattegat in 1981 (Rydberg, 1982), the Belt and south western Baltic in 1981 (Miljöstyrelsen, 1984; Ehrhardt & Wench, 1984) and the North Sea in 1982 (Dethlefsen & von Westernhagen, 1983). The concentrations were in the Kattegat, Belt and Baltic in most cases below 2 ml l^{-1} and in the North Sea below 3 ml l^{-1}.

waters. There is now increasing evidence that nitrogen (N) is the critical limiting nutrient throughout most of the year for phytoplankton growth in coastal areas of the north American east coast (Ryther & Dunstan, 1971), of the Swedish west coast (Graneli, 1981) and in the central Baltic Sea (Larsson, 1984). Comparative analysis of measurements of inorganic P and N in the surface waters around Sweden indicates that N is the critical limiting nutrient for algal growth in most areas, but that P takes the role in brackish waters of the Bothnian Bay in the northern Baltic (Fonselius, 1978). In Laholm Bay (Fig. 1), a large and productive shallow embayment on the west coast of Sweden, where intensive studies of eutrophication have been initiated, the surface concentrations of inorganic N drop to almost zero within 1–2 km from the mouth of a river carrying high nutrient concentrations into the bay (Rydberg, 1982). This indicates a rapid uptake of N by marine phytoplankton and suggests that particular attention should be paid to the role of N in promoting or limiting primary production in marine areas. The concentration of inorganic P is of particular importance for the growth of blue green algae, which are generally abundant in more hyposaline areas like the Baltic.

Eutrophication in waters surrounding Sweden

At the request of the Swedish National Environment Protection Board a group of 16 scientists compiled analytical reports on eutrophication and related phenomena observed recently in Swedish coastal waters. These reports are summarized in a book edited by Rosenberg (1984), which includes sections on both the Baltic (Larsson, 1984) and on the Swedish west coast (Edler, 1984). The results given below are quoted from that compilation, if not otherwise stated.

The effects of eutrophication are usually observed as increased densities of green macroalgae at the surface, decreased transparency in surface water and/or oxygen deficiency at the bottom sometimes associated with mortality of bottom fauna and demersal fish. Laholm Bay has provided a typical example of such effects. In that area large accumulations of the macroalgae *Cladophora glomerata* have occurred during several summers over the past 10 years, and have created a nuisance by forming substantial wind-driven deposits along recreational beaches. During the late summer period, from 1980 onwards, low oxygen levels in the bottom waters of the bay have periodically reduced both the benthic fauna

...the catches of demersal fish. Other signs of abnormalities in Laholm Bay were a mass mortality in August ...so of the bivalves *Mya arenaria* and *Cardium edule*. Following strong winds (13 m/s) approximately 67 million individuals of these two species, weighing 260 live ...nes, were washed up along a 15 km shore line. These ...anisms were probably resident at 2–8 m depth. In May 1984 half-dead and dead bivalves (mainly *Cardium* ...le) were found at the same depths all over the Bay. These kills seem to have been caused by periodically low oxygen concentrations causing the bivalves to leave their burrows in the sediment. It is probable that such exposure at the sediment surface also increased the predation ...these organisms by fish. Laholm Bay is known to be an important nursery area for several bottom feeding flat fish species, especially plaice.

More than 60% of the river transport of N to Laholm Bay has been shown to originate from agricultural activities, which occupy about 10% of the drainage area (Fleischer and Rydberg, 1982), and the discharge of N from the rivers is known to have increased substantially during the 1970's. The annual primary production in the outer central part of Laholm Bay has recently been found to be higher than in the central Kattegat, but a direct causal relationship to the increased fluvial N inputs has yet to be established.

The major sources of N for the Kattegat as a whole are through rivers and atmospheric fall out (Table 1). The oxygen concentration in the bottom waters of the Kattegat below the halocline varies with season, with the lowest values being found in late summer and autumn. The halocline is at about 15m depth below which oxygen depletion is found for longer periods (weeks to months) in some localities, notably Laholm Bay and adjacent areas (Rydberg, 1982) (Fig. 1). Low oxygen concentrations have also been recorded on the Danish side of the Kattegat, in the Belt Sea and in the south eastern Baltic in the 1980's, especially in 1981 (Fig. 1). The effects have been reduced bottom fauna and demersal fish kills (Weigelt, 1983; Ehrhardt and Wenck, 1984; Miljöstyrelsen, 1984).

The Kattegat is an important fishing area for the Norway lobster (*Nephrops norvegicus*). In the Swedish *Nephrops* fishery catch per unit effort rose gradually between 1980 and 1982, but dropped dramatically in 1983 (Fig. 2) (Baden *et al.*, 1984). These statistics are consistent with the hypothesis that *Nephrops* is readily available to the fishery during periods of low bottom water oxygenation, because of their tendency to emerge from their burrows during such periods, and that persistent exposure of this type has resulted in diminished stock densities. Similar observations and conclusions were presented for adjacent areas of the Kattegat in the mid-1970's (Bagge & Munch-Petersen, 1979).

TABLE 1.

Total estimated inputs of nutrients in t yr^{-1} to the Baltic proper (Larsson, 1984) and to the Kattegat (Edler, 1984).

	Baltic proper		Kattegat	
	Tot-P	Tot-N	Tot-P	Tot-N
Municipal	11 700	53 500	2 190	7 600
Industrial	600	5 700	130	1 200
Rivers	38 200	447 400	1 150	43 000
Atmosphere	3 500*	260 000*	265	26 000
N_2-fixation	—	130 000	—	—
Total	54 000	896 600	3 750	78 000

*Includes Gulf of Finland and the Sound

In the Skagerrak (Fig. 1) some semi-enclosed Swedish fjords have been affected by reduced transparency, reduced vertical distribution of macroalgae and, it seems, increased temporal and spatial deoxygenation of bottom water (e.g. Lindahl & Hernroth, 1983). The permanently eutrophic Byfjord has been studied in detail and some results are summarized by Rosenberg *et al.* (1977). In recent years intense blooms of the potentially toxic dinoflagellates (*Gyrodinium aureolum* and *Prorocentrum minimum*) have been recorded in both the Kattegat and the Skagerrak and *Gyrodinium* has caused massive kills among free-living fish, caged fish, cultivated blue mussels (*Mytilus edulis*) and bottom animals (e.g. Edler *et al.*, 1982; Linahl & Hernroth, 1983; Tangen, 1977). It has been suggested that such blooms could be a further consequence of nutrient enrichment in these waters, but again direct evidence of a causal relationship is as yet unavailable. However, in summary, it can be concluded that there are now a number of varied symptoms suggesting that the Kattegat, the Sound (between Denmark and Sweden) and some Swedish coastal areas in the Skagerrak are influenced by eutrophication.

The large bottom areas in the Baltic proper of about 100 000 km^2 with more or less permanent low oxygen concentrations have been described in many publications (e.g. Andersin and Sandler, 1983). Various

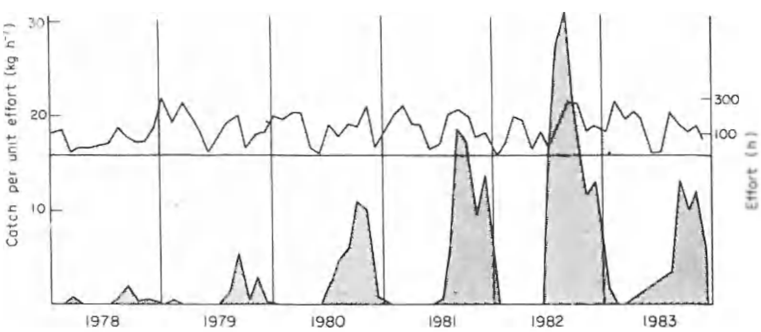

Fig. 2 Effort (top) and catch per unit effort (bottom) in the Swedish *Nephrops* fishery shown monthly in 1978–1983 for the south eastern Kattegat north of Laholm Bay (from Baden *et al.*, 1984).

reasons have been suggested for the development of these lower oxygen concentrations. There is no evidence for recent changes in the water exchanged between the Baltic and Kattegat. However, recently compiled figures of inputs of nutrients to the Baltic (Table 1) support the contention that the effect stems primarily from the results of eutrophication. Thus the new estimates are much higher than those reported earlier, although it must be emphasized that the overall figures are still relatively crude. Again it can be shown that most of the N comes from rivers and from atmospheric fallout. Total inputs of P have increased approximately 8 times and of N 4 times since the beginning of the century and these increases together with the elevated nutrient concentrations now being recorded from Baltic surface waters could suggest that the Baltic Sea as a whole is gradually becoming eutrophic. Conclusive evidence to support this hypothesis is not yet available however, although a number of suggestive trends in different parts of the Baltic ecosystem have been reported. Measurements of primary production over time in the Baltic as a whole are too few to show any trends. However, the biomass of benthic macrofauna has increased in some areas compared with about 50 years ago (Cederwall & Elmgren, 1980). At the same time the catches of fish have increased by about nine times. Such changes could be attributable to the increasing influence of eutrophication, but such a general conclusion must, for the present, be treated with caution, as alternative explanations (e.g. changed predator–prey interactions and intensified fishing effort) have been advanced.

One worrying consequence of the increased deoxygenation of the Baltic bottom waters is worthy of further note. Thus the reproduction of cod could be affected by the low oxygen at about 70–80 m depth where the salinity is about 10‰. Cod eggs float in a salinity of not less than 10‰, and sampling in the central Baltic in 1968–69 showed that the majority of eggs were then in the low oxygen zone (Ojaveer *et al.*, 1981). Although there is as yet no evidence from fishery statistics that cod populations have suffered low recruitment, either from this or other causes related to eutrophic effects, the consequences for the Baltic cod populations, of any further upward or outward extension of the deoxygenated areas in the central Baltic, could be serious.

Eutrophication in other marine areas

Apart from reports of localized marine eutrophication, principally in shallow embayments, there is little in the literature about this subject. Low oxygen concentrations in bottom water have been recorded in areas of the North Sea off the German and Danish west coasts (Fig. 1). This occurred below the thermocline in those areas in the summer–autumn of 1981–83 (Dethlefsen & von Westernhagen, 1983; Dyer *et al.*, 1983). Extensive mortality of bottom organisms and fish were recorded. The only explanation of these events advanced by these authors involved a combination of adverse meteorological and hydrographic conditions and eutrophication.

In the Mediterranean eutrophication resulting in high densities of dinoflagellates and mortality of bottom animals due to anoxic conditions in the bottom water (Chiaudani *et al.*, 1980) has been reported. P is suggested as the limiting factor for primary production in this area. Recently a mass-mortality of benthic animals has been reported from several hundred km^2 of the north eastern part of this sea. The mortality was extremely rapid and in 2–3 days all dominant benthic animals were wiped out, probably due to low oxygen concentrations (Stachowitsch, 1984).

In North America the nutrient load in five estuaries of the Chesapeake Bay has been analysed in detail, and the influence of N/P ratios and concentrations on eutrophic conditions are discussed (Jaworski, 1981). San Francisco Bay receives large inputs of nutrients, but in this area no lasting adverse effects have yet occurred. It has been convincingly argued by Cloern (1982) and Officer *et al.*, (1982) that in the Bay area phytoplankton biomass is controlled by the large populations of benthic filter feeding bivalves. Should their hypothesis be true, then the consequences of the removal of such organisms following deoxygenation brought about by too intense a bloom, or by other causes, would be to precipitate a more intense sequence of blooms and thus perpetuate eutrophic conditions.

Causes and mechanisms

It has been shown that the dominant nutrient input sources for N are from the rivers and the atmosphere. It seems that a large proportion of the N entering coastal waters from rivers originates from fertilizers used in agriculture. In Sweden and Denmark the use of fertilizers has greatly increased since the 1940s, and in general only about half of the N added is bound in the crop at the time of harvesting (Andersson, 1981). It may be assumed that a significant part of the unbound fraction eventually finds its way to the sea. The atmospheric deposition of N occurs as nitrogen oxides and originates from the combustion of fossil fuels, e.g. from car engines and power stations. For most of the southern Baltic and the Kattegat the annual wet deposition of nitrate is between 3 and 5 kg N ha^{-1}. The input of ammonium with precipitation in these areas is of the same magnitude (Grennfelt, 1983).

The reason why effects have been observed earlier in the Baltic and Kattegat than in other areas is a result of restricted water exchange in combination with special hydrological conditions. The Baltic is an enclosed water body and the Kattegat could be considered as its extension, also partly enclosed. In both areas the tidal flow is negligible, and the water is vertically stratified with water exchange near the bottom being reduced. The effects reported from the North Sea in 1980–83 also occurred under a stratified water column.

At present observations of severe environmental perturbations such as mass mortalities of benthic organisms and fish are necessary to alert concern and speculation over the occurrence of eutrophication in marine areas. It would, however, be preferable to have earlier and less catastrophic warnings of such large scale ecosytem disturbances.

Action plan

In Sweden studies have been initiated of the reaction of the ecosystem to eutrophication in Laholm Bay and in the Himmerfjärd in the Baltic. Research will be concentrated principally on the N cycle and the possible links between nutrient enrichment and subsequent observable effects of any enhanced planktonic production and bottom water deoxygenation. A primary goal of the project is to be able to give predictive advice, based on sound background knowledge, about where to introduce counter measures in potentially eutrophic areas. One important research aim is to assess the extent of denitrification, i.e. how much N is lost from marine waters under different environmental conditions. Increased attention has been paid to this question in recent years (e.g. Nixon, 1981; Blackburn & Henriksen, 1983) as a result of a greater awareness of the crucial importance of this process.

It is particularly important in eutrophication research to link the biological investigations closely to those of physical oceanography. Although eutrophication is considered the major contributory factor to the events described from waters around Sweden, some connection with other large-scale changes can not be dismissed. Therefore, the effect of long term climatic changes and the influence of changes in fish stock composition on benthic communities will be assessed with respect to their likely effect on the eutrophication-like changes being recorded.

It seems probable that nutrient inputs, principally of N, from terrestrial drainage, atmospheric deposition and urban discharges, have increased progressively throughout the world during this century. It is also likely that further increases will occur in the future as populations continue to expand and the use of fertilizers continues to escalate as the industrialization of agriculture intensifies in the developed world and spreads even more rapidly in some third world countries. Shallow coastal areas and shelf seas in many parts of the world, where conditions prevail which tend to lead to stratification during high temperature conditions, can thus be regarded as potentially eutrophic risk areas. Indeed eutrophication of inshore marine areas may not be a potential, but a present, threat. Should this be true there is an urgent need to understand the risk, and assess cause and effect fully, as a prelude to establishing adequate control and preventative measures.

I sincerely thank Dr. Tom H. Pearson for improving the style of the manuscript.

Andersin, A-B. & Sandler, H. (1983). Recent changes in the macrozoobenthos communities in the deep areas of the Baltic proper and the Gulf of Finland. Paper held at the 8th Symposium of the Baltic Marine Biologists, Lund, 10–14 August. 15 pp.

Andersson, R. (1981). Växtnäringsförluster från åkermark—en översikt. *Swed. Natl. Envir. Protect. Bd. PM* **1455**, 85–101.

Baden, S. P., Rosenberg, R., Hagerman, L. & Bagge, O. (1984). Varför minskar fångsten av havskräfta i Kattegatt? *Yrkesfiskaren 15/16*, 16–17.

Bagge, O. & Much-Petersen, S. (1978). Some possible factors governing the catchability of Norway lobster in the Kattegat. *Rapp. P.-v. Reun. Cons. Int. Explor. Mer.* **175**, 143–146.

Blackburn, T. H. & Henriksen, K. (1983). Nitrogen cycling in different types of sediments from Danish waters. *Limnol. Oceanogr.* **28**, 477–493.

Cederwall, H. & Elmgren, R. (1980). Biomass increase of benthic macrofauna demonstrates eutrophication of the Baltic Sea. *Ophelia. Suppl. 1*, 287–304.

Chiaudani, G., Marchetti, R. & Vighi, M. (1980). Eutrophication in Emilia-Romagna coastal waters (north Adriatic Sea, Italy): a case history. *Prog. Wat. Tech.* **12**, 185–192.

Cloern, J. E. (1982). Does the benthos control phytoplankton biomass in South San Francisco Bay? *Mar. Ecol. Prog. Ser.* **9**, 191–202.

Dethlefsen, V. & von Westernhagen, H. (1983). Oxygen deficiency and effects on bottom fauna in the eastern German Bight 1982. *Meeresforsch.* **60**, 42–53.

Dyer, M. F., Pope, J. G., Fry, P. D., Law, R. J. & Portmann, J. E. (1983). Changes in fish and benthos catches off the Danish coast in September 1981. *J. Mar. Biol. Ass. UK* **63**, 767–775.

Edler, L. (1984). The West coast. In *Eutrophication in Marine Waters Surrounding Sweden—a Review* (R. Rosenberg, ed.), Swedish National Environment Protection Board, Report 1808, 74–111.

Edler, L., Aertebjerg, G. & Graneli, E. (1982). Exceptional plankton blooms in the entrance to the Baltic Sea—the Kattegat and Belt Sea area. *ICES, C.M. 1982/L:20*, 6 pp.

Ehrhardt, M. & Wenck, A. (1984). Wind pattern and hydrogen sulphide in shallow waters of the Western Baltic Sea, a cause and effect relationship? *Meeresforsch.* **30**, 101–110.

Fleischer, S. & Rydberg, L. (1982). Transport of nitrogen and phosphorus to the Laholm Bay. (In Swedish with English abstract.) *Vatten* **38**, 451–460.

Fonselius, S. H. (1978). On nutrients and their role as production limiting factors in the Baltic. *Acta hydrochem. hydrobiol.* **6**, (4), 329–339.

Graneli, E. (1981). Experimental investigations of limiting nutrients for phytoplankton production in the brackish water Öresund, SW Sweden. Ph.D. thesis, University of Lund.

Grennfelt, P. (1983). Atmospheric concentrations and depositions of oxidized nitrogen compounds at coastal regions in Sweden. Seminar on the Investigation of airborne pollution of the Baltic Sea, Tallin, USSR, (mimeo), 8 pp.

Jaworski, N. A. (1981). Sources of nutrients and the scale of eutrophication problem in estuaries. In *Estuaries and Nutrients* (B. J. Neilson & L. E. Cronin, eds.) pp. 83–110. Humana Press, Clifton.

Larsson, U. (1984). The Baltic. In *Eutrophication in Marine Waters Surrounding Sweden—a Review* (R. Rosenberg, ed.) Swedish National Environment Protection Board, Report 1808, 17–73.

Larsson, U., Elmgren, R. & Wulff, F. (1985) Eutrophication and the Baltic Sea—causes and consequences. *Ambio* **14**, 9–14.

Lindahl, O. & Hernroth, L. (1983). Phyto-zooplankton community in coastal waters of western Sweden—an ecosystem off balance? *Mar. Ecol. Prog. Ser.* **10**, 119–126.

Miljöstyrelsen (1984). Iltsvind og fiskedöd i 1981. Omfang og arsager. *The National Agency of Environmental Protection*, Denmark (mimeo), 247 pp.

Nixon, S. W. (1981). Remineralization and nutrient cycling in coastal marine ecosystems. In *Estuaries and Nutrients* (B. J. Neilson & L. E. Cronin, eds.), pp. 111–138. Humana Press, Clifton.

Officer, C. B., Smayda, T. J. & Mann, R. (1982). Benthic filter feeding: a natural eutrophication control. *Mar. Ecol. Prog. Ser.* **9**, 203–210.

Ojaveer, E., Lindroth, A., Bagge, O., Lehtonen, H. & Toivonen, J. (1981). Fishes and fisheries. In *The Baltic Sea.* (A. Voipo, ed.), Elsevier Oceanography Ser. 30, pp. 275–350. Elsevier Publishing Company.

Rosenberg, R. (ed.) (1984). *Eutrophication in Marine Waters surrounding Sweden—a review.* Swedish National Environment Protection Board, Report 1808, 140 pp.

Rosenberg, R., Olsson, I. & Ölundh, E. (1977). Energy flow model of an oxygen-deficient estuary on the Swedish west coast. *Mar. Biol.* **42**, 99–107.

Rydberg, L. (1982). Nutrient conditions and nutrient flow within the southeastern Kattegat. (In Swedish with English abstract). *Vatten* **38**, 436–450.

Ryther, J. H. & Dunstan, W. M. (1971). Nitrogen, phosphorus and eutrophication in the coastal marine environment. *Science* **171**, 375–380.

Stachowitsch, M. (1984). Mass mortality in the Gulf of Trieste: The course of community destruction. *Mar. Ecol.* **5**, 243–264.

Tangen, K. (1977). Blooms of *Gyrodinium aureolum* (Dinophyceae) in north European waters, accompanied by mortality in marine organisms. *Scarsia* **63**, 123–133.

Weigelt, M. (1983). Untersuchungen zur situation des benthos nach einer ausgedehnten Periode vollständigen Sauerstoffschwunds im Bodenwasser der Kieler Bucht. Diplomarbeit, Universty of Kiel, Germany, 126 pp.