Hydrobiologia **514:** 227–241, 2004.
H. Kautsky & P. Snoeijs (eds), Biology of the Baltic Sea.

Baltic Sea eutrophication: area-specific ecological consequences

Cecilia Rönnberg* & Erik Bonsdorff
Environmental and Marine Biology, Åbo Akademi University, Akademigatan 1, FIN-20500 ÅBO, Finland
*E-mail: cecilia.ronnberg@abo.fi (*Author for correspondence)*

Key words: eutrophication, nutrient over-enrichment, ecological consequences, conceptual models, Baltic Sea

Abstract

Eutrophication of coastal waters is a global phenomenon. the amounts of nutrients in the brackish water of the Baltic Sea have increased several times during the last century, with severe ecological effects on the biota. With the increasing environmental problems caused by nutrient over-enrichment, public awareness to the problem has also risen. The Baltic Sea cannot be regarded as a uniform water mass, and area-specific ecological responses can be described. Changes in and detection of eutrophication-related parameters are discussed in relation to a generalized conceptual eutrophication model for the Baltic Sea. The cascading trophic and ecosystem-responses to eutrophication in 9 different sub-regions of the Baltic Sea are illustrated and discussed. The results clearly show the need not only for a common remedy for the Baltic Sea, but primarily show the importance of regional ecological assessment in relation to basin-wide eutrophication.

Introduction

Eutrophication has become a widespread matter of concern especially in coastal and inland waters during the last 50 years. Definitions, causes and consequences of eutrophication are explained and discussed in numerous papers, e.g. Gray (1992), Nixon (1995), Jørgensen & Richardson (1996) and Cloern (2001). The correlation between the eutrophication phenomenon and the brackish water of the Baltic Sea is also well studied and summarised in 'Marine eutrophication', a special issue of Ambio [19(3), 1990], as well as in Jansson & Velner (1995), HELCOM (1996, 2001), Rönnberg (2001) and http://www.grida.no/boing.

The Baltic Sea drainage area is densely populated, with over 85 million inhabitants in 14 countries, and the Helsinki Commission for protection of the marine environment of the Baltic Sea (HELCOM) has identified over 100 environmental hotspots within the catchment area (http://www.helcom.fi/pitf/ hotspots.html). The amount of nutrients and the deposition of organic matter in the Baltic Sea have increased considerably since the beginning of the 20th century (Larsson et al. 1985). According to Stålnacke (1996), 1 360 000 tons of nitrogen and 59 500 tons of phosphorus are annually discharged to the Baltic Sea through riverine load, coastal point sources, atmospheric deposition and nitrogen fixation.

A rising public and political awareness of the situation is seen in a variety of reports from governmental authorities in the countries around the Baltic Sea. Hence, Kauppila & Bäck (2001) for Finnish coastal waters, Anon. (2001) for the state of the Swedish coast, and Christensen (1998) for the Danish marine environment give detailed descriptions of the current state of these waters, primarily in relation to eutrophication. The programme BERNET (Baltic Eutrophication Regional NETwork) has evaluated and recommended measures for 7 restricted regions around the Baltic in BERNET (2000a, b). This awareness is also documented in Elmgren (1989), Partanen-Hertell et al. (1999) and in 'Man and the Baltic Sea' a special issue of Ambio [30(4–5), 2001]. The actual state of our knowledge of the processes affecting eutrophication in the Baltic Sea, how authorities and decision-makers can accurately improve the present situation, and cost-effective ways to achieve positive results are discussed in Bonsdorff et al. (2002), Elliott & de Jonge (2001) and Wulff et al. (2001).

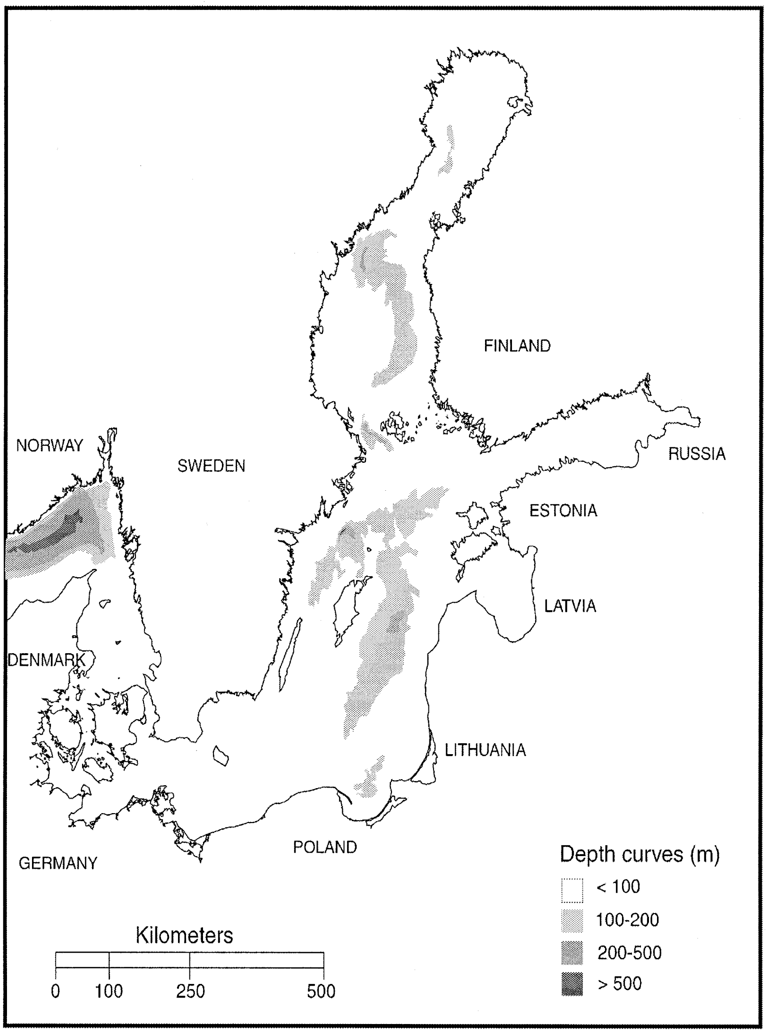

Figure 1. The Baltic Sea area.

For successful results in the rehabilitation of the Baltic Sea in the future, the background and consequences of eutrophication must be analysed and evaluated. This study describes the pathways of the eutrophication process in the Baltic Sea in a region-specific manner. The basic assumption was that all regions in the Baltic respond similarly to the same type of environmental stress (nutrient over-enrichment), but reality shows that local variations in the secondary (i.e. biological and ecological) responses of the ecosystem are important. Only if we describe and recognize them individually, can we present realistic measures to counteract the negative trends (Wulff et al., 2001; Bonsdorff et al., 2002).

The Baltic Sea – not an uniform water body

The Baltic Sea (Fig. 1) has an area of 415 000 km^2 with large variances and gradients in topography, geology, hydrography and climate (Leppäkoski & Bonsdorff 1989). The salinity gradient provides the basic difference between the southern and the northern part. There are also significant environmental variations between the coastal areas and the open sea, and between the archipelagos and the open coasts. All these large-scale patterns contribute to the fact that the Baltic Sea cannot be regarded as a uniform water body. The consequences of eutrophication take different pathways in different parts of the sea, with hypoxia and secondary effects on the benthic ecosystem as common problems, regardless of region (Karlson

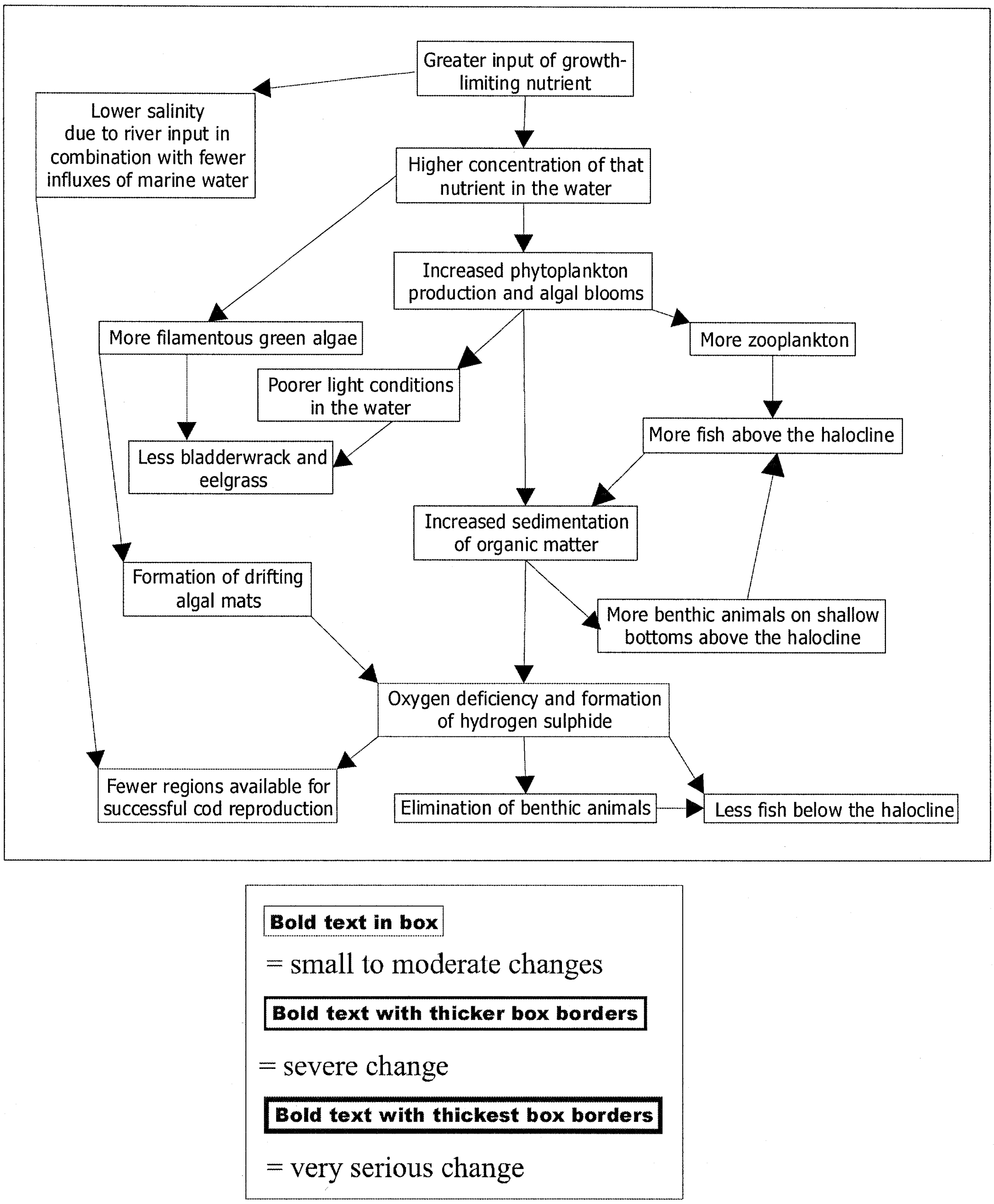

Figure 2. A conceptual flow-model of the eutrophication process (after Bernes 1988, Bonsdorff et al. 1997a, and Rönnberg 2001).

et al., 2002). For successful action plans and for real improvements to take place, we need information from each specific area of concern, and on the ecological effect-parameters that have undergone changes and for how long. For this analysis of potential regional differences in ecosystem responses to eutrophication (regardless of the sources of nutrient over-enrichment) in the Baltic Sea, we divided the area into 9 sub-regions, based on topographical, hydrographical and ecological considerations (Bonsdorff et al., 2002): The (1) Gulf of Bothnia, (2) Archipelago region, including the Archipelago Sea, Åland Islands and the Stockholm archipelago, (3) Gulf of Finland, (4) Gulf of Riga, (5) Gulf of Gdansk, including the Curonian and Vistula Lagoons, (6) East Coast of Sweden, from the Askö area in the north to Hanö Bay in the south, (7) Cent-

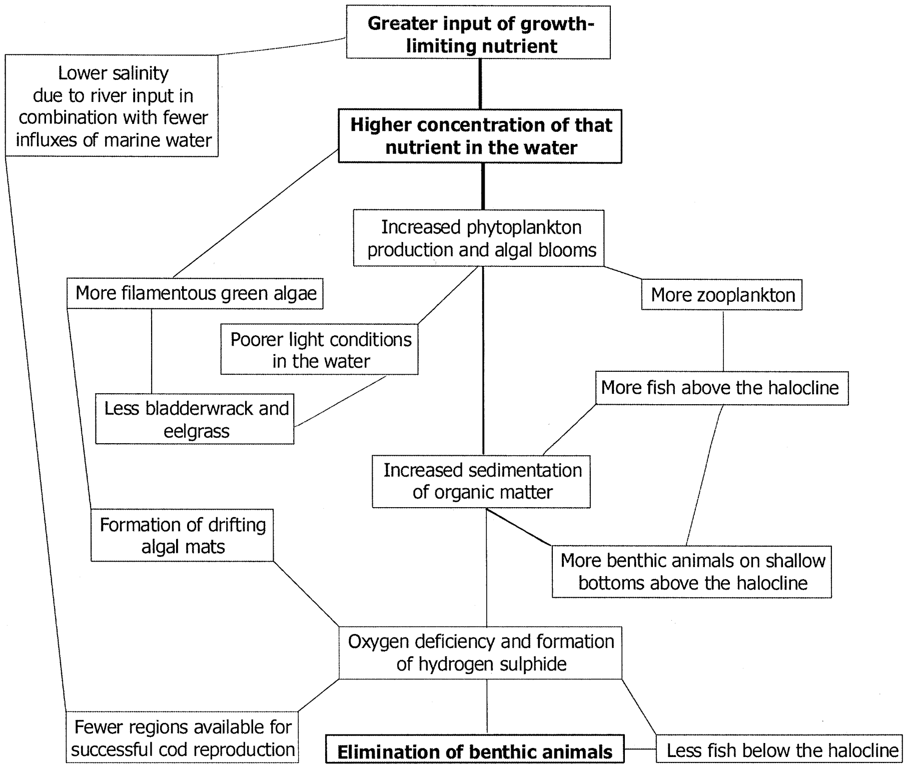

Figure 3. Gulf of Bothnia. Potential effects of eutrophication.

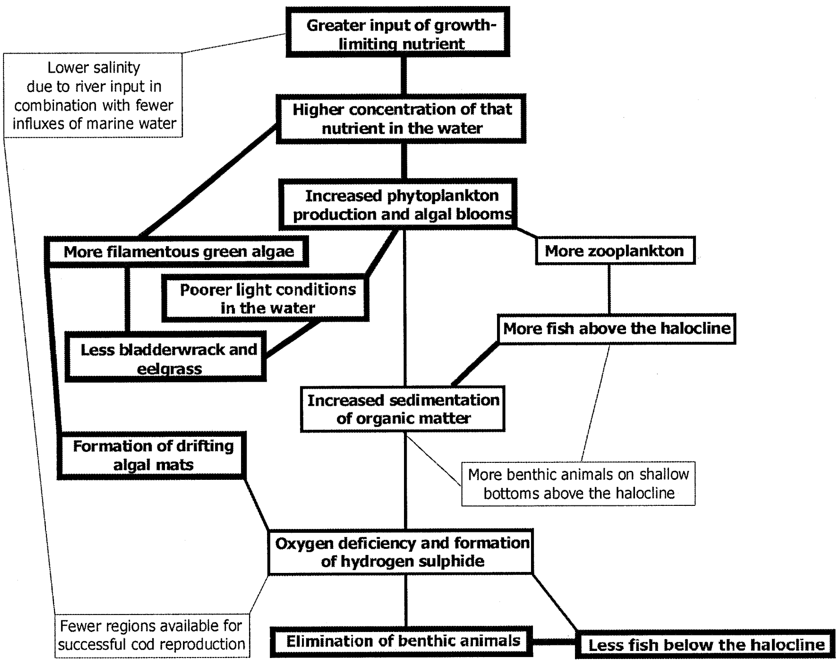

Figure 4. Archipelago region. Large-scale consequences of long-term eutrophication.

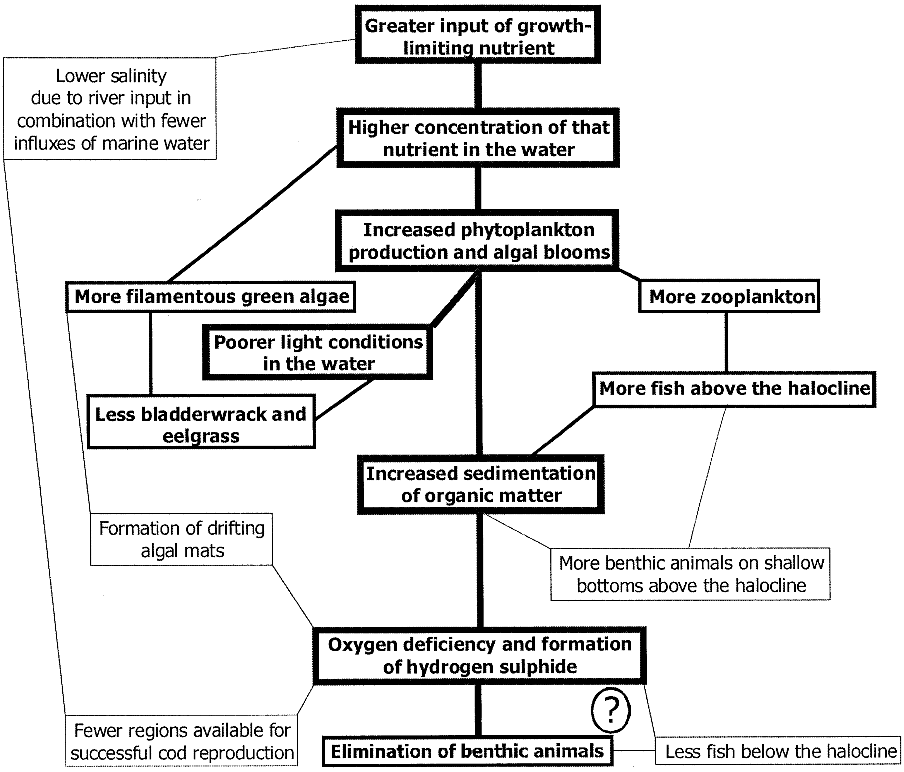

Figure 5. Gulf of Finland. Large-scale consequences of long-term eutrophication.

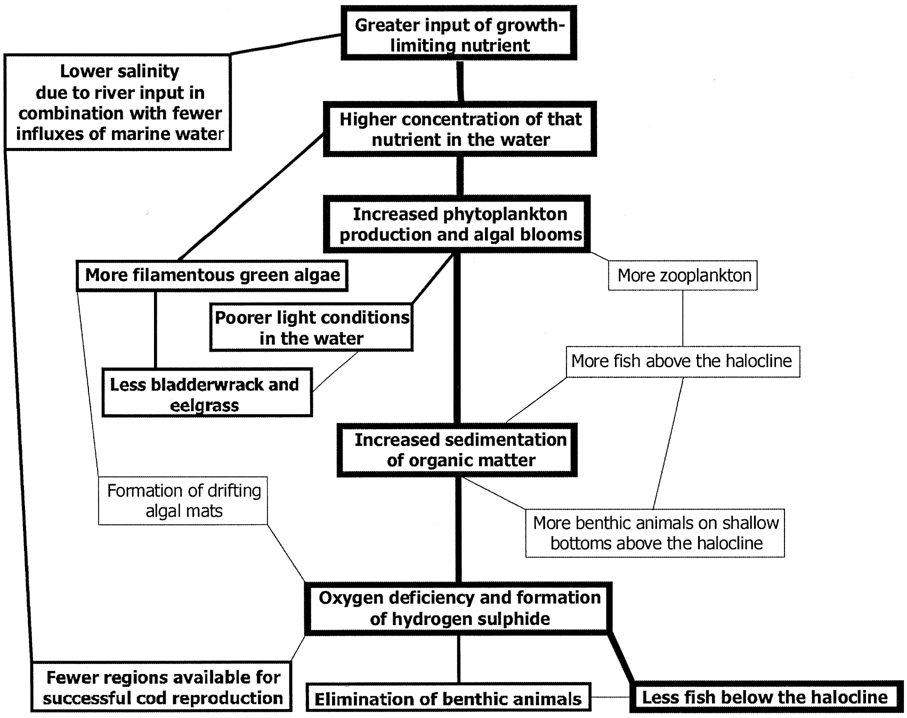

Figure 6. Gulf of Riga. Consequences of regional eutrophication.

Table 1. Characteristics for the nine designated sub-areas of the Baltic Sea.

Area	Specific characteristics
Gulf of Bothnia	– consists of two sub-basins, Bothnian Sea (mean depth: 68 m, max. 230 m) and Bothnian Bay (mean depth: 43 m, max. 147 m) separated by the Northern Quark – salinity: 1–6 psu – land uplift: 8–9 mm yr^{-1} in the northern Bothnian Bay – days with ice-cover: 60 in the Bothnian Sea, 120 in the Bothnian Bay
Archipelago region	– includes Archipelago Sea, Åland Island, Åland Sea, and Stockholm archipelago ∼30.500 islands on the Finnish side, ∼30.000 islands on the Swedish side, separated by the Åland Sea – mean depth: 23 m, max. 294 m in the Åland Sea – salinity: 5–7 psu
Gulf of Finland	– direct extension of the Baltic proper, mean depth: 38 m, max. 120 m – salinity: 3–6 psu – days with ice-cover: 30 in the western gulf, 120 in the eastern – largest source of nutrients: runoff from River Neva
Gulf of Riga	– semi-enclosed, mean depth: 26 m, max. ∼60 m – salinity: 5 psu – largest source of nutrients: runoff from River Daugava
Gulf of Gdansk	– includes the open Gulf of Gdansk and the lagoons of Curonia and Vistula – mean depth: 3 m, max. 9 m – salinity: 5–7 psu in the Gulf of Gdansk, 0.5–6.5 in the lagoons – large catchment area with runoff from River Vistula
Swedish East-coast	– coastal area – includes studies especially from Himmerfjärden (mean depth: 17 m), St. Anna’s archipelago and Hanö Bay – salinity: 5–11
Central Baltic	– consists of 5 deep basins – Arkona, Bornholm, Gdansk, Eastern- and Northern Gotland – separated by shallow sills – max. depth: 459 m (Landsort Deep in the Northern Gotland basin) – salinity: 6–16 psu (highly dependent of influxes of marine water from the North Sea)
Belt Sea region	– consists of Great- and Little Belt, Sound, Kiel Bight, Fehmarn Belt, Mecklenburger- and Pomeranian Bights – mean depth: 16–17 m, max. 80 m (in Little Belt) – salinity: 9–20 psu
Kattegat	– transition area between the Baltic Sea and the Skagerrak (North Sea) – mean depth: 23 m – salinity: 12–30 psu at surface, 32–34 psu at bottom – tidal amplitude: 20 cm

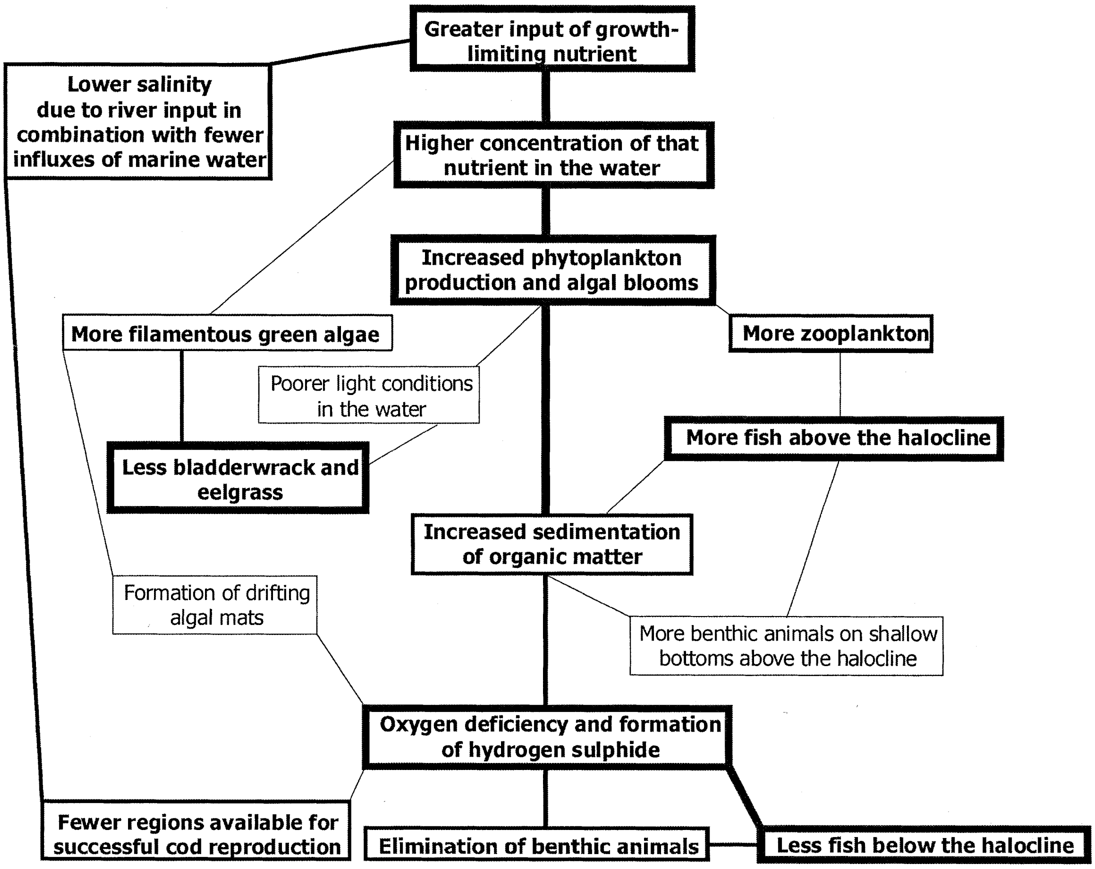

Figure 7. Gulf of Gdansk. Consequences of regional eutrophication.

ral Baltic, (8) Belt Sea region, including the Belt Sea and the Sound, Fehmarn Belt, and the bights of Kiel, Mecklenburg and Pomerania, and (9) Kattegat. Specific features for each region are presented in Table 1. For a detailed list of environmental and ecological features of the Baltic Sea, see, e.g. Leppäkoski & Bonsdorff (1989).

A more comprehensive description relating to eutrophication including characteristics of the areas, and changes for a variety of parameters (oxygen, nutrients, primary production and chlorophyll *a*, phytoplankton and algal blooms, macrovegetation, zoobenthos and fish) is found in Rönnberg (2001). An extensive review of the state of the zoobenthos in relation to eutrophication and hypoxia in the Baltic Sea area is presented in Karlson et al. (2002), and an analysis of the coupling between eutrophication and macroalgal assemblages is presented in Dahlgren & Kautsky (2001). The analysis of the parameters described for each region is based on public and available information, with special consideration to the access and availability to the sources.

Visualization of responses to eutrophication by conceptual models

A general conceptual model of the consequences of eutrophication is sometimes used to describe how an aquatic ecosystem is affected by an excess input of nutrients. Figure 2 shows an example of such a principal box model, modified after Bernes (1988) and Bonsdorff et al. (1997a), illustrating the main patterns of ecosystem responses above and below the semi-permanent halocline in the central Baltic Sea. By using this kind of generalized flow-charts for every sub-area, and by stressing the factors and processes that have undergone most changes in each area, one can obtain comprehensive summaries for any studied part of the Baltic Sea, provided there is published information available (Wulff et al., 2001; Bonsdorff

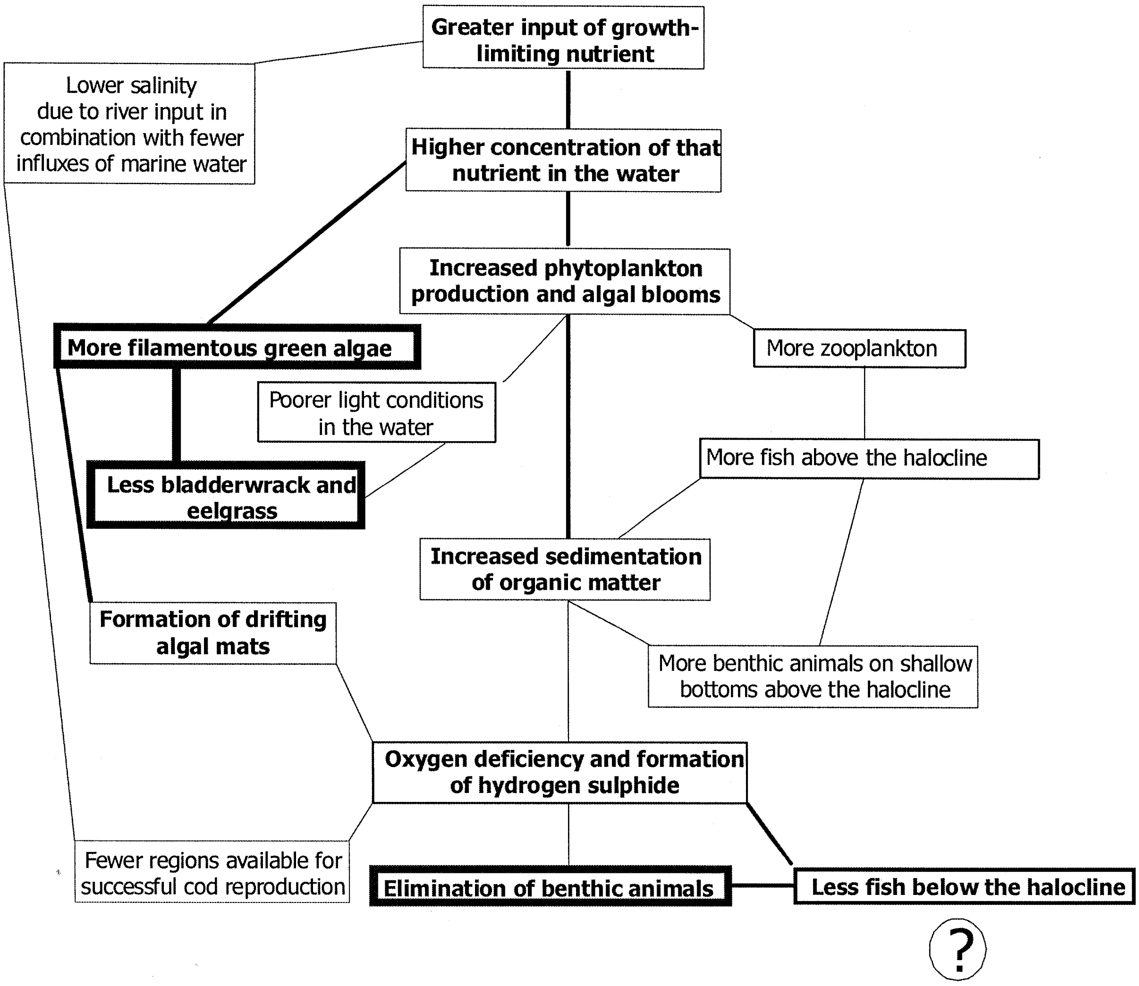

Figure 8. Swedish East-coast. Consequences of regional eutrophication.

et al., 2002). As the Baltic Sea is a heterogeneous water body, exact or uniform (chemical, biological or ecological) standards for water- and environmental quality are hard to define (cf. the demands of the EC Water Framework Directive (EC WFD 2000/60/EC, at http://europa.eu.int/comm/environment/water/index.html). Guidelines for assessing the extent of the changes are mainly based on the environmental quality parameters such as in Anon. (1999) suggested for the coastal waters of Sweden. The presented evaluations of the sub-regions of the Baltic Sea (Figs 3–11) are not quantitative, but rather qualitative assessments and summaries, based on available published and on-line information [see Bonsdorff et al. (2002) for further details on the sources]. Table 2 presents the basic quality-criteria followed in constructing the conceptual models, and serves as guidelines for interpreting the box-models. Transparency, oxygen concentration, nutrients, chlorophyll *a* and occurrences of harmful algal blooms (HAB) are easy to measure, and some long-term data is generally available. The problem is rather to generalize the overall assessment. The severity of the changes may differ between different regions. The values change seasonally and depend on what the pristine or unaffected conditions were like (defined as 'reference conditions' under the EC WFD). To evaluate the status of macrovegetation, zoobenthos and fish in relation to environmental change and altered biotic conditions is far more complicated, as these factors can be regarded as secondary effects, affected by the other components analysed. For example, factors as behavioural and physiological responses in the organisms to the changes in the environment may be specific for a given situation (Rabalais

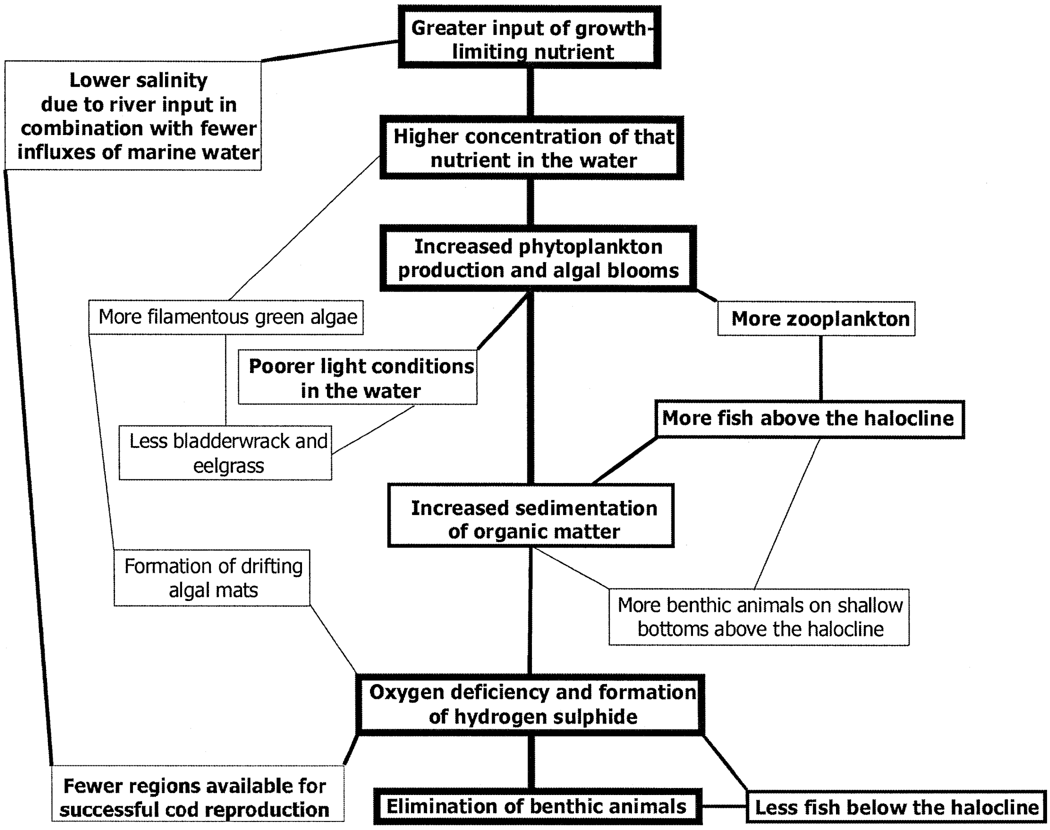

Figure 9. Central Baltic. effects of eutrophication in the open Baltic Sea Waters.

& Turner, 2001). It is also hard to specify the portion of the community responses that are due to *eutrophication* in a multiple-stress situation, such as in the Baltic Sea (Gunnarson et al., 1995; Skei et al., 2000). A variety of other factors will also influence the biota, such as variations in oxygen, salinity and climate, pollutants and contaminants, traffic, introduction of non-native species, and overfishing. This holistic approach is presented in the status-reports by HELCOM (1990, 1996, 2001).

Area-specific patterns of ecosystem-responses to eutrophication

The identified pathways of eutrophication in the 9 subareas of the Baltic Sea are presented in Figs 3–11. From these graphs, the following general patterns, effects and consequences of long-term eutrophication can be identified for each individual region:

(1) *Gulf of Bothnia*

During the last 30 years, a slight increase in the concentration of nutrients in the Gulf of Bothnia has taken place (HELCOM, 1996; Karjalainen, 1999). Overall, however, there are no clear signs of eutrophication (Fig. 3). Contributing reasons are the open character of the Gulf with an effective water exchange (Kirkkala, 1998). Some industries around the coast act as local point sources (HELCOM, 1996). There is a potential risk that problems related to eutrophication will appear as increased frequencies and magnitudes of pelagic offshore harmful algal blooms, and as increased problems with loose lying filamentous algal mats in near shore and coastal waters.

(2) *Archipelago region*

The Archipelago region is one of the most studied areas in the Baltic Sea, and therefore the processes of eutrophication are well documented (Bonsdorff et al., 2002). These complex and shallow (mean depth only 23 m) areas act as potential ‘filters’ for nutrients

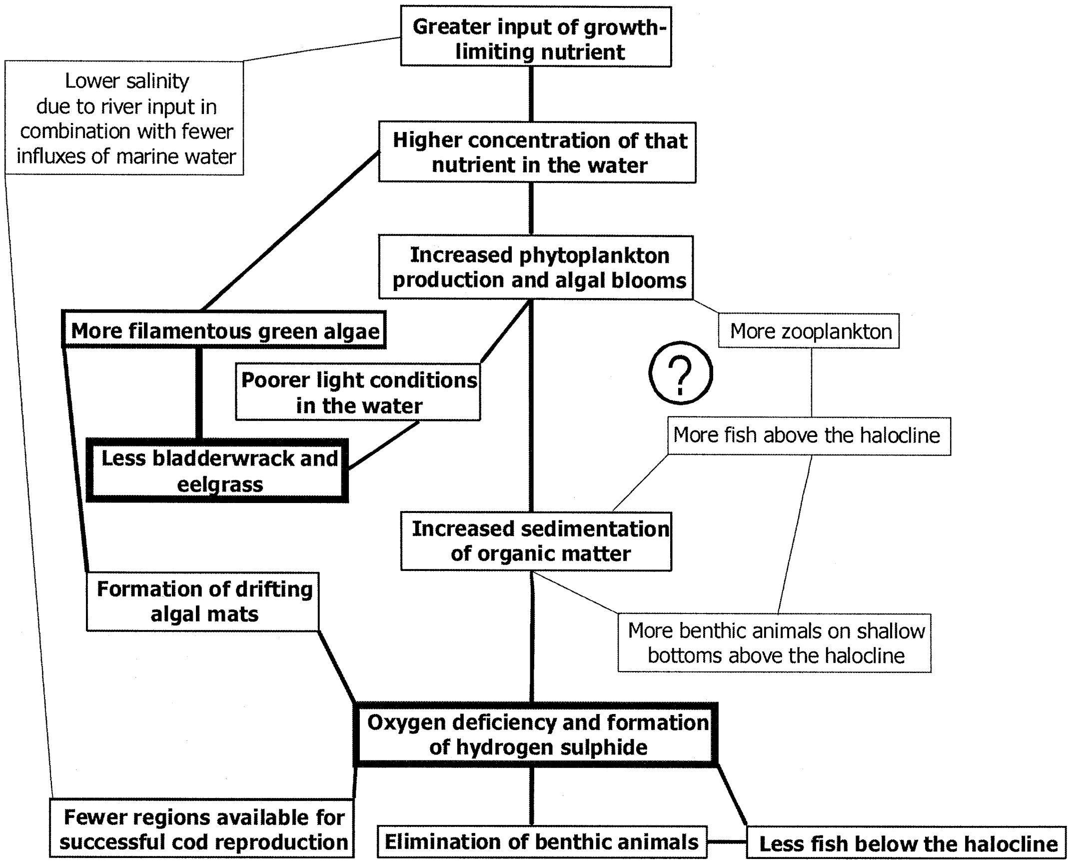

Figure 10. Belt Sea region. Eutrophication-related effects on coastal ecosystems.

and particles between the coastline and the open sea, and also between the Baltic proper and the Bothnian Sea (Jumppanen & Mattila, 1994; Bonsdorff et al.,1997a,b). As is shown in Fig. 4, the consequences of diminishing (locally disappearing) macrovegetation (perennial brown algal belts; *Fucus vesiculosus*) and the formation of dense benthic filamentous algal mats (Vahteri et al., 2000) have given rise to large changes. Changes in community composition and in zoobenthic and fish populations are also detected (Bonsdorff et al., 1997a,b; Kauppila & Bäck, 2001). In this area it is evident that nutrient over-enrichment has given rise to severe and cascading trophic effects throughout the ecosystem, leading to acute demands for management- and restoration plans.

(3) *Gulf of Finland*

The Gulf of Finland is regarded as one of the most polluted areas of the Baltic Sea (HELCOM, 1990). The Russian multimillion city of St. Petersburg and the River Neva estuary are the main, but not the only, sources of nutrient input. The lack of thresholds at the entrance of the Gulf of Finland makes the area a direct extension of the Baltic proper. As the water has an anticlockwise circulation, this results in an eastward transport along the Estonian coast, and a westward transport along the Finnish coast (HELCOM, 1996). This means that the Finnish coast is most exposed to nutrients transported from local sources around the entire Gulf. Harmful algal blooms and problems due to hypoxia are the topics of special concern in the Gulf of Finland (Fig. 5). Recently, modelling efforts have been performed to assist in planning remedies for this region (Kiirikki et al., 2001), but for the coastal waters, the total extent of the problem has only lately been described (Kauppila & Bäck, 2001). The problems are further complicated by the fact that in the inner Gulf, the system is phosphorus-limited, whereas the entrance of the Gulf shows clear nitrogen-limitation (Pitkänen, 1991). This is reflected in correlations between pelagic primary production

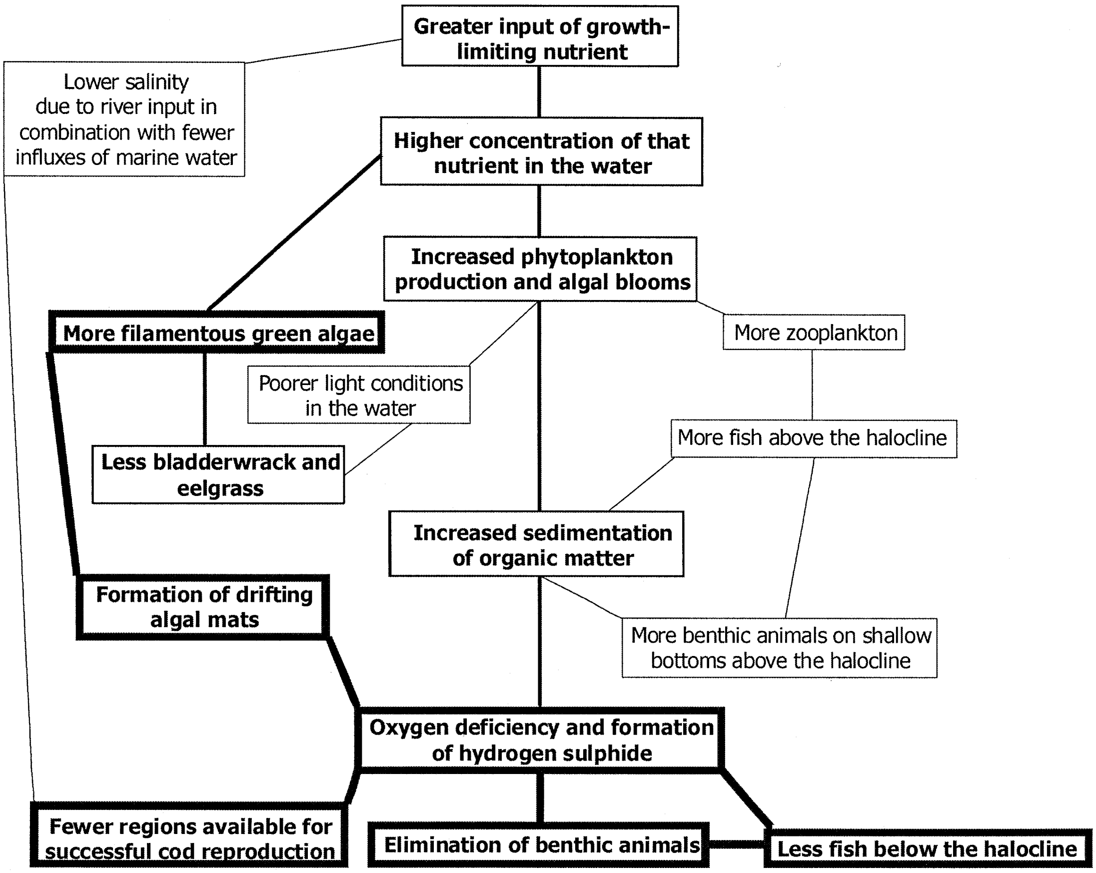

Figure 11. Kattegat. Marine eutrophication in the mixing zone between the Baltic Sea and the North Sea.

(chl-*a*) and phosphorus, nitrogen, oxygen concentrations in the bottom water, and Secchi depth of the water body. With increasing P-limitation (inner Gulf), primary production shows increasing positive relationships to phosphorus and oxygen, whereas towards the open Baltic Sea, there is a positive correlation to nitrogen, but an increasing negative correlation to transparency (Rönnberg, 2001).

(4) *Gulf of Riga*

The Gulf of Riga has a small volume and restricted water exchange, which makes it sensitive to pollution and other local sources of stress (Fig. 6). On the other hand, the Gulf has a large buffering capacity. The flat topography and extensive wetland areas on land together with a long retention time in the soil and groundwater prevent the nutrients from direct entry to the Gulf. In a Nordic Environment Research Programme 1993–1997, the Gulf of Riga was thoroughly studied, and the results showed that the nutrient concentrations in the area have been relatively stable during the 1990s (Wassmann & Tamminen, 1999). The most concrete sign of eutrophication is seen on the fish populations. The Gulf of Riga has been one of the most important fishing areas in the Baltic (Ojaveer, 1995). There has been an increase in the mortality of herring (*Clupea harengus membras*) embryos, disturbed reproduction and nursery areas for eelpout (*Zoarches viviparus*) and smelt (*Osmerus eperlanus*), while the populations of perch (*Perca fluviatilis*) have increased (Ojaveer & Gaumiga, 1995). Also, increased occurrences of annual filamentous algae affect the ecosystem (Kotta & Orav, 2001).

(5) *Gulf of Gdansk*

The Gulf of Gdansk, and especially the Puck Lagoon, has been rich and diverse in macrophytes. In the 1950s 80 taxa were present, dominated by *Fucus vesiculosus* and *Furcellaria lumbricalis*. Eutrophication-related responses, such as increase in nutrient-levels

Table 2. Guidelines for the degree of changes in all the parameters considered in relation to the scale of changes in the conceptual flow-models. the estimates are based on standards in Jumppanen & Mattila (1994), Rumohr et al. (1996), Anon. (1999), and Dahlgren & Kautsky (2001). Note that the values for the six first parameters represent summer values (August value for chlorophyll *a*).

Parameter	Effects: Small-moderate	Severe	Very serious
Transparency	3–5 m	2–3 m	<2 m
Oxygen	4–6 ml l^{-1}	2–4 ml l^{-1}	<2 ml l^{-1}
Tot-P	15–19 μg l^{-1}	19–24 μg l^{-1}	>24 μg l^{-1}
Tot-N	250–310 μg l^{-1}	310–360 μg l^{-1}	>360 μg l^{-1}
Chlorophyll *a*	1.5–2.2 μg l^{-1}	2.2–3.2 μg l^{-1}	>3.2 μg l^{-1}
Harmful Algal Blooms (HAB)	Few colonies 1–5 g m^{-3}	Formation of floating algae 5–11 g m^{-3}	Bloom-areas and layer of cyanobacteria >11 g m^{-3}
Macrovegetation	*Fucus* species, meadows of *Zostera* with associated charophytes, relatively sparse abundances of filamentous algae.	Filamentous algae as epiphytes on *Fucus*, sporadic occurrences of *Zostera*, no charophytes. Filamentous algae dominate.	No *Fucus* present. Filamentous algae dominate. Drifting algal mats and sulphur-bacteria.
Zoobenthos	Dominated by molluscs and long-lived polychaetes. Increased total biomass/ production. Low species richness, high adundance, low biomass.	Animals live close to or at the sediment. Small worms (e.g. *Capitella capitata*) dominate.	No macrofauna. Lack of bioturbation, lamination of the sediment.
Fish	Decrease in flatfishes.	Decrease in cod, increase in herring, sprat and cyprinides.	

through discharges from land, and consequently decreased transparency, have dramatically altered the environment. In the beginning of the 1990s, only 28 macrophyte taxa were left, and fast growing filamentous and annual species of *Ectocarpus* and *Pilayella* dominated on 70% of the bottoms (Fig. 7). The diminishing underwater meadows of *Zostera marina* and of perennial (brown) algae have further affected the fish communities in the Gulf. The commercial species, such as eel (*Anguilla anguilla*) and pike (*Esox lucius*) have decreased, and been replaced by cyprinids, such as roach (*Rutilus rutilus*) (Ciszewski et al., 1991, 1992). Local remedies have been implemented, and a slow recovery of the ecosystem seems to be taking place (Rönnberg, 2001).

(6) *East coast of Sweden*

The East Coast of Sweden is a long coastal area where mainly local point sources contribute to eutrophication. Most changes are seen in the biomass of macrovegetation (Fig. 8). Increases in the amounts of filamentous algae coupled to decreased transparency have lead to reductions and even disappearances of *F. vesiculosus*. The reductions in bladder wrack further affect the fauna associated with the vegetation, through food deficiencies for grazers and loss of nursery areas (Wulff & Hallin, 1994; Kautsky, 1998), and there seems to be a coupling between eutrophication, pollution and local failure of fish recruitment (Andersson et al., 2000).

(7) *Central Baltic*

The Central Baltic consists of some deep basins separated by shallow sills, restricting circulation and causing periodic stagnation (HELCOM, 1996; Karlson et al., 2002). The occurrences of cyanobacterial blooms in the Central Baltic have increased since the 1960s, mainly due to the increase in anthropogenic nutrients in the water. Warm and calm conditions in July and August further aggregate the cyanobacteria in the surface water (Finni et al., 2001 a). Cyanobacterial blooms are, however, no new phenomena in the Baltic Sea. According to Bianchi et al. (2000) blooms have occurred since the present brackish water phase of the Baltic was developed 7000 years B.P. The accumulation of organic material on the bottoms enhances the oxygen consumption, leading to hypoxia in the bottom waters, causing mortality among benthic animals (Fig. 9). The hypoxia or anoxia is, however, also a consequence of rare influxes of oxygenated, saline and subsequent prolonged stagnation periods of the water (HELCOM, 1996).

(8) *Belt Sea Region*

The effects of eutrophication in the Belt Sea Region are mainly seen as a reduction in geographic and in depth distribution of macrovegetation, in oxygen deficiency, and in formation of hydrogen sulphide (Fig. 10). In the Danish waters substantial reductions in the abundances of *Zostera marina* are observed as is reported from the Kiel Bight and the Greifswalder Bodden in the Pomeranian Bight, where also brown- and red-algal species have been reduced (e.g., Anon., 1991; Messner & von Oertzen, 1991; HELCOM, 1996). From Danish waters positive signs to measures taken can be seen, stressing the importance of broad ecological advisory programmes (Conley et al., 2002).

(9) *Kattegat*

The strong halocline in the Kattegat (Fig. 11) increases the rate of primary production in the surface waters, and the stratification of the bottom waters, which leads to regional hypoxia (Karlson et al., 2002). The hypoxia affects the zoobenthos and the ichthyofauna negatively: the Norway lobster, *Nephrops norvegicus*, and young flatfish are examples of species affected (Baden et al., 1990). The increased amounts of filamentous algae, primarily green algae, cause drifting mats before decomposition (Nielsen & Dahl, 1992; Pihl et al., 1999). This also contributes to the poor bottom conditions, and to habitat deterioration.

General patterns and measures

Irrespective of the area-specific effects of the increased loads of nutrients to the Baltic Sea, the sources are more or less similar in the whole region. The extent and the severity of the discharges may differ, however. As is seen in e.g. HELCOM (1996) and Rönnberg (2001), the major sources in the input of nutrients are derived from agriculture, industry, municipal sewage and transports. Nitrogen emissions in form of atmospheric depositions are also important, as well as local point sources, such as aquaculture and leakage from forestry.

A reduction in nutrients from agricultural runoff and industrial production has been seen in all the former communist states in Eastern Europe. This is mainly due to the collapse in economy after the end of the Soviet Union era. The use of mineral fertilizers has also decreased in the market economic countries during the 1990s as a consequence of national legislation for a more environmental-friendly agriculture (Karjalainen, 1999). It may, however, take time before any positive ecological effects are seen. Stores of nutrients in soil, groundwater and sediments must be depleted before real reductions in the water environment are detected (Conley et al., 2002). Loading from industries and other point sources is less complicated to manage than the municipal sewage water or agricultural runoff, which can be more diffuse. Scattered dwellings on the countryside are impossible to connect to wastewater treatment plants, and the situation is therefore under better control in more densely populated areas. In the former socialist countries, the wastewater treatment is still under construction (Karjalainen, 1999), but progress is being made (Finni et al., 2001 b). In order to focus our efforts to combat eutrophication, it is important that we know the components and their linkage in any regional ecosystem that suffers from nutrient over-enrichment. Improvements in nutrient reductions in for example Sweden are presented in Elmgren & Larsson (2001).

Eutrophication is a serious problem in the entire Baltic Sea area. Despite the fact that more or less the same ecological parameters are involved in the processes in the different parts of the sea (Wulff et al., 2001; Bonsdorff et al., 2002), the effects and consequences may vary, which underlines the importance of area-specific assessment and advice, measures and ecosystem rehabilitation. We must, however, be aware of the varying and potentially long time span before positive signs of reductions are seen in the aquatic environment.

Acknowledgements

This study is a part of the research programme MARE ('Marine Research on Eutrophication'; http://www.mare.su.se).

References

Andersson, J., J. Dahl, A. Johansson, P. Karås, J. Nilsson, O. Sandström & A. Svensson, 2000. Utslagen fiskrekrytering och sviktande fiskbestånd i Kalmar läns kustvatten. Sweden National Board of Fisheries, Report 5, 42 pp. (in Swedish with an English summary).

Anonomous, 1991. Eutrophication of coastal waters. Coastal water quality management in the county of Funen, Denmark, 1976–1990. Legislation – nutrient loads and eutrophication effects – causes and trends. Funen County Council Department of Technology and Environment, Hagen og Sørensen, 288 pp.

Anonomous, 1999. Kust och hav. Bedömningsgrunder för miljökvalitet. Naturvårdsverkets rapport 4914, Uppsala, 134 pp. (in Swedish).

Anonomous, 2001. Environmental quality in Swedish coast and sea, official statistics of Sweden. Naturvårdsverket, Statistiska centralbyrån, Db Grafiska, Örebro, 98 pp. (in Swedish).

Baden, S. P., L.-O. Loo, L. Pihl & R. Rosenberg, 1990. Effects of eutrophication on benthic communities including fish: Swedish West Coast. Ambio 19: 113–122.

Bernes, C. 1988. Sweden's marine environment – ecosystems under pressure. National Swedish Environment Protection Board, 207 pp.

BERNET, 2000a. Aquatic Monitoring and Assessment. Volume I, Synthesis BERNET Theme Report Fyn County, Odense, Denmark, 50 pp.

BERNET, 2000b. Water Quality Planning. BERNET Theme Report. Fyn County, Odense, Denmark, 156 pp.

Bianchi, T. S., P. Westman, C. Rolff, E. Engelhaupt, T. Andrén & R. Elmgren, 2000. Cyanobacterial blooms in the Baltic Sea: natural or human-induced? Limnol. Oceanogr. 4: 716–726.

Bonsdorff, E., C. Rönnberg & K. Aarnio, 2002. Some ecological properties in relation to eutrophication in the Baltic Sea. Hydrobiologia 475/476: 371–377.

Bonsdorff, E., E. M. Blomqvist, J. Mattila & A. Norkko, 1997a. Coastal eutrophication: causes, consequences and perspectives in the Archipelago areas of the northern Baltic Sea. Estuar. Coast. Shelf Sci. 44: 63–72.

Bonsdorff, E., E. M. Blomqvist, J. Mattila & A. Norkko, 1997b. Long-term changes and coastal eutrophication. Examples from the Åland islands and the Archipelago Sea, northern Baltic Sea. Oceanol. Acta 20: 319–329.

Christensen, P. B. 1998. The Danish marine environment: has action improved its state? Havsforskning fra Miljøstyrelsen no. 62, Danish Environmental Protection Agency, Ministry of Environment and Energy, Denmark, 120 pp.

Ciszewski, P., L. Kruk-Dowgiallo & E. Andrulewicz, 1991. A study on pollution of the Puck Lagoon and possibility of restoring the Lagoon's original ecological state. Acta Ichthyologica et Piscatoria, XXI supp. (Proc. 11th Baltic Marine Biologists): 29–37.

Ciszewski, P., I. Ciszewska, L. Kruk-Dowgiallo, A. Osowiecki, D. Rybicka, J. Wiktor, M. Wolska-Pys, L. Zmudzinski & D. Trokowicz, 1992. Trends of long-term alterations of the Puck Bay ecosystem. Studia i materialy oceanologiczne no. 60. Marine Biology 8: 33–84.

Cloern, J. E., 2001. Our evolving conceptual model of the coastal eutrophication problem. Mar. Ecol. Prog. Ser. 210: 223–253.

Conley, D. J., S. Markager, J. Andersen, T. Ellermann & L. M. Svendsen, 2002. Coastal eutrophication and the Danish national aquatic monitoring and assessment program. Estuaries 25: 848–861.

Dahlgren, S. & L. Kautsky, 2001. Patterns and changes in benthic vegetation in the Baltic Sea area linked to eutrophication processes. Dept. of Botany, Stockholm University & MARE Report, 62 pp.

Elliott, M. & V. N. de Jonge, 2001. The management of nutrients and potential eutrophication in estuaries and other restricted water bodies. Hydrobiologia 475/476: 513–524.

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.

Elmgren, R. & U. Larsson, 2001. Nitrogen and the Baltic Sea: managing nitrogen in relation to phosphorus. The Scientific World 1(S2): 371–377.

Finni, T., K. Kononen, R. Olsonen & K. Wallström, 2001a. The history of cyanobacterial blooms in the Baltic Sea. Ambio 30: 172–178.

Finni, T., S. Laurila & S. Laakkonen, 2001b. The history of eutrophication in the sea area of Helsinki in the 20th century long-term analysis of plankton assemblages. Ambio 30: 264–271.

Gray, J. S., 1992. Eutrophication in the sea. In Colombo, G. C., I. Ferrari, U. V. Ceccherelli & R. Rossi (eds), Proc. 23rd EMBS. Olsen & Olsen, Fredensborg: 3–13.

Gunnarsson, J., D. Broman, P. Jonsson, M. Olsson & R. Rosenberg, 1995. Interactions between eutrophication and contaminants: towards a new research concept for the European aquatic environment. Ambio 24: 383–385.

HELCOM, 1990. Second periodic assessment of the state of the marine environment of the Baltic Sea, 1984–1988; background document. Baltic Sea Environ. Proc. No. 35B, 432 pp.

HELCOM, 1996. Third periodic assessment of the state of the marine environment in the Baltic Sea 1989–1993; background document. Baltic Sea Environ. Proc. No. 64B, 252 pp.

HELCOM, 2002. Fourth periodic assessment of the state of the environment of the Baltic marine area 1994–1998. Baltic Sea Environ. Proc. No. 82B, 215 p.

Jansson, B.-O. & H. Velner, 1995. The Baltic: the sea of surprises. In Gunderson, L. H., C. S. Holling & S. S. Light (eds), Barriers and Bridges to the Renewal of Ecosystems and Institutions. Columbia University Press, New York: 292–372.

Jumppanen, K. & J. Mattila, 1994. The development of the state of the Archipelago Sea and the environmental factors affecting it. Lounais-Suomen Vesiensuojeluyhd. Julk. 82: 1–206 (in Finnish, with English summary).

Jørgensen, B. B. & K. Richardson, 1996. Eutrophication in coastal marine ecosystems. Coastal and Estuarine Studies 52. American Geophysical Union, Washington, DC: 1–272.

Karjalainen, M., 1999. Effect of nutrient loading on the development of the state of the Baltic Sea – an overview. Walter and Andrée de Nottbeck Foundation Scientific Reports No. 17, 35 pp.

Karlson, K., R. Rosenberg & E. Bonsdorff, 2002. Temporal and spatial large-scale effects of eutrophication and oxygen deficiency on benthic fauna in Scandinavian and Baltic waters – a review. Oceanogr. Mar. Biol. Annu. Rev. 40: 427–489.

Kauppila, P. & S. Bäck, 2001. The state of Finnish coastal waters in the 1990s. The Finnish Environment 472. Finnish Environment Institute, Helsinki: 1–134.

Kautsky, H., 1998. Vegetationsklädda bottnar. Östersjö '97, årsrapport från miljöövervakningen i egentliga Östersjön Juli 1998 (Swedish marine monitoring in the Baltic proper July 1998), Stockholm Marine Research Centre, Sweden: 34–35 (in Swedish).

Kiirikki, M., A. Inkala, H. Kuosa, H. Pitkänen, M. Kuusisto & J. Sarkkula, 2001. Evaluating the effects of nutrient load reduction on the biomass of toxic nitrogen-fixing cyanobacteria in the Gulf of Finland, Baltic Sea. Boreal Env. Res. 6: 131–146.

Kirkkala, T., 1998. Miten voit Saaristomeri? Sydvästra Finlands Miljöcentral. Kirjapaino Astro Oy, Åbo (in Finnish, also available in Swedish), 70 pp.

Kotta, J. & H. Orav, 2001. Role of benthic macroalgae in regulating macrozoobenthic assemblages in the Väinameri (north-eastern Baltic Sea). Annales Zoologici Fennici 38: 163–171.

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

Leppäkoski, E. & E. Bonsdorff, 1989. Ecosystem variability and gradients. Examples from the Balyic Sea as a background for hazard assessment. In Landner, L. (ed.), Chemicals in the Aquatic Environment. Springer-Verlag, Berlin: 6–58.

Messner, U. & J. A. von Oertzen, 1991. Long-term changes in the vertical distribution of macrophytobenthic communities in the Greifswalder Bodden. Acta Ichthyologica et Piscatoria, XXI Suppl. (Proc. 11th Baltic Marine Biologists): 135–143.

Nielsen, R. & K. Dahl, 1992. Macroalgae at Briseis Flak, Schultzs Grund and Store Middelgrund, stone reefs in the southern and eastern part of Kattegat, Denmark. In Bjørnestad, E., Hagerman, L. & Jensen, K. Proc. 12th Baltic Marine Biologists Symp. Olsen & Olsen, Fredensborg: 109–118.

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

Ojaveer, E. & R. Gaumiga, 1995. Cyclostomes, fishes and fisheries. In Ojaveer, E. (ed.), Ecosystem of the Gulf of Riga between 1920 and 1990. Estonian Academy Publishers, Tallinn: 212–267.

Ojaveer, E., 1995. Large-scale processes in the ecosystem of the Gulf of Riga. In ojaveer, E. (ed.), Ecosystem of the Gulf of Riga between 1920 and 1990. Estonian Academy Publishers, Tallinn: 268–277.

Partanen-Hertell, M., P. Harju-Autti, K. Kreft-Burman & D. Pemberton, 1999. Raising environmental awareness in the Baltic Sea Area. The Finnish Environment 327. Finnish Environment Institute, Helsinki: 1–128.

Pihl, L., A. Svenson, P.-O. Moksnes & H. Wennhage, 1999. Distribution of green algal mats throughout shallow soft bottoms of the Swedish Skagerrak archipelago in relation to nutrient sources and wave exposure. J. Sea Res. 41: 281–294.

Pitkänen, H. 1991. Nutrient dynamics and trophic conditions in the eastern Gulf of Finland: the regulatory role of the Neva Estuary. Aqua Fennica 21: 105–115.

Rabalais, N. N. & R. E. Turner, 2001. Coastal hypoxia. Consequences for living resources and ecosystems. Coastal and Estuarine Studies 58. American Geophysical Union, Washington, DC, 463 pp.

Rumohr, H., E. Bonsdorff & T. H. Pearson, 1996. Zoobenthic succession in Baltic sedimentary habitats. Arch. Fish. Mar. Res. 44: 179–214.

Rönnberg, C., 2001. Effects and consequences of eutrophication in the Baltic Sea – specific patterns in different regions. Licentiate thesis, Åbo Akademi University, Åbo, Finland, 140 pp.

Skei, J., P. Larsson, R. Rosenberg, P. Jonsson, M. Olsson & D. Broman, 2000. Eutrophication and contaminants in aquatic ecosystems. Ambio 29: 184–194.

Stålnacke, P., 1996. Nutrient loads to the Baltic Sea. PhD thesis, Linköping Studies in Arts and Science, No. 146, 78 pp.

Vahteri, P., A. Mäkinen, S. Salovius & I. Vuorinen, 2000. Are drifting algal mats conquering the bottom of the Archipelago Sea, SW Finland? Ambio 29: 338–343.

Wassmann, P. & T. Tamminen, 1999. Pelagic eutrophication and sedimentation in the Gulf of Riga: an introduction. J. Mar. Syst. 23: 1–10.

Wulff, F. & A.-K. Hallin, 1994. Näringsämnen och hydrografi. Östersjö '93, årsrapport från den marina miljöövervakningen juni 1994 (Swedish marine monitoring June 1994), Stockholm Marine Research Centre, Sweden, 17–20 (in Swedish).

Wulff, F., E. Bonsdorff, I-M. Gren, S. Johansson & A. Stigebrandt, 2001. Giving advice on cost effective measures for a cleaner Baltic Sea: a challenge to science. Ambio 30: 254–259.