Coastal Eutrophication: Causes, Consequences and Perspectives in the Archipelago Areas of the Northern Baltic Sea

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Coastal eutrophication has, since the early 1970s, become the foremost threat to the marine ecosystem of the Archipelago Sea (the Åland Islands and the SW Finnish archipelago) in the northern Baltic Sea. Nutrient levels (N, P) have risen significantly both in coastal areas and basin-wide, which has led to increased primary production (both pelagic and benthic), decreased transparency, increasing amounts of oxygen-consuming drift-algal mats at shallow and intermediate bottoms, and changes in zoobenthos and fish communities.

Local nutrient input originates mainly from agriculture, riverine input, municipal wastewaters, aquaculture and airborne loading. Levels indicate an even distribution of nutrients from the inner areas to the open coast, reducing the natural diluting or filtering effects of the mosaic archipelago system.

Future prospects for the archipelago and coastal ecosystem are poor unless local and regional measures to drastically reduce nutrient levels of the archipelago are undertaken. Even then, positive effects are unlikely to show immediately.

Introduction

The Baltic Sea, with a short and dramatic geological history (about 10,000 years with alterations between limnic, marine and brackish conditions) and marked physical, chemical and biological gradients characterizing the system (Voipio, 1981; Leppäkoski & Bonsdorff, 1989), is one of the most severely affected and best studied sea areas of the world. The awareness of environmental hazards stems from the 1960s and 1970s, when the effects of pollution (heavy metals, organochlorines, oil spills) and eutrophication became obvious. Since the mid-1970s, the state and condition of the Baltic Sea and its sub-regions have been monitored closely under the supervision of the Baltic Marine Environment Protection Commission—Helsinki Commission (HELCOM, 1990). As one result of this awareness, and of measures taken consequently, the levels of 'traditional' pollutants in the system have decreased, and some endangered species have recovered both in terms of levels of toxicants and decreased habitat disturbance (Elmgren, 1989; HELCOM, 1990). Not as much attention has been focused on the remedial measures associated with eutrophication, however, although the phenomenon has been documented in some detail at all levels in the marine ecosystem both in coastal waters and in the open sea (e.g. Cederwall & Elmgren, 1980, 1990; Larsson et al., 1985; Kautsky et al., 1986; Kääräniemi et al., 1988; Elmgren, 1989; Hansson & Rudstam, 1990; Kautsky et al., 1991; Bonsdorff & Blomqvist, 1992; Nehring, 1992, 1994; Schulz et al., 1992; Pitkänen, 1994; Wulff et al., 1994; Bonsdorff et al., 1997).

The state of the coastal areas was emphasized by HELCOM (1993a,b), and two archipelago areas (the Archipelago Sea and the Åland archipelago) were listed as environmental hot-spots, with eutrophication as the main threat to the ecosystem, and agriculture and fish farming (net cages with rainbow trout; Oncorhynchus mykiss) as the main sources. As the effects of eutrophication can be found at all levels of coastal ecosystem organization, the authors feel that it is of importance to analyse some pathways of the chain reaction caused by increased nutrient levels (Bonsdorff et al., 1997).

Eutrophication has recently been defined as the effects of 'an increase in the supply of organic matter to an ecosystem' (Nixon, 1995), which is largely generated by an increase of nutrient input followed by an increased primary (and secondary) production. Eutrophication has also been recognized as one of the major threats to (coastal) marine ecosystems on a global scale (Nixon, 1990; Gray, 1992; Pearl, 1995), and some comparisons have been made on European
and North Atlantic scales (Dederen, 1992; de Jonge et al., 1994). For the Baltic Sea, the coastal areas have been recognized as specifically vulnerable (Cederwall & Elmgren, 1990; Schulz et al., 1992; HELCOM, 1993b; Anonymous, 1994; Bonsdorff et al., 1997).

As the archipelago of SW Finland (northern Baltic Sea) is the most extensive and island-rich archipelago of the Baltic Sea and possibly the world (v. Numers, 1995), the aims of this paper are to briefly describe the present status of eutrophication in this area, analyse the causes of eutrophication (local vs basin-wide), illustrate some ecological consequences, and discuss possible perspectives in the light of the present situation.

Study area and methods

The Baltic Sea is an enclosed basin, connected to the world ocean only through the narrow and shallow Danish Sounds (Voipio, 1981; Leppäkoski & Bonsdorff, 1989). The drainage area is large, and populated by an estimated 70–80 million people (Figure 1). The geological history of the Baltic basin is still influenced by the previous glaciation, some 10–15 000 years ago, undergoing relatively rapid changes (Voipio, 1981). Thus, in the northern parts, land uplift prevails at 50–100 cm century⁻¹, constantly forming new coastal and archipelago areas. Water exchange is slow (long retention time), the inflow of freshwater is large, and salinity is low with extreme vertical and horizontal gradients (including a permanent halocline at about 50–70 m depth in the Baltic proper) as a consequence (Mäikki & Tamsalu, 1985; Leppäkoski & Bonsdorff, 1989; de Jonge et al., 1994). The salinity ranges from 4 to 8 from the inner archipelago to the open coast. In the archipelago areas, bottom topography is characterized by sills and trenches that further reduce the exchange of deep water. For the entire Baltic Sea, nutrient concentrations in the water and organic content of the sediments have increased significantly during this century through increased sedimentation (Jonsson & Carman, 1994; Wulff et al., 1994).

The Archipelago Sea and the Åland archipelago (59°45'–60°45'N and 19°30'–23°00'E; Figure 2) are characterized by an enormous topographic complexity (Figure 3), including some 30 500 islands, over 20 000 km shoreline covering an area of more than 15 000 km². The average water depth is only 23 m, but has some deep trenches reaching over 100 m. The mosaic structure and the sharp environmental gradients (salinity, temperature, oxygen, exposure etc.) create numerous biotopes and complicated ecological webs (Bonsdorff & Blomqvist, 1993; v. Numers, 1995). As the topography is complex and the water is shallow, much of the primary production is linked to the benthic system (Kautsky & Kautsky, 1995). The archipelago is affected by nutrient inflow from a multitude of sources, and hydrographically, physically and biologically, such areas may act as a buffer or filter between the coastline and the open sea. This has long been the case for the Archipelago Sea, where the widespread mosaic archipelago has had a diluting effect on nutrient levels. However, with the high diversity of nutrient sources to the system, the diluting effects today are less evident (Jumppanen & Mattila, 1994; Bonsdorff et al., 1997).

The material for this analysis is collected from recent literature for the area (Table 1), and data from unpublished reports.
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Results and discussion

Nutrient increase affects the ecosystem

The state of the marine archipelago ecosystem has undergone rapid changes since the late 1960s (Jumppanen & Mattila, 1994; Bonsdorff et al., 1997), and consequences of eutrophication are recorded throughout the system (Table 1; references therein). Thus, increased nutrient levels have lead to altered N/P ratios, increased sedimentation rates and increased input of organic matter to the benthic system. This has lead to increased pelagic and benthic primary production with both structural and functional changes in the system (Bonsdorff et al., 1997), increased turbidity and reduced transparency of the water, reduced oxygen reserves even above the halocline, increased occurrences of benthic sulphur bacteria indicating benthic anoxia, and increased frequency and amounts of drifting benthic algal mats (Bonsdorff, 1992; Norkko & Bonsdorff, 1996a,b). These changes have significantly affected both zoobenthos and fish (Table 1; Bonsdorff et al., 1997). Although similar changes (when measured at several trophic levels) have also been recorded in the open Baltic Sea, the effects of eutrophication are generally more pronounced in the coastal areas (Schulz et al., 1992). Further, in the open sea, nitrogen is generally acknowledged as the limiting nutrient, but in the
TABLE 1. Examples of indications and consequences of eutrophication in the archipelago and coastal waters of the northern Baltic Sea

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Trend</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>N/P ratio</td>
<td>Decreasing</td>
<td>Jumppanen &amp; Mattila (1994), Bonsdorff et al. (1997)</td>
</tr>
<tr>
<td>Si pool</td>
<td>Decreasing</td>
<td>Wulff et al. (1994), Bonsdorff et al. (1997)</td>
</tr>
<tr>
<td>Sedimentation, organic matter</td>
<td>Increasing</td>
<td>Jonsson &amp; Carman (1994) (entire Baltic basin)</td>
</tr>
<tr>
<td>Sulphur bacteria (benthic)</td>
<td>Increasing</td>
<td>Rosenberg &amp; Diaz (1993)</td>
</tr>
<tr>
<td>Pelagic primary production</td>
<td>Increasing</td>
<td>Grönlund &amp; Leppänen (1990), Jumppanen &amp; Mattila (1994)</td>
</tr>
<tr>
<td>Frequency of toxic blooms</td>
<td>Increasing</td>
<td>Schultz et al. (1992), Leppänen et al. (1995)</td>
</tr>
<tr>
<td>Growth of annual algae</td>
<td>Increasing</td>
<td>Rönberg et al. (1985), Kautsky et al. (1986)</td>
</tr>
<tr>
<td>Fucus vesiculosus</td>
<td>Decreasing</td>
<td>Bonsdorff (1992), Norkko &amp; Bonsdorff (1996a,b)</td>
</tr>
<tr>
<td>Zoobenthos</td>
<td>Increasing</td>
<td>Anonymous (1994)</td>
</tr>
<tr>
<td>Dead bottoms</td>
<td>Increasing</td>
<td>Hansson &amp; Rudstam (1990) (entire Baltic basin)</td>
</tr>
<tr>
<td>Fish standing stocks</td>
<td>Increasing</td>
<td>Bonsdorff et al. (1997)</td>
</tr>
</tbody>
</table>

Baltic Sea, phosphorus becomes more important towards the gulfs of Bothnia and Finland, and in the archipelago, the limiting nutrient is often phosphorus (Jumppanen & Mattila, 1994). Thus, the pelagic ecosystem of the inner and middle archipelago functions in a different manner than that of the open coastal zone, with intricate consequences (Smith, 1984).

Relevance of local sources: the importance of aquaculture

Nutrient load and organic enrichment from the main population and industrial centre in the area, the City of Turku with 160 000 inhabitants, and a surrounding area with about 40 municipal and industrial wastewater treatment plants, has decreased dramatically for BOD7 (80% reduction) and phosphorus (reduction by over 90%), whereas the nitrogen loading has remained almost constant since the early 1970s (Figure 4). At present, the nitrogen reduction in municipal wastewater treatment plants is about 30% with further reduction anticipated in the near future. As a direct consequence of this, the trend in nutrient levels in the inner archipelago waters of the Archipelago Sea is decreasing (Jumppanen & Mattila, 1994; Bonsdorff et al., 1997).

In the central and outer parts of the entire archipelago area, the trend is the opposite (Figure 5). At monitoring stations in the outermost archipelago areas, least affected by loading from land, the increase has been significant for both phosphorus and nitrogen. This can partly be explained by the overall increase in the open Baltic, but local sources are also important. In this case, fin fish culture (mainly rainbow trout; Oncorhynchus mykiss) was used as an example of a local source of nutrients and organic enrichment of visible importance. These farms affect the ecosystem by a constant, year-round input of nutrients, which prolongs the season for primary production, and eliminates the natural nutrient limitation. The distribution of fin fish farms in the archipelago of SW Finland covers the entire area concentrated to the middle and outer regions (Figure 6). In the Åland archipelago, 35-40 fish farms produce about 5000 tonnes year \(^{-1}\), with an average production of some 150 tonnes year \(^{-1}\) per unit (1995), whilst about 100 operating units in the Archipelago Sea produce about the same amount (average farm size about 50 tonnes year \(^{-1}\)). All these farms may be considered as 'local point sources', but it is evident that their pooled area of influence is much larger (Figure 6). The loading of nutrients (nitrogen and phosphorus) from the farms to the Åland archipelago area is estimated at 40 tonnes of phosphorus and 270 tonnes of nitrogen year \(^{-1}\) (Provincial Government of Åland). This equals the loading from
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FIGURE 5. Long-term (1968-93) trends (winter values) in nutrient concentrations (phosphorus, □, \( y=0.51x-19.8, r=0.82, P<0.01 \); nitrogen, ○, \( y=7.36x-288.31, r=0.74, P<0.01 \)) in the productive water layer (0-10 m) at Station Kumlinge in the outer Archipelago Sea (encircled triangle in Figure 3).

treated municipal wastewaters (90% reduction for phosphorus and 30% reduction for nitrogen) of approximately 370 000 persons for phosphorus, and 90 000 persons for nitrogen. The entire local population in the Åland area is 25 000 inhabitants. The 35-40 operating fish farms thus contribute 15 times the load from municipal wastewater for phosphorus, and 3-6 times the nitrogen input through treated wastewater. For the entire Archipelago Sea and Åland archipelago, aquaculture alone stands for an input of phosphorus corresponding to about 740 000 person-equivalents, and for nitrogen, 180 000 person-equivalents. Thus, in the archipelago environment, the impact of aquaculture in terms of eutrophication is highly significant. For the marine coastal and archipelago ecosystem, the gross effects of eutrophication are shown in Table 1. Such effects are also clearly detectable for specific sites or local clusters of fish farms, where the increase in fish production is inversely related to the state of the zoobenthic communities at both shallow (less than 10 m) and deep (below 20 m) bottoms (Figure 7; Jumppanen & Mattila, 1994).

The ‘healthy zone’ gets narrower

As the archipelago ecosystem is stressed from all directions (Figure 3), the need for accurately selecting monitoring stations or areas becomes more important (Figure 2). The innermost areas have been studied for decades, and proven to be affected by pollution and to be highly variable over time (Leppäkoski, 1975; Jumppanen & Mattila, 1994; Bonsdorff et al., 1997). The open sea area has been shown to be influenced by the halocline, causing long periods of hypoxia or anoxia (Andersin & Sandler, 1989, 1991). Simultaneously, increased phytobenthic production in the archipelago has lead to an increase in benthic drifting algal mats, presently covering large areas of intermediate depths in the archipelago. These mats, with an average biomass of 300 g dry weight m\(^{-2}\), or 2000 g wet weight m\(^{-2}\) (1995), are highly oxygen-demanding, and have serious effects on both zoobenthos and fish (Bonsdorff, 1992; Norkko & Bonsdorff, 1996a). The intermediate depth zone in the outer archipelago is normally not affected by hypoxia or anoxia, but the increasing amounts of drift algal mats induce hypoxia to the sediment, with effects on nutrient dynamics and zoobenthic community development (Bonsdorff, 1992; Norkko & Bonsdorff, 1996a). Similarly, negative effects of algal mats and loose-lying macroalgae have also been described from other sea areas, and the need for monitoring them has been emphasized (Everett, 1994;,

<table>
<thead>
<tr>
<th>Year</th>
<th>BOD7</th>
<th>Nitrogen</th>
<th>Phosphorus</th>
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<tbody>
<tr>
<td>1970</td>
<td>10000</td>
<td>9000</td>
<td>8000</td>
</tr>
<tr>
<td>1975</td>
<td>7000</td>
<td>6000</td>
<td>5000</td>
</tr>
<tr>
<td>1980</td>
<td>4000</td>
<td>3000</td>
<td>2000</td>
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<td>1985</td>
<td>1000</td>
<td>900</td>
<td>800</td>
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<tr>
<td>1990</td>
<td>300</td>
<td>200</td>
<td>100</td>
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<tr>
<td>1995</td>
<td>60</td>
<td>50</td>
<td>40</td>
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Aland Sea

FIGURE 6. The distribution of fish farms (○, open-water net cages; ▲, land-based hatcheries) in the SW Finnish archipelago in 1993–1995. Fish farm production in the Åland Sea (35–40 operating farms) is \( \approx 5000 \) tonnes year\(^{-1} \) and \( \approx 5000 \) tonnes year\(^{-1} \) in the Archipelago Sea (about 100 operating farms). H, Houtskär area.

Kolbe et al., 1995). Thus, the transition zone between the archipelago and the open sea becomes ecologically more important as a recruitment area for both the deeper offshore areas and the archipelago system. Sampling zoobenthos in depth strata along the archipelago gradient indicates that the community composition is changed and the number of species is slightly reduced with depth, whereas abundance, primarily due to increased abundance of amphipods, increases with depth. Biomass values are highest in the central archipelago zone, and significantly lower with increasing depth as a consequence of amphipod dominance over bivalves (Elmgren et al., 1984; Bonsdorff, 1988). Benthic biomass in the archipelago has almost doubled since the 1970s (Bonsdorff et al., 1991, 1997). The intermediate zone (and depth stratum) offers a mixture of both the characteristic archipelago benthos and the open-sea benthos, and should therefore be included in coming monitoring. This zone has so far been neglected in much of the monitoring in Finnish waters, even though biomass changes in benthic macrofauna along the depth gradient were indicative of eutrophication in Swedish coastal waters in the 1970s (Cederwall & Elmgren, 1980, 1990) and other areas of the Baltic Sea (Brey, 1986; Baden et al., 1990; Weigelt, 1991; Prena, 1995). Long-term monitoring in the archipelago has concentrated on hydrographic parameters (including nutrient concentrations) and zoobenthos, with time sets starting in the 1960s (Leppäkoski, 1975; Jumpanen & Mattila, 1994; Bonsdorff et al., 1997). Meiofauna has rarely

FIGURE 7. The development of fish farming in one area (Houtskär in the Archipelago Sea; Figure 6) in 1977–1991 (a), and the subsequent deterioration of the zoobenthic communities in the area at shallow (<10 m) (b) and deep (>20 m) (c) bottoms. A, total abundance (individuals m\(^{-2}\), hatched bars); B, total biomass (g wet weight m\(^{-2}\), solid bars), S, total number of species (■).
been analysed in the Finnish archipelago (Elmgren et al., 1984). As meiofauna community responses to organic enrichment are small (or suppressed by the macrofauna) in comparison to those of the macrofauna (Widbom & Frithsen, 1995), macrozoobenthos seems to be more important as a tool in monitoring.

The benthic biota correlate with the environment

In connection with analysing the benthic community, several environmental parameters have been analysed, and various methods are employed in the Åland archipelago. Hence, the following have been measured: the hydrography and nutrients in the bottom water, the organic content (loss on ignition) of the surface sediment and (through Sediment Profile Imaging, as described in Rosenberg & Diaz, 1993) sediment type; surface relief of the sediment; softness (as penetration of the gear used), the redox potential discontinuity layer (RPD) in the sediment; and location of possible dark (anoxic) layer in the sediment. These were correlated with the number of macrobenthic species present, total community abundance, and total community biomass. The number of species recorded has a prime significant positive correlation with oxygen saturation of the bottom water ($P<0.05$; $r=0.40$). Total abundance correlates best with organic content of the sediment ($P<0.001$; $r=0.69$), sediment type ($P<0.001$; $r=0.68$), and RPD layer ($P<0.001$; $r=0.61$). Biomass, again, correlates best with organic content of the sediment ($P<0.05$; $r=0.44$). Biomass and species number also correlate significantly ($P<0.01$; $r=0.59$), and the present authors have shown previously that the benthic community parameters correlate significantly with oxygen, organic content and nutrients (primarily nitrogen content) in the bottom water of the same area (Bonsdorff et al., 1991). Thus, it is evident that the changes recorded in the environment as a consequence of increased nutrient and organic input, are directly reflected in the sediment [as shown by Jonsson & Carman (1994) in their sediment studies] and further in the zoobenthos (Pearson & Rosenberg, 1978, 1987). With the increasing trends in overall eutrophication of the archipelago ecosystem, the problems for monitoring increase, and the question of reliable control sites becomes crucial (Chapman et al., 1995).

Concluding remarks

Eutrophication in the marine environment has attracted much attention lately, and several conceptual models have been put forward in order to facilitate the understanding of the process, including analysis of multiple factors (Kaydy & Cocolossi, 1990) and couplings to pollutants and contaminants (Gunnarsson et al., 1995). The evident processes of eutrophication of Baltic archipelago waters is summarized in Figure 8 and Table 1. The model (Figure 8) is limited to published information (references given in the graph), with the purpose of illustrating the complexity of the couplings and effects arising from the seemingly simple impact of increased nutrient input to the aquatic environment. The increase of nutrient concentrations in the sea stems from numerous sources, and it is important to separate local and regional aspects from a basin-wide analysis. In the archipelago waters of SW Finland, local input is highly important, although the total input to the Baltic Sea from this region may be only a fraction of the entire nutrient load in the Baltic Sea. Due to topography and water movements, local sources primarily affect local ecosystems. In order to tackle the problems caused by eutrophication, management measures are vital. Marine ecologists can participate with adequate monitoring and interpretation of long-term data (or data involving spatial variability due to environmental gradients), but the final measures will have to be decided upon by politicians with financial considerations. Legal and economic feedback loops to environmental monitoring seem to offer the best way to improve the state of the sea (Gray, 1994; Hildén, 1995). In this context, monitoring must not just be a statistical tool, but also be a tool for giving (early) warning signals (Gray, 1990), which should be taken seriously, as no safe limits of environmental stress can be defined (Leppänen et al., 1995; MacGarvin, 1995). Warnings must be given in time, however, as future ecosystem response may already be determined by the time the signals are recorded. Thus, as an example, Barica (1993) classified algal community responses at early warning levels as 'sustainable', at serious warning levels as 'reaching the limits', and at late warning levels as 'unsustainable'. This is also true of the risk of potentially toxic algal blooms and their interactions with the soft-bottom biota (Olsgaard, 1993; Pearl, 1995). As the topography of the archipelago waters in the northern Baltic Sea is highly complex, modelling of the water exchange and nutrient dynamics is very difficult in comparison to open coastal systems, such as the Gulf of Riga (Yurkovskis et al., 1993). As episodic events, such as hypoxia or anoxia, occur frequently, modelling is even more speculative (Chapelle et al., 1994), and it seems that pinpointing sources and effects of eutrophication to facilitate management and measures is of prime importance.
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