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Hypoxia and cyanobacterial blooms are not natural features of the Baltic Sea

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Abstract

During the last century (1900s) industrialized forms of agriculture and human activities have caused extensive eutrophication of Baltic Sea waters. As a consequence, the Baltic Sea developed a hypoxic zone that has caused serve ecosystem disturbance. Climate forcing has also been proposed to be responsible for the reported trends in hypoxia (<2 mg/l O_2) both during the last c. 100 years and during the Medieval Period. By contrast, investigations on the degree of anthropogenic forcing on the ecosystem on long time-scales (millennial) have not been thoroughly addressed. This paper critically examines evidence for anthropogenic disturbance of the marine environment beyond the last century through the analysis of the population growth, technological development and land-use changes in the drainage area. Natural environmental changes, i.e. changes in the morphology and depths of the Baltic basin and the sills, were probably the main driver for large-scale hypoxia during the early Holocene (8000–4000 cal. yr BP). We show that hypoxia during the last two millennia has followed the general expansion and contraction trends in Europe and that human perturbations have been an important driver for hypoxia during that time. Hypoxia occurring during the Medieval Period coincides with a doubling of the population (from c. 4.6 to 9.5 million), a massive reclamation of land in both established and marginal cultivated areas and significant increases in soil nutrient release. The role of climate forcing on hypoxia in the Baltic Sea has yet to be convincingly demonstrated, although it could have contributed to sustain hypoxia through enhanced salt water inflows or through changes in hydrological inputs. In addition, cyanobacteria blooms are not natural features of the Baltic Sea as previously hypothesized, but are a consequence of enhanced phosphorus release that occurs together with hypoxia.

1 Introduction

One of the largest impacts on the Baltic Sea ecosystem health is eutrophication and associated hypoxia (HELCOM, 2007). The area covered by laminated sediments in the Baltic Sea (Fig. 1) is estimated to have increased about four times since 1960 (Jonsson et al., 1990) due to surplus loads of waterborne and airborne nutrients (nitrogen and phosphorus) from anthropogenic sources (Wulff et al., 2007). Hypoxia alters nutrient biogeochemical cycles (Vahtera et al., 2007), it causes large ecosystem disturbances and may be the single strongest factor affecting the biodiversity of the macrobenthic communities, disrupting benthic food webs in the Baltic basin (Karlson et al., 2002; Conley et al., 2009). Hypoxia results in a high internal load of phosphorus released from sediments, which causes low nitrogen/phosphorus (N/P) ratios during summer; a factor that favors cyanobacterial blooms (Vahtera et al., 2007).

There is currently considerable public concern over the rate of climate change and recent human impact on the Baltic Sea. However, notions that human activity could have influenced the Baltic Sea on longer time-scales (i.e. centennial and millennial) have not been systematically addressed. A common perception is one of a naturally eutrophic enclosed sea, which has regularly experienced hypoxia and cyanobacteria blooms throughout its history (Bianchi et al., 2000). Another, very different widely-held view is that the Baltic Sea was a pristine oligotrophic clear-water sea prior to the turn of the last century, i.e. AD 1900 (Österblom et al., 2007; Savchuk et al., 2008). This latter view has become especially prevalent in discussions regarding the establishment of "reference" or "background" conditions that can be targeted in the future for management actions.

But how pristine was the pre-1900 Baltic Sea and how much variability did the basin experience while in a "natural" state? To what degree did early human impact alter the bottom water oxygen conditions and how do previous alterations compare to those affected by the more recent impact? To answer these questions requires knowledge on past climate and environmental variability, but also detailed understanding of long-term human impact upon aquatic ecosystems. Though it may difficult to separate natural and human-induced changes on ecosystems, it is possible to critically examine and consider all supporting evidence.

Humans have always had effects on their environment, including substantial impacts on the movement and transport of elements, such as the essential nutrients C, P and N (Schlesinger, 2004). Palaeoecologists, therefore, routinely describe and account for human impact over millennia to discriminate between the effects of climate change and human activity on the environment. Human forcing (via eutrophication) of aquatic ecosystems has been reconstructed by various palaeoecological studies in the Baltic Sea drainage area (e.g. Renberg et al., 2001; Bradshaw et al., 2005). Nevertheless, it is not often appreciated that significant human impact on the Baltic Sea watershed occurred one millennia ago. As a consequence, most previous paleoenvironmental research has focused on ecosystem responses to climate forcing (Andrén et al., 2000; Bianchi et al., 2000; Leipe et al., 2008), although a few studies have investigated anthropogenic influences during the last 100 years (Risberg, 1990; Andrén, 1999). Thus, there is a need to assess the degree of human forcing on the Baltic Sea and the impact on sustainability of such impacts, on both historical and recent time-scales.

A recent review of hypoxia in the Baltic Sea has defined periods of hypoxia in the geological record (Zillén et al., 2008). They suggested that there was a relationship between hypoxia in the past and human population growth and large-scale changes in land use that occurred in much of the watershed during the early-Medieval expansion (AD 700–1300) and the Industrial Revolution (intensifying around AD 1850). This conclusion implies that anthropogenic impacts may have been the most important driving factor for hypoxia during the last two millennia (Zillén et al., 2008).

In this paper, we will explore this hypothesis further and show that hypoxia in the Baltic Sea is human induced and that cyanobacteria blooms are a consequence of enhanced phosphorus release that occurs together with hypoxia. We delineate the level of population growth, technological development and cultural landscape changes during the last two millennia and their implications for the presence of past hypoxia. This study challenges the hypothesis that the occurrence of hypoxia in the past was climate related. We will demonstrate the sensitively of this large enclosed sea to anthropogenic perturbations on centennial and millennial time-scales.

2 Occurrence of hypoxia in the Baltic Sea

It has been demonstrated that trends in human-induced hypoxia during the modern era in the Baltic Sea are related to variations in salt water inflows, with less stratification and less hypoxia during "stagnation periods" (i.e. in the 1920/1930s, 1950/1960s and the 1980/1990s). During these "stagnation periods" the salt water inflows are reduced and the salinity of the Baltic Sea decreases by about 0.5 salinity units lower than the mean value (Conley et al., 2002).

During the Holocene, there has been 3 major periods of hypoxia in the deeper depressions of the Baltic Proper; during the early Littorina Sea sensu stricto or s. str. (c. 8000–4000 cal. yr BP; Berglund et al., 2005) during the middle Late Littorina Sea (c. 2000-800 cal. yr BP; Berglund et al., 2005) and during the last c. 100 years, although an intensification of hypoxia after 1950 has occurred (Fig. 2). During the early Littorina Sea s. str. the opening with the Öresund Strait (or Drogden Sill) where salt water enters the Baltic Sea was about twice its size compared to today (Gustafsson and Westman, 2002) and the surface water of the Baltic was more saline, i.e. 10–15, than at present, i.e. 7–8, (Gustafsson and Westman, 2002; Berglund et al., 2005). Not until c. 5000 cal. yr BP did salinities began to decrease significantly as the opening was reduced in size due to sea level changes (Gustafsson and Westman, 2002). Hypoxia in the Baltic Proper between 8000–4000 cal. yr BP can be explained by the relative high surface salinity, which would result in a steep salinity stratification of the water column and limited ventilation of oxygen to deeper waters. It may be argued that natural environmental changes (i.e. changes in the morphology and depths of the Baltic basin and the sills) were the main triggers for millennial scale changes in hypoxia during the early Holocene (Gustafsson and Westman, 2002). During this initial and more saline development of the Littorina Sea s. str. hypoxia was even present in the northern Baltic Sea (Bothnian Sea and Bothnian Bay; Zillén et al., 2008) where salinities of 7–8 (similar as the present Baltic Proper) have been reconstructed (Widerlund and Andersson, 2006). The salinity gradually decreased throughout the Littorina Sea and the halocline in the northern Baltic Sea diminished, as well as, bottom water oxygen depletion.

Hypoxia in the Baltic Proper during the last 2 millennia (between 2000–800 cal. yr BP and post AD 1900) does not show a relationship to any known changes in salinity (Fig. 2). During this time, the surface salinity in the Baltic Proper probably ranged between 7–8, i.e. similar to the modern era (Gustafsson and Westman, 2002). However, the periods of hypoxia correlate to population growth and large-scale changes in land use that occurred in the Baltic Sea watershed during the early-Medieval expansion between AD 750–1300 and the beginning of the industrial revolution at AD 1850 in Northwestern Europe (Fig. 2). In contrast, more oxic conditions in the Baltic Sea between c. AD 1300–1500 correspond to population declines and farm desertion in Europe that took place at the beginning of the late-Medieval crisis (Andersson Palm, 2001; Antonson, 2009). Furthermore, geological evidence identifies the Medieval Period as the interval of maximum sediment carbon sequestration, highest nitrogen accumulation and chlorophyll concentrations during the entire Littorina phase, indicating more productive conditions (Voss et al., 2001). The oceanographic conditions during the Medieval Period cannot explain this productive phase and persistent hypoxia, and why it should differ from the period of oxygen deficency during the early Littorina Sea s. sr. when temperatures and salinities were even higher as a response to the larger inlet area (Gustafsson and Westman, 2002) and the Holocene Thermal Maximum in Fennoscandia, which took place between 8000 and 6000 years ago (Snowball et al., 2004). Consequently, the late Holocene record of hypoxia in the Baltic Sea may not have a natural cause, but result from anthropogenic impacts (Zillén et al., 2008).

3 Addressing human impact variability in the Baltic Sea watershed during the last two millennia

3.1 Population dynamics

Europe has experienced long-term demographic expansion and contraction during the last two millennia (Table 1). Characteristic for this period is a phase of low population levels during the plague epidemics c. AD 300–500, which was followed by a population increase and expansion during the early-Medieval, most prominent from AD 1000 to 1300 but starting already in the 7th century AD (Fig. 3). For example, in Sweden and Denmark the number of villages at least doubled during the latter time interval (Lagerås, 2007). Subsequently this population expansion was followed by a significant contraction in the late 14th century (late-Medieval crisis) and a new period of growth in association with the beginning of the first Industrial Revolution from approximately AD 1700 (Table 1). In post AD 1700-time, the most rapid population increase took place after the start of the second Industrial Revolution around AD 1850, when technological and economic progress gained momentum with the development of steam-powered ships and railways.

In the majority of the countries in the Baltic Sea region, the early-Medieval time included a doubling of population over a period of less than c. 300 years (Fig. 3). This rapid increase in population is believed to be a result of the high-Medieval economic expansion and growth in agricultural production (Myrdal, 1997, and Sect. 3.2).

The period of stagnation and population decline that followed the early-Medieval expansion in the late 14th and early 15th centuries was mainly due to the loss of life during famines and the Black Death. In AD 1400 the population of Europe was less than 25% below its early-Medieval peak. In many countries the fall was even more catastrophic (Fig. 3). A detailed study from Sweden suggests that the population decreased from 1 100 000 to 347 000 (c. 68%) between AD 1300 and AD 1413 (Andersson Palm, 2001). In Germany, the decline reached around 55% in some regions (Simms, 1976). This period is also known as the late-Medieval agricultural crisis and was characterized by decreased total agricultural production and abandonment of farms (Simms, 1976; Lagerås, 2007; Antonson, 2009). A compilation of field surveys and studies of historical maps alongside conventional written sources suggests a rate of farm desertion in Sweden around 57–58% (Antonson, 2009). It is also demonstrated that the late-Medieval desertion was not only high in marginal agricultural areas, but also in more fertile areas with a long history of settlement continuity (Simms, 1976). Thus, the agricultural crisis affected most parts of Europe and had an impact on all levels of society (Lagerås, 2007). In addition, population development (increase or decrease) has served as a main driver for agricultural expansion and contraction during the last two millennia. However, the population rise during the Medieval expansion would not have been possible without the Medieval agricultural revolution during which new agricultural tools, implements and techniques were introduced.

3.2 Technological development

Technological developments have had major impacts on agriculture during the last two millennia. One of the largest impacts on agricultural soils is plowing (Dawson and Smith, 2007). Plow tillage loosens the soil, buries crop residues and exposes the soil to rainfall and winds that result in erosion. Water runoff removes topsoils, nutrients (P and N) and soil organic carbon (C) derived from manure and fertilizers, and transports them to water bodies, such as rivers and streams, and finally into coastal zones. Accelerated erosion is one of the major causes of agriculture soil degradation and eutrophication of water bodies. It often results in irreversible impacts on the cycles of soil C, P and N and aquatic ecosystem health (Ulén et al., 2007).

The first plow (the ard) was made of wood, and was a simple digging stick or a paddle-shaped spade that could be pulled by humans or animals. The greater availability of iron allowed for stronger, sharper and more efficient implements to be used. The ard evolved into the "Roman plow" around 1 AD with an iron share and was widely used in Europe about AD 500 (Lal et al., 2007). The Roman plow subsequently developed into a soil-inverting plow (or moldboard) around AD 800–1000 (Lal et al., 2007) and was widely used on fertile plains while the more stony upland areas in e.g. Sweden were managed with iron spades and ards all the way up to the beginning of the 20th century (Lagerås, 2007). The largest change with the moldboard plow was that the soil could ride up the moldboard and be inverted (similar as the modern moldboard plows). This made the soil more exposed to rain and wind erosion. With the introduction of the soil-inverted moldboard plow, accelerated erosion and agriculture soil degradation progressed (Lal et al., 2007).

The majority of the carbon in the global terrestrial pool is stored in soils (Dawson and Smith, 2007). Arable soils contain less organic carbon than for example grasslands (Smith et al., 1996; Freibauer et al., 2004; Dawson and Smith, 2007). Long-term experiments show that converting grassland to arable agriculture can result in a 20–50% loss of soil organic C over an initial period of 15–20 years (Whitmore et al., 1992; Smith et al., 1996). In addition, plowing permanent grassland can lead to increases in nitrate leaching of c. $4\,\mathrm{t\,N\,ha^{-1}}$ over 20 years, 50% of it in the first 5.5 years (Fig. 4; Whitmore et al., 1992). The same is true for phosphate, given that soil content of organic P is primarily a function of its organic carbon content (Ulén et al., 2007). Phosphate is also more likely to be carried from the soil on colloidal or particulate matter rather than in solution, and the greatest losses of phosphate from the soil occurring by surface run-off and erosion (Feller, 2009).

It should also be recognized that forestry and deforestation also causes losses of soil organic C, N and P (Likens and Bormann, 1995). The magnitude of soil organic carbon depletion may be 25 to 50% in temperate climates during the first 5 to 20 years following deforestation (Lal, 2004). Significantly enhanced increases in both dissolved and particulate fluxes occur through deforestation with disruption of the cycle of uptake and retention in forests and the mechanisms are multi-fold (Feller, 2009). Due to less vegetation cover after forest clearance surface runoff may increase. The increase in runoff may, in combination with soil disturbances, induce erosion and increase sediment transport into surface waters. Clear-cutting, which is common in Fennoscandia, greatly increases the rates of leaching (Löfgren et al., 2009).

Land-use changes during the Medieval expansion (clearance of grassland and forest etc.) and the Industrial Revolution in Europe (tiling and rapid expanded forest industry etc.) are known to have increased the rate of P loading to aquatic ecosystems in Europe changing the nutrient status of lakes (Renberg et al., 2001; Bradshaw et al., 2005). The degree of expansion of arable land and land-use changes in the past are discussed below.

3.3 Land use changes

The change from a one-field agrarian system to a two-field system, with fallow every second year, was gradually introduced to large areas in Sweden around AD 1000 (Myrdal, 1997). The first soil-inverting moldboard plow facilitated the introduction of this system with regular fallow. A similar connection between a change of cropping system and change of plowing implement is also valid for Denmark (Poulsen, 1997) and Germany (Simms, 1976) and most probably for the vast majority of the Baltic countries. A regular fallow also had to be combined with a massive reclamation of land. The transition to a two-field system meant that, if the sown area was not to be reduced, then the extent of arable land had to be doubled, e.g. a 1 hectare (ha) field in the old one-field system would require a 2 ha field in the new system. The introduction of the two-field system thus occurred contemporaneously with an expansion of the cultivated area. A doubling of the arable land during the Medieval expansion has been reported from palaeoecology studies in e.g. southern Sweden (Berglund et al., 1991).

To meet the demand for more arable land for cultivation, the clearance of forests and grasslands became a general practice (Berglund et al., 1991; Myrdal, 1997; Lagerås, 2007; Fig. 5). Clearance was common in both established and marginal agricultural areas in Northwest Europe. Archaeological and historical data indicate that the eastern Baltic region was a period of general demographic and economic expansion around AD 800–1300 (Taavitsainen et al., 1998; Stančikaite et al., 2009). There is evidence of intensive human impact starting around AD 900 in Northwest Lithuania, eastern Baltic region (Stančikaite et al., 2009). The most prominent early agricultural activity has been dated to c. AD 1050–1250, when forested areas were converted into cultivated fields and sophisticated settled agriculture developed (Stančikaite et al., 2009). Furthermore, palaeoecological studies from the remote eastern interior of Finland reveal an exponential rise in cereal pollen concentrations at the turn of the last millennia, indicating significant increase of arable land during the early Medieval expansion (Taavitsainen et al., 1998). Expansion of arable land in remote regions probably developed in a wide area of the northern Boreal forests (Taavitsainen et al., 1998).

The minimum amount of agricultural land (without intensive use of synthetic fertilizers) for sustainable food security, with a diversified diet (including meat) is 0.5 ha per person (FAO, 1993). For comparison, 0.30 ha per person is used as arable land (with intensive use of synthetic fertilizers) in Sweden today (c. 2.7 million ha; Morell, 2001). Due to our high living standard we consume c. 0.41 ha per person. The difference between the amount of consumption and actual area of arable land is imported from other countries. The greatest area of arable land in Sweden occurred in AD 1920, i.e. 3.8 million ha (Morell, 2001) when the Swedish population reach c. 6 million (c. 0.6 ha per person). A large decline in the arable area occurred after AD 1960 with the introduction of synthetic fertilizers (Morell, 2001).

As area of 0.5 ha per person (FAO, 1993) scales up to about 2.3 million ha arable land in the Baltic Sea drainage area around AD 1000 (i.e. 4.6 million inhabitants × 0.5 ha) and 4.75 million ha around AD 1300 with the expected population increase (9.5 million inhabitants × 0.5 ha; Fig. 6). As shown earlier, 4 tonnes organic N ha^{-1} become released after plowing permanent grassland (Fig. 4). If one applies this estimate to the estimated increase in arable land during the Medieval expansion (2.45 million ha) it would generate 9 800 000 tonnes of organic nitrogen release over the period of time just from plowing new land (Fig. 6). For comparison, average annual N-inputs to the Baltic Sea over the period 1997–2003 amounted 737 000 tonnes. Although the estimated annual organic N-release is almost a magnitude less than the modern N-inputs (Fig. 6), one has to account for supplementary significant soil organic C and P-discharges during plowing, C, N, P-release from deforestation when reclaiming new land and from continuous annual manuring of the fields to improve harvest. The introduction of the two-field system in large areas around AD 1000 would have resulted in a rapid increase in arable land during this time period, which not is included in the estimates presented in Fig. 6. Although, our approximation is broad and probably associated with large uncertainties associated with the long-term demographic estimates and the quantification of arable land, the result demonstrates that nutrient leakage from plowing must have been significant during the Medieval expansion. Further studies are needed to quantify nutrient transports and inputs in the Baltic Sea drainage area. However, such analyses are not the scope of this study.

The next great agrarian revolution was during the Industrial Revolution starting around AD 1800 in Northwestern Europe. Again, the European population increased rapidly (about 6 times between AD 1700–2005; Table 1) and technological advances in agriculture and forestry exploded, in which the use of fertilizers was an important part. Another important cause was tiling, which provided a pathway by which water on the fields was rapidly drained away and discharged into nearby waters. The use of steel moldboard plows expanded rapidly with the introduction of the steam tractor during the first half of the 20th century (Lal et al., 2007). Agricultural production increased and in the 19th century and the forest industry rapidly expanded, especially in Fennoscandia. Between c. AD 1830 and 1880 Swedish and Finnish export of wood increased about 3–4 times (Larsson and Olsson, 1992). The forests were heavily exploited and numerous saw mills were built along the main rivers in Fennoscandia (Schybergson, 1974).

4 Cyanobacteria abundance in the Baltic Sea

Blooms of cyanobacteia comprised of *Aphanizomenon* spp. and the N_2-fixing cyanobacteria *Nodularia spumigena*, are recurrent phenomena in the Baltic Sea during summer. The areal extent, duration and intensity of cyanobacteria differ greatly from year to year, especially those species such as *N. spumigena* which form prominent surface accumulations (Kahru et al., 2007). A historical compilation of water column records since 1887 show that the abundance of cyanobacteria was low prior to World War II (Finni et al., 2001). However, since the 1960s, blooms of cyanobacteria are common in the open sea in both the Baltic Proper and the Gulf of Finland (Finni et al., 2001).

The fossil pigment record in sediments provides insight into the long-term historical changes that have occurred in the Baltic Sea beyond the modern time period with water column phytoplankton records. Rapid increases in zeaxanthin, a particularly stable biomarker for cyanobacteria, occurred during the transition from the Ancylus Lake to a brackish marine system during the Littorina (Bianchi et al., 2000; Westman et al., 2003). Excess P released during the transition from a freshwater to a marine system probably caused wide-spread cyanobacteria blooms (Bianchi et al., 2000). The presence of low levels of zeaxanthin throughout their piston core suggested that cyanobacteria had been present throughout the geological history (Bianchi et al., 2000), although the upper modern period was likely lost during sampling. The presence of zeaxanthin was interpreted that N-fixing cyanobacteria were a characteristic, natural feature of the Baltic Sea. Poutanen and Nikkilä (2001) used myxoxanthin and echinenone, also cyanobacteria specific pigments, in addition to zeaxanthin to examine historical trends in cyanobacteria abundance in three sediment cores. They showed that the occurrence and intensity of cyanobacteria blooms were seldom recorded before World War II (Poutanen and Nikkilä, 2001) similar to the finding in the water column records (Finni et al., 2001).

Cyanobacteria are common during summer in the Baltic Sea today due to excess dissolved inorganic phosphorus (DIP) left over after the spring bloom of phytoplankton depletes available dissolved inorganic nitrogen (Vahtera et al., 2007). The frequency of accumulation of cyanobacteria blooms has been positively correlated with the residual phosphate (RP) concentration after the spring bloom in May–June (Kahru et al., 2007). In a historical perspective, cyanobacteria blooms should be prevalent during periods of hypoxia due to the release of DIP from sediments and higher water column DIP concentrations (Conley et al., 2002). Certainly, during periods of historical hypoxia described above (Zillén et al., 2008) the sediment release of DIP was higher and one could hypothesize that cyanobacteria blooms were present.

One important question is whether DIP concentrations were high enough during periods when the Baltic was oxic to create conditions favorable for cyanobacteria as suggested by Bianchi et al. (2000)? Given that there are no large-scale geological phosphorus deposits in the watershed, and that there is abundant iron in the northern Baltic Sea that has the ability to sequester phosphorus in sediments when the water column is oxic, there is no evidence to suggest that DIP concentrations would be high enough to create conditions favorable for cyanobacteria. We, therefore, hypothesize that cyanobacteria blooms were present primarily during periods of hypoxia and therefore are not a natural feature of the Baltic Sea. This could be tested by examining sediment pigments during periods of hypoxia and when bottom water oxygen is present, although enhanced preservation of pigments during hypoxic periods will interfere with the interpretation. Unfortunately, there are no studies that have compared fossil pigment concentrations in the Baltic with periods of hypoxia recorded in the sediments.

5 Discussion

5.1 Human forcing and climate change

This is the first study to focus on long-term trends in human activities and their relation to Baltic Sea ecosystem responses. The changes in population growth, technological development and land-use changes during the last two millennia can be linked to observed shifts in oxygen conditions in the bottom waters of the Baltic Proper (Fig. 2). The view that the Baltic Sea is a basin relatively unaffected by human perturbations prior to the last century and that the Baltic has naturally has experienced prolonged hypoxia throughout its history is not supported by the data we have assimilated. The large mobility of nutrients (C, N and P) in association with changes in land-use and agricultural practices that had such substantial impacts on the nutrient status of lakes (Renberg et al., 2001; Bradshaw et al., 2005) must have affected the Baltic Sea. An interesting observation is that human stressors during the Medieval Period (e.g. population growth and agricultural expansion) succeed the Medieval Climate Optimum (peaking between AD 1000–1100). A possible scenario is that hypoxia during the Medieval was caused by increased eutrophication and partly sustained by a change in climate. However, due to the poor time control of Baltic Sea sediments, new studies must be made to constrain the time period when the Medieval hypoxia was present to disentangle the effects of anthropogenic impacts and regional climate forcing. Furthermore, if linkages between marine and terrestrial archives of human impact are to be accurately reconstructed, effort should be made in the development of quantitative reconstruction of past land-use changes, nutrient transport and inputs.

Temperature has often been suggested as the key factor that triggers the formation of cyanobacteria blooms (Pearl and Huisman, 2008). However, Stal et al. (2003) showed that summer temperature is not the only requirement for the formation of cyanobacteria blooms in the Baltic Sea. The blooms only occur in warmer years when the vertical mixing depth of the water column does not exceed the critical depth (i.e. the depth below which cyanobacteria are unable to photosynthesize), which occurs only during summer months when thermal stratification is present. The temperature effect is therefore only a contributory factor, since it causes a stabilization of the water column and decreasing the mixing depth, thereby increasing the light irradiance needed for the growth of cyanobacteria (Stal et al., 2003).

Based on advanced coupled physical-biogeochemical model simulations, Zillén and Gustafsson (2010) demonstrated that changes in productivity have a significant influence on the hypoxic and anoxic area in the Baltic Sea. Climate parameters, such as, temperature and fresh-water variability had only minor effects on the size of the hypoxic zone, implying that temperature is not a significant driver for hypoxia in the Baltic Sea. In addition, Zillén and Gustafsson (2010) showed that decreased wind activity in combination with a significant productivity (25–50% less than the control) was required to produce a hypoxic zone similar to today; a scenario that could explain the wide-spread hypoxia during the Medieval Period (Zillén et al., 2008).

From the discussions above, it is clear that anthropogenic pressures have played an important role as drivers of hypoxia through time in the Baltic Sea. It is also clear that increased temperature has neither affected the growth of cyanobacteria nor the occurrence of hypoxia. However, long-term Baltic Sea ecosystem responses are probably due to multiple stressors and complex interplays between various terrestrial and marine processes, where both climate and human impacts may have interacted. Further studies are needed to identify and quantify hypoxia related processes to determine the relative importance of the two driving mechanisms.

5.2 Management implications

The increase in salinity during the change from the Ancylus Lake to the Littorina Sea c. 8000 cal. yr BP allowed for the sediment release of P creating favorable conditions for cyanobacteria blooms (Bianchi et al., 2000; Westman et al., 2003). The high salinity during the next 4000 years, coupled with warmer temperatures during the Holocene Thermal Maximum, allowed for enhanced stratification and sustained hypoxia (Zillén et al., 2008). Changes in the morphology and depths of the Baltic basin, especially the sills in the Danish Straits reduced salinity (Gustafsson and Westman, 2002), enhancing ventilation of bottom waters and terminating hypoxia. Therefore, the main driver for millennial scale changes in hypoxia during the early Holocene was natural. However, such large-scale changes in basin morphology, salinity and temperature have not been observed in the Baltic Sea since. It is not relevant to today's discussion regarding the causes of hypoxia today in the Baltic to compare hypoxia that occurred 8000–4000 cal. yr BP when environmental conditions were completely different.

We can conclude that blooms of nitrogen-fixing cyanobacteria are not a natural feature of the Baltic Sea as claimed by Bianchi et al. (2000). Blooms of cyanobacteria are likely connected to hypoxia due to release of phosphorus from bottom sediments

(Kahru et al., 2000, 2007; Vahtera et al., 2007). In addition, given the large scale changes in land use, the development of agriculture and population growth over the last two millennia it is doubtful that the Baltic Sea could have been an oligotrophic clear water sea ca. 1900 AD (Österblom et al., 2007; Savchuk et al., 2008). It is likely that the Baltic Sea has become progressively eutrophic over the last two millennia with rapid ecosystem changes occurring in the ecosystem since the 1950s due to rapid increases in nutrient loading and overfishing (Poutanen and Nikkilä, 2001; Österblom et al., 2007).

It follows that a goal for the restoration of the Baltic Sea must be to reduce the intensity and size of hypoxia in bottom waters. The present agreed-upon goal in the Baltic Sea Action Plan for nutrient reductions (HELCOM, 2007) cannot be expected to eliminate hypoxia and cyanobacteria blooms, but only to reduce their size (Wulff et al., 2007). Thus, the goal of restoration is not to return the ecosystem back to natural conditions, but to ensure that the dynamics of natural ecosystem processes are again operating efficiently so that both ecosystem structure and function can be recovered (National Research Council, 1992).

6 Conclusions

- Population dynamics, technological development (e.g. introduction of the moldboard plow) and land-use changes (e.g. the change from a one-filed system to a two-filed system and clearance of forests) have most likely influenced the Baltic Sea ecosystem health since the early-Medieval expansion, which started around AD 700 in Northern Europe.

- Periods of hypoxia (centered around AD 1000 and during the last c. 100 years) coincide with intervals of increased human pressures in established and marginal agricultural areas, suggesting that long-term Baltic Sea ecosystem responses are due to multiple stressors where anthropogenic forcing may have been the most important driving factor.

- Plowing new arable land during the early-Medieval expansion increased soil nutrient leakage significantly in the Baltic Sea watershed, i.e. a minimum of c. 10 million tonnes of organic N over a 200–300 year period. Further studies are needed to quantify long-term land-use changes and nutrient leakage and transport to accurately assess the degree of human forcing on the Baltic Sea ecosystem on both historical and recent time-scales.

- Cyanobacteria abundance is connected to the hypoxia-driven release of phosphorus from bottom sediments. Therefore, cyanobacteria are abundant during periods of hypoxia and are not natural features of the Baltic Sea.

- Proposed decreases in nutrient loading will not eliminate the deleterious effects of hypoxia in the open waters of the Baltic Sea, although nutrient reductions are essential for reducing the intensity and size of the hypoxia area. Management actions must focus on regaining ecosystem functioning and services and will not return the Baltic Sea to natural conditions.

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Table 1. Estimates of the total population of Europe since AD 400 (McEvedy and Jones, 1978) and in the Baltic Sea drainage area. The estimate for the population in the Baltic Sea drainage basin is based on the assumption that the population in the Baltic region always been approximately 12% of the total European population (i.e. as today) and should therefore be considered with caution, since local differences over time will not be recorded.

Year AD	Population level	Population estimates Europe	Tentative population estimates Baltic Sea area
400–1000	Stable at a low level	25–30 million	3–3.6 million
1000–1300	Population boom and expansion	From 38 to 79 million (c. 100% increase)	4.6–9.5 million
1300–1350	Stable at a high level	79–80 million	9.6 million
1350–1420	Steep decline	From 80–60 million (c. 25% decline)	9.6–7.2 million
1420–1470	Stable at a low level	60 million	7.2 million
1470–1500	Expansion to AD 1350–1420 values	81 million	9.7 million
1500–1700	Slow expansion gaining momentum in the early 16th century.	From 81 to 120 million	9.7–14.4 million
1700–2005	Population boom and expansion	From 120–731 million (c. 600% increase)	14.4–85 million

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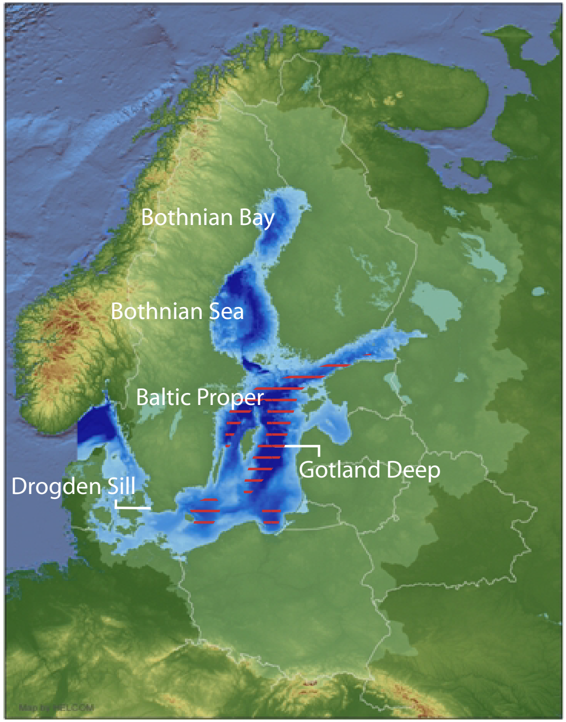

Fig. 1. Map of the Baltic Sea identifying its major sub-basins (Bothnian Bay, Bothnian Sea and Baltic Proper) and the major sill in the inlet area (Drogden Sill). The red lines designate the maximum hypoxic area that occurs in the Baltic Sea. Hypoxia is common in the deeper basins of the Baltic Proper where a permanent restricts the ventilation of the deeper waters and supports the development of persistent hypoxia (Conley et al., 2009). The low salinity waters of the Bothnian Sea and, in particular, the Bothnian Bay have weaker haloclines and better ventilation. In combination with a lower productivity this better ventilation makes these basins mostly oxic. Also, the Baltic Sea drainage area in light green, where 85 million people live today.

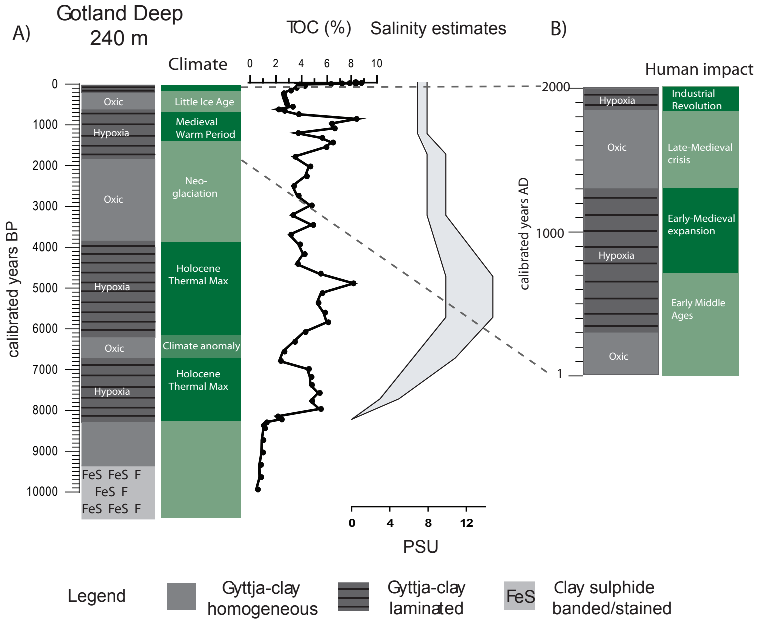

Fig. 2. (A) Figure showing the occurrence of laminated sediments, total organic carbon content (TOC) and salinity estimates, plotted against a calendar year time scale, based on a compilation of sediment records from the Baltic proper (Zillén et al., 2008). The sediment records suggest that during the last c. 8500–7800 cal. yr BP hypoxia has occurred intermittently in the deeper sub-basins in the Baltic Proper. The hypoxia during the early Littorina Sea s. str. (8000–4000 cal. BP) coincides with intervals of maximum salinity estimates. Hypoxia during the Medieval period and the modern historical period (post-1850) do not correlate to any alterations in salinity but to periods of maximum TOC values. **(B)** The figure shows the same sediment records as in (A), but compared to anthropogenic expansion and contraction phases during the last 2000 years. Note that due to the poor chronological control associated with Baltic Sea sediments, the age error estimates of the periods of hypoxia the last 2000 years are approximately ±500 years (Zillén et al., 2008).

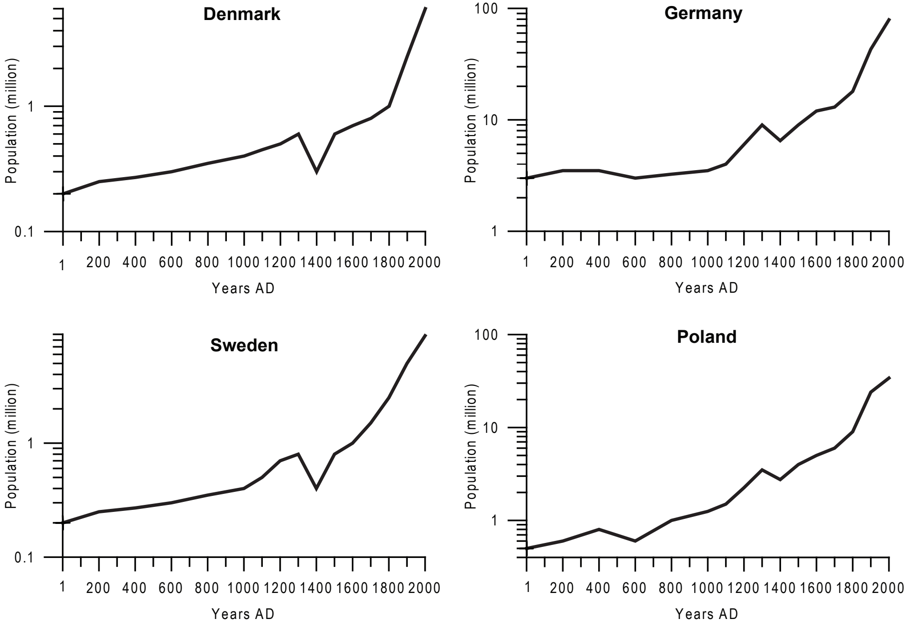

Fig. 3. Estimates of the total population of some the major Baltic countries i.e. Denmark, Germany, Sweden and Poland since AD 1 (McEvedy and Jones, 1978). Note the rapid increase between AD 700–1300, followed by an equal prompt decrease in the early 14th century, in all of the countries.

Fig. 4. Losses of soil organic nitrogen as a function of number of years after plowing permanent grassland in a temperate climate zone (UK). After 20 years, c. 4 t N ha^{-1} had leached from the natural soil, 50% of that in the first 5.5 years (after Whitmore et al., 1992).

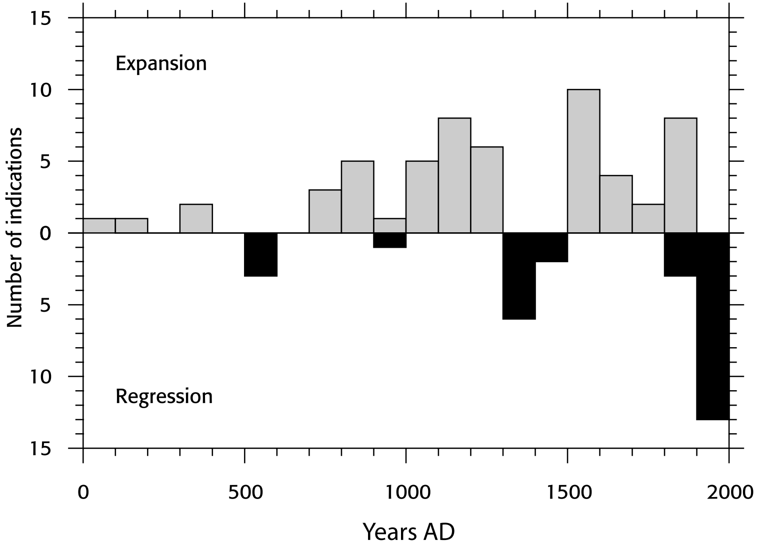

Fig. 5. Indicators of land-use expansion and regression during the last 2000 years in Southern Sweden (Lagerås, 2007). The figure shows distinctive expansions during the early-Medieval period around AD 700 and the Industrial Revolution.

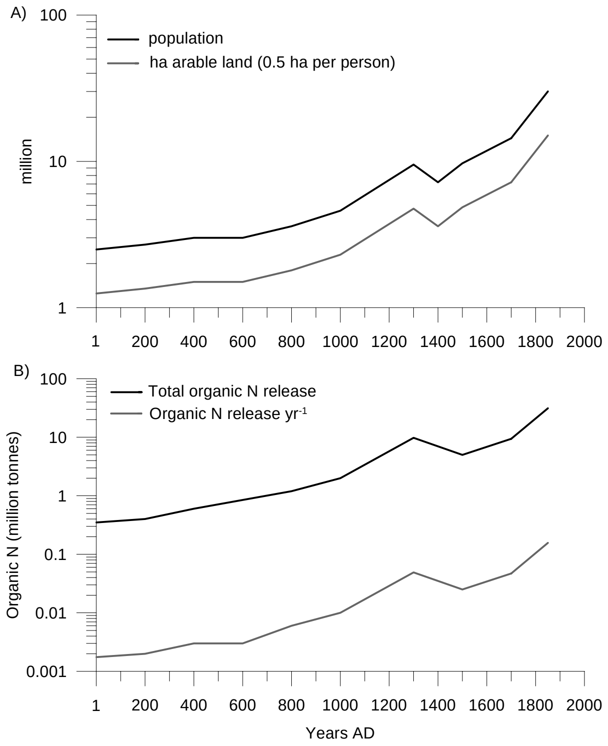

Fig. 6. **(A)** The population development in the Baltic Sea drainage area between AD 1–1900 (after McEvedy and Jones, 1978; Table 1). Also, the estimated area (ha) of arable land as a function of population decreases/increases (calculated as 0.5 ha per person) for the same time period. **(B)** The release of organic N, expressed as total organic N and organic N yr^{-1}, from plowing new arable land during AD 1–1900, using the areal estimates above and the organic N-release from Fig. 4 (4 t N ha^{-1}). Although the organic N release per year from plowing new arable land is almost a magnitude less than the modern total annual average N-inputs, the estimates demonstrate that nutrient leakages during pre-historic and historical times were significant.