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– Research Topic on **“Research and Management of Eutrophication in Coastal Ecosystems”**

Past, present and future eutrophication status of the Baltic Sea

Ciaran Murraya\*, Bärbel Müller-Karulisb,c, Jacob Carstensend,e,

Daniel Conleyf, Bo Gustafsonb,c, Jesper H. Andersena

*a NIVA Denmark Water Research, Copenhagen, Denmark*

*b Stockholm University, Stockholm, Sweden*

*c Baltic Nest Institute, Stockholm, Sweden*

*d Aarhus University, Roskilde, Denmark*

*e Baltic Nest Institute Denmark, Roskilde, Denmark*

*f Lund University, Sweden*

*\** [cjm@niva-danmark.dk](mailto:cjm@niva-danmark.dk)

ABSTRACT

We model and assess the past, present and future eutrophication status of the Baltic Sea. The assessment covers the period 1850-2200 and is based on: (1) input scenarios for nitrogen (TN) and phosphorus (TP), (2) modelling of concentrations of DIN, DIP, chlorophyll-a, Secchi depth, and oxygen, and (3) the application of a multi-metric indicator-based tool for assessment of eutrophication status, i.e. HEAT 3.0. Our study covers a period of 350 years ranging from 1850 to 2200 and reveals significant changes in eutrophication status in most Baltic Sea sub-basins. The change for a health state without eutrophication problem in the open parts of the Baltic Sea took place in late 50ies and early 60ies. In some basins, the recovery started in the late 90ies, whilst is other in commenced just after the turn of the century. Based on modelling, a status without eutrophication can be expected around 2050? in the xxxx, xxxx and xxxx. For other basins, i.e. xxxx, xxxx, xxxx and xxxx, a good status in regard to eutrophication can be expected in 2100? or later. Further, we conclude than not all basins are likely to meet the targets agreed upon and to attain a status unaffected by eutrophication, i.e. the Gulf of Riga and xxxxx. The results, especially the later, can be used in support of continuous development and implementation of the regional ecosystem-based nutrient management strategy, the HELCOM Baltic Sea Action Plan.

*Keywords*:

Eutrophication, Baltic Sea, Nutrient loads, Scenarios, Modelling, Integrated assessment, Status classification

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**1. Introduction**

The causes, process and significances of nutrient enrichment and eutrophication in the Baltic Sea is well understood and documented (Larsson et al. 1985, Rönnberg et al. 2004, Vahtera et al. 2007, Andersen et al. 2011, Fleming-Lehtinen et al. 2015). There is no commonly agreed definition, but instead a conceptual understanding what the consequences of nutrient enrichment are (Andersen et al. 2006, HELCOM 2009). Discharges, losses and inputs of nutrients from upstream catchments, atmosphere, neighbouring sea (i.e. the North Sea) and sediment pools lead to elevated concentration of nutrient in seawater. In most parts of the Baltic Sea, the direct consequences of elevated nutrient concentrations are increased production of phytoplankton (reference xxxx, reference xxxx), in some areas manifested as bluegreen algae blooms (Finni et al. 2001, reference xxxx). The increase production of organics matter has indirect consequences in most parts of the Baltic Sea. The turnover of sedimented material has reduced oxygen concentrations significantly and hypoxia is a large scale problem (Conley et al. 2011, Carstensen et al. 2014). Subsequently, reduced oxygen concentrations have affected not only benthic invertebrates (Villnãs & Norkko 200x) but also the spawning success of cod, a commercially important fish species (MacKenzie et al. 2000, Kõster et al, 2001). A crucially important indirect effect of eutrophication is the remineralisation and flux of phosphorus from seabed sediment to surface waters (Vahtera et al. 2007), a process referred to as a vicious circle.

Baltic Sea states have worked reducing inputs and improving eutrophication status for decades, primarily under the umbrella of the Helsinki Convention on the Protection of the Marine Environment of the Baltic Sea Area, often referred to as the Helsinki Convention, or in short HELCOM. With the adoption of the Baltic Sea Action Plan (BSAP) in 2007 (HELCOM 2007), this work turned into a new phase being based on numerical target values and model calculations for basin-wise Maximum Allowable Inputs and Country-wise Allocated Reduction Targets.

With the 2013 update of the BSAP’s eutrophication segment, the Baltic Sea States not only implement the Ecosystem Approach to management of human activities but also set a new standard for the development of an adaptive and evidence-based nutrient management strategy (reference 2013). The end target for the BSAP is to attain, in 2020, a healthy Baltic Sea unaffected by eutrophication, including (1) concentrations of nutrients close to natural levels, (2) clear water, (3) natural levels of algae blooms, (4) natural distribution and occurrence of plants and animals, and (5) natural oxygen levels.

The objectives of this study are: (1) to classify eutrophication status of nine Baltic Sea sub-basins for the period 1850-2200, (2) to identify sub-basins expected to improve to not being affected by eutrophication, (3) to estimate if any sub-basins may shift from affected by eutrophication to being unaffected, and (4) to assess if there are any sub-basins not likely to improve status. Our results will be discussed in general, and specifically in regard to year 2020, 2050, 2100 and 2200.

**2. Methods and data**

This study congregates two processes: (1) the regular assessment of eutrophication status in the Baltic Sea region, in particular the development of indicator-based eutrophication assessment tools, and (2) the implementation of the BSAP, in particular the expected future reduction in nutrient inputs from land-based sources and the atmosphere.

*2.1. Study area*

The Baltic Sea is an inland sea in northern Europe surrounded by Sweden, Finland, Russia, Estonia, Latvia, Lithuania, Poland, Germany and Denmark and with a surface area of 415,200 km2 (Table 1). The Baltic Sea is usually divided into several sub-basins separated by sills, including a transition zone to the North Sea entailing the Kattegat and the Danish Straits (Fig. 1, Table 1).

The sub-basins vary substantially in regard to ice cover, temperature, salinity, maximum depth and residence times. The composition of the biota, both below and above water surface, changes strongly along these gradients. More information about Baltic Sea characteristics can be found in Bonsdorff (2006), Johannesson & André (2006), Österblom et al. (2007), and Leppäranta & Myrberg (2009). Nutrient enrichment and eutrophication signals within the study area is very well studied and documented (HELCOM 2009, Andersen et al. 2011, Carstensen et al. 2014, Fleming-Lehtinen et al. 2015). Root causes and inputs and fluxes of nitrogen and phosphorus are in general well understood and documented (HELCOM 2015, Vahtera et al. 2007).

Actions to improve the ecosystem health of the Baltic Sea, including the currently impaired status in regard to eutrophication, are under way (Baltic Sea Action Plan, HELCOM 2007 and EU Marine Strategy Framework Directive, Anon. 2008). With the most recent update of the Baltic Sea Action Plan, the countries bordering the Baltic Sea have – in the context of the eutrophication segment of the plan – agreed on a fully fledged ecosystem-based nutrient management strategy (Anon. 2013).

*2.2. Data sources*

Baltic sea Long-Term large-Scale Eutrophication Model (BALTSEM; Gustafsson, 2003; Savchuk, 2002).

X

X

X

X

Bo, do you want to write this up?

Input scenarios

The past eutrophication status of the Baltic Sea in 1850–2006 was simulated by forcing the BALTSEM model with reconstructed nutrient inputs and atmospheric conditions as described in Gustafsson et al. (2012). Its future status was then assessed by extending the model runs for another 194 years with different nutrient loads, while hydrodynamics were driven by a statistical representation of present climate (Bo, reference???). Load scenarios simulate present nutrient inputs, as well as declining and increasing nutrient loads. Present inputs (PLC5.5) correspond to the loads observed in the BSAP reference period 1997 – 2003 as described in the review of the 5th HELCOM Pollution Load Compilation (HELCOM 2013b). Load reductions simulate nutrient inputs according to the 2013 update of the BSAP’s eutrophication segment, implemented either instantaneously (BSAP 2013) or with a linear decrease in loads over 30 years (BSAP 2013t). Further, a high nutrient input scenario (BAUt) mimics intensified agriculture in the Eastern Baltic States (Hägg et al. 2013, Meier et al. 2011) with a 30 year transition from present inputs.

So far text only, if we need to add a table with final loads, we can do that later … and also a table with the 4 scenarios ….

*2.3. HEAT 3.0*

In this study, we apply the recent version of the HELCOM Eutrophication Assessment Tools (HEAT 3.0), which has been used for assessing eutrophication in the Baltic Sea for the periods 2007-2011 (Fleming-Lehtinen et al. 2015) and 1901-2012 (Andersen et al. 2015). For description of the assessment principles and methods, please confer with these references including the Supplementary Online Material to these. Information on the development process and earlier versions can be found in Andersen et al. (2010, 2011, 2014) and Fleming-Lehtinen et al (2015).

The target values applied in HEAT 3.0, for the indicators TP, TP, Chl-a, Secchi, oxygen, are taken directly from Fleming-Lehtinen et al. (2015). Table?

**3. Results**

X

X

**4. Discussion**

X

X

**5. Conclusions and perspectives**

X

X

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**Supplementary data**

Supplementary datat associated with this article can be found in the online version, at http://xxxxxxxxx.

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**TABLES**

**Table 1**

Key characteristic of the Baltic Sea and the nine assessments units in this study. Based on Andersen et al. (2015) and Fleming Lehtinen et al. (2015).

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Unit** | **Basin** | **Area** | **Max depth** | **Avg. depth** | **Surface salinity** | **N input** | **TP input** |
|  |  | km2 | m | m | PSU | t yr-1 | t yr-1 |
| 1 | Bothnian Bay | 33,232 | 127 | 41 | 1.8–3.9 | 55,780 | 2,580 |
| 2 | Bothnian Sea | 83,908 | 270 | 55 | 3.8–6.6 | 74,530 | 2,660 |
| 3 | Gulf of Finland | 29,911 | 123 | 34 | 1.2–5.6 | 125,050 | 6,810 |
| 4 | Gulf of Riga | 18,797 | 53 | 22 | 4.1–6.2 | 89,060 | 2,810 |
| 5 | Baltic Proper | 149,697 | 459 | 71 | 5.0–7.5 |  |  |
| 6 | Bornholm Basin | 42,161 | 100 | 44 | 4.3–8.1 | 413,680 | 16,510 |
| 7 | Arkona Basin | 16,405 | 50 | 25 | 7.6–11.3 |  |  |
| 8 | Danish Straits | 21,022 | 50 | 14 | 6.9–22.9 | 53,970 | 1,470 |
| 9 | Kattegat | 23,557 | 120 | 22 | 12.2–30.2 | 69,170 | 1,550 |
| Total |  | 418,690 | 459 | 51 | 1.2–30.2 | 881,240 | 34,390 |

**Table 2**

Overview of the four scenarios modelled for the classification of eutrophication status 1850-2200.

|  |  |  |
| --- | --- | --- |
| **Scenario** | **Name** | **Description** |
| 1 | PLC5.5 | X  x |
| 2 | BSAP 2013 | x  x |
| 3 | BSAP 2013t | X  X |
| 4 | BAUt | X  x |

**Table 3**

Basin-specific target values for winter mean concentration of total inorganic nitrogen (DIN), winter mean concentration of total inorganic phosphorus concentrations (DIP), summer mean concentration of chlorophyll-a (Chl-a), summer mean Secchi depth corrected for CDOM (Secchi) and oxygen debt (Oxygen). From Andersen et al. (2015).

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Basin** | **DIN** | **DIP** | **Chl-a** | **Secchi** | **Oxygen** |
|  | µg L-1 | µg L-1 | µg L-1 | m | mg L-1 |
| 1. Bothnian Bay | 5.2 | 0.07 | 2.0 | 5.8 | - |
| 1. Bothnian Sea | 2.8 | 0.19 | 1,5 | 6.8 | - |
| 1. Gulf of Finland | 3.8 | 0.65 | 2.0 | 5.5 | 8.7 |
| 1. Gulf of Riga | 5.2 | 0.41 | 2.7 | 5.0 | - |
| 1. Baltic Proper | 2.5 | 0.29 | 1.6 | 7.7 | 8.7 |
| 1. Bornholm Basin | 2.5 | 0.3 | 1.8 | 6.9 | 6.4 |
| 1. Arkona Basin | 2.9 | 0.36 | 1.8 | 7.2 | - |
| 1. Danish Straits | 4.6 | 0.53 | 1.6 | 8.0 | - |
| 1. Kattegat | 5.0 | 0.49 | 1.5 | 7.6 | - |

**FIGURES**

|  |
| --- |
|  |

**Figure 1**

Map of the Baltic Sea including baseline in regard to eutrophication status (2001-2006?).

Based on Figure 1.2 in HELCOM (2013).

|  |
| --- |
| A |
| B |
| C |
| D |
| E |

**Figure 2**

Modelled trajectories for DIN, DIP, Chl-a, Secchi, and oxygen debt during 1850-2200.

|  |  |  |
| --- | --- | --- |
| A | B | C |
| D | E | F |
| G | H | I |

**Figure 3**

1850-2200 for 9 basins.

|  |
| --- |
|  |

**Figure 4**

“Everything in a single picture” – based on Figure 3. In colours. Should be area weighted.

**Figure 5**

Correlation for the period 1901-2012 comparing the integrated assessment from Andersen et al. (2015) with the integrated assessment based on modelled data (this study).

|  |  |
| --- | --- |
| A | B |

**Figure 6**

Panel A: Number of years with impaired status per sub-basin (before 2012). Panel B: Number of years to GEnS in the future (from present).

|  |
| --- |
| A |
| B |
| C |
| D |
| E |
| F |
| G |
| H |

**Figure 7**

Population density (A), fertilizer use (B), discharges (C) and trajectories for DIN (D), DIP (E), Chl-a (F), Secchi depth (G), oxygen debt (H) and the Eutrophication Index (I) for the period 1850-2200. Based on xxxxxxxxxxxxx (A), xxxxxxxxxxxxxxxxxxx (B), xxxxxxxxxxxxxxxxxxxxxxxxxx (C), the modelled data on which this study is based (D-H; Fig. 2) and the integrated assessment of eutrophication status from this study (E; Fig 4),

**SUPPLEMENTARY ONLINE MATERIAL**

Figure S1

Figure S2

Figure S3

Figure S4

Figure S5

Figure S6

Figure S7

Figure S8

Figure S9

**POTENTIAL REVIEWERS**

Markus Meyer

Thomas Neumann

Heikki Pittkãnen

Gerald Schernewski

Morten Skogen

Norbert Wasmund