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Long-term temporal and spatial trends in eutrophication status of the Baltic Sea

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ABSTRACT

Much of the Baltic Sea is currently classified as 'affected by eutrophication'. The causes for this are twofold. First, current levels of nutrient inputs (nitrogen and phosphorus) from human activities exceed the natural processing capacity with an accumulation of nutrients in the Baltic Sea over the last 50–100 years. Secondly, the Baltic Sea is naturally susceptible to nutrient enrichment due to a combination of long retention times and stratification restricting ventilation of deep waters. Here, based on a unique data set collated from research activities and long-term monitoring programs, we report on the temporal and spatial trends of eutrophication status for the open Baltic Sea over a 112-year period using the HELCOM Eutrophication Assessment Tool (HEAT 3.0). Further, we analyse variation in the confidence of the eutrophication status assessment based on a systematic quantitative approach using coefficients of variation in the observations. The classifications in our assessment indicate that the first signs of eutrophication emerged in the mid-1950s and the central parts of the Baltic Sea changed from being unaffected by eutrophication to being affected. We document improvements in eutrophication status that are direct consequences of long-term efforts to reduce the inputs of nutrients. The reductions in both nitrogen and phosphorus loads have led to large-scale alleviation of eutrophication and to a healthier Baltic Sea. Reduced confidence in our assessment is seen more recently due to reductions in the scope of monitoring programs. Our study sets a baseline for implementation of the ecosystem-based management strategies and policies currently in place including the EU Marine Strategy Framework Directives and the HELCOM Baltic Sea Action Plan.

Key words: eutrophication, assessment, nutrient enrichment, chlorophyll-*a*, benthic communities, hypoxia, indicators, Baltic Sea, Danish Straits, evidence-based management.

CONTENTS

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I. INTRODUCTION

Nutrient enrichment and abatement of the effects of eutrophication have been an issue for decades in the Baltic Sea region (Larsson, Elmgren & Wulff, 1985; Conley *et al.*, 2007; Andersen *et al.*, 2011). Significant efforts and resources have been spent on research, monitoring, and assessment as well as reduction in the discharges, losses, and emissions of nitrogen and phosphorus (HELCOM, 2010). Our understanding of the links between human activities causing eutrophication and the structures and functions of Baltic ecosystems is well developed (Rönnberg & Bondroff, 2004; Vahtera *et al.*, 2007; HELCOM, 2009; Conley *et al.*, 2011).

Eutrophication in the Baltic Sea has been evaluated to have intensified after the 1950s (Elmgren, 2001). Increasing spread of hypoxia and decreasing water transparency in the 20th century are well documented through long-term observational data sets (Conley *et al.*, 2009; Fleming-Lehtinen & Laamanen, 2012; Carstensen *et al.*, 2014*a*) and there is strong evidence that a massive increase in anthropogenic nutrient load is the primary controlling factor for these trends (e.g. Gustafsson *et al.*, 2012; Carstensen *et al.*, 2014*a*). Nutrient loads peaked in the early 1980s, especially phosphorus loads, which have since decreased primarily due to implementation of efficient sewage treatment. Recent decades have been characterized by large hypoxic zones (Carstensen *et al.*, 2014*a*) and frequent occurrences of cyanobacteria blooms (Karhu, Savchuk & Elmgren, 2007). The major reasons are that nutrient loads accumulate over decades (Gustafsson *et al.*, 2012) and the increase in hypoxic area has reduced phosphorus retention capacity in sediments (Mort *et al.*, 2010).

The first integrated thematic assessment of the effects of nutrient enrichment for the period 2001–2006 was published by HELCOM (2009). Eutrophication status was assessed and classified in 189 areas of the Baltic Sea (Andersen *et al.*, 2011). Only the open waters in the Bothnian Bay and in the Swedish parts of the north-eastern Kattegat were classified as 'areas not affected by eutrophication'. The assessment was updated recently for the period 2007–2011 (HELCOM, 2014*a*) and now classifies all the open-sea areas as 'affected by eutrophication'. While both assessments measured the status of overall eutrophication, they were not completely comparable due to differing assessment methodology (Fleming-Lehtinen *et al.*, 2015).

Eutrophication status of the Baltic Sea has been assessed using models. Almroth & Skogen (2010) proposed a model-based methodology for eutrophication assessment in which results from an ensemble of different models were weighted according to their accuracy. The advantage of this approach could be that model results with quantified accuracy give an effective spatial and temporal interpolation of observations. However, using this approach, spatial resolution is limited by the resolution of targets and by data availability for model quality assessment.

We assess here the temporal and spatial development of eutrophication status for a 112-year period, during which the open Baltic Sea developed from an oligotrophic/mesotrophic sea to a highly eutrophied sea. In order to achieve a fully harmonized and coordinated assessment, we use a multi-metric indicator-based assessment tool HEAT 3.0 (Fleming-Lehtinen *et al.*, 2015) applying indicators with commonly agreed targets of good environmental status and combine information from the two previous eutrophication assessments (HELCOM, 2009, 2014*a*). Secondly, we analyse variation in the confidence of the eutrophication status assessment based on a systematic quantitative approach in combining the relative uncertainties of different indicators using coefficients of variation. The two elements represent a substantial step forward in our understanding of eutrophication status in the past, first as a baseline study, and further to estimate whether present monitoring provides sufficient data for assessing the state of the Baltic Sea.

II. METHODOLOGY

(1) Study area

The Baltic Sea is a semi-enclosed shallow water body with an estuarine circulation displaying a salinity gradient from ~30 PSU at the entrance to ~1 PSU in the northern parts of the Bothnian Bay. It is connected to the North Sea and the entrance area is shallow and narrow with sills separating the deeper basins. The Baltic Sea has been subdivided into a number of basins (Fig. 1) with varying water residence times. The residence time for salt in the entire system is more than 30 years (Stigebrandt & Gustafsson, 2003), while residence times for separate basins can be considerably lower, e.g. 1–3 months for the Kattegat and Danish Straits (Gustafsson, 2000) and 1 year for the Gulf of Finland (Andrejev, Myrberg & Lundberg, 2004). The central part of the Baltic Sea features a relatively deep permanent halocline (at 70–80 m) and a shallower seasonal thermocline. Restricted ventilation of the deep waters below the halocline and substantial export production causes permanent hypoxia in large parts of the Baltic Proper. Moreover, seasonal and episodic hypoxia is widespread in coastal areas, partly caused by local nutrient inputs and partly due to imported hypoxic water from adjacent areas in the Baltic Sea (Conley *et al.*, 2011). The Baltic Sea is among the best-studied regional marine seas globally and the current state of the environment is well documented, both on an overall level as well as in regard to specific threats (HELCOM, 2010). For the purposes of this review, the Baltic Sea is sub-divided into nine basins, or assessment units (Fig. 1, Table 1).

(2) Data sources

Data on nutrients, chlorophyll-*a* and dissolved oxygen concentrations were extracted from the Data Assimilation System (DAS) at The Baltic Nest Institute, Stockholm University. DAS is a distributed database allowing direct access to databases hosted in Denmark, Finland, Germany and Sweden, as well as monitoring data from other countries and research cruises submitted to a central database (Sokolov & Wulff, 2011). The chlorophyll-*a* data were further supplemented with data collected for the EUTRO-PRO project and HELCOM Indicator Fact Sheets (Fleming-Lehtinen *et al.*, 2008).

The data set from DAS contained more than 5 million records in total with observations of varying quality across time. An automated procedure for data quality control was employed. For nutrients known to display some degree of co-variation, outliers in the data set were identified by first applying the Blocked Adaptive Computationally Efficient Outlier Nominators (BACON) algorithm for multivariate covariance estimation as implemented in the R-package 'RobustX' (Stahel & Maechler, 2009) for each basin followed by visual inspection of the data. For other parameters observations outside the 99% confidence interval of the distribution were identified.

A data set containing Secchi depth measurements dating back to 1903 was compiled from numerous sources, including the database of the International Council for the Exploration of the Seas (ICES) with observations from the entire Baltic Sea between the years 1903 and 2009 (Aarup, 2002), complemented with the Finnish Institute of Marine Research (now SYKE Marine Research Centre) data sets. Data from Sweden and Poland were from the SHARK database of the Swedish Meteorological and Hydrological Institute (SMHI), and the Oceanographic databases of the Institute of Meteorology and Water Management (IMWM) in Poland, respectively, and data from the Latvian Institute of Aquatic Ecology and the Centre of Marine Research in Lithuania received during the HELCOM EUTRO-PRO project were also included (see Fleming-Lehtinen & Laamanen, 2012, for detailed information).

Benthic invertebrate data originated from two sources. For the Baltic Sea east of the Arkona Basin, extensive long-term monitoring data from 1964 to 2011 were collected by the former Finnish Institute of Marine Research and the Finnish Environment Institute. Data from multiple monitoring stations per sea area over the period 1964–2006 were used for target setting. Only data from sampling occasions during the summer season, comprising three replicate samples per station were utilized (Villnäs & Norkko, 2011). For the Kattegat, Danish Straits and Arkona Basin, data originated from national monitoring activities and assessments carried out according to the Water Framework Directive and stored in the database of the Danish National Aquatic Monitoring and Assessment Programme (DNAMAP) and its successors (Borja *et al.*, 2007; Josefson *et al.*, 2009). Data from the Baltic Proper were collected in May/June and data from the Kattegat and the Danish Straits were primarily collected in the period April–October.

(3) Indicators and numerical targets

We applied the indicators used in the HELCOM assessments of eutrophication status for the periods 2001–2006 and 2007–2011 (HELCOM, 2009, 2014*a*), using the latest targets agreed by HELCOM (2013, 2014*a*). The targets were developed combining information achieved through data mining, modelling and harmonization performed in an expert workshop (HELCOM, 2009, 2014*a*) and are presented in Table 2. These indicators are also used in the implementation of the Marine Strategy Framework Directive, in which eutrophication as 1 of the 11 descriptors of good environmental status is assessed through nutrient levels, as well as the direct and indirect effects of eutrophication (Anonymous, 2008, 2010).

The average inorganic nitrogen and phosphorus concentrations at the surface (0–10 m depth) during the winter months (December to February) are used as indicators for nutrient levels. Anthropogenic increases in nutrients are the primary cause for eutrophication, causing increased production of phytoplankton and perennial macroalgae. The pelagic nutrient pool is best measured during the winter

Fig. 1. The Baltic Sea and the sub-divisions used in this study for assessment of eutrophication in offshore sub-regions. Details of the assessment units are provided in Table 1. Note that coastal waters are not included in the classification of eutrophication status.

Table 1. Assessment units used in this study

Basin	Acronym	Size (km^2)	Volume (km^3)	Max depth (m)	Mean depth (m)	Surface salinity (PSU)
Kattegat	KAT	23557	507	120	22	12.2–30.2
Danish Straits	DAS	21022	293	50	14	9.6–22.9
Arkona Basin	ARK	16405	413	50	25	7.6–11.3
Bornholm Basin	BOR	42161	1854	100	44	4.3–8.1
Baltic Proper	BAP	149697	10696	459	71	5.0–7.5
Gulf of Riga	GoR	18797	415	56	22	4.1–6.2
Gulf of Finland	GoF	29911	1028	123	34	1.2–5.6
Bothnian Sea	BoS	83908	4598	270	55	3.8–6.6
Bothnian Bay	BoB	33232	1348	127	41	1.8–3.9
Total		418690	21152	459	51	1.2–30.2

Size, volume, depth and typical surface salinity were calculated including both offshore and coastal waters. Morphological characteristics were calculated using the bathymetry of Al-Hamdani & Reker (2007), while typical surface salinities were calculated as long-term averages (1970–2008).

months when uptake of inorganic nutrients is low and inputs from land and atmosphere accumulate in the surface layer.

The average chlorophyll-*a* concentration at the surface (0–10 m depth) from June to September is the only indicator describing the amount of algae, which together with Secchi depth expresses the direct effects of eutrophication. The months between June and September are in most areas considered to represent the summer period after the spring bloom, which typically occurs between March (southern part) and May (northern part).

Table 2. Target values used in this study

	Causative factors		Direct effects		Indirect effects	
	DIN	DIP	CHL	SD	OD	BI
Kattegat	5.0	0.49	1.5	7.6	—	0.68[a]
Danish Straits	4.6	0.53	1.6	8.0	—	0.68[a]
Arkona Basin	2.9	0.36	1.8	7.2	—	0.68[a]
Bornholm Basin	2.5	0.30	1.8	6.8	6.4	7.20[b]
Baltic Proper	2.5	0.29	1.6	7.7	8.7	5.25[b, c]
Gulf of Riga	5.2	0.41	2.7	5.0	—	—
Gulf of Finland	3.8	0.65	2.0	5.5	8.7	3.91[b]
Bothnian Sea	2.8	0.19	1.5	6.8	—	2.11[b, d]
Bothnian Bay	5.2	0.07	2.0	5.8	—	1.37[b]

DIN, total inorganic nitrogen concentration (μM), winter mean; DIP, total inorganic phosphorus concentration (μM), winter mean; CHL, chlorophyll-*a* concentration ($\mu g\, l^{-1}$), summer mean; SD, Secchi depth (m), summer mean, corrected for Coloured Dissolved Organic Matter (CDOM); OD, oxygen debt ($mg\, l^{-1}$); BI = benthic invertebrates (see below footnotes for information on indicators applied).
[a]Dansk Kvalitets Indeks (DKI), an index ranging from 1.0 to 0.0 – see Borja *et al.* (2007) and Carstensen *et al.* (2014*b*) for more information.
[b]Average regional diversity – see Villnäs & Norkko (2011) for more information.
[c]Only data from the south-eastern Gotland Basin was used to represent average regional diversity in the Baltic Proper.
[d]The target value for the Bothnian Sea during 2004–2011 is corrected to 2.98 due to the invasion of *Marenzilleria* spp.

Average summer (June–September) Secchi depth is used to describe water clarity. Water clarity, especially where it can be related to changes in algal biomass, is regarded as a direct effect of eutrophication. However, Secchi depth is a complex indicator also expressing non-eutrophication related signals (Fleming-Lehtinen & Laamanen, 2012; V. Fleming-Lehtinen & S. Simis, unpublished data), and is thus given an area-specific weight in relation to other indicators in its aggregate in the HEAT calculations.

Indirect effects of eutrophication are represented by an oxygen debt indicator and benthic invertebrates. The bottom oxygen debt indicator describes deviation from natural oxygen levels. Oxygen depletion in deep bottom waters has occurred intermittently in the permanently stratified parts of the Baltic Sea (Zillén *et al.*, 2008) during the history of the modern Littorina Sea (approximately 8000 years), and is influenced by saltwater inflows from the North Sea. However, the spread of oxygen-depleted areas during the last century is primarily caused by excessive nutrient inputs from land modulated by inflow events (Carstensen *et al.*, 2014*a*). The current spatial extent of hypoxia is mainly limited by the location of the halocline (Carstensen *et al.*, 2014*a*). Temperature influences dissolved oxygen concentrations with warmer temperatures reducing the solubility of oxygen and stimulating respiration. To account for reduced solubility with temperature, the oxygen debt (or apparent oxygen utilisation) was calculated as the oxygen saturation (a function of temperature and salinity) minus the measured oxygen concentration. A statistical approach for parameterizing salinity and oxygen profiles over time and space has been developed to calculate the oxygen debt in the bottom waters of the Bornholm and Gotland basins (HELCOM, 2013) as an indicator of indirect effects of nutrient enrichment. Oxygen debt is calculated as an annual mean, since hypoxia is perennial in these two basins.

The targets for benthic invertebrates in the southern, central, eastern and northern Baltic Sea are based on Villnäs & Norkko (2011), but recalculated according to the subdivisions applied in this study (see Fig. 1). Due to the subdivision of the study area (Fig. 1) data from the south-eastern Gotland Basin were selected to represent the entire Baltic Proper. For the Kattegat, Danish Straits and Arkona Basin, target values for benthic invertebrates are derived using the Danish Quality Index (Dansk Kvalitetsindeks, DKI) (Borja *et al.*, 2007; Josefson *et al.*, 2009), recently modified to cope with low-salinity environments (Henriksen *et al.*, 2014; Carstensen, Krause-Jensen & Josefson, 2014*b*). The index includes both the Shannon diversity and the AZTI Marine Biotic Index (AMBI) sensitivity classification of species (Borja, Franco & Perez, 2000). An indicator for submerged aquatic vegetation in offshore parts of the Baltic Sea has not yet been developed, although some potential candidate indicators are under development (Carstensen *et al.*, 2014*b*).

(4) HEAT 3.0

Classifications of eutrophication status were made using the third version of the HELCOM Eutrophication Assessment Tool (HEAT 3.0). The first version (HEAT 1.0) was designed for assessment of eutrophication status of the Baltic Sea and was applied to a data set with both coastal and open-water areas. The methodology is described by Andersen *et al.* (2010, 2011), and a comprehensive overview of the results can be found in HELCOM (2009) and Andersen *et al.* (2010; see online supporting information). With the adoption of the EU Marine Strategy Framework Directive (Anonymous, 2008), a slightly modified version of the tool was developed for assessment of eutrophication status of the eastern part of the North Sea, Skagerrak and Kattegat (J. H. Andersen & C. Murray, unpublished data). HEAT 2.0 was structured according to Anonymous (2010) and the classifications were based on a wide range of criteria and indicators, including benthic invertebrates and supporting indicators.

The step-wise approach applied by HEAT 3.0, which builds on the previous versions of HEAT, is described below. A simplified version has recently been applied for an assessment of eutrophication status in 2007–2011 (Fleming-Lehtinen *et al.*, 2015).

(*a*) *Step 1: Targets (Eutrophication Quality Target or ET)*

The majority of targets used for this assessment originate from the HELCOM CORE EUTRO process described in Section II.3. However, the target value of the benthic invertebrates indicator (DKI), the Good/Moderate border (*sensu* the Water Framework Directive), was estimated from pollution gradients according to Josefson *et al.* (2009). The ET was calculated as:

$$ET = RefCon \times (1 - AcDev) \tag{1}$$

where *RefCon* is reference conditions and *AcDev* is acceptable deviation from RefCon [see HELCOM (2009) and Andersen *et al.* (2010) for details regarding this target-setting principle].

(*b*) *Step 2: Calculation of Eutrophication Ratio (ER)*

Most of the indicators used for the assessment have a numerically positive (+ve) response to the stressor in question, e.g. human activities resulting in discharges, losses and emission of nutrients. Hence, a Eutrophication Ratio (ER) for an indicator is calculated as:

$$ER = ES/ET, \ (+\text{ve response}) \tag{2}$$

where *ES* is eutrophication state, i.e. the measured value for a given indicator in a given year.

Some indicators show a numerically negative (−ve) response to nutrient enrichment, e.g. Secchi depth, oxygen concentration and benthic invertebrate indices. For these indicators, the ER is calculated as follows:

$$ER = ET/ES, \ (-\text{ve response}). \tag{3}$$

By calculating the ER for each indicator, a eutrophication response or signal is translated into a number, either below (0–1.00) or above (≥1.00) the target (ET). ER values for different indicators can subsequently be combined (see steps 3 and 4).

(*c*) *Step 3: Grouping of indicators*

The indicators are categorized as: C1 = nutrient levels, C2 = direct effects of eutrophication (chlorophyll-*a* and Secchi), and C3 = indirect effects of eutrophication (oxygen debt and benthos). This categorization was chosen in order to assess eutrophication status in accordance with Anonymous (2008, 2010).

(*d*) *Step 4: Classification of status*

The average or weighted average of ER values within an indicator category is denoted the category-specific ER (see Fleming-Lehtinen *et al.*, 2015, for details). The value 1.00 represents the boundary for assessing whether an indicator group shows an area to be affected or unaffected. Areas with values <1.00 are regarded as 'unaffected by eutrophication', while areas with values ≥1.00 are considered impaired and 'affected by eutrophication'. The two classes are subsequently divided into five sub-classes to enable comparisons with earlier assessments as well as the classification of the ecological status of coastal water *sensu* the EU Water Framework Directive. 'Unaffected by eutrophication' is divided into 'high' and 'good' status, and 'affected by eutrophication' is divided into 'moderate', 'poor' and 'bad' status (Table 3).

(*e*) *Step 5: Integrated assessment*

The classifications made for each category are subsequently combined into an integrated assessment of eutrophication status using the 'one out–all out' principle (Anonymous, 2000; Andersen *et al.*, 2011). This implies that the category, i.e. the group of indicators most sensitive to human activities, i.e. scoring lowest, defines the overall status of eutrophication within an assessment unit.

(*f*) *Step 6: Confidence rating*

Earlier HEAT eutrophication assessments arrived at a confidence assessment by assigning a classification to each indicator (Andersen *et al.*, 2010; Fleming-Lehtinen *et al.*, 2015). In the present study we make use of the standard error reported for the annual indicators. These are approximately normally distributed since they are based on a substantial number of observations. The coefficient of variation (CV) is a normalized measure of the uncertainty of these indicator values and calculated in a given year as the standard error of the indicator [*StdErr(Indicator)*] divided by the indicator value (*obs indicator value*):

$$CV = \frac{StdErr\,(Indicator)}{obs\ indicator\ value}. \tag{4}$$

For oxygen debt, no standard error was specifically given in HELCOM (2013), but we used the variation around the trend regression line in that study as a general measure of the uncertainty (i.e. $StdErr(O_2debt) = 1.1131$ for the Bornholm Basin and $StdErr(O_2debt) = 0.7653$ for the Baltic Proper and Gulf of Finland). The standard error of individual years was approximated by scaling the actual number of observations used for each annual value, n_{O2debt}, with the average number of observations per year, $n_{average}$. Although this approximation is not an exact measure of the standard error of annual oxygen debts, it does describe the changing confidence in annual oxygen debts over time.

$$CV_{O2debt} = \frac{StdErr\,(O2debt)}{obs\ O2debt\ value} \cdot \sqrt{\frac{n_{average}}{n_{O2debt}}}. \tag{5}$$

Table 3. Eutrophication Ratio (ER) intervals and corresponding eutrophication status, eutrophication classes, and deviation range used for the classification of eutrophication in the Baltic Sea

ER	Status	Class	Deviation range
$0.0 \leq ER \leq 0.5$	Unaffected by eutrophication	High	No or insignificant deviation from background values
$0.5 < ER < 1.0$		Good	Slight deviation below target value
$1.0 \leq ER < 1.5$	Affected by eutrophication	Moderate	Slight deviation above target value
$1.5 \leq ER < 2.0$		Poor	Major deviation above target value
$ER \geq 2.0$		Bad	Significant deviation above target value

The CV for a criterion for a given year/basin combination is given by the root mean square of the CV values for the relevant indicators.

$$CV_{Criterion} = \sqrt{\frac{\sum_{nind} CV_{ind}^2}{nind^2}} \quad (6)$$

where CV_{ind} is the CV for each of the *nind* indicators used for that criterion in a given basin and year. Similarly, the CV for the basin in a given year is obtained from the root mean square of the criteria's CV values:

$$CV_{Basin} = \sqrt{\frac{\sum_{ncrit} CV_{Criterion}^2}{ncrit^2}} \quad (7)$$

where *ncrit* is the number of criteria used in the basin assessment for a given year. Finally, a CV for the entire Baltic Sea is calculated from the CVs of the individual basins:

$$CV_{Baltic} = \sqrt{\frac{\sum_{nbasin} CV_{Basin}^2}{nbasin^2}} \quad (8)$$

where *nbasin* is the number of basins used in the assessment in a given year.

III. RESULTS

In this study emphasis is on temporal and spatial variations in nutrient levels (C1), direct effects (C2), indirect effects (C3), and integrated assessment of eutrophication status. Temporal trends with regard to individual indicators are described elsewhere, e.g. Fleming-Lehtinen *et al.* (2008), HELCOM (2009, 2013), Fleming-Lehtinen & Laamanen (2012), and Carstensen *et al.* (2014*a*).

(1) Primary assessment: classification of status

Classifications of nutrient-level status were completed for all nine basins (see online Fig. S1) and cover the period from 1970 to 2012. With only a few exceptions, all areas are impaired for the entire period. Exceptions are the Bothnian Bay and the Kattegat, with the Bothnian Bay fulfilling the nutrient targets during the last two decades.

In some basins, the classifications reveal considerable perturbations (values >2.0) from target levels, e.g. in the Danish Straits, Arkona Basin, Bornholm Basin, Baltic Proper, Gulf of Riga, Gulf of Finland and Bothnian Bay (see online Fig. S1). The maximum deviations from target levels were recorded in the Gulf of Finland in the late 1960s and mid 1970s with values >4.0 (Fig. 2). The trends in ER for nutrient levels show large year-to-year variation, but in some basins the temporal trends indicate improving conditions, e.g. in the Kattegat, Danish Straits, Arkona Basin, Bornholm Basin, Gulf of Riga and Bothnian Bay (see online Fig. S1).

In contrast to nutrient levels, the data used for classifying direct effects of eutrophication date back more than 100 years (see online Fig. S2). Despite some gaps in the time series and the fact that the chlorophyll-*a* indicator was used only since the early 1970s, they enable classification of direct effects of eutrophication in times when the Baltic Sea was supposedly not affected by nutrient enrichment and eutrophication. In eight of the nine basins, with the Gulf of Riga as an exception, ER was in general lower than 1.0 until the 1960s (see online Fig. S2). In most basins, ER increased to above 1.0 in the late 1960s or early 1970s indicating the onset of large-scale eutrophication problems. Recent decreasing trends in ER are observed in the Kattegat and Danish Straits, whilst increasing ER values are observed in the Baltic Proper and Bothnian Bay.

In three basins (Bornholm Basin, Baltic Proper and Gulf of Finland) the oxygen debt indicators could be calculated for a 112-year period, while the bottom invertebrate indicators in some basins date back to the mid 1960s (see online Fig. S3). For the Bornholm Basin, Baltic Proper and Gulf of Finland, we observe a pre-eutrophication period until the late 1950s following which ER values increase. Based on this study, the Gulf of Finland is the sub-basin most affected by eutrophication during the two most recent decades (1993–2012). In the Arkona Basin we observe increasing ER values and in the Bornholm Basin, Baltic Proper and Gulf of Finland, large inter-annual variations occur since the 1970s. In the Kattegat and Danish Straits ER values decrease slowly in recent years, with values below 1.0 indicating a reduction of the indirect effects of eutrophication in open parts of these basins. For the Bothnian Sea stable ER values indicate impaired status, while for the Bothnian Bay relatively low

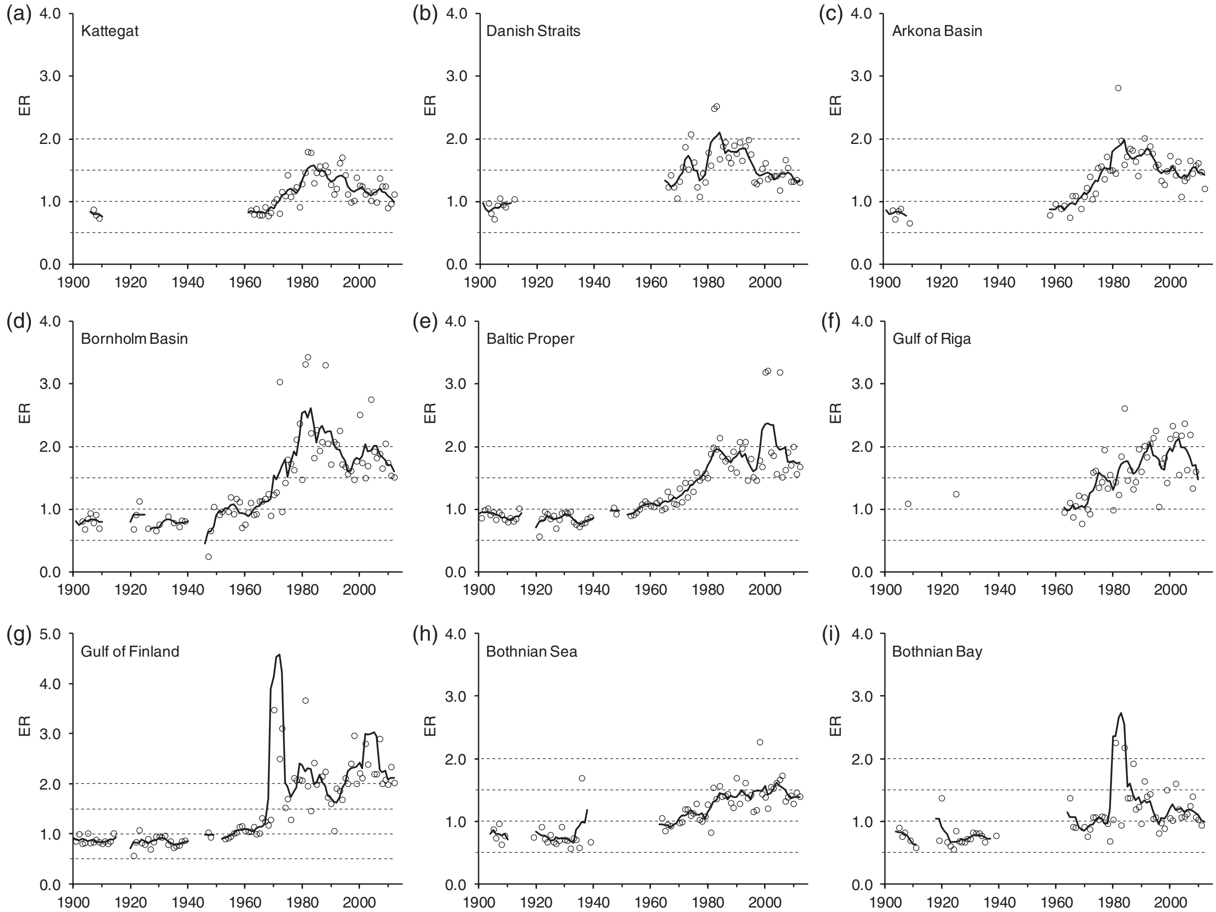

Fig. 2. Integrated assessment of eutrophication status (eutrophication ratio, ER) for the period 1901–2012, in nine Baltic Sea basins (A–I). Dashed lines represent boundaries for eutrophication status classes (see Table 3). The solid line is the 5-year average.

ER values indicate that there are only slight deviations from an 'unaffected' status. In some years, the Bothnian Bay is classified as having an 'unaffected' status.

HEAT 3.0 combines the three criteria-specific classifications discussed above into an integrated classification of eutrophication status to allow us to assess eutrophication status in those basins and years for which data are available (Figs 2 and 3).

The number of potential assessments is 9 basins × 112 years = 1008, but the available data allowed only 621 assessments (Fig. 3). Major data gaps occur in the period 1916–1919 (World War I), in 1940–1946 (World War II), and for the Gulf of Riga. Despite this, a comprehensive set of Baltic Sea data are available since the early 1960s. Until the late 1950s, eutrophication was not a large-scale problem in any sub-region of the Baltic Sea. In the western sub-regions (e.g. open parts of the Kattegat and Arkona Basin) pre-eutrophication conditions persisted into the mid 1960s.

From the late 1950s, several distinct patterns and periods can be identified. Interestingly, 'high' overall eutrophication status (i.e. 'unaffected by eutrophication', see Table 3) was determined only in 1 out of the 621 assessments: in the Bornholm Basin in 1947. This particular assessment was based on a single indicator: oxygen debt. The overall status in the Baltic Sea changed from being moderately affected by eutrophication to substantially affected (status 'poor' or 'bad') from the 1970s, although the Bothnian Sea and Bothnian Bay were classified as poor in only a few years (Figs 2 and 3). The basin most affected by eutrophication is the Gulf of Finland. The Bothnian Bay varies with some years classified as unaffected by eutrophication, while in other years it is classified as moderately affected or bad.

In the Kattegat, Danish Straits and Arkona Basin, eutrophication status improved substantially since the mid 1990s resulting in 'good' eutrophication status in the open parts of the Kattegat in 2010 and 2011 (Figs 2 and 3).

(2) Secondary assessment: estimation of confidence

There are large variations in the number of indicators available over time. Prior to the 1960s, overall coefficients of variation (CVs) showed a great degree of variability related to the sensitivity of the estimated oxygen debt CV to the number of observations (see Fig. 4). From the 1960s there was an increase in the number of indicators available as national monitoring programs became established, resulting

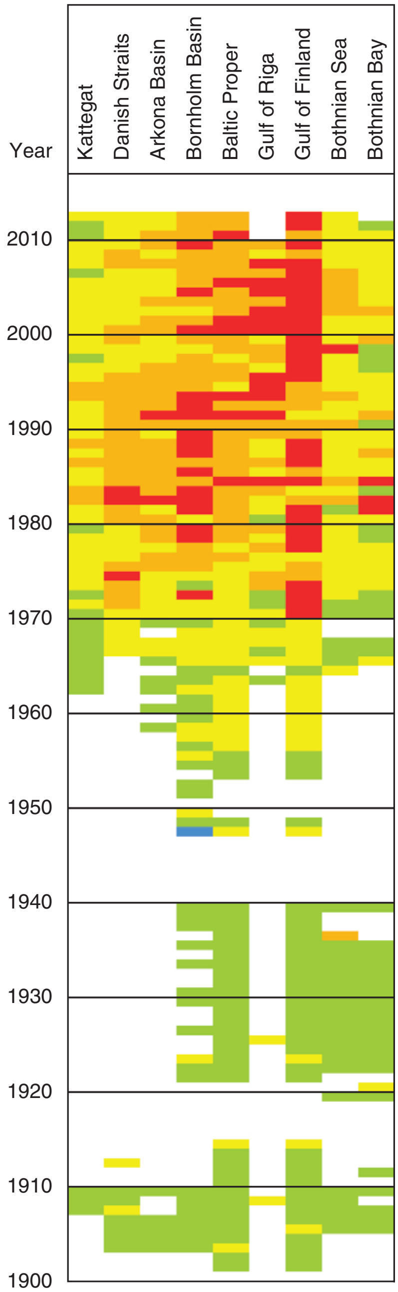

Fig. 3. Integrated annual classification of eutrophication status in the Baltic Sea 1901–2012. For colour coding see Table 3. An integrated classification of eutrophication status based on 5-year running averages is shown in Figs S1–S3 for the three criteria used in the integrated classification.

in a continuous reduction in the 5-year average CV from 0.06 in 1960 to below 0.02 in the 1990s. CV remained below 0.02 until 2009 but during the final years of the period studied increased to 0.026.

We observe declining confidence in recent years as CVs increase, both on a basin level (Fig. 5) and for the Baltic Sea overall (Fig. 4). The causes underlying this decline are not yet fully clear – in some areas (e.g. the Kattegat, Danish Straits and Arkona Basin) it is probably caused by a decline in monitoring activities; in other areas (e.g. the Bornholm Basin, Baltic Proper, Gulf of Riga, Gulf of Finland, Bothnian Sea and Bothnian Bay) we attribute it to declining monitoring activities in combination with incomplete access to the most recent data.

The criteria-specific CVs (see online Figs S4–S12) largely reflect implementation of new methods as well as the establishment of coordination of national monitoring activities. For example, there was a reduction in CV for nutrient concentrations (C1) and direct effects (C2) from 1970 to 2000 in most basins due to the introduction of monitoring of nutrient concentrations and chlorophyll-*a* (1970s). There was an increase in coefficients of variation for C1 and C2 since 2000 in most basins. This is pronounced for C2 in the Kattegat, Danish Straits, Arkona Basin, Bornholm Basin, and Baltic Proper.

IV. DISCUSSION

This study was made possible by the availability of extensive long-term data sets from the Baltic Sea. We used a combination of data from historical research activities and national monitoring programmes resulting from the HELCOM COMBINE programme (HELCOM, 2014*b*) coordinating a variety of long-term national monitoring activities.

(1) Eutrophication assessment 1901–2012

The data used herein date back to 1901. Even though for some periods data were scarce, inconsistently sampled or did not include all relevant variables (indicators), they provide important information on the state of the Baltic Sea more than a century ago. Data from recent decades are probably amongst the best in any European regional context.

Indicator and basin-specific target values were set prior to this study through a scientific and political process (HELCOM, 2013). The classification methods used for status assessments have followed the same principle for many years, using indicators with a target value in combination with indicators in groups and integration under the 'one out–all out' principle. The recently updated HEAT tool used here ensured a direct link to the legislative framework of the EU Marine Strategy Framework Directive (MSFD). HEAT 3.0 was optimised for assessment of eutrophication status in offshore parts of the Baltic Sea but in principle can be applied to other regional seas, such as the Black Sea, Mediterranean Sea, and North Sea. The key difference compared to earlier versions of HEAT is calculation of the eutrophication ratio based on two types of information, i.e. a target value and a status value. Earlier versions of HEAT were based on other principles and three types of information. The target value was calculated based on a value representing 'reference conditions' and a value representing 'status' and subsequently classifications were made comparing the target values with an

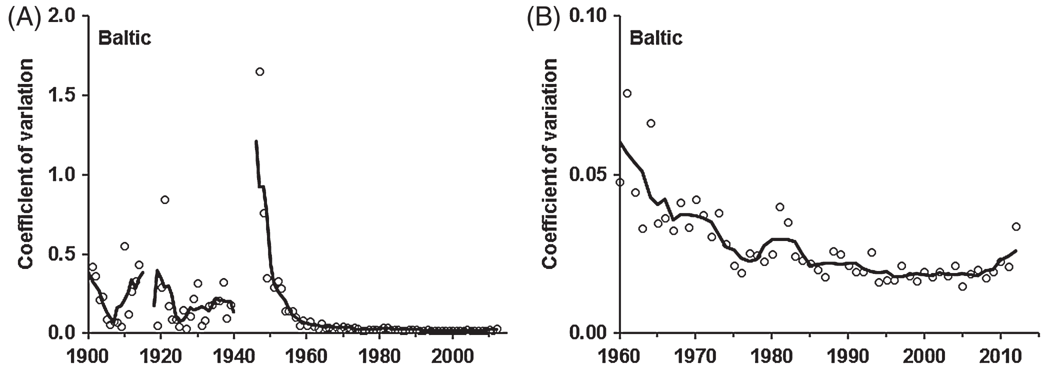

Fig. 4. Coefficient of variation for the Baltic Sea in the period 1901–2012 (A) and 1960–2012 (B). Note different *y*-axis scales. The solid line is the 5-year average.

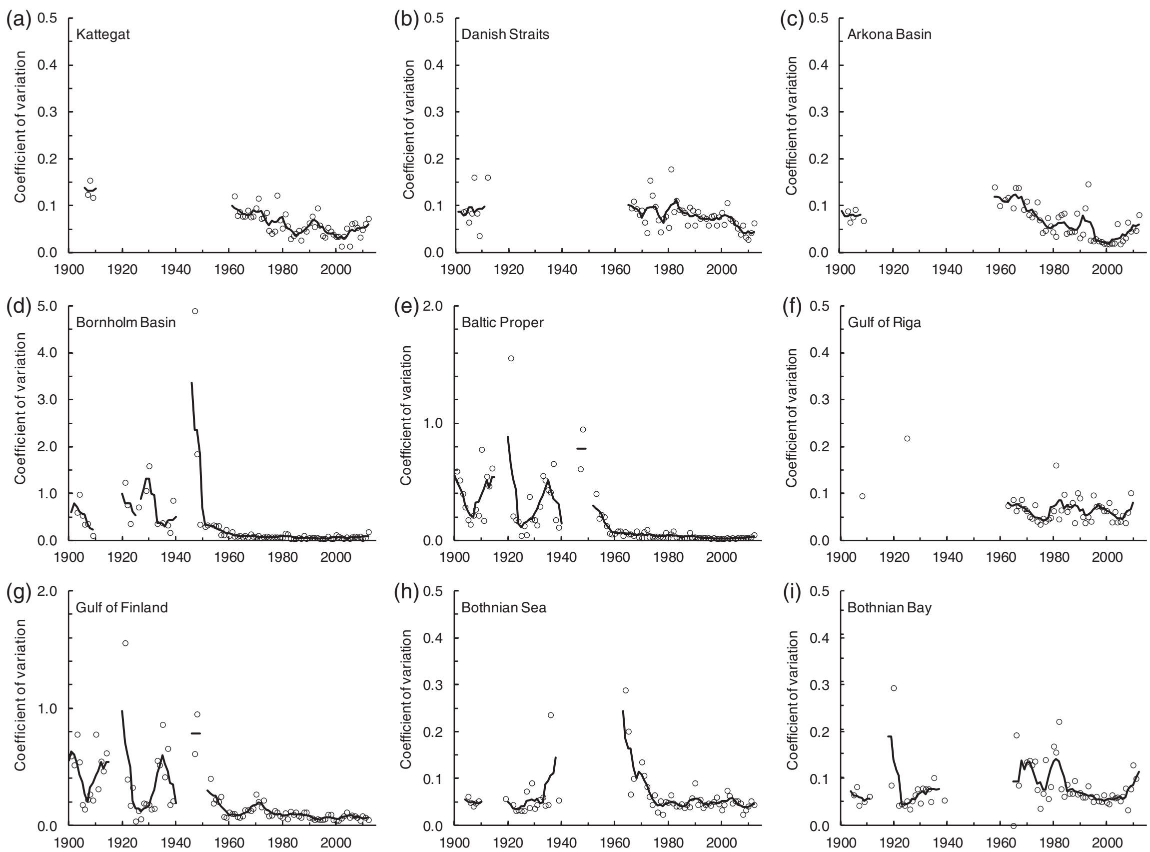

Fig. 5. Coefficient of variation in nine Baltic Sea basins (A–I). Note different *y*-axis scales. Other details are as in Fig. 4.

ecological quality ratio (Andersen *et al.*, 2011, 2014). Earlier versions of HEAT could therefore not be used in a MSFD context where targets are represented by only one value, the target itself.

The present classification is simple and is based on target values classified either as: 'affected by eutrophication' or 'unaffected by eutrophication'. A supplemental classification divides these two principal classes into five classes that can be considered to facilitate better tracking of temporal changes and potentially direct comparison with classifications of coastal waters under the EU Water Framework Directive.

Clear messages to the management community arise from the present classification of the long-term eutrophication status of the Baltic Sea. A pre-eutrophication period can be identified in most basins as can the onset of eutrophication with classification changing from 'unaffected' (good) to 'affected' and thus providing a time frame when conditions began to deteriorate. Periods where the status changed from slightly affected (moderate) to significantly affected (poor and bad) can also be identified in most basins as well as periods without improvement or further degradation ('eutrophication stagnation periods' *sensu*

HELCOM, 2013). For example in the Kattegat there was a major increase in ER during the 1970s and into the 1980s (Fig. 2), which is supported by independent data on a supplementary indicator, benthic biomass in oxygenated parts of the area. A major large-scale increase in biomass (and also a reduction in the number of species) occurred during this period likely due to increased nutrient levels and enhancement of primary production partly mediated by increased freshwater runoff (Josefson, 1990; Austen *et al.*, 1991; Josefson & Jensen, 1992; Josefson, Jensen & Ærtebjerg, 1993).

More importantly, periods of improvements, sometimes referred to as 'oligotrophication periods' (Nixon, 2009; HELCOM, 2013), can be identified in several basins, especially in the western, south-western and the northern parts of the Baltic Sea. The variability observed in the Bothnian Bay is a consequence of year-to-year variation in chlorophyll-*a* concentrations; in some years below the target value and other years above the target. This is in line with the general understanding that the Bothnian Bay is relatively less impacted compared to other areas of the Baltic Sea (HELCOM, 2009; Andersen *et al.*, 2011), although a recent study indicates a worsening of its status (Fleming-Lehtinen *et al.*, 2015).

The observed trends of eutrophication and oligotrophication are not unique to the Baltic Sea, although the Baltic Sea is probably the most well-studied region, where significant reductions in nutrient inputs have taken place. The southern North Sea was also severely affected by eutrophication in the 1980s, and due to the relatively short flushing time of the system, responses in primary production were more rapid and stronger than in the Baltic Sea (Carstensen *et al.*, 2011). However, despite an almost 50% reduction of nitrogen inputs to coastal waters in both the southern North Sea and south-western Baltic Sea, phytoplankton biomass has not decreased at similar rate and biomass concentrations at present are elevated compared to past conditions with the same nutrient pressure (Duarte *et al.*, 2009). Duarte *et al.* (2009) concluded that other pressures associated with global change may have shifted the baseline. In North America signs of oligotrophication have also been observed, typically for coastal ecosystems that were strongly affected by sewage discharges such as the Potomac River estuary (Jaworski, 1990), Tampa Bay (Greening & Janicki, 2006), and Boston Harbor (Diaz *et al.*, 2008).

The 'good' status in the Kattegat in 2010 and 2011 (Fig. 3) can be interpreted as a first sign of recovery due to large reductions in nutrient loadings to the Kattegat, Baltic Sea and North Sea. Although loads are projected to be reduced even further, we envisage the observation of variability in status similar to the pattern observed in the Bothnian Bay due to natural variations in precipitation, runoff and fluxes into the Kattegat from adjacent sea areas. We stress that there are large north–south gradients within the Kattegat and that our results display a simple average across these variations. However, we believe that our findings represent an on-going recovery process, indirectly confirmed by trends in ecological status of benthic macroinvertebrates in the open part of the Kattegat (Fig. 6).

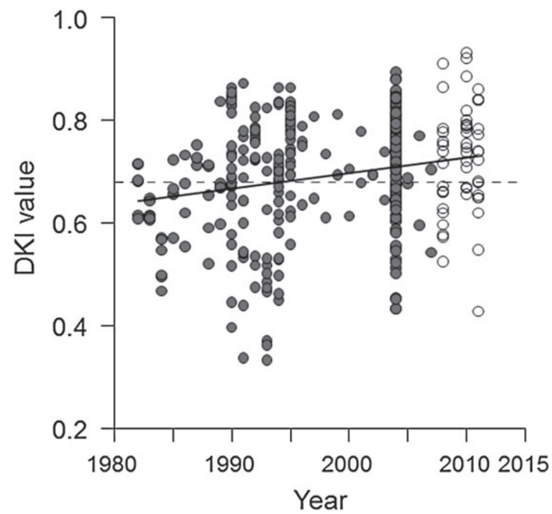

Fig. 6. Trends in environmental status of macrozoobenthos communities (based on the Danish benthic quality index; DKI) in the Kattegat, 1982–2011. The horizontal dashed line indicates the agreed numerical target value (0.68). Filled dots denote samples covering approximately 0.1 m^2 (Van Veen size) bottom area, while open dots indicate samples covering a 30% smaller area. The temporal trend test (solid line) was carried out using permutations regression with DistML (9999) in PRIMER (Anderson, Gorley & Clarke, 2008) and was highly significant ($P = 0.0001$, PseudoF = 15.98, d.f. = 342).

This study of long-term temporal and spatial trends in eutrophication status would not have been possible without long-term ecological research and coordinated monitoring networks across the Baltic Sea. The current collaboration across this region with regard to monitoring, data sharing and assessment is unique and sets a high international standard. Future assessments will be in jeopardy if these activities are not continued with reductions in monitoring efforts having both short- and long-term implications. Over the short term, eutrophication assessments will potentially be compromised. Potential long-term consequences will include a reduction in our ability to document changes in eutrophication status as well as limitations in data for documentation of changes in internal nutrient cycling processes or the effects of climate change.

(2) Confidence

The CV for an individual indicator in any given year decreases with increasing number of observations upon which it is based. The CV gives us a means of estimating overall confidence in eutrophication assessments: lower CV values allow more confidence in the results of the assessment.

The relatively large amount of monitoring data and broad coverage of indicators explains the relatively stable 15-year period with consistently small CV values for the Baltic beginning in the mid 1990s (Fig. 4). During this period after the establishment of national monitoring programs,

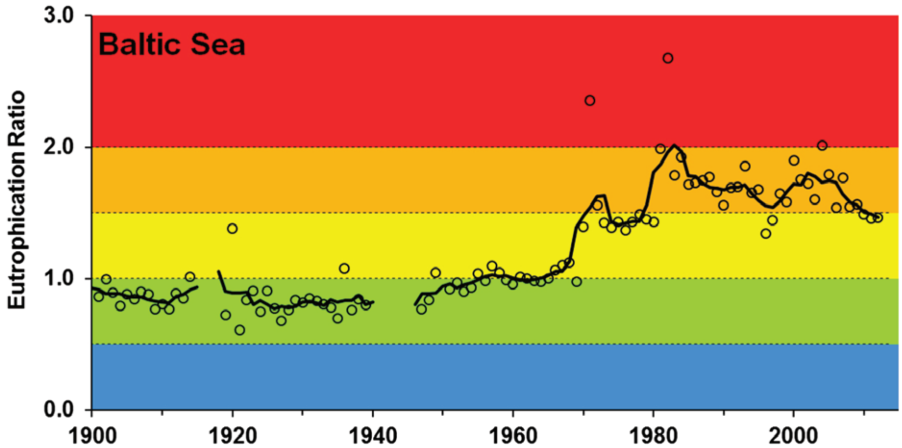

Fig. 7. Integrated assessment of eutrophication in the Baltic Sea 1901–2012, combining all 621 individual classifications of eutrophication status into a single assessment. Colour coding as in Table 3. The solid line is the 5-year average.

including measurement of nutrient levels and chlorophyll-*a*, there are on average five indicators available per basin. An abrupt end of this 'golden age' of monitoring occurred after 2005, by 2012 only 2.3 indicators per basin are available on average. CV increased in all basins between 2008 and 2012 (Fig. 5). A reduction in the number of available indicators and observed subsequent increase in CVs means that our confidence in these assessments is reduced. In the Bornholm Basin, Baltic Proper, Gulf of Riga, Gulf of Finland, Bothnian Sea and Bothnian Bay, this result relates to several different processes, incomplete reporting of data as well as declining monitoring activities. However, in some areas, such as the Kattegat, Danish Straits and Arkona Basin, it is a direct consequence of declining monitoring activities.

(3) Applications and implications

The HEAT 3.0 tool contributes to a better understanding of temporal and spatial trends in eutrophication status of the Baltic Sea and also supports evidence-based implementation of nutrient management strategies such as the MSFD and the eutrophication segment of the Baltic Sea Action Plan (BSAP). HEAT is now embedded in Baltic Sea monitoring and assessment activities and will likely be used in future assessments of ecosystem health in the Baltic Sea. Assessments carried out to date have focused on individual indicators, specific mandated periods (2001–2006 and 2007–2011) and mostly on open waters. Figure 7 combines all 621 individual assessments into one single graph for the Baltic Sea, and shows evidence of (*i*) a pre-eutrophication period, (*ii*) a eutrophication period, and, perhaps most importantly, (*iii*) the onset of what we consider a recovery period. Since the early 1980s, eutrophication status has improved considerably for the Baltic Sea, an improvement directly related to large reductions in the inputs of both nitrogen and phosphorus. Nutrient management and reduction strategies remain debated, especially in regard to whether nitrogen, phosphorus or both should be reduced (Conley *et al.*, 2009).

HELCOM is striving to produce regularly updated high-quality thematic assessments of eutrophication status through an operational and streamlined process. Such assessments require efficient data flows, which currently are not in place. The HELCOM EUTRO-OPER project, during which the entire assessment process, from monitoring and data aggregation to final classification of eutrophication status will be defined and documented, has been established to develop this process. In addition, this project will harmonise assessments in offshore waters with assessments made in coastal waters.

The HELCOM assessments are focused on multi-annual periods, i.e. 2001–2006 (HELCOM, 2009) and 2007–2011 (Fleming-Lehtinen *et al.*, 2015), while this study concerns annual assessments. The advantage of our approach is better resolution in temporal trends enabling identification of early signs of change. For example, for the Kattegat, the 'good' status in 2010 and 2011 might not have been observed when averaging over a longer period. Averaging over longer periods might not reveal the complexity of the eutrophication problem.

Taking the ecological as well as political importance of the BSAP into account, it may be most informative to use HEAT 3.0 in combination with scenario modelling and thereby try to predict future eutrophication status (e.g. Meier *et al.*, 2012). Such studies considering future conditions should indicate (*i*) the extent of areas unaffected by eutrophication, (*ii*) the extent of areas affected by eutrophication after implementation of agreed nutrient reductions, and (*iii*) additional load reductions required to reach the agreed basin-wise eutrophication target values.

The HEAT 3.0 tool can be applied to other large marine ecosystems affected by eutrophication, e.g. the Aegean Sea, Black Sea, Celtic Sea, the Mediterranean, and the North Sea. A key objective would be to carry out fully harmonised and coordinated assessments focusing on classification of eutrophication status and spatial variation. A secondary objective would be to analyse temporal trends and to identify eutrophication periods and potential recovery.

V. CONCLUSIONS

(1) We identify long-term temporal and spatial trends in Baltic Sea eutrophication status using the HELCOM Eutrophication Assessment Tool (HEAT 3.0) and long-term monitoring data. We report: (*i*) a pre-eutrophication period, (*ii*) a eutrophication period, (*iii*) in some basins a continued eutrophication period, (*iv*) trend reversal and oligotrophication processes, and (*v*) finally, in the Kattegat the first signs of recovery.

(2) We document improvements in eutrophication status that are direct consequences of long-term efforts to reduce nutrient inputs. The overall target of a Baltic Sea unaffected by eutrophication has not yet been met, but progress has been made. Hence, we report that reductions in both nitrogen and phosphorus loads has led to large-scale alleviation of eutrophication and to a healthier Baltic Sea.

(3) This assessment documents the value of long-term ecological research and monitoring. We observed large variation in confidence of the assessments of eutrophication status. In all basins we document an increase in coefficients of variation in recent years related to reductions in the intensity of monitoring programs. This trend of reductions in monitoring programs has important implications for our ability to document long-term trends and status in the Baltic Sea. If monitoring activities are not sustained at relevant scales (temporal and spatial), data availability will limit our ability to document long-term trends and status and to understand yet unidentified large-scale ecological changes especially regarding changes in climate.

(4) Our results have led to an improved scientific understanding of eutrophication trends in the Baltic Sea and will act as a baseline for implementation of the ecosystem-based management strategies and policies currently in place including the EU Marine Strategy Framework Directives and the HELCOM Baltic Sea Action Plan.

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VIII. SUPPORTING INFORMATION

Additional supporting information may be found in the online version of this article.

Fig. S1. Trends (1901–2012) in criteria-specific eutrophication ratios (ER) for nutrient levels (criterion 1) in nine Baltic Sea basins. Dashed lines represent boundaries for eutrophication status classes (see Table 3). The solid line is the 5-year average. The figure for the Bothnian Bay does not show the point for 1982 which has an ER = 6.9. This point is included in the 5-year average shown.

Fig. S2. Trends (1901–2012) in criteria-specific eutrophication ratios (ER) for direct eutrophication effects (criterion 2) in nine Baltic Sea basins. Other details are as in Fig. S1.

Fig. S3. Trends (1901–2012) in criteria-specific eutrophication ratios (ER) for indirect eutrophication effects (criterion 3) in nine Baltic Sea basins. The figure for the Gulf of Finland does not show the point for 1971 which has an ER = 12.3. This point is included in the 5-year average shown. There were no data for indirect effects for the Gulf of Riga. Other details are as in Fig. S1.

Fig. S4. Trends (1901–2012) in criteria-specific coefficients of variation for nutrient levels (C1), direct eutrophication effects (C2) and indirect eutrophication effects (C3) for Kattegat. Other details are as in Fig. S1.

Fig. S5. Trends (1901–2012) in criteria-specific coefficients of variation for nutrient levels (C1), direct eutrophication effects (C2) and indirect eutrophication effects (C3) for Danish Straits. Other details are as in Fig. S1.

Fig. S6. Trends (1901–2012) in criteria-specific coefficients of variation for nutrient levels (C1), direct eutrophication effects (C2) and indirect eutrophication effects (C3) for Arkona Basin. Other details are as in Fig. S1.

Fig. S7. Trends (1901–2012) in criteria-specific coefficients of variation for nutrient levels (C1), direct eutrophication effects (C2) and indirect eutrophication effects (C3) for Bornholm Basin. Other details are as in Fig. S1.

Fig. S8. Trends (1901–2012) in criteria-specific coefficients of variation for nutrient levels (C1), direct eutrophication effects (C2) and indirect eutrophication effects (C3) for Baltic Proper. Other details are as in Fig. S1.

Fig. S9. Trends (1901–2012) in criteria-specific coefficients of variation for nutrient levels (C1) and direct eutrophication effects (C2) for Gulf of Riga. There were no data for indirect effects (C3) for the Gulf of Riga. Other details are as in Fig. S1.

Fig. S10. Trends (1901–2012) in criteria-specific coefficients of variation for nutrient levels (C1), direct eutrophication effects (C2) and indirect eutrophication effects (C3) for Gulf of Finland. Other details are as in Fig. S1.

Fig. S11. Trends (1901–2012) in criteria-specific coefficients of variation for nutrient levels (C1), direct eutrophication effects (C2) and indirect eutrophication effects (C3) for Bothnian Sea. Other details are as in Fig. S1.

Fig. S12. Trends (1901–2012) in criteria-specific coefficients of variation for nutrient levels (C1), direct eutrophication effects (C2) and indirect eutrophication effects (C3) for Bothnian Bay. Other details are as in Fig. S1.

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