Baltic Sea biodiversity status vs. cumulative human pressures

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ABSTRACT

Many studies have tried to explain spatial and temporal variations in biodiversity status of marine areas from a single-issue perspective, such as fishing pressure or coastal pollution, yet most continental seas experience a wide range of human pressures. Cumulative impact assessments have been developed to capture the consequences of multiple stressors for biodiversity, but the ability of these assessments to accurately predict biodiversity status has never been tested or ground-truthed. This relationship has similarly been assumed for the Baltic Sea, especially in areas with impaired status, but has also never been documented. Here we provide a first tentative indication that cumulative human impacts relate to ecosystem condition, i.e. biodiversity status, in the Baltic Sea. Thus, cumulative impact assessments offer a promising tool for informed marine spatial planning, designation of marine protected areas and ecosystem-based management, and may prove useful for setting limits on allowable levels of human impact on ecosystems.

Keywords:
marine biodiversity
multiple stressors
cumulative effects
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impacts
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1. Introduction

One of the most daunting tasks for ecosystem-scale management, but also one of the most important, is to reliably assess and track ecosystem condition. Management ultimately aims to improve ecosystem condition, yet must achieve this task by sifting through hundreds of potential indicators, none of which individually tell the whole story and which collectively are expensive to monitor.

Recently a synthetic indicator has been proposed to solve this problem that pulls together the many different measures of human impact on ecosystems. This cumulative human impact indicator (Halpern et al., 2008) models the combined effect of all stressors (for which data exist) on all habitat types (and the taxa within). To date, however, these modelled impact scores have not been validated with empirical data on ecosystem condition, largely because such empirical data are rare and their integration still not common practice. Here we take advantage of a convergence of comprehensive empirical assessments of biodiversity status in the Baltic Sea with concurrent cumulative human impact measures to test how well models match reality.

2. Materials and methods

We have analysed linkages between human activities, pressures and impacts and the status of the marine biodiversity in the Baltic Sea.

The Baltic Sea is an inland regional sea in Northern Europe shared by nine countries whose habitats and species are widely recognized to be heavily impacted and impaired across most, but not all, sub-basins (HELCOM, 2010). In this study, we focus on the open parts of 9 Baltic Sea sub-basins. Assessments units 1 and 2 collectively form the Gulf of Bothnia. The Gulf of Bothnia is together with the Gulf of Finland (unit no. 3) connected to the Baltic Proper, which in this study is subdivided into the following assessment units: Northern Baltic Proper (unit no. 4), Eastern Baltic Proper (unit no. 5), south-eastern Baltic Proper (unit no. 6), the Bornholm Basin (unit no. 7) and the Arkona Basin (unit no. 8). The Kattegat (unit no. 9) forms the transition area, together with the Danish Straits, between the Baltic Sea and the North Sea region.

We have combined and re-analysed two existing data sets for these sub-basins, a detailed mapping of human pressures based on 52 individual Baltic-wide pressure layers (HELCOM, 2010; Korpinen et al., 2012; Fig. 1) and an integrated assessment of biodiversity status applying a multi-metric indicator-based assessment tool that assessed biodiversity status from the period 2001-2007 (HELCOM, 2010; Andersen et al., 2014). The methods and data used are briefly described in the following sections.

2.1. Pressures and impacts – data and methods

The Baltic Sea Pressure Index and the Baltic Sea Impact Index (BSPI/BSII) represent the first attempt in a European context to estimate potential impacts of multiple human stressors or so-called 'cumulative effects' of human activities (HELCOM, 2010; Korpinen et al., 2012). Similar studies have recently been carried out in the Mediterranean Sea and Black Sea as well as parts of the North Sea (Coll et al., 2012; Micheli et al., 2013; Andersen & Stock, 2013). The indices followed the methodology of the global index (Halpern et al. 2008), but were able to use more realistic pressure and ecosystem data sets than the global study and used regional expert knowledge to estimate impact strengths on habitats and species. In the BSII, cumulative impacts (I) for a 5km × 5 km grid were estimated by formula 1,

$$I = \sum_{i=1}^{n} \sum_{j=1}^{m} P_i \times E_j \times \mu_{i,j} \tag{1}$$

where P_i is the log-transformed and normalised value of an anthropogenic pressure (scaled between 0 and 1) in an assessment unit, E_j is the presence or absence of an ecosystem component j (i.e. populations, species, biotopes or biotope complexes; 1 or 0, respectively), and $\mu_{i,j}$ is the weight score for P_i in E_j (range 0-4) (Halpern et al., 2008; Korpinen et al., 2012). In brief, the pressure intensity was estimated by the underlying activities in the grid cells, such as number of wind turbines, biomass of caught fish, average number of ships or amount of nitrogen deposited from atmosphere (see Korpinen et al., 2012). The ecosystem components consisted of underwater habitat maps, water-column habitat maps, distribution areas of marine mammals and spawning and nursery areas of cod. They were either present (value=1) or absent (value=0) in an assessment unit. The weight scores were formed on the basis of three criteria – functional impact, recovery time and resistance of the ecosystem against the pressure – by an expert panel through a workshop and a following expert survey. In total, 52 GIS data layers depicting human stressors and 14 GIS data layers depicting species and habitat distribution. The data was collected from the period of 2003-2007 and originates from HELCOM (2010), Korpinen et al. (2012) and Andersen et al. (2014). Values of each P were multiplied by each E and their common μ (formula 1). If a pressure or an ecosystem component did not occur in an assessment unit, the zero value excluded it from the index. Also zero values in μ resulted in an exclusion of that P×E combination. The resulting BSII value was, hence, an additive sum of those pressures and ecosystem components which occur in the assessment unit and are each weighted by μ. Detailed description of the pressures, ecosystem components, weighting scores and the calculation of the index were given by Korpinen et al. (2012) and the method has been further discussed by Halpern and Fujita (2013). In the BSPI, the calculation lacked the E component and the μ component was an average of the BSII weight scores over all the ecosystem components (E). The BSPI is thus a weighted sum of pressure layers in the assessment units.

For this study, we extracted the average BSPI and BSII value for 9 sub-basins of the Baltic Sea (Table 1). The top underlying human stressors for those areas are: (1) inputs of nutrients and organic matter from land and atmosphere, (2) fisheries, (3) inputs of hazardous substances from land and atmosphere and (4) physical damage to seabed (e.g. dredging, bottom trawling, sand extraction) (HELCOM, 2010). Other stressors in the study were hunting of marine mammals, temperature increase, physical loss of seabed habitats, marine litter and underwater noise.

Further, we re-analyzed the HELCOM dataset of impacts to rank the major pressures in the 9 sub-basins of this study. The data consisted of impact values which were specific for each of the 52 pressures in the BSII. Thus, each P was multiplied by E and μ but not yet summed to the index (see formula 1). We extracted the impact values of the sub-basins and used the mean value to rank the pressures from highest to lowest.

2.2. Biodiversity assessment – data and classifications

In the biodiversity assessment, we included indicators for benthic and pelagic habitats, benthic and fish communities, population indicators of zooplankton, fish, seabirds and marine mammals, and water transparency and nutrient concentrations (dissolved inorganic nitrogen and dissolved inorganic phosphorus) as supporting indicators. The latter are relevant as most parts the Baltic Sea are classified as affected by eutrophication. All indicators and their targets were developed under co-operation of the Helsinki Convention on the Protection of the Marine Environment of the Baltic Sea Area (HELCOM; www.helcom.fi).

The integrated status of biodiversity in this study was based on (1) the Initial Holistic Assessment of the Baltic Sea (HELCOM, 2010) and (2) the Danish Initial Assessment for the EU Marine Strategy Framework Directive (Andersen et al., 2014). In addition, (3) data from the HELCOM indicator reports for chlorophyll-a, water transparency and nutrient concentrations were used to fill gaps.

The assessments were made using the biodiversity assessment tool BEAT 2.0, which is a multi-metric tool integrating four groups of indicators: (1) state of habitats and broad-scale habitats, (2) state of communities, (3) state of species populations and (4) state of supporting indicators. The supporting indicators included, as mentioned, water transparency (a proxy for light penetration) and nutrient concentrations (dissolved inorganic nitrogen and phosphorus). The methodology of the BEAT 2.0 tool has been described in detail by Andersen et al. (2014), but a short description follows. BEAT 2.0 is a spreadsheet-based assessment tool, which uses numerical indicators. Three values are required for each indicator: (1) the observed value (Obs) of indicator, aggregated to assessment units and time periods as necessary, (2) a reference condition (RefCon) defining the value of the indicator which would be seen in a pristine state and (3) the percentage acceptable deviation (AcDev) from the reference condition, within which there still is favourable biodiversity status (equivalent to good ecological status cf. the HELCOM Baltic Sea Action Plan).

A biological quality ratio (BQR) is obtained by comparing the observed value of the indicator with the reference value, depending on the direction of response to pressures. Here we define an indicator which shows an increasing value in response to increasing pressures as having a positive (+ve) response. That is it increases with worsening biodiversity. An indicator which shows decreasing values in response to increasing pressures has a negative (-ve) response: (1) BQR = RefCon/Obs (+ve response) or (2) BQR = Obs/RefCon (-ve response). BQR will vary from 0 to 1, increasing as indicator values come closer to reference conditions.

The biological quality objective (BQO) is defined as follows, indicating how far below the value of 1.0 the BQR may fall whilst still giving a good environmental status: (1) BQO = 1/(1+ AcDev) (+ve response) or (2) = 1 – AcDev (-ve response).

The biodiversity status for each of the 4 groups of indicators (elements) is given by the weighted average of the ratio of BQR to BQO for all indicators within the element. The element is assigned a classification of High, Good, Moderate, Poor or Bad, according to the result. A value of 1.0 indicates the boundary between Good and Moderate (acceptable/unacceptable) status. This classification approach has recently been used for assessment of eutrophication status in the Baltic Sea (Fleming-Lehtinen et al., 2014).

Finally, the overall biodiversity status is obtained from the average of the 4 element BQR/BQO ratios (Table 2).

Benthic community indicators were not applied in two sub-basins (Northern Baltic Proper, Eastern Baltic Proper) in the calculation of the biodiversity status, because of the long-term accumulation of nutrients and organic matter over the catchment area, causing permanent hypoxia (Carstensen et al., 2014). The Baltic Sea suffers from severe hypoxia, which is more or less permanent in the central (deepest) sub-basins. In the semi-enclosed Baltic Sea, hypoxia has caused a loop of nutrient cycling, releasing sediment-bound phosphorus reserves to the water and enhancing blooms of planktonic and macroalgae, which again settle on seabed. The results of the biodiversity assessment and the number of biodiversity indicators in the sub-basins and elements are summarised in Tab. 2.

2.3. Correlation methods

Correlation of the normalised average biodiversity status with average cumulative impacts and with cumulative pressures was tested using the SAS procedure PROC CORR (SAS Institute, 2014) to obtain Pearson's correlation coefficient and Spearman's rank correlation coefficient.

3. Results and discussion

Statistically significant (negative) correlations between biodiversity status and cumulative pressures (Pearson's $r = -0.77$; $p = 0.015$; $n=9$; Fig. 2) and cumulative impacts ($r= -0.70$; $p = 0.034$; $n=9$) provide support for cumulative impact assessments as a measure of overall ecosystem condition. The slightly weaker relationship with cumulative impacts, which translate pressures into predicted impacts based on expected habitat vulnerabilities, is likely due to relatively limited empirical information (and thus higher uncertainty) about these vulnerabilities (Halpern et al., 2007). Moreover, the location of assessment units 8 and 9, close to the entrance to the North Sea where inflowing oceanic water supports better water quality and biodiversity (Fig. 1), may be responsible for their slightly better biodiversity status in Fig. 2.

Use of Pearson's correlation coefficient is justified because the Baltic Sea is probably one of the best studied areas globally, and data availability is second to none. The key environmental problems in the Baltic Sea are well understood and well-documented (HELCOM, 2010). Further, functional relations are also well described, mostly in relation to eutrophication, fishing, and contamination which indirectly affect the biodiversity status in the Baltic Sea. We consider therefore the relationship to be valid and not simply an artefact arising from interpolation between two distinct data clusters.

A more robust test of the correlations can be made by use a non-parametric method. Spearman's rank correlations also show negative relationships between biodiversity status and cumulative pressures (r=-0.63; p=0.067; n=9) and between biodiversity status and cumulative impacts (r=-0.45; p=0.22; n=9) yet these are not statistically significant. This indicates a need for further studies with finer spatial resolution comparing biodiversity and pressure/impacts to strengthen the conclusions we draw here.

The results suggest that cumulative impact assessments, based on existing data and information, offer a good indicator of ecosystem condition. As such, they provide a scientific basis for the actions suggested in the HELCOM Baltic Sea Action Plan (HELCOM, 2007; Backer et al., 2010), which focus on reducing the cumulative impacts of human activities on the marine habitats, communities and species in the Baltic Sea. Importantly, they also provide an efficient and quantitative tool for measuring progress towards achieving those outcomes. However, our study did not analyse causality between pressures, impacts and the biodiversity status and hence the results need to be interpreted in the light of wider understanding of the pressure-state relationship.

It would be desirable to identify potential threshold values or "tipping points" beyond which an ecosystem having good biodiversity status begins to respond to increased cumulative impacts/pressures, showing a decline in ecosystem condition. The limited number of data points in our datasets precludes any meaningful analysis of such nonlinear effects.

Thresholds could, once documented, be used to set management targets, and potentially caps to total cumulative impact. Furthermore, the cumulative impact assessments allow identification of pressures contributing most to cumulative impact at any scale (local to regional), such that management can tailor actions to these pressures and root human activities at the appropriate scale. One could also assess potential trade-offs, where mitigating a dominant stressor at great cost may not be necessary if mitigation of a modest stressor at much lower cost could also reduce cumulative pressures sufficiently to achieve desired ecosystem conditions (i.e., reduce cumulative impact below the threshold). In the Baltic Sea, key causes of impairment are as described related to nutrient enrichment (eutrophication), fishing activities, contamination and physical modification, which are all addressed by the Baltic Sea Action Plan.

By using the linear regression of biodiversity status on cumulative pressures (Fig. 2B), we can estimate the pressure score corresponding to a biodiversity status of 1.0, which indicates the good biodiversity status. In our study the number of data points was, however, too low for an iteration of any thresholds for cumulative impacts, but an indicative range can be estimated (Fig. 2). Further, we can analyse and rank the pressures and impacts (Fig. 3). The rankings could potentially serve as a tool for prioritisation of area-specific measures targeting relevant human activities and the subsequent development of ecosystem-based management strategies.

To our knowledge, this study is the first attempt to show the linkage between cumulative impacts and biodiversity status on a wider scale. In a longer perspective, our finding should lead to more detailed assessment of both potential cumulative impacts and biodiversity status, not only in the Baltic Sea but also other regional sea. Ultimately, we envisage the development of evidence-based decision support tools.

4. Conclusions and perspectives

With a simple analysis of two assessment products – biodiversity status and cumulative impacts – we have shown that it is possible to give scientific basis for regional and sub-regional management measures which aim to a better environmental status with decreased cumulative pressures and impacts. Although our approach can give a robust result at a regional level, uncertainties in the assessments of both cumulative pressures and impacts (Halpern & Fujita, 2013) and marine biodiversity status (Borja, 2014) suggest that the relationship should be further tested at greater spatial resolution, at local scales and in other regions. If greater precision (i.e., reduced uncertainty) is needed, key approaches would be to ensure collection of geo-referenced information on human activities and associated pressures and to improve the mapping of the sea floor habitats. To achieve outcomes, we propose that regional actors, in particular regional sea conventions, should improve collaboration in the field of integrated assessments.

Countries around the world face great challenges in protecting biodiversity and defining programmes of measures to reduce human impacts on marine ecosystems. We have shown that it is possible to scientifically link management measures and the state of the environment, leading to spatial predictions of biodiversity or environmental status. With this result, we can use the correlation to test how different management scenarios (e.g., x% reduction in fishery effort) affect the spatial extent of good environmental status, which is at the core of the concept of ecosystem-based management policy initiatives such as the Baltic Sea Action Plan, and also the EU Marine Strategy Framework Directive.

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FIGURES

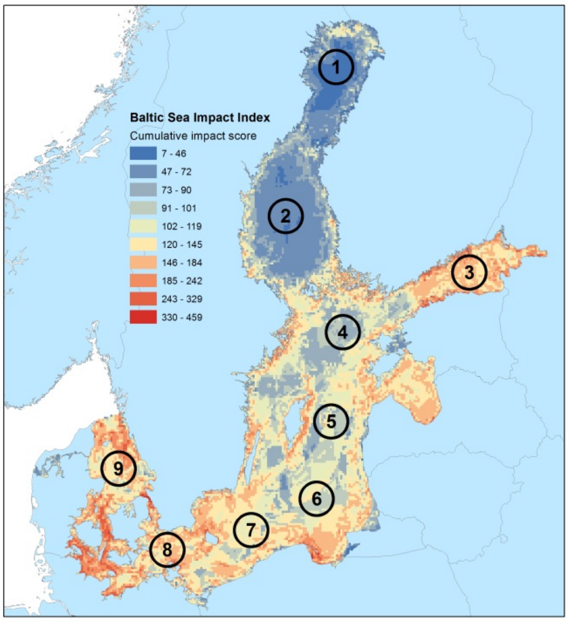

Fig. 1. Mapping of potential cumulative impacts in the Baltic Sea. Numbers indicate offshore biodiversity assessment units. The cumulative impact map is based on Korpinen et al. (2012).

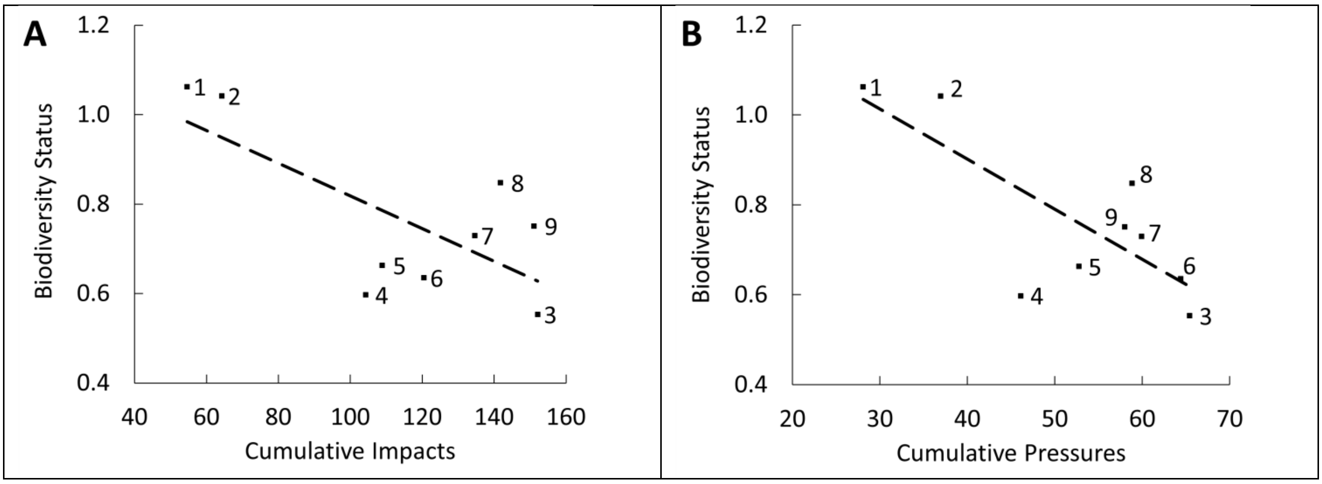

Fig. 2. Correlations between normalised biodiversity status and cumulative pressures as well as cumulative impacts. Panel A: Correlation between cumulative impacts and average normalised marine biodiversity status, where 1.00 represents the border between good vs. impaired biodiversity status. Panel B: Correlation between cumulative pressures and average normalised marine biodiversity status. Dashed lines show linear regressions. Sub-basins with a biodiversity status greater than 1.0 are classified as having a good biodiversity status (HELCOM 2010) and the numbers refer to assessment units in Fig 1. Please see Table 3, which shows Pearson's and Spearman's rank correlation coefficients.

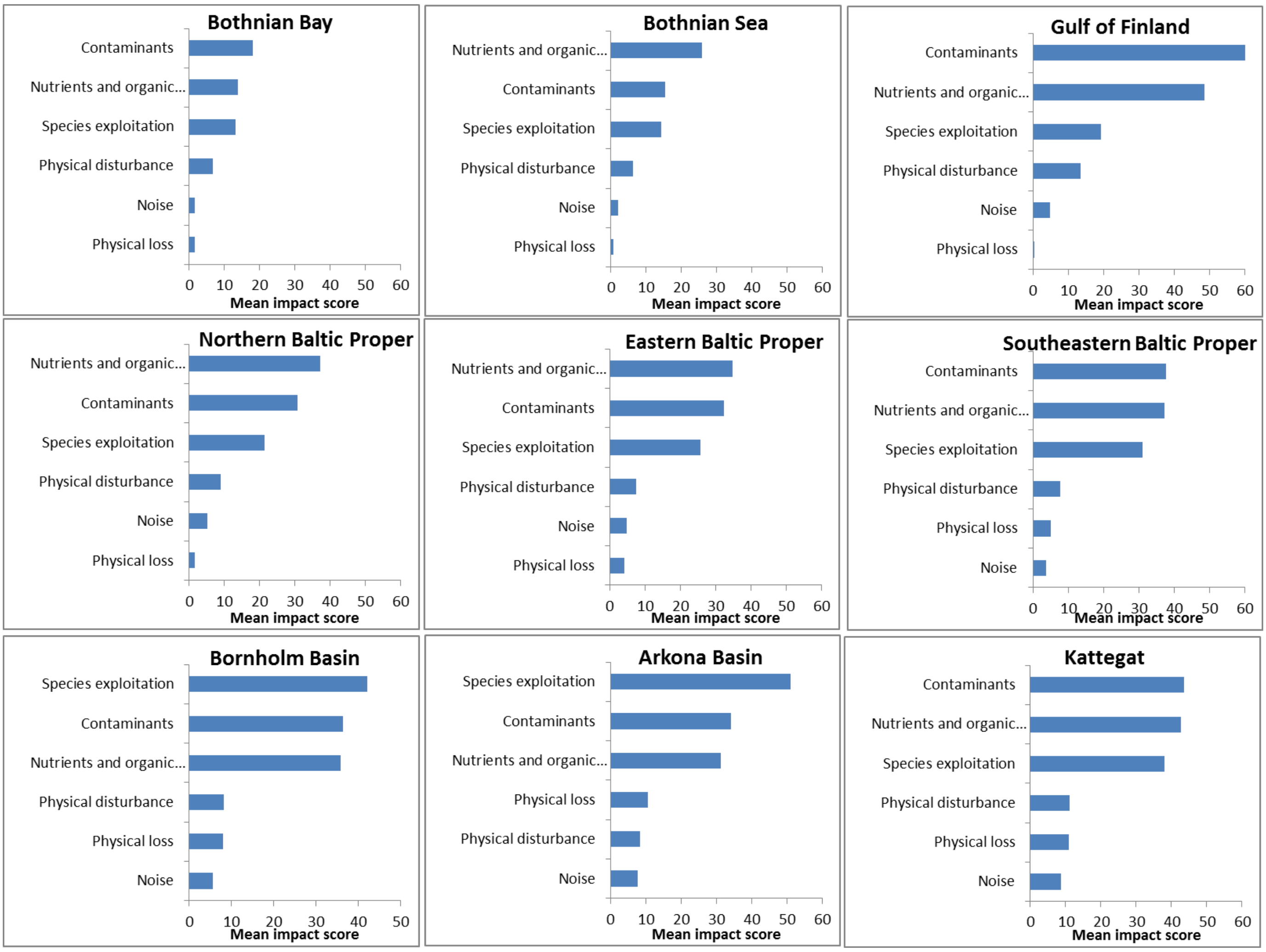

Fig. 3. Ranking of impacts in the open parts of the 9 assessment units. Only the six highest ranked groups of pressures are shown. The impact scores are calculated as mean values of the grid cells and based on data from Korpinen et al. (2012).

TABLES

Table 1. Mean pressure values and impact values for the open parts of each assessment unit. Calculations are based on data from Korpinen et al. (2012).

Assessment unit	**Pressure value**	**Impact value**
1. Bothnian Bay	28	55
2. Bothnian Sea	37	64
3. Gulf of Finland	65	152
4. N. Baltic Proper	46	104
5. E. Baltic Proper	53	109
6. SE. Baltic Proper	64	120
7. Bornholm Basin	60	135
8. Arkona Basin	59	142
9. Kattegat	58	151

Table 2. Results of the assessment of biodiversity status in the open parts of each assessment unit. Number of indicators is indicated in parentheses. The integrated values of biodiversity status are a mean of the normalized values. Updated classifications are based on HELCOM (2010).

Area	**Normalised value (and number of indicators)**				**Biodiversity status**
	Habitats	**Communities**	**Species**	**Supporting**	
1. Bothnian Bay	1.01 (1)	1.32 (1)	0.87 (5)	1.06 (3)	1.06
2. Bothnian Sea	0.72 (1)	1.30 (1)	1.08 (5)	1.06 (3)	1.04
3. Gulf of Finland	0.35 (1)	0.54 (1)	0.60 (6)	0.72 (3)	0.55
4. N. Baltic Proper	0.52 (1)	-	0.53 (7)	0.75 (3)	0.60
5. E. Baltic Proper	0.65 (3)	-	0.64 (7)	0.70 (3)	0.66
6. SE. Baltic Proper	0.62 (3)	0.38 (1)	0.64 (7)	0.90 (1)	0.64
7. Bornholm Basin	0.83 (1)	0.40 (1)	0.82 (3)	0.87 (3)	0.73
8. Arkona Basin	0.80 (3)	0.85 (1)	0.82 (3)	0.91 (7)	0.85
9. Kattegat	0.48 (1)	0.95 (14)	0.65 (9)	0.92 (8)	0.75

Table 3. Pearson's coefficient and Spearman's rank coefficients for correlation of normalised biodiversity status with cumulative impacts and cumulative pressures.

Correlation parameter	**Cumulative impacts**		**Cumulative pressures**	
	Pearson	Spearman	Pearson	Spearman
Correlation coefficient	-0.70	-0.45	-0.77	-0.63
p value	0.0343	0.2242	0.0149	0.0671