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Knowledge and monitoring gap analysis with respect to the EU Directives

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Contents

Summary

This report presents the results of a review on gaps in Baltic Sea monitoring based on two different information sources: peer-reviewed scientific articles, and BONUS and HELCOM project reports. The reviews are part of the BONUS project FUMARI. Our main questions are:

(1) does the current monitoring of the Baltic Sea sufficiently address the requirements set by the Marine Strategy Framework Directive, the Water Framework Directive and the HELCOM´s Baltic Sea Action Plan?
(2) what are the most critical shortcomings (gaps) in the current Baltic Sea monitoring programs?

We found that scientific articles dealing with Baltic Sea monitoring present a view on main monitoring gap occurrence, that differs from the view presented in reports dealing with the same topic. Both scientific articles and reports agreed that many thematic assessment categories are not monitored sufficiently, often due to insufficient spatial coverage. However, whereas articles often highlight both that a category is not sufficiently monitored, and that there is a lack of indicators, the reports focused more on gaps in data storage or handling, coordination of monitoring, or highlighted plans for new but non-operational indicators. Articles mainly mentioned gaps in relation to Eutrophication, Contaminants, Biodiversity, Commercial fish and shellfish, Food webs, Hydrographical conditions, and No alien species. Reports however indicated primarily Biodiversity gaps, followed by Contaminants and Healthy wildlife, Marine litter, and Sea-floor integrity. Our review also showed that certain categories are underrepresented in the scientific literature, i.e. with few scientists developing indicators or assessing data related to them, potentially indicating a knowledge gap in these fields.

Introduction

The state of the Baltic Sea is evaluated through monitoring and assessment programs with the clear political aim to improve water quality and the environmental status of the Baltic marine environment, which has been reported as be in less than good condition. To achieve this, Baltic Sea countries (Sweden, Finland, Denmark, Germany, Poland, Latvia, Lithuania, Estonia and Russia) need to collaborate. By far the most comprehensive approach to collaborate in order “to protect the marine environment of the Baltic Sea from all sources of pollution, and to restore and safeguard its ecological balance" (HELCOM 2001) is the Helsinki Commission (HELCOM), founded in 1974. HELCOM is an intergovernmental organization including all the countries bordering the Baltic Sea, and it governs the Convention on the Protection of the Marine Environment of the Baltic Sea Area. In order to attain its aforementioned main goal, HELCOM developed the Baltic Sea Action Plan (BSAP), which is an ambitious program to restore the good ecological status of the Baltic marine environment by 2021. A prerequisite to an understanding of the status of the Baltic Sea and to fulfil the requirements of current legislation is biological, chemical and physical monitoring. Many different long standing monitoring programs continuously evaluate the environmental state of the Baltic Sea and illustrate its poor ecological and environmental state (HELCOM 2018). However, since these monitoring programs are regulated under different national and regional legislations that adhere to differing national as well as EU requirements, one of HELCOM's functions is to harmonize the monitoring programs for improved comparability of methods, monitoring parameters as well as resolution in time and space.

To achieve a holistic assessment of the Baltic Sea, it is imperative that the monitoring data of the entire Baltic Sea region can be evaluated. HELCOMs attempts to coordinate monitoring and data sharing of the Baltic Sea pioneers the requirements of the MSFD to coordinate regional monitoring of a marine water body shared by different countries (Baltic Boost project, 2017). HELCOM has indeed succeeded in developing joint assessment approaches and has helped to set up data hosts and databases to support indicator-based assessments of the state of the Baltic Sea. However, while HELCOM has a long tradition monitoring certain components of the Baltic marine environment, there are still gaps in coordinated monitoring of other components, partly due to new data needs put forth in the update of the Commission decision (Com DEC 2017/848). HELCOM monitoring is especially strong in the areas of monitoring Eutrophication, Biodiversity, Hazardous substances and Maritime traffic. However, it has been pointed out that there are still gaps to be filled when it comes to harmonization and legislative requirement (HELCOM 2018).

BONUS FUMARI was funded to provide a proposal for a renewed monitoring system of the Baltic Sea marine environment. This requires an extensive review of the gaps between the monitoring requirements set in the international legislation and the existing monitoring and data management which are presented in this report. A further task in the BONUS FUMARI will also explore the possibilities that novel monitoring methods can offer to address identified shortcomings in the existing monitoring system. Overall, BONUS FUMARI aims to provide suggestions to enhance the spatial coverage, comparability, sensitivity and cost effectiveness of Baltic Sea monitoring.

For a holistic Baltic Sea monitoring, there are three important international legislations to adhere to: (1) the EU Marine Strategy Framework Directive (MSFD) (European Parliament and Council, 2008), (2) the EU Water Framework Directive (WFD) (European Parliament and Council, 2000), and (3) the HELCOM Baltic Sea Action Plan (BASP) (HELCOM, 2019), all having the aim to achieve a good environmental or ecological status of the Baltic Sea. Further important legislation with concrete requirements to monitor certain indicators are the EU Habitat Directive (HD, 92/43/EEC) and the Common Fisheries Policy (Regulation (EU) No 1380/2013). For the gap analysis, we have focused on the MSFD, WFD and the BSAP. The BSAP's overarching goal is to help the Baltic Sea achieve ''good environmental status by 2021'', and includes four strategic goals: ''Baltic Sea unaffected by eutrophication,'' ''Baltic Sea with life undisturbed by hazardous substances,'' and ''Maritime activities carried out in an environmentally friendly way,'' all of which should lead to a ''Favourable conservation status of biodiversity''. While the BSAP actions in national and international monitoring are coordinated with the efforts within WFD and MSFD, it often is a challenge. Superficially the WFD and MSFD have the same aim as the BSAP to assure a healthy (Baltic) Sea, but the EU directives differ in their structure and requirements from the BSAP: As an example, the WFD does not explicitly consider a certain threat or pressure (e.g. eutrophication), instead it highlights biodiversity monitoring for status assessment. The MSFD on the other hand takes a more functional approach using a total of 11 holistic quality descriptors for status assessment.

The detailed requirements of WFD, MSFD and BSAP are as follows:

The Marine Strategy Framework Directive (MSFD) requires regional cooperation for the implementation of the MSFD between EU Member States. The MSDF aims to achieve Good Environmental Status (GES) of the EU's marine waters by 2020 and to protect the resource base upon which marine-related economic and social activities depend. To achieve this assessment, the MSFD relies on eleven *descriptors* and a varying number of subordinate criteria and indicators (see Zampoukas et al. 2012; Com Dec 2017/848). Overall, the MSFD attempts a holistic assessment by focusing on function and sustainability of the Baltic Sea marine environment (Patrício et al., 2016).

The 11 MSFD *descriptors* are:
D1: Biodiversity
D2: Non-indigenous species
D3: Commercial fish and shellfish
D4: Food webs
D5: Eutrophication
D6: Sea-floor integrity
D7: Hydrographical conditions
D8: Contaminants
D9: Contaminants in seafood
D10: Marine litter
D11: Energy including underwater noise

In comparison, The Water Framework Directive (WFD) aims at achieving Good Status for all EU surface and groundwater, including coastal areas. WFD status assessment is based mainly on the structure of biological assemblages, and second on physical and chemical parameters. The assessed measures are defined as *quality elements*.

The WFD *quality elements* to assess are:
QE1: Biological
QE2: Hydromorphological
QE3: Physico-chemical
QE4: Priority list pollutants
QE5: Other pollutants

HELCOM's vision for the future in the Baltic Sea Action Plan (BSAP) is a healthy Baltic Sea environment with diverse biological components functioning in balance, resulting in a good ecological status and supporting a wide range of sustainable economic and social activities.

The Baltic Sea Action Plan *Objectives* are:
BS1: Clear water
BS2: Concentrations of hazardous substances
BS3: Concentrations of nutrients
BS4: Healthy wildlife
BS5: Natural level of algal blooms

BS6: Natural oxygen levels
BS7: No alien species
BS8: Radioactivity
BS9: Safe maritime traffic
BS10: Thriving and balanced communities of plants and animals
BS11: Viable populations of species

In the following BONUS FUMARI uses the umbrella term “thematic categories” to address the MSFD descriptors, BSAP objectives and WFD quality elements, which all address characteristic ecosystem features relevant for the assessment and classification of status. For a compiled summary of the terminology of BONUS FUMARI see the appendix.

Indicators constitute specific attributes of each parameter that can be measured, and which allow to follow subsequent change over time. They represent the smallest unit of ecosystem assessment and need to be specified in terms of their spatial and temporal coverage and the matrix/habitat of measurement. The term “indicator” is used in the MSFD but can be regarded as a synonym to “metric”. HELCOM has decided on a list of “Core Indicators” which form the basis for HELCOM environmental assessment (http://www.helcom.fi/baltic-sea-trends/indicators/core-indicators). These Core indicators have regional agreed quantitative threshold values to evaluate progress towards the goal of achieving good environmental status in the Baltic Sea.

Besides the HELCOM Second Holistic Assessment of the Ecosystem Health of the Baltic Sea (HELCOM 2018) report, several other reports have highlighted gaps in monitoring and data sharing of the Baltic Sea area, among them also the BONUS project SEAM which runs in parallel to FUMARI (SEAM 2019). Many of those reports focused only on a specific legislation or certain thematic categories. Other studies attempted a holistic scientific review of the achievements of different Baltic Sea legislations and give recommendations for the future, e.g. Borja et al. (2010) covering MSFD, Hering et al. (2010) covering WFD and Backer et al. (2010) covering HELCOM). Regarding the MSFD, Borja et al. (2010) states that, regardless of the thematic category to monitor, there is a general lack of indicators with a functional approach. And both Hering et al. 2010 and Backer et al. 2010 state that there is a general need for better cooperation between countries and monitoring programs in order to explore and use synergies of monitoring for different directives, especially for other pressures than eutrophication.

Whereas the above reports and scientific articles have a top down view regarding the analysis of gaps in monitoring, i.e. they compare legislative requirements with the monitoring programs in action, BONUS FUMARI takes a bottom up approach. We asked stakeholders directly about their view on monitoring gaps (*BONUS FUMARI report on stakeholder survey*). BONUS FUMARI also conduct a systematic, critical and quantitative literature review of scientific articles and reports to summarize the reported gaps in Baltic Sea monitoring and data sharing (for a qualitative gap analyses, refer to the gap report of BONUS SEAM 2019). We further identify knowledge gaps and future research needs regarding Baltic Sea monitoring and data handling. We focused in this review on the requirements set by the EU Marine Strategy Framework Directive, the EU Water Framework Directive and HELCOM´s Baltic Sea Action Plan.

Main questions

Does the current monitoring of the Baltic Sea sufficiently address the requirements set by the Marine Strategy Framework Directive, the Water Framework Directive, and the HELCOM´s Baltic Sea Action Plan?

What are the most critical shortcomings in the current Baltic Sea monitoring programs?

Methods

Our research collected currently available information on Baltic Sea monitoring from two main sources:

- Peer-reviewed scientific articles.
- BONUS, other EU financed, and HELCOM projects from the past 10 years.

The two types of information were classified in two separate datasets; afterwards, the results from the analyses of the two datasets were compared to identify similarities, differences and knowledge gaps.

Systematic Scientific Literature Review

Literature search

We searched the Web of science core collection with the search terms "Baltic Sea" AND "monitor* OR assessment" for all articles published between 2008 (when the MSFD was adopted) and February 2019 (search date: 28.2.2019). The 1865 resulting hits were used for a detailed systematic literature review, and additionally for graphical systematic mapping.

Systematic mapping

Systematic mapping does not aim to answer a specific question as does a systematic review, but it can be used to find knowledge gaps by visualizing topics that are underrepresented in the literature that would benefit from primary research. Here we visualized the thematic focus of the 1865 found scientific articles, in order to identify underrepresented topics. We searched in all hits for the thematic categories of the MSFD, the WFD and the BSAP, i.e. search terms were the descriptor names, the quality element terms, and the BSAP Objectives. The descriptors "Commercial fish and shellfish" and "Energy including underwater noise" were also searched for separately for each of the two included terms (i.e. "fish" and "shellfish" separately, as well as "energy" and "underwater noise" separately). Likewise, WFD and BSAP terms were also searched for separately in case several terms were included in one category. MSFD descriptors were found 1163 times, WFD quality element terms 556 times and BSAP Objective terms 2066 times. Those results were used to create a treemap, basically showing the frequency that a thematic category was mentioned in the 1865 articles. Seldom mentioned categories were assumed to be gaps in science as they were underrepresented compared to other thematic categories. Thus, such categories were potentially underrepresented also in monitoring, as few researchers worked with them, i.e. developed indicators or analysed them.

Systematic detailed review

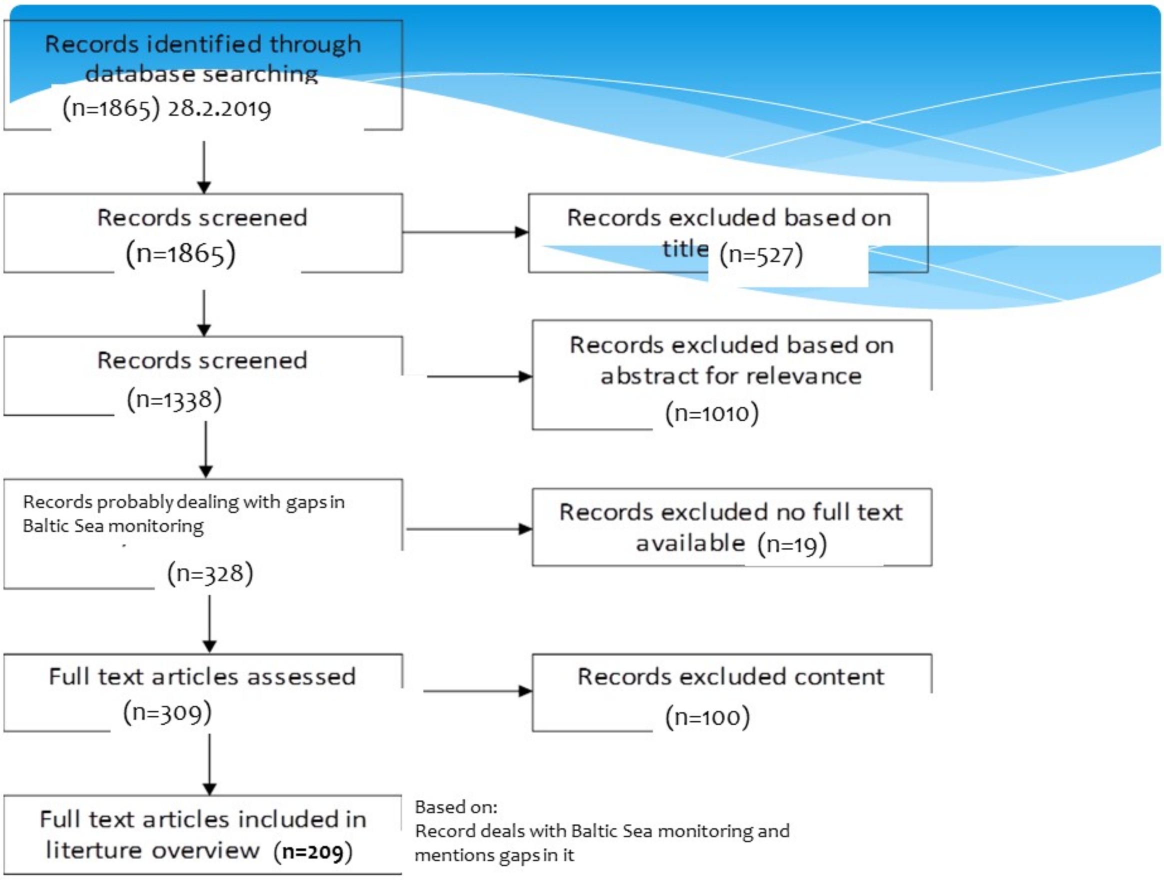


Fig. 1 Flow of systematic review.

The aim of our systematic literature research was to give a comprehensive and exhaustive overview on the scientific literature dealing with Baltic Sea monitoring since the MSFD was adopted in an attempt to understand if the current monitoring of the Baltic Sea sufficiently addressed the requirements set by the HELCOM´s Baltic Sea Action Plan, Marine Strategy Framework Directive and Water Framework Directive, and to identify the most critical shortcomings in the current marine monitoring programs of the Baltic Sea. To identify relevant articles among the 1865 hits including the search terms “Baltic Sea” AND “monitor* OR assessment”, we first screened each article by title. This initial screening discarded 527 articles that clearly were not relevant. Second, we then screened all abstracts for a match with our selection criteria. 328 articles remained, 19 of which were not available in fulltext and were therefore excluded. The full text of the 309 remaining articles was read, but a further 100 were excluded because they did not mention possible monitoring gaps at all, but rather dealt only with management or status classification. 209 articles were then used for the systematic analysis. While reading the 209 relevant articles, we searched for the four keywords “monitor*”, “descriptor”, “indicator” and “gap” to find the relevant sections in each article that deal with our research question.

Analysis

All articles were assessed using a template with questions, to parse knowledge gaps into manageable categories. “EU legislation requirements” was translated into the required thematic categories, i.e. the

MSFD descriptors, the WFD quality elements and the BSAP objectives (and their indicators), and gap analysis was performed in relation to them. The template included the following questions:

Did the authors

1. describe gaps regarding the monitoring of an existing indicator for a certain thematic category?
2. identify the need for another indicator to reflect the thematic category adequately?
3. identify gaps regarding data storage or handling of a certain indicator?
4. propose to include a new thematic category in the monitoring programs?
5. identify further monitoring gaps?

We defined and searched for several gap types that have been mentioned in discussion with stakeholders, and have also been taken up in earlier gap analyses of the Baltic Sea monitoring program (Table 1). A certain theme or indicator can be described as not sufficiently monitored (Gap type 1/G1), having a too low spatial (G1A) or temporal coverage (G1B), or because of another specified reason (G1C), or without additional information about where exactly the problem is (G1). There is no indicator, or the current indicators are not adequate to assess a certain pressure (G2). There is a certain pressure not covered in todays' monitoring (G3). There are problems in data storage or handling (G4). There is an improved or new indicator or method which should be taken up in today's monitoring, but it is still in development and not yet operational or decided upon (G5). There are problems in the coordination of monitoring, often including non-harmonized methods (G6), or the costs of the methods today are too high (G7). See appendix for a compiled summary of the terminology of BONUS FUMARI.

Table 1. List of gap types studied in BONUS FUMARI gap analysis of the Baltic Sea monitoring:

G1: not sufficiently monitored (no additional information)
G1A: not sufficiently monitored (spatially)
G1B: not sufficiently monitored (temporally)
G1C: not sufficiently monitored (other)
G2: missing or not appropriate indicator
G3: missing thematic category (e.g. missing "descriptor") in monitoring
G4: problems with data storage or handling
G5: indicator in development, not yet operational or decided upon
G6: coordination of monitoring
G7: costs too high
GNI: no information

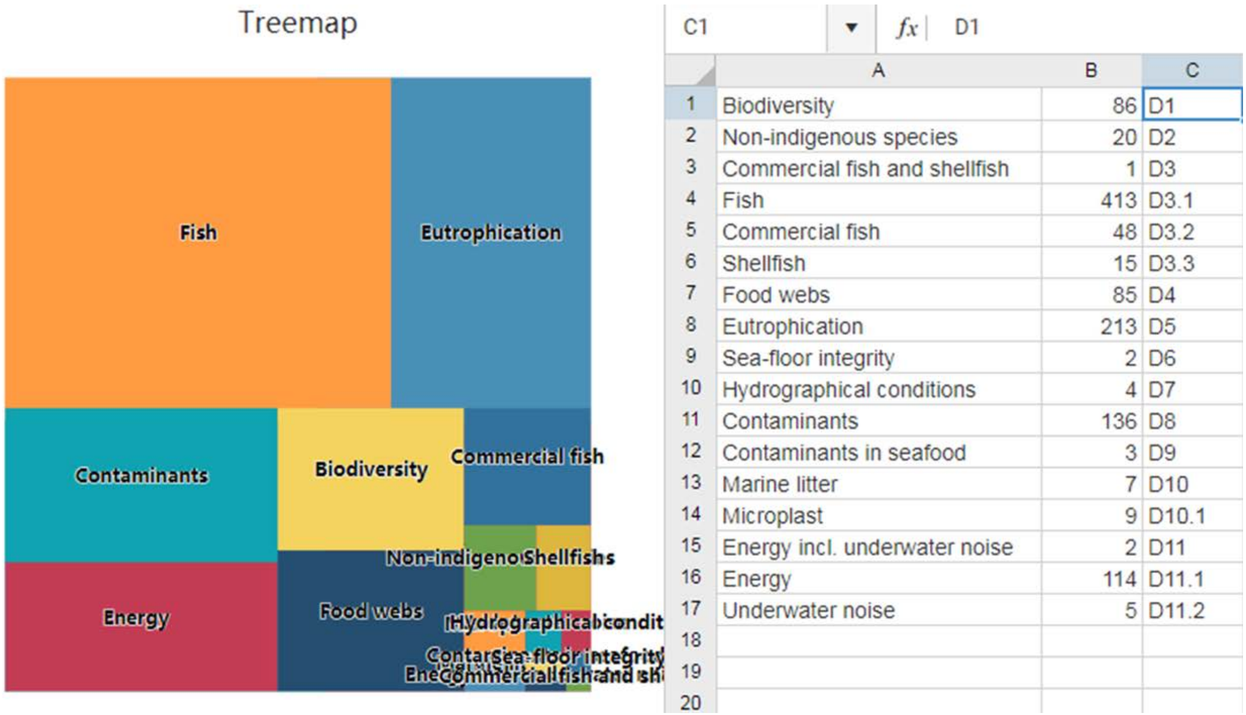
Review of relevant reports

Reports dealt in different ways with the monitoring and assessment of the status of the Baltic Sea, especially within HELCOM and the BONUS programs. Due to the restricted time available, we used expert knowledge to select the 27 relevant reports from the last 10 years (2008-2019) dealing most probably with gaps in monitoring. Reports were read using the same template as for the scientific articles, focusing on the same questions. We also compared our results with the BONUS SEAM report 'Holistic synthesis of reviews and analysis of current Baltic Sea monitoring and assessment' 2019.

Results & Discussion

Systematic Scientific Literature Review

Systematic mapping



	A	B	C
1	Biodiversity	86	D1
2	Non-indigenous species	20	D2
3	Commercial fish and shellfish	1	D3
4	Fish	413	D3.1
5	Commercial fish	48	D3.2
6	Shellfish	15	D3.3
7	Food webs	85	D4
8	Eutrophication	213	D5
9	Sea-floor integrity	2	D6
10	Hydrographical conditions	4	D7
11	Contaminants	136	D8
12	Contaminants in seafood	3	D9
13	Marine litter	7	D10
14	Microplast	9	D10.1
15	Energy incl. underwater noise	2	D11
16	Energy	114	D11.1
17	Underwater noise	5	D11.2
18			
19			
20			

Fig. 2. Systematic mapping of the MSFD descriptors showing the frequency of occurrence of a thematic category in all of the 1865 articles. Categories seldom mentioned are probably less dealt with in science (i.e. potential gaps).

Through the systematic mapping of the MSFD descriptors (found 1163 times in the 1865 articles), we found that in the total number of publications derived by our literature search on “Baltic Sea” and “monitor* OR assessment”, the following descriptors were underrepresented: “Sea-floor integrity”, “Hydrographical conditions”, “Contaminants in seafood”, “Marine litter (incl. microplastics)” and “Underwater noise” (Fig. 2). For the WFD “quality elements” (found 556 times), “Angiosperms”, “Hydromorphology”, and “Priority list pollutants” were underrepresented, as were “Healthy wildlife”, “No alien species” and “Radioactivity” among the BSAP Objectives (found 2066 times).

Systematic detailed review

General results

In the 209 fully screened articles, we found that while “monitor*” and “indicator” were found frequently, “descriptor” was found relatively seldom, and “gap” the least often. However, even if the word “gap” was not mentioned in an article, the authors still often mentioned that monitoring was somehow insufficient, which we then noted as a gap in monitoring.

Gap types – In the 209 articles, gaps in monitoring were mentioned 293 times (sometimes more than one gap per article). 42% of the 293 gaps were gap type 1 (indicator exists, but is not sufficiently monitored; see Fig. 3) and 13% were of gap type 2 (missing or inappropriate indicator for a thematic category; Fig. 3; Table 2). In 33% of the cases when a gap was mentioned for a certain thematic category, no further information was given to explain why this gap was perceived to be a gap. Gap type 1 was due to a need of increased coverage in space, time, or due to other reasons (Fig. 3; Table 2).

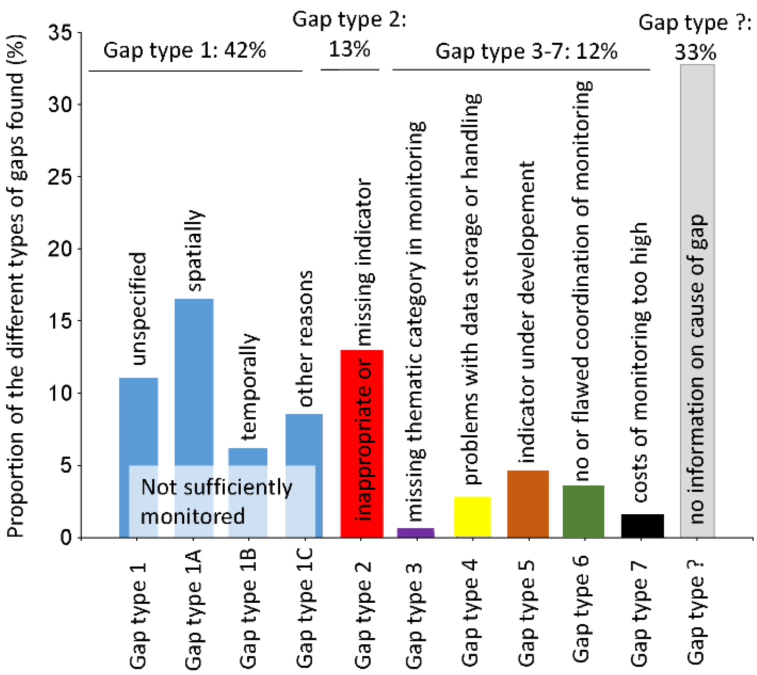


Fig. 3. Gaps in monitoring noted in the 209 scientific articles of the systematic review. Total number of gaps: 293.

Thematic categories with gaps – The thematic categories most often mentioned in connection with a monitoring gap (Fig. 4, Table 2) were Eutrophication (MSFD, 15% of all gaps) and Contaminants (MSFD, 13% of all gaps). When counting also related thematic categories Contaminants in seafood (MSFD), Concentrations of hazardous substances (BSAP) and Healthy wildlife (BSAP), the category Contaminates was equally often mentioned in combination with a gap in monitoring as Eutrophication. The following thematic categories were also often mentioned in connection with a gap in monitoring: Commercial fish and shellfish (MSFD, 8%), Food webs (MSFD, 6%), Hydrographical conditions (MSFD, 5%), Biodiversity (MSFD) plus the related categories Biological quality elements (WFD) and Viable population of species (BSAP) (12%), and No alien species (BSAP) plus Non-indigenous species (MSFD) (4%). "Other category" gaps, i.e. ones other than those listed in MSFD, WFD or BSAP were mentioned in 19% of the cases.

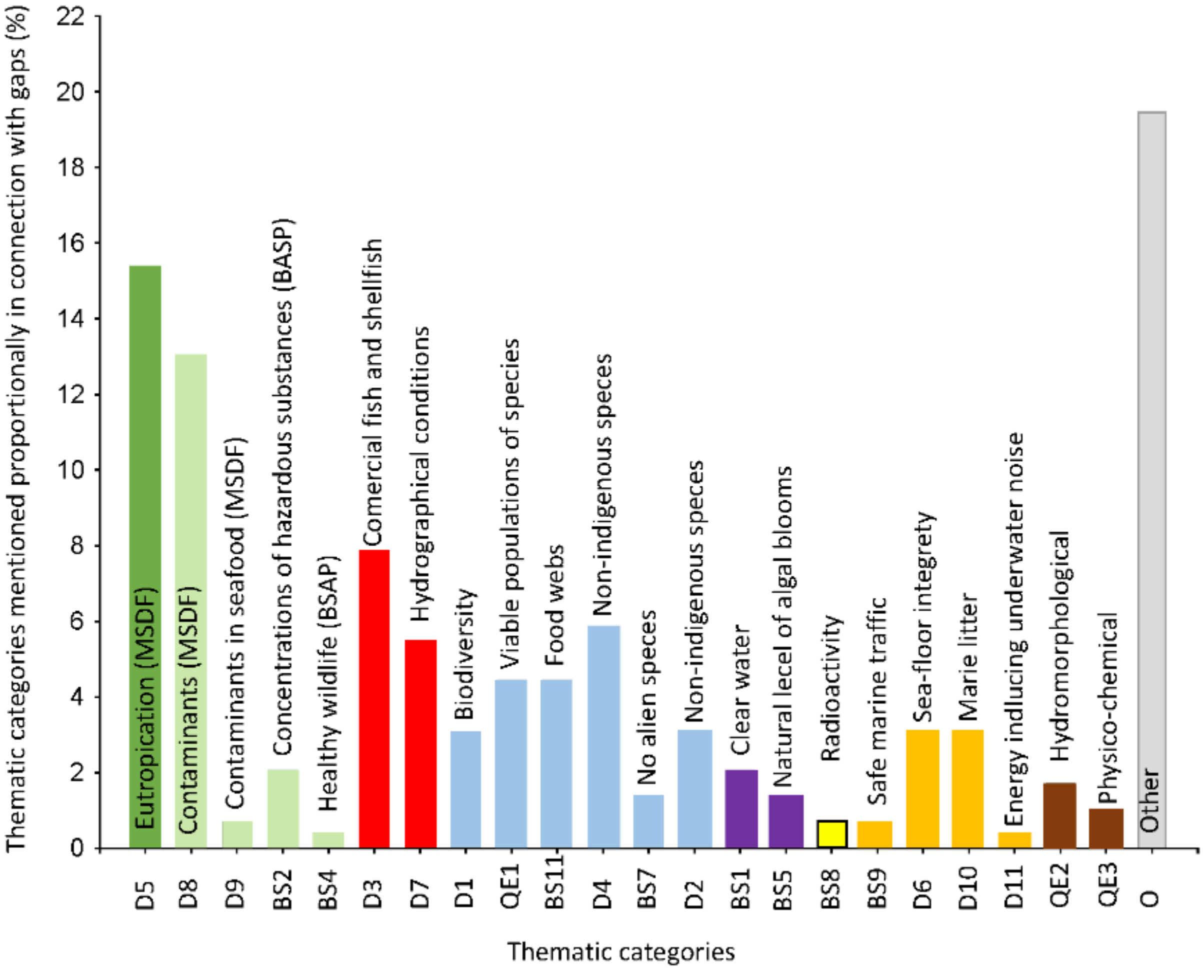


Fig. 4. Thematic categories most often mentioned in connection with a monitoring gap in the 209 scientific articles of the systematic review.

Suggestions for improvement – We found suggestions of a different or additional monitoring indicator of a thematic category in 65% of the articles. In half of these cases, this was a novel indicator, or an indicator that may be developed but is not yet in use. Suggestions of new methods to include in current monitoring were not only given in cases where the gap “G2: missing or not appropriate indicator” was stated, but also for other gap types, e.g. quite often for gap type 1 “Not sufficiently monitored”.

Table 2. Summary of results from 209 scientific articles of the systematic review. 293 Gaps in Baltic Sea monitoring (columns) found in the different thematic categories (rows).

Thematic categories	G1: not sufficiently monitored (no additional information)	G1A: not sufficiently monitored (spatially)	G1B: not sufficiently monitored (temporally)	G1C: not sufficiently monitored (other)	G2: missing or not appropriate indicator	G3: missing thematic category (e.g. missing "descriptor") in monitoring	G4: problems with data storage or handling	G5: indicator in development, not yet operational or decided upon	G6: coordination of monitoring	G7: costs too high	GNI: no information	Totalsumma	in %
D5: Eutrophication	2	10	8	3	3		1	3			15	45	15
D8: Contaminants	3	4		5	5		1	2	1		17	38	16
D9: Contaminants in seafood	2											2	
BS2: Concentrations of hazardous substances	1			2	2						1	6	
BS4: Healthy wildlife					1							1	
D3: Commercial fish and shellfish	3	2		2	9		2	3			2	23	8
D7: Hydrographical conditions	1	6	2	2	1						4	16	5
D1: Biodiversity	2	1			2			2		1		8	12
QE1: Biological		2		1	1				2	1	6	13	
BS11: Viable populations of species	2	1		1	1		1		3	2	2	13	
D4: Food webs	2	3	3		2						7	17	6
BS7: No alien species	2		1								1	4	4
D2: Non-indigenous species	5										4	9	
BS1: Clear water		4	1	1								6	
BS5: Natural level of algal blooms	2	1		1								4	
BS8: Radioactivity		1									1	2	
BS9: Safe maritime traffic		1									1	2	
D6: Sea-floor integrity		4			3						2	9	
D10: Marine litter	1				3		1	1			3	9	
D11: Energy incl. underwater noise											1	1	
QE2: Hydromorphological		1		3							1	5	
QE3: Physico-chemical		1	1	1								3	
O: Other category	4	6	2	3	5	1	2	2	4		28	57	
Sum	32	48	18	25	38	1	8	13	10	4	96	293	
in %	11	16	6	9	13	0	3	4	3	1	33	100	

Detailed analysis of gaps in Baltic Sea monitoring mentioned in scientific articles

A detailed analysis of the reviewed scientific articles is given below to highlight which issues were most often mentioned, and how they were connected to gaps in Baltic Sea monitoring and eventual proposed solutions related to indicators or other issues. We first describe the currently used HELCOM Core Indicators for the most commonly mentioned thematic categories. Then we confront these with the critique brought forth in the articles, and possible solutions. We ordered the gaps and problems according to how often these were mentioned in the articles. We argue that also rarely mentioned gaps in monitoring are important to take up here, since they may be understudies topics, and as such an even more severe gap, due to lack of research attention. The treemap (Fig. 2) indicates these potentially important but understudies topics (e.g. Energy and underwater noise). Finally, we end each section with a holistic view of the monitoring gaps of each thematic category.

Eutrophication

For the descriptor Eutrophication, the gap most often identified by the authors was insufficient spatial coverage. To assess eutrophication, several core indicators are taken up in the Core Indicator List of the HELCOM CIH Baltic Sea Action Plan: CIH1: Water clarity, CIH2.10: Dissolved inorganic nitrogen (DIN), CIH3.1: Dissolved inorganic phosphorus (DIP), CIH3.2: Inputs of nutrients to the subbasins, CIH3.3: Total nitrogen (TN), CIH3.4: Total phosphorus (TP), CIH5.1: Chlorophyll-a, CIH5.2: Cyanobacterial bloom index, CIH6: Oxygen debt, CIH10.6: State of the soft-bottom macrofauna community.

Of the articles stating that the thematic category eutrophication is not monitored sufficiently, eight are taking up the indicator chlorophyll-a as in need of improvement. Six are stating that this indicator is not monitored with sufficient spatial coverage (G1A) (Attila et al., 2018, Tilstone et al., 2017, Harvey et al., 2015, Kratzer et al., 2014, Vaiciute et al., 2012, Kratzer et al., 2011). Two articles state additionally insufficient temporal extent of monitoring (Attila et al., 2018, Harvey et al., 2015). All articles deal with remote sensing, and recommend remote sensing to bridge the obvious gaps in spatial and temporal monitoring. Two articles present an improvement of the remote sensing method by separating the light absorption by phytoplankton from non-algal particles (Meler et al., 2017), or by testing different colour algorithms (Tilstone et al., 2017)). Kratzer et al. (2011) suggests additionally the use of autonomous in situ techniques such as Ferrybox and fixed platforms seatruthing. Remote sensing is also suggested as the new method to assess the indicator Water clarity. Water clarity is another Core Indicator for the assessment of eutrophication insufficiently monitored in space and time (Alikas and Kratzer, 2017).

Remote sensing was also proposed as the method to measure cyanobacterial and algal blooms (Soja-Wozniak et al., 2018, Banks and Melin, 2015, Kowalewska et al., 2014, Banks et al., 2014), to distinguish between different algal groups (Banks et al., 2015, Ferreira et al., 2011), and to fill the gap of insufficient temporal monitoring of blooms (Kong et al., 2017, Ferreira et al., 2011). Three further studies present improvements on remote sensing (Banks et al., 2015, Banks and Melin, 2015, Banks et al., 2014). In addition to remote sensing, further novel methods (i.e. continuous measurements with in situ sensors, ships-of-opportunity, algorithm/model development) to monitor algal, cyanobacterial, and other blooms were suggested (Raateoja et al., 2018, Kong et al., 2017, Kowalewska et al., 2014, Ferreira et al., 2011).

In situ sensors were suggested as method to measure nitrate and hydrogen sulphide which are spatio-temporally not sufficiently monitored (Meyer et al., 2018). Regarding phosphorus, an improved laboratory assessment method could be more appropriate (Felgentreu et al., 2018). One article stated that monitoring of atmospheric phosphorus deposition is lacking completely, but needed (The BACC II Author Team 2015).

Other biological indicators used for eutrophication assessment are the monitoring of macrophytes (Rinne et al., 2018, Wikstrom et al., 2016, Hansen and Snickars, 2014) and macroinvertebrates (Lauringson et al., 2012, Aarnio et al., 2011a, Aarnio et al., 2011b), both are Quality elements of the WFD. Regarding the macroinvertebrates, there are uncertainties regarding the pressure-impact relationship, i.e. too little is known about the impact of stressors other than eutrophication. One article suggests to add functional traits to the assessment. Regarding macrophytes, different problems and solutions are discussed, including adding vegetation cover (Wikstrom et al., 2016), the use of a macrophyte index for soft bottom (Hansen and Snickars, 2014), or of a beach wrack macrovegetation index (Torn et al., 2016). Even the inclusion of certain macroalgal indicators, such as the functionality of cumulative algal cover, covers of late-successional and opportunistic algae, and fraction of opportunistic algae (Rinne et al., 2018) are suggested. However, there are large uncertainties about the natural lower level of occurrence of many macroalgae, an indicator included already (Rinne et al., 2011). Other articles take up benthic microalgae as potential new indicators (Grzegorczyk et al., 2018, Desrosiers et al., 2013).

One article provided an overview of eutrophication indicators to assess environmental status within the European Marine Strategy Framework Directive (Ferreira et al., 2011). This study identified three main gaps in monitoring: many different indicators are not sufficiently monitored, which could be improved by the systematic use of remote sensing of the surface chlorophyll content and other automated sampling techniques such as buoys, ferry boxes, and gliders. The study states that primary production and algal biomass regulation is not sufficiently monitored temporally, also here the development of monitoring tools that account for rapid changes in algal communities, allowing detection of bloom peaks (e.g. continuous measurements, ships-of-opportunity, remote sensing tools, algorithm development, etc.) could improve the data coverage. Finally, the study recommends to assess eutrophication with eight indicators related to nutrient levels, direct and indirect effects of nutrient enrichment. The eight indicators are (1) nutrient concentration in the water column; (2) nutrient ratios (silica, nitrogen and phosphorus); (3) chlorophyll concentration in the water column; (4) water transparency related to increase in suspended algae; (5) abundance of opportunistic macroalgae; (6) species shift in floristic composition, such as diatom to flagellate ratio, benthic to pelagic shifts, as well as bloom events of nuisance/toxic algal blooms caused by human activities; (7) abundance of perennial seaweeds and seagrasses adversely impacted by decrease in water transparency; (8) dissolved oxygen changes due to increased organic matter decomposition and size of the area concerned.

Another study (Andersen et al., 2017), co-funded by HELCOM (TARGREV project) used the HELCOM tool HEAT3.0 to calculate eutrophication status in the Baltic Sea. The authors conclude that the confidence of the status calculations became lower at the end of the time series due to lower spatial and temporal monitoring efforts. They warn that there is a risk of future continuous monitoring quality deterioration, and thus for too low confidence in status assessments.

Contaminants, Contaminants in seafood, Hazardous substances and Healthy wildlife

To assess contaminants, several core indicators are taken up in the Core Indicator List of the HELCOM CIH Baltic Sea Action Plan: CIH2.1: Diclofenac, CIH2.2: Hexabromocyclodocecane (HBCDD), CIH2.3:

Metals (lead, cadmium and mercury), CIH2.4: Perfluorooctane sulphonate (PFOS), CIH2.5: Polyaromatic hydrocarbons (PAHs) and their metabolites, CIH2.6: Polybrominated diphenyl ethers (PBDEs), CIH2.7: Polychlorinated biphenyls (PCBs) and dioxins and furans, CIH2.8: Reproductive disorders: malformed embryos of amphipods, CIH2.9: TBT and imposex, CIH4: White-tailed eagle productivity, CIH8: Radioactive substances: Cesium-137 in fish and surface seawater, CIH9: Operational oil-spills from ships. For clarification, the thematic category of the BSAP "Healthy wildlife" relates to hazardous substances, Healthy wildlife (via core indicator CIH4) reflects an environment un-disturbed by hazardous substances.

For this thematic category, it was mentioned 17 times that monitoring was not sufficient in some way (G1), of which four times insufficient spatial coverage was named, six times no additional info was provided, and seven times authors gave some other explanation. Looking closer into the latter group of articles, it was obvious that all authors chose to state an insufficient monitoring because they aimed to propose either a novel or improved method, which should rather be classified as missing or an inappropriate indicator (G2). New methods were also often proposed without the authors specifying a specific monitoring gap or naming an *existing* indicator to be replaced. We thus summarized the types of novel methods suggested by the authors for this thematic category, irrespective of whether they identified a specific gap or not.

Contaminants – direct water or sediment concentration measurement

Contaminants are measured either directly in the water or sediment, or as concentrations in biota. It is also possible to assess toxic effects on biota, for example by assessing a change in the biological community structure, the reproductive success, by identifying malformations in different organs, by physical tests or through genotoxic assays.

Regarding metals, the Core Indicator list HELCOM CIH of the Baltic Sea Action Plan includes only CIH2.3: Metals (lead, cadmium and mercury) which are measured in water, biota (fish and mussels) and sediments. One study stated that cadmium and mercury concentrations averaged over the whole fish provide a better status assessment then assessments based on liver or muscle tissue alone, thus the currently main indicator method using only parts of the fish is not appropriate (Boalt et al., 2014). Other issues taken up are a need to measure vanadium (Turner et al., 2017), and a need to include metal speciation in the monitoring of metals (Wallin et al., 2015).

Other contaminants currently not monitored are pharmaceuticals (Borecka et al., 2013) and PFC (Theobald et al., 2012). Additionally, one study identified a need to analyse UV stabilizers and UV filters in the sediment to achieve more sediment toxicity data (Apel et al., 2018).

A special case of monitoring contaminants is the detection of contamination by oil spills. There is a gap in monitoring oil spills (Ferraro et al., 2009), especially spatially (Babichenko et al., 2016, Drozdowska et al., 2013). The latter two articles take up the new method of detecting oil film on the water surface by the oil fluorescence spectra. Another article presents a method to detect geographical areas sensitive to oil spills (Depellegrin et al., 2010). In contrast, three articles (Vuorinen et al., 2017, Kreitsberg et al., 2012, Hanson and Larsson, 2008) suggest to monitor oil spills indirectly in biota, by analysing PAH in fish bile instead.

Contaminants – direct measurements as concentration in biota, indirect via effects on biota

In general, several articles suggest to monitor contaminants not (only) by direct measurement of the concentrations, but by measuring the toxic effects on biota (Vethaak et al., 2017, Lehtonen et al., 2014, Hanson, 2009, Hanson et al., 2009, Chec et al., 2008). In direct chemical analyses one can only find the targeted chemical, whereas the indirect analysis of toxic effects can potentially detect also non-target contaminants, and the effect of mixtures.

Eelpout. An example indicator organism mentioned in three articles is the fish species eelpout, which is suggested to be used for direct contaminant detection (Fliedner et al., 2018). Additionally, several new indirect indicators are in development, and are suggested to be used for monitoring, such as reproductive success, endocrine disruption and biomarkers (Bergek et al., 2012, Hedman et al., 2011)referring to the projects BEAST and BALCOFISH). It is however noted that there is an urgent need to coordinate the use of such new indicators (Hedman et al., 2011), and also that there is need for further development to reduce indicator uncertainties.

Other direct contaminant detection methods from tissue that are suggested for the use in monitoring are contaminant analyses of blue mussels (Fliedner et al., 2018), cod (Karl et al., 2016), the analysis of POP concentrations of herring gonads (Schubert et al., 2016) or organochlorides in guillemot eggs (Liversage et al., 2019).

Many other existing or novel indirect contaminant detection methods are also suggested. Suggested methods included the ratio between abundances of copepods and nematodes (Raffaelli and Mason Index)(Berezina et al., 2017), fish parasite metrics (Palm, 2011), the heart rate recovery time of mussels (Kholodkevich et al., 2017), the embryo malformation frequency in amphipods (Berezina et al., 2017), a Fish Disease Index (Lang et al., 2018), or the biomarker relative gonad size in perch (*Perca fluviatilis*) (Hanson, 2009, Hanson et al., 2009). A suggested method including novel molecular tools is a mutagenicity assay for assessment of accumulation of mutagenic pollutants based on the use of the bacterium *Vibrio harveyi* (Chec et al., 2008). Assessing the genotoxicity response was also suggested for fish, bivalves, and crustaceans tissues (Butrimaviciene et al., 2018), but noting that the pressure-response relationships of these new methods are equally as unsatisfying as for the classical EROD method (Chec et al., 2008).

General on contaminant monitoring

Seven articles highlight in a holistic view that there are gaps in monitoring of hazardous substances in the Baltic Sea. Views range from the total exclusion of this thematic category from the analysis of human pressures due to the large gaps in the availability of data on contaminants (Korpinen et al., 2012), to Ojaveer and Eero (2011) stating the opposite, i.e. there is sufficient monitoring data on hazardous substances are sufficient for an ecological assessment. Noring et al. (2016) take up the fact that socioeconomically aspects should be included in monitoring to be able to evaluate the economic impact of toxins.

Other articles are detailed studies of the gaps in contaminant monitoring and include suggestions on how to fill them (Tornero and Hanke, 2016, Anna et al., 2016, Ojaveer and Eero, 2011). Tornero and Hanke (2016) analysed Baltic Sea contaminant monitoring and data availability holistically. Their conclusion is that nearly one-third of the chemicals potentially identified as threat to the Baltic Sea appear not to be considered under any current framework. Those chemicals monitored have poor data accessibility which is in need of improvement. Anna et al. (2016) reviewed available data in order to investigate which substances are included in environmental monitoring programs of Baltic Sea fish. They conclude that non-target screening projects for prioritizing chemicals for large-scale monitoring are needed. They further call for novel methods to identify new POPs and better knowledge on the dietary source of contaminants.

Wolz (2009) suggested that monitoring is needed to understand how the results obtained by analytical methods in the laboratory correlate to field measurements regarding the ecotoxicological characterization of sediment cores. Also Bettinetti et al. (2009) advised sedimentary monitoring to complement contaminant monitoring in biota. They discuss that biota monitoring is currently not harmonized, and that sediment monitoring could be harmonized easier. Finally, Spiridonov et al. (2011) stated that the geological hazard potential of coastal zones should be part of monitoring programs.

Commercial fish and shellfish

The monitoring of fish and shellfish in the Baltic Sea covers the abundance, distribution, growth, population dynamics and exploitation of fish. Much of this monitoring is carried out under the umbrella of ICES (International Council for the Exploration of the Sea). ICES is an international network of scientists that provides advice to governments for the conservation, management, and sustainability goals of marine ecosystems, with a focus on fishing. The different monitoring programs regarding fish include surveys, monitoring of commercial catches and direct assessments of population (stock) dynamics. The improvement of the latter was often a focus in the reviewed articles dealing with the thematic category Commercial fish and shellfish.

HELCOM core indicators are 'Abundance of key fish species' and 'Abundance of fish key functional groups' (in the sub-programme coastal fish), 'Abundance of sea trout spawners and parr' and 'Abundance of salmon spawners and smolt' (Migratory fish), 'Proportion of large fish in the community' (Offshore fish) and 'Number of drowned mammals and water birds in fishing gears' (Fisheries by-catch).

One overview article focused on the monitoring of MSFD descriptor D3: Commercial fish and shellfish and how it could be improved (Probst et al., 2016). It states that indicators are missing, and suggests several new indicators (Fishing mortality (F), Spawning stock biomass (SSB), Mean length in the commercial catch (LC), Size-based fish indicators, Growth overfishing, Genetic impacts of fishing). Four of the suggested indicators are novel. Also other articles take up the issue that appropriate indicators are missing. They suggest improving current dietary assessment methods by comparing morphological analysis and DNA metabarcoding of gut contents, and by including tissue chemical markers (fatty acid profiles of blubber, stable isotopes of liver and muscle) (Tverin et al., 2019), request that vessel fishing strategy (for human use or for fishmeal) be recorded in order to interpret vessel monitoring data (Mikkonen et al., 2008), and suggest a novel method of forecasting the long-term qualitative composition of ecosystem and fish stocks (Ojaveer and Kalejs, 2012). Twelve articles criticize that fish stock assessments are not accurate today, and suggest modifications of monitoring methods to improve data availability for modelling fish stocks.

Food webs

HELCOM Core Indicators for Food webs are the Abundance of coastal fish key functional groups, the Seasonal succession of dominating phytoplankton groups and the Zooplankton mean size and total stock (MSTS).

The gap type mostly mentioned for this category was “not sufficiently monitored” (8 cases), in both space and time. The main problem mentioned is the uncertainty involved in the currently used models to assess food webs. Different problems, sometimes with a suggestion to be solved by monitoring, are mentioned. One problem is the lack of sufficient data on abundance and biomass of total zooplankton, copepods, microphagous mesozooplankton (Gorokhova et al., 2016). Overall, all trophic levels (phytoplankton, zooplankton and top predators) are in need of better spatial and temporal coverage (Olsson et al., 2015). Moreover, coastal and benthic habitats are weakly represented in current monitoring programs (Strandmark et al., 2015). Samhouri et al. (2009) give a holistic overview and a plethora of recommendations of certain taxa groups etc. to monitor, to assess whether changes in Food webs have occurred. The authors recommend the use of indicator groups in the food web, complementing each other by reacting to different environmental changes and pressures, and suggest to monitor phytoplankton, zooplanktivorous fish, piscivorous fish, and trophic level of the catch. Ecosystem indicators consisting of lower-trophic level with higher-productivity functional groups (such as detritivores, phytoplankton, benthic invertebrates) tended to perform particularly well to indicate food web changes.

Hydrographical conditions

The monitoring of hydrography includes measuring physical oceanographic parameters like temperature, salinity, turbidity and water transparency. The topic also includes monitoring of waves, currents and sea ice extent and thickness. However, the only HELCOM Core Indicator linked to the monitoring of hydrographical conditions is Water clarity measured by Secchi depth.

The gap type mostly mentioned for this category was “not sufficiently monitored” both in space and time, and the indicators related were mainly temperature and salinity, waves, surface currents and hydrodynamic structures. Almost all articles suggested to take in new methods, and most often mentioned were Argo float observations and satellite-based techniques.

No alien species and Non-indigenous species

The HELCOM core indicator is 'Trends in arrival of new non-indigenous species'.

Also for this category, the gap type mostly mentioned for this category was “not sufficiently monitored” (8 cases). Potential solutions included the port surveys, models to detect risks for arrival, by using molecular probes or automatic plankton recorders. The articles dealt with different organisms, but most of them pointed out that the entire category of Non-indigenous species is not sufficiently monitored. One holistic article covering only estuarine and coastal areas dealt with this thematic category (Olenin and Minchin, 2011). It suggested to first identify areas with the highest risk for invasive species, and then concentrate on monitoring at those high risk areas. Besides ports, the article suggests that wind farms are in need of monitoring because they could act as “stepping-stones” for alien species. Wind farms are even otherwise in need of more monitoring because of more risks to the environment. These risks include disturbed sediments from cable trenching, noise from pile driving, working vessels and turbines, lubricants from turbines and electric fields from cables. Regarding monitoring such risk areas, Olenin and Minchin (2011) state that at first a list of target organisms to search should be compiled. Afterwards, different alien species monitoring programs may be instigated, depending on the purposes and further use of information. One suggestion is to set up survey monitoring on floating artificial substrates enabling a fast screening for alien species. Olenin and Minchin (2011) also note that monitoring programs never can cover everything, thus emphasizing the need for taxonomical training of both experts and the public to identify alien species. Informing the public in order to report alien species, and developing cost-effective methods such as DNA barcoding and automatic image analysing is also of prime importance.

Biodiversity, Biological Quality Elements and Viable population of species

The monitoring of biodiversity (MSFD) and the Viable population of species (BSAP) has been integrated by the programs coordinated by HELCOM. The thematic category BS10: Thriving and balanced communities of plants and animals is also included here, but was not mentioned in the reviewed scientific articles. Additionally, we explored the WFD related articles dealing with gaps in Biological Quality Element monitoring. In total, 33 articles reported gaps in these categories. Several HELCOM Core Indicators are connected, most of them dealing with fish, birds or mammals: CIH10.2: Abundance of key coastal fish species, CIH10.3: Abundance of sea trout spawners and parr, CIH11.1: Abundance of salmon spawners and smolt, CIH11.2: Abundance of waterbirds in the breeding season, CIH11.3: Abundance of waterbirds in the wintering season, CIH11.5: Number of drowned mammals and waterbirds in fishing gear, CIH11.4: Distribution of Baltic seals, CIH11.6: Nutritional status of seals, CIH11.7: Population trends and abundance of seals, CIH11.8: Reproductive status of seals; and only one with other organism groups: CIH10.4: Diatom/Dinoflagellate index.

For this thematic category, many different gap types were noted in the review articles, which reflect in summary the diversity of problems faced when monitoring biodiversity. Not sufficiently monitored (G1) was mentioned nine times, of which three were on insufficient spatial monitoring, four gave no additional info, one stated that taxonomical resolution was too low and one criticized the lack of harmonized methods. A missing or not appropriate indicator (G2) was mentioned by three articles, problems with data storage or handling (G4) by one, indicator in development, not yet operational or decided upon (G5) by two, insufficient coordination of monitoring (G6) by five, and too high costs (G7) by four articles. Eight articles did not classify the gap type, however six of them mentioned that uncertainty in existing indicators were too high or unknown.

The indicator “presence of harbour porpoise” illustrates the diversity of gaps in this thematic category. Different articles noted that the indicator “presence of harbour porpoise” is a) not sufficiently monitored without giving a cause (G1, 61), that b) spatial monitoring is insufficient today (G1A), that c) the costs for today’s monitoring of point transect distance sampling are too high (G7) (Kyhn et al., 2012), and d) that the coordination of today’s monitoring is insufficient (G7, (Sveegaard et al., 2011). Passive acoustic monitoring is mentioned four times as method to close these gaps. One study suggested to complement harbour porpoise monitoring with targeted eDNA sampling (Foote et al., 2012).

In general, 13 of the identified gaps dealt with fish, birds or mammals. The remaining gaps dealt with other organism groups: Phytoplankton and macrophytes (including macroalgae) related gaps were mentioned three times and macroinvertebrate related gaps nine times. Further gaps are that microzooplankton biomass is not monitored sufficiently, that standardised protocols for soft-bottom benthic foraminiferal monitoring are missing, and that DNA metabarcoding is a promising method for monitoring biodiversity, but that this method still is in development; 2 times (G5).

Finally, Ojaveer and Eero (2011) take a holistic approach on the assessment of biodiversity, and highlight both gaps and solutions in an overview. The authors summarize that the Baltic Sea biodiversity status is associated with a broad spectrum of indicators, which show heterogeneous performance. Especially lacking are indicators related to the central Baltic, and for habitats and communities. However, the greatest challenge is assessing the status of biodiversity in Baltic Sea assessment. The authors recommend to more emphasis on biodiversity assessments, including the separate analysis of the major trophic levels (i.e., plankton, benthos, fish, birds, and mammals) and habitats. This should be followed by development of algorithms for an aggregated biodiversity estimate.

Other category

19% of the gaps noted were in other thematic categories than the ones specifically listed in MSFD, WFD or BSAP. Gaps were found in topics - in order of decreasing occurrence - Wind farm construction, Climate change, Sustainable use of ecosystems, Munitions, Vulnerability of resources, Water colour, Acidification, Sea ice, Temperature and salinity. Other themes mentioned only once were Ionizing radiation, Light reflectance from above-sea-surface, Threats to wooden marine structures, Waves, Bioaccumulation of cyanobacterial toxins in freshwater food webs, Impact of hazardous substances on reproductive success of fish in the marine environment, Abrupt regime shifts in natural ecosystems and Marine habitat types. In several articles, no theme was specified, but the articles referred to MSFD, WFD or BSAP in general.

Review of relevant reports

Reviewed reports

The relevant larger reports covering many or all thematic categories were HELCOM (2018), BALSAM and BOOST, all projects coupled to HELCOM. Whereas HELCOM (2018) covers the entire HELCOM monitoring with respect to the State-of-the-Baltic-Sea assessment 2011-2016, BALSAM and BOOST were more restricted. BALSAM carried out a preliminary assessment of gaps in monitoring against different MSFD descriptors and indicators with the aim to improve coordination of monitoring. BALSAM focused on earlier identified gaps of the monitoring of seals and seabirds, non-indigenous species, benthic habitats and the coordinated use of research vessels. The BalticBOOST project was designed to contribute to improved coordinated monitoring with HELCOM as the coordination platform for the regional implementation of the MSFD for EU Member States. BOOST focused on biodiversity and hazardous substances, and additionally seabed habitats and underwater noise.

The relevant shorter reports included in the review were the BONUS projects AFISMON addressing microbial biogeochemical processes, BALTHEALTH - Food webs, ECOMAP - Sea-floor integrity, FERRYSCOPE - water quality assessment, ESABALT - Safe maritime traffic, HARDCORE - geophysical parameters, INTEGRAL and PINBAL – eutrophication, GEOILWATCH - Marine Oil Spill Recognition, SEAMOUNT - submarine groundwater discharge, MICROPOLL - Healthy wildlife, and BIO-C3 - Biodiversity. We also took into account the HELCOM projects SPICE, addressing marine litter and TAPAS, reviewing existing economic data and environmental economic accounts systems.

No other reports were not relevant because they either developed methods or models belonging to none of the above mentioned project's umbrellas, gave recommendations on monitoring without mentioning or referring to monitoring gaps, or were strategic overview articles without an own gap analysis, often also referring to the above mentioned projects. For example, the EU project DEVOTES, which explicitly aimed at recommending monitoring strategies, refers to the gap analysis of BALSAM/HELCOM 2013/2015 to give an overview of the monitoring activities in the Baltic (Patrício et al., 2016).

Results of review

Gaps in monitoring were mentioned 60 times in the relevant reports. Large reports typically included more than one gap, the smaller reports typically focused on one gap only. 23% of the 60 gaps were of type 1 (indicator exists, but is not sufficiently monitored), halve of them related to a need of increased spatial coverage. Also gap type 6 was equally often mentioned in the reports, i.e. 23% of all 60 gaps were related to gaps in the coordination of monitoring. 18% of the gaps were related to G5: indicator in development, not yet operational or decided upon, and 17% to G4: problems with data storage or handling. In only 13% of the cases when a gap was mentioned for a certain thematic category, no further information was given on the gap problematic, and only 5% of the gaps were classified as G2: missing or not appropriate indicator for a thematic category (Table 3).

The thematic categories most often mentioned in connection with a monitoring gap (Table 3) were Biodiversity (42% of the gaps), followed by "Other category" (17%), Contaminants and Healthy wildlife (11%), Marine litter (8%), and Sea-floor integrity (7%). Other thematic categories are taken up as well, but less often (Energy incl. underwater noise, Eutrophication, Non-indigenous species, Safe maritime traffic and Food webs).

In circa 50% of the reports we found suggestions to replace a currently used indicator, or to add a new one to todays' monitoring of a thematic category. However, these indicators were seldom called novel indicators. Suggestions to improve monitoring included the development of databases for sharing monitoring data on birds, coastal fish and seals, and Baltic Sea monitoring data and methods in general. Furthermore, the development or adoption of common guidelines for the monitoring of seals, birds, invasive species, benthic habitats and microplastics was suggested, plus better tools to evaluate fisheries impact. Furthermore, certain novel or new methods are proposed for Baltic Sea monitoring. One of them is the "drop-video" technique to assess species composition in certain benthic habitats, another novel methods is automated monitoring complementing or replacing current monitoring for pH, water colour, ice cover, waves, and other parameters. Different devices for automated monitoring were suggested, such as autonomous underwater vehicles (AUV), coastal radars, integrated sensor systems, autonomous in situ fixation multi-samplers, ship-borne devices. Of the ship-borne devices, commercial fish surveys may be used as an opportunity for potential additional data collection (e.g. marine litter, chlorophyll, nutrients, abundance of various other organisms, marine mammals, zooplankton etc.). Last, there is a need for improved coordination of monitoring with ICES activities, and for improved regional coordination of monitoring activities and information sharing of the data gained by the 14 large research vessels in use for marine environmental monitoring. These suggestions include improvements on the webpages providing the data, and better correlation of ship-borne observations (of e.g. water colour) with today's satellite observation capability.

Table 3. Summary of results from 17 reports of the systematic review. 60 Gaps in Baltic Sea monitoring (columns) found in the different thematic categories (rows).

Thematic categories	G1: not sufficiently monitored (no additional information)	G1A: not sufficiently monitored (spatially)	G1C: not sufficiently monitored (other)	G2: missing or not appropriate indicator	G4: problems with data storage or handling	G5: indicator in development, not yet operational or decided upon	G6: coordination of monitoring	GNI: no information	sum	in %
D1: Biodiversity		2	1	1	7	6	8		25	42
D8: Contaminants	1			1	1	1		1	5	8
BS4: Healthy wildlife			1					1	2	3
D10: Marine litter		1				2	2		5	8
D6: Sea-floor integrity				1		1		2	4	7
D11: Energy incl. underwater n	1					1	1		3	5
D5: Eutrophication			2						2	3
D2: Non-indigenous species		1						1	2	3
D4: Food webs								1	1	2
BS9: Safe maritime traffic								1	1	2
O: Other category		3	1		2		3	1	10	17
Sum	2	7	5	3	10	11	14	8	60	100
in %	3	12	8	5	17	18	23	13	100	

Detailed gap analyses in selected reports

BONUS SEAM

Another available report analysing key gaps in Baltic Sea monitoring and improvement requirements is the report "Holistic synthesis of reviews and analysis of current Baltic" (Emmerson et al., 2019) of the BONUS SEAM project. This report identifies gaps by studying key policy drivers for monitoring and their monitoring requirements with existing monitoring and data delivery programs. The report identifies, similar to BONUS FUMARI, the EU Water Framework Directive (WFD), The EU Marine Strategy Framework Directive (MSFD) and the HELCOM Baltic Sea Action Plan (BSAP) as key policy instruments providing detailed specification of the monitoring that should be implemented. Additionally, the report identifies a list of monitoring parameters that EU Member States are required to collect and submit to ICES/STECF under the EU Common Fisheries Policy data collection programs financed through the EU Data Collection Multi-annual Union Programme (EU-MAP). The report also considers that other EU legislation introduced common standards in monitoring, analysis, and data infrastructure, and notes that within the EU Integrated Maritime Policy (IMP), the development of a common European Marine Observing and Data Network (EMODnet) has started. Like BONUS FUMARI, BONUS SEAM reports the monitoring gaps mentioned in the HELCOM (2018) report. The report also analyses the regional and national monitoring programs of the HELCOM countries. The BONUS SEAM report provides an overview of the reviewed reports with gap analyses in their table 7. Regarding for example the monitoring of the MSFD, BONUS SEAM concludes from Dupont et al. 2015, that "gaps were highlighted in the coherence of monitoring of birds, fish, benthic habitats, hydrographic changes, contaminants and underwater noise. The regional coherence of marine litter was rated as low." Using these reports and HELCOM (2018), BONUS SEAM makes a detailed analysis of the gaps and possibilities to close them for different thematic categories of monitoring. The analyses firstly identify the main policies and policy instruments to which the monitoring is relevant. Then, the assessment requirements and specifications that are specified by relevant policies are identified for specific parameters or parameter groups. A second table sets out a review of the monitoring for each component of the monitoring programme synthesising information from recent reviews and the most recent assessments, including the 2018 HELCOM indicator assessments (HELCOM, 2018). Lastly, key conclusions are drawn out in terms of the coverage of MSFD GES criteria according to the 2017 review of the European Commission GES Decision (EC, 2017a); gaps that could be closed by adjustments to existing work and opportunities for making use of new technologies and innovations. The result of the gap analysis is given in table 9. In summary, BONUS SEAM report that Baltic Sea monitoring still suffers of partial low spatial and temporal coverage, that benthic monitoring does not cover many of the MSFD needs, and especially does not support requirements for area-based assessment of broad habitat types, plus that standardization and data flow need to be improved. Regarding pelagic monitoring, taxonomic level is not standardized between programs thus data comparison suffers, additionally, both chlorophyll and zooplankton monitoring has temporal gaps, as well as other organism groups such as pico- and microplankton. Regarding hazardous substances, monitoring requires more coordination, and especially databases provide large gaps. Both methods and which substances to monitor is not agreed upon yet among countries. Gaps have also been identified in the monitoring of non-indigenous species, microlitter and incidental bycatch.

HOLAS II

The Second Holistic Assessment of the Ecosystem Health of the Baltic Sea (HOLAS II, HELCOM 2018) was published in 2018 with the focus to provide an assessment of the environmental situation of the Baltic Sea for the period 2011-2016. The report is comprehensive, covering all thematic categories and areas of Baltic Sea monitoring. It is noted that for the thematic categories biodiversity, eutrophication and contamination, it is possible to evaluate established HELCOM Core Indicators, whereas for marine litter, underwater noise, seabed loss and disturbance, indicators are still under development. In summary, it is thus not surprising that HELCOM (2018) concludes that those four thematic categories are not monitored sufficiently. Additionally, the report concludes that biodiversity (both benthic and pelagic habitats, and marine mammals) and hazardous substances are not sufficiently monitored (HELCOM 2018). The report however assures that the further development of core indicators to reach a more complete assessment is a prioritised HELCOM activity.

In detail, many of the HELCOM Core Indicators are not assessed despite them being applicable for a certain area of the Baltic Sea, and despite HELCOM's aim that the parameters required for the core indicators are monitored by all Contracting Parties when ecologically relevant.

Also for thematic categories which are overall quite well monitored according to HELCOM (2018), the report notes gaps in data availability due to lack of monitoring. For eutrophication, time series are not complete (G1B). For Hazardous substances, it is suggested to include PFAS as additional Core Indicator currently missing, that indicators for pharmaceuticals should be developed, but that more research is needed first to understand their fate in the environment, and that an indicator for diclofenac is currently being tested in HELCOM and not yet available.

For most of the thematic categories with Core Indicators under development some monitoring is already ongoing. Regarding marine litter, seafloor litter is monitored in connection to fish trawling surveys. The survey provides an indication of litter on the seafloor, but does not cover shallow water areas or complex substrates, and not all parts of the Baltic Sea. Monitoring of beach litter at Baltic Sea regional scale is under development. Microlitter has only been sampled for a few years, and the many different methods are not harmonized between countries. Coordinated regular monitoring is under development. Monitoring of ambient sound is carried out by several countries on a temporary basis, and a regional programme for monitoring continuous underwater sound is under development.

Regarding the assessment of biodiversity, the monitoring is divided into benthic habitats, pelagic habitats, fish, mammals and birds. Regarding benthic habitats the applied indicators are biased towards addressing impacts from eutrophication, i.e. indicators are missing to assess other thematic categories, e.g. disturbances. HELCOM is currently developing a core indicator on 'Condition of benthic habitats' aiming to evaluate the area, extent and quality of specific benthic habitats in relation to a quantitative threshold value, and on 'Cumulative impact on benthic biotopes' to assess adverse effects from physical disturbance. In addition, the development of indicators for benthic communities on hard bottoms is identified as a priority. Furthermore, the monitoring of softbottom habitats has gaps in both missing indicators as well as missing assessment due to lack in data handling because of missing agreement on threshold values. Regarding pelagic habitats, it is noted that zooplankton cannot be assessed in all Baltic Sea areas due to missing agreement on threshold values and due to a varying coverage of data in time and space. Also here, some indicators are still under development. Regarding fish, the main gap of the Core Indicators in use is given as varying spatial assessment of the different indicators. Regarding mammals, the lack of an indicator to monitor harbour porpoise is taken up. For birds, it is stated that species in the open sea are not adequately assessed. Also for mammals and birds, several indicators are under development.

National reports

BONUS FUMARI has focused on the review of scientific articles and international reports (mainly HELCOM and BONUS associated). However, there are other sources and compilations of gaps in Baltic Sea monitoring, not least the national technical assessments of the MSFD reporting on monitoring programs. As an example, the Swedish report on the national Baltic Sea monitoring of 2015 (Dupont et.al 2015) is targeting each of the MSFD descriptors, describes the monitoring programs and the assessment of the results, and assesses if the EU Commission Criteria are met, or if there are gaps. For most of the MSFD descriptors, Sweden reports only partial coverage of the monitoring needs for the assessment of environmental status. The only descriptors fully covered are Commercial fish and shellfish, Eutrophication and Hydrographical changes. For Energy, including underwater noise, there is not even a program started. Sweden agrees that several gaps in the monitoring programs exist, examples are the lack of data on seabed habitat distribution and extend. There is however no prioritizing or detailed description of monitoring gaps, thus it is not clear where the largest gaps are found. Furthermore, the report does not take up if there are problems with the scale of the monitoring, with data management, or cooperation of monitoring activities and harmonization of methods within or between countries and programs.

Conclusions

Review results

In summary, scientific articles and reports taking up Baltic Sea monitoring are giving somewhat different pictures on where the main gaps in monitoring are, and which actions should be taken to improve the situation.

Starting with the gaps, both scientific articles and reports agree that many thematic categories in need of assessment are not monitored sufficiently, often due to a lack in spatial coverage. However, whereas articles often highlighted that a category is not sufficiently monitored, and that there is a lack of indicators, the reports focused more on gaps in data storage or handling, coordination of monitoring, or highlighted that there are plans for new indicators that are not operational yet (Table 4).

Table 4. Comparison of main gaps mentioned in the reviewed scientific articles vs reports (in % of mentioned gaps).

	Articles	Reports
G1: not sufficiently monitored (no additional information)	42	14
G2: missing or not appropriate indicator	13	3
G4: problems with data storage or handling	3	10
G5: indicator in development, not yet operational or decided upon	4	11
G6: coordination of monitoring	3	14
GNI: no information	33	8

Scientific articles often focused on a novel method, and how this method could improve existing monitoring, implying that the gaps in monitoring are related to the novel method in question, and not necessarily to legislative requirements. Scientists may be unaware of ongoing programs to improve monitoring, and also unaware of problems in the coordination of monitoring or other administrative issues. Many articles were written during a period when the legislations were new and potentially not well known by the scientists. Reports, on the other hand, are based on the countries' well-established reporting to the EU and HELCOM, where countries are interested to report that monitoring and indicators exists, and that legislative requirements are fulfilled. Therefore, reports might miss issues that have not been taken up before in legislation or earlier analyses. In summary, reports focused on already identified gaps and ongoing activities to improve monitoring, while scientists pointed out that the monitoring of the Baltic Sea in general needs to be improved to get better data on the Baltic Sea ecosystem.

Thematic categories. Like the gaps, the highlighted thematic categories are different between scientific articles and reports. Whereas articles mention gaps mainly in relation to (in falling order) Eutrophication, Contaminants, Biodiversity, Commercial fish and shellfish, Food webs, Hydrographical conditions, and No alien species (Table 2), reports have Biodiversity first, followed by Contaminants and Healthy wildlife, Marine litter, and Sea-floor integrity (Table 3). So even if HELCOM (2018) states that the monitoring of Eutrophication and Contaminants is quite comprehensive and sufficient to meet legislative requirements, scientific reports take those two categories up most often as in need of improvement. Last but not least, a look on all 1865 articles found dealing with Baltic Sea monitoring in a broad sense clearly showed that studies on certain categories are very seldom published, and should therefore as well be considered as underrepresented categories with respect to Baltic Sea assessment. These are “Sea-floor integrity”, “Hydrographical conditions”, “Contaminants in seafood”, “Marine litter (incl. microplastics)”, “Underwater noise”, “Angiosperms”, “Hydromorphology”, “Priority list pollutants”, “Healthy wildlife”, “No alien species” and “Radioactivity”. Actually, several of these categories (Marine litter, Underwater noise, Seabed loss and Disturbance) match those taken up by HELCOM (2018) as not being monitored sufficiently. Thematic categories not listed in MSFD, WFD or BSAP, but taken up by the scientific articles, were the needed monitoring of wind farm construction, climate change, the sustainable use of ecosystems, and of munitions.

Suggestions for improvements in monitoring, and risks in setting up priority lists

Method limitations. Even if BONUS FUMARI has tried to quantify monitoring gaps to help managers to prioritize, our results should be viewed with the knowledge that there are limitations to our methods. First, most *scientific articles* are not written with the focus to find monitoring gaps related to requirements in legislation, but rather to promote novel methods, or to use monitoring data for assessments or other research questions. Even if the articles were holistic and actually dealt with WFD, MSFD or BSAP, their conclusions on which thematic categories, indicators or gaps in monitoring they relate to are seldom clearly stated in the articles. The majority of the scientific articles mentioning gaps in Baltic Sea monitoring were written to promote science, i.e. new findings, which are in most cases novel or improved methods. Very few articles focused on some kind of holistic analysis of Baltic Sea monitoring, and monitoring gaps in relation to the legislative requirements. The thematic categories and indicators were often described without using the terminology of BSAP/HELCOM, MSFD or WFD. Probably scientists are not necessarily aware of all legislation, or how their research relates to it. Thus, our review was evaluating articles having a different focus than matching our main questions. Since the articles often did not explicitly name a descriptor or indicator, the thematic category in the papers were more difficult to pin-point in the papers compared to the reports.

Second, the three analyses we did have different conceptions. Mapping, systematic review of scientific articles, and the report review, are not reflecting gaps in monitoring in the same way. Mapping gave an overview on all articles found and the main topics handled, whereas the review of the scientific articles only included articles mentioning gaps. Mapping thus showed which thematic categories actually were dealt with in science, and highlighted the thematic categories not dealt with, thus representing possible gaps in science, and maybe to a lesser degree gaps in monitoring. The review then presented the view of scientists on which thematic categories or indicators are in need of improved monitoring. A scientist's view is naturally focused on their field of science, and only seldom on legislative requirements for monitoring. Therefore it required some interpretation of the article text to be able to find the relevant gap category that matched with a legislative requirement. This bias of researchers towards their research fields is also shown by the fact that "descriptor", a key word in the MSFD legislation, was rarely used in the articles. Nonetheless, the review of the scientific articles provided us with a quite comprehensive view of the scientific community on which monitoring data are missing to assess Baltic Sea ecology sufficiently. In contrast to the scientific articles, the choice of reports was based on projects that explicitly focused on improving Baltic Sea monitoring by analysing monitoring gaps, or suggested how to close them. While very relevant for our analysis, they are directed towards certain goals and are thus biased towards already identified gaps, and often dealt only with one or few categories, or even indicators only. They seldom aimed at giving a holistic overview, with the major exception of the HELCOM (2018) report.

Gaps in monitoring & suggestions for managers. Summarizing the results of both articles and reports, it is clear that many categories are in need of improvements, but also that there are many projects already underway. As many Core Indicators were found not to be sufficiently monitored, even if the HELCOM countries have agreed to do so, there is not only a need for the development of new indicators, but certainly also a need to use more cost-efficient methods. To enable sufficient monitoring all possibilities of more automatized monitoring should be looked at more closely. Especially important is the introduction of methods that allow the assessments of wider areas, like drones or satellites, which were often mentioned as candidates of future methods. Methods aiming at wide area monitoring would suit the new monitoring needs formulated by the updated commission decision (COM DEC 2017/845). Furthermore, there is a clear need for better coordinated monitoring between countries in the HELCOM area in order to increase both the spatial and temporal coverage of ongoing monitoring, to harmonize methods, and to improve data sharing. Coordinated monitoring should include the use of the same infrastructure (e.g. scientific vessels). Coordinated monitoring would also enable the establishing of integrated monitoring campaigns, e.g. to combine monitoring for pelagic habitats with off shore bird monitoring (Shephard et al., 2015).

We agree in general with earlier studies (Carstensen J, 2011, Freire-Gibb et al., 2014) that there is a risk to suggest prioritized areas for monitoring improvements, but we hope that more cooperation between countries will lead to agreed decisions on significant objectives to prioritize. Analyses as ours, that express the view of a variety of researchers and managers on Baltic Sea monitoring gaps, will hopefully allow for an objective decision on cost-effective methods serving the entire Baltic Sea area, instead of decisions in risk of been taken following certain lobbying actions (Freire-Gibb et al., 2014). As Freire-Gibb et al. (2014) nicely pointed out, "… the MSFD currently has the potential to be the most effective policy to achieve and maintain healthy waters in the EU marine regions…".

We would like to point out that this report on monitoring gaps marks only the first step of BONUS FUMARI's recommendations for a renewed monitoring of the Baltic Sea. Together with a review on novel methods and a cost analysis, we will report a comprehensive final recommendation in April of 2020.

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Appendix

BONUS FUMARI Terminology

TERMINOLOGY

Objective

This document provides a proposal of key terms for the BONUS FUMARI project in order to assure a harmonized use of terms (and related concepts) across all project outcomes.

Introduction

The BONUS FUMARI project aims to provide a proposal for a renewed monitoring system of the Baltic Sea. Different policies require the monitoring of the Baltic Sea, each built on slightly varying concepts and terminologies. In this document, we collect the key terms used in the different policy directives and propose a common terminology to be used in the BONUS FUMARI context. We use a hierarchical framework to introduce the proposed terms, building on the concept of *indicators* as the basic unit for which data are acquired in environmental monitoring. Furthermore, we specify the three types of *monitoring gaps* expected to be potentially replaced by novel monitoring methods.

General terms

Status refers to the qualitative condition of the ecosystem. It is categorized into different classes, whereas the achievement or preservation of a **good status** is the main environmental objective of the different directives. Synonyms used in current monitoring concepts are *(good) environmental status* (Marine Strategy Framework Directive - MSFD), *(good) ecological status* (Water Framework Directive - WFD) and *(favourable) conservation status* (Habitats Directive).

Monitoring is the acquisition of environmental data relevant for the classification of the *status*.

Monitoring methods are techniques to acquire environmental data to assess and classify *status*.

Novel monitoring methods are *monitoring methods*, which are not in general use or have only been applied in some regions/by some countries of the Baltic Sea.

State monitoring is the continuous observation of an ecosystem to get an overview on its *status* and to detect long-term changes. In case of the achievement of *good status* of an ecosystem component, conducting *state monitoring* is sufficient. The term *state monitoring* is used in the MSFD, whereas *surveillance monitoring* is used in the WFD.

Target and measure monitoring is the supplementary *monitoring* of areas and ecosystem elements failing *good status* and the *monitoring* of the pressures being responsible for this risk. For instance, it constitutes the *monitoring* of additional sampling stations or a higher sampling frequency, to assess progress towards achieving *good status* and to establish local management options. The term *target and measure monitoring* is used in the MSFD, whereas *operational monitoring* is used in the WFD.

Investigative monitoring is the targeted *monitoring* to identify the causes for failing *good status*, as well as to determine the magnitude and effect of accidental pollution. The term *investigative monitoring* is used in both WFD and MSFD.

Hierarchical framework of terms used for the monitoring of the Baltic Sea

As defined above, *monitoring methods* acquire environmental data to assess and classify *status*. The basic unit for the assessment of *status* is the *indicator* (see below). We thus propose to establish the review of *novel monitoring methods* against this basic assessment unit, using a hierarchical framework, which comprises the various categorical levels of monitoring (Figure 1).

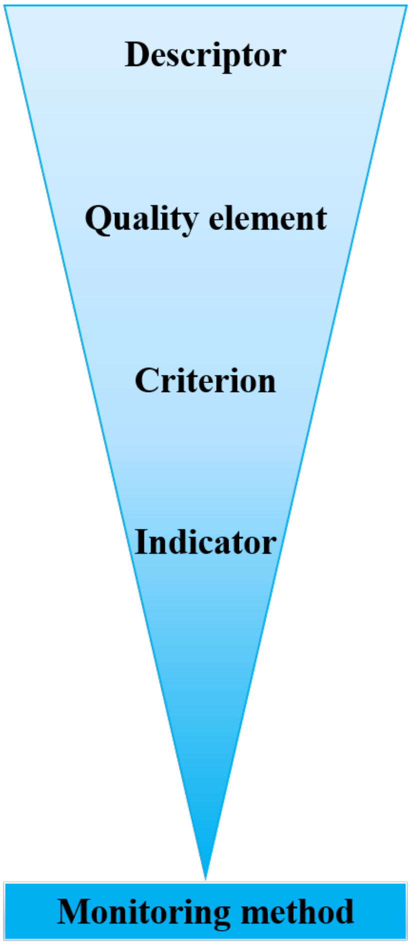

Figure 1: Proposed BONUS FUMARI terminology scheme for the hierarchical organization of the terms used in environmental monitoring.

Descriptors are thematic categories addressing characteristic ecosystem features relevant for the assessment and classification of *status*, but may also be used in assessments of ‘climate change’ or ‘ecosystem services’.

The MSFD defines eleven *descriptors*: Biodiversity, non-indigenous species, commercial fish, food webs, eutrophication, sea-floor integrity, hydrographical conditions, contaminants and pollution effects, contaminants in fish and seafood, marine litter and underwater noise/energy.

Quality elements are ecosystem elements, which describe the *status* of the ecosystem. They include biological, physical, chemical, hydrological or morphological elements. The term *quality element* is used in the WFD, synonyms used in the context of the MSFD are *criteria element* or *monitoring element.*

Criteria constitute the properties of the *quality elements*, which are used to describe the *status*. *Criterion* is used in the MSFD, whereas *indicative parameter* is used in the WFD.

Indicators constitute specific attributes of each *criterion*, which can be measured, and which allow to follow subsequent change in the *criterion* over time. They represent the smallest unit of ecosystem assessment and need to be specified in terms of their spatial and temporal coverage and the matrix/habitat of measurement. The term *indicator* is used in the MSFD.

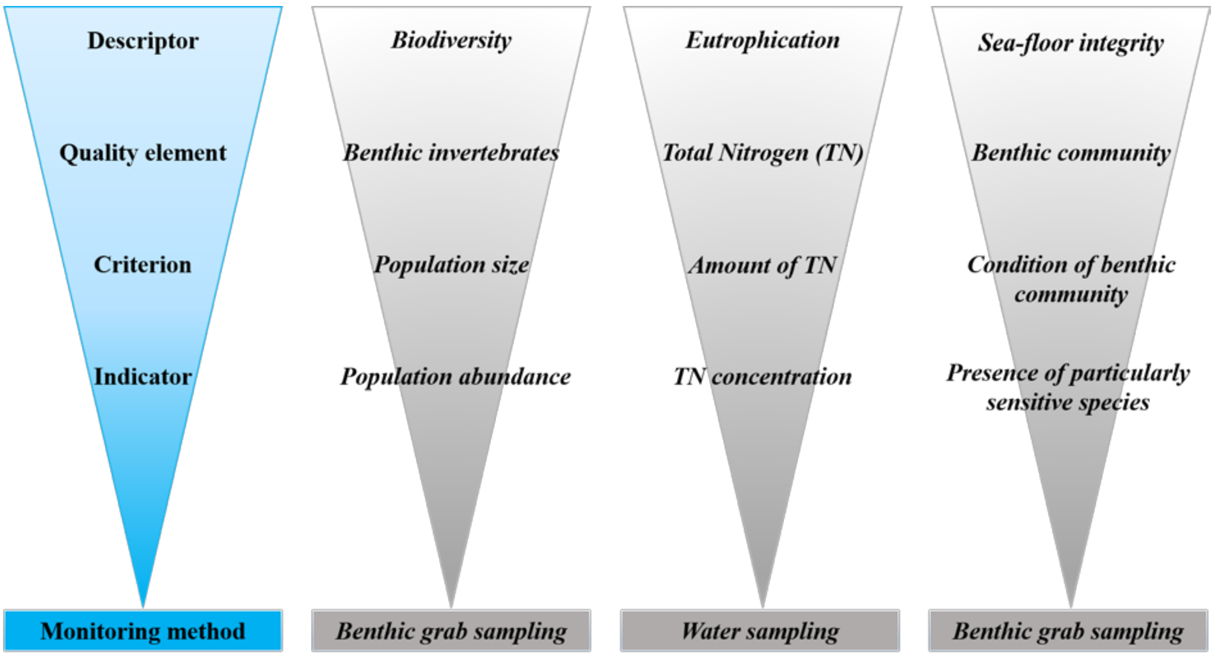

Figure 2: Examples for using the BONUS FUMARI terminology.

Types of monitoring gaps and related novelties

Here, a

Type 1 gap is defined as an *indicator,* which is not sufficiently monitored using the currently applied methods. This may occur when the acquired data do not meet the desirable quality or quantity, or when there are no acquired data for an *indicator*. This gap is furthermore divided into **Type 1A**: insufficient spatial coverage of monitoring; **Type 1B**: insufficient temporal resolution of monitoring; **Type 1C**: other insufficiencies.

Type 1 novelty encompasses *novel monitoring methods* providing data to fill the *Type 1 gap*. *Type 1 novelty* methods provide, for instance, better data quality, spatio-temporal coverage or cost-efficiency than currently applied methods.

Type 2 gap is defined as an appropriate *indicator*, which is missing for the assessment of *status*, either because a currently applied *indicator* is inadequately reflecting the *descriptor,* or because no *indicator* for the *descriptor* has been established so far.

Type 2 novelty encompasses *novel monitoring methods* providing data to fill the *Type 2 gap*. These novel methods acquire data for an *indicator,* which has not been measured so far.

Type 3 gap is defined as an aspect of the ecosystem (comparable to *descriptors*), which is currently not considered in applied *monitoring* at all. Such additional aspects may be ‘climate change’ or ‘ecosystem services’.

Type 3 novelty encompasses *monitoring methods* providing data to fill the *Type 3 gap,* accounting for the monitoring of aspects for the Baltic Sea, which have not been considered before.

Moreover, following gaps are in development:

Type 4 gap is defined as insufficient regulations on data storage or handling.

Type 5 gap is defined as an indicator, which is in development but not yet operational or decided upon.

Type 6 gap is defined as a missing coordination of monitoring between the countries.

Type 7 gap is defined as the insufficient monitoring due to costs, which are too high.

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