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ECOMAR: A data-driven framework for ecosystem-based Maritime Spatial Planning in Danish marine waters

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ECOMAR:
A data driven framework for ecosystem-based Maritime Spatial Planning in Danish marine waters

THE VELUX FOUNDATIONS
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REPORT

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Summary

We report the developments and results of the ECOMAR project, which have taken place 2018-2020 and was funded by THE VELUX FOUNDATIONS. ECOMAR has established state-of-the-art data sets for the distribution of human activities and pressures as well as ecosystem components in Danish marine waters. ECOMAR has mapped the combined effects of multiple human pressures, ranked pressures and analysed the potential effects of changes in pressure intensities and new human activities. ECOMAR has also outlined how zoning could be initiated in Denmark. Further, ECOMAR has modelled scenarios for 2030 and 2050 and concludes that agreed strategies and plans will probably not lead to reductions in human activities and pressures and accordingly unlikely to lead to improvements in environmental status.

Fire emneord	Four keywords
1. Havplanlægning	1. Marine Spatial Planning (MSP)
2. Økosystem-baseret forvaltning	2. Ecosystem-based Management (EBM)
3. Havplandirektivet (HPD)	3. Maritime Spatial Planning Directive (MSPD)
4. Havstrategidirektivet (HSD)	4. Marine Strategy Framework Directive (MSFD)

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ECOMAR

A data-driven framework for ecosystem-based Maritime Spatial Planning in Danish marine waters

Results and conclusions from
a development and demonstration project

-

Preface

ECOMAR is an abbreviation of 'Development and testing of a data-driven framework for ecosystem-based marine spatial planning'.

The ECOMAR project, which has been funded by the VILLUM Foundation for the period 2018-2020, is as indicated a project focusing on ecosystem-based maritime spatial planning, especially on the development and demonstration of state-of-the-art methods informing future decision making.

The following institutions participated in ECOMAR: NIVA Denmark Water Research (lead partner), the Department of Bioscience (BIOS) at Aarhus University, the Department of Geosciences and Natural Resource Management (IGN) at the University of Copenhagen, DTU Institute for Aquatic Resources (DTU Aqua) and the Geological Survey of Denmark and Greenland (GEUS). Further, the International Council for the Exploration of the Seas (ICES) and the National Centre for Ecological Analysis and Synthesis (NCEAS) have also contributed to the project.

The ECOMAR project has developed, tested and applied different tools for ecosystem-based maritime spatial planning and analysed in detail how Danish marine waters can be used sustainably, taking into account existing legislation, both national and international, in particular the EU Maritime Spatial Planning Directive and also the EU Marine Strategy Framework Directive, the EU Water Framework Directive and the Nature 2000 Directives (Habitats Directive and Birds Directive).

Copenhagen, 11 December 2020

Jesper H. Andersen

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ECOMAR partners:

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Summary

Key objectives of the ECOMAR project, which took place between spring 2018 and autumn 2020 and was funded by THE VELUX FOUNDATIONS, were:

- Compilation of distribution maps covering all relevant pressures and human activities and ecosystem components in Danish marine waters.
- Estimation of the potential combined effects of multiple human pressures, nationally and regionally, and ranking of pressures and also to analyse the potential effects of future changes in pressure intensities.
- Mapping existing human activities, to identify potential conflicts between spatially overlapping activities and to outline how zoning could be done.

ECOMAR has gathered state-of-the-art data sets regarding spatial distributions of human activities, pressures and ecosystem components in Danish marine waters. A wide range of relevant pressures (n = 42) are included as well as a broad range of ecosystem components (n = 56) covering pelagic habitats, benthic habitats, fish, seabirds and marine mammals. ECOMAR has applied existing tools such as SeaSketch and EcoImpactMapper, but also developed specific codes for postprocessing of results.

Further, ECOMAR has demonstrated how data and tools can be used, both as analytical tools and as decision support tools in relation to not only the Maritime Spatial Planning Directive, but also the Marine Strategy Framework Directive as well as the the Water Framework Directive .

With this synthesis report, key ECOMAR results imply that: i) the combined stress on marine ecosystems and their species, habitats and communities will probably increase toward 2030 and 2050, and ii) there is no evidence suggesting that the Danish implementation of the Maritime Spatial Planning Directive will support the implementation of the MSFD and WFD and thus lead to improved environmental conditions in Danish waters.

Reviewing the methods used for assessing the confidence of the individual data layers in ECOMAR has revealed that uncertainty is quantified very differently, and in many cases does not take all relevant uncertainty components into account. This may affect the ECOMAR results. Therefore, ECOMAR has outlined and demonstrated a new general methodology for assessing the uncertainty in data layers derived from discrete data points, irregularly distributed in time and space.

Implementation of ecosystem-based Maritime Spatial Planning in Denmark faces two obstacles. Firstly, it starts almost from scratch following decades-long focus on pollution by nutrients and hazardous substances. Secondly, it must include not only all sectors and pressures, including land-sea interactions, but it must take into account the fact that the environmental conditions are impaired leaving limited or no room for sustainable Blue Growth. In fact, increasing pressures in the marine environment can potentially compromise environmental status goals both for the Danish open waters (the MSFD domain) and coastal waters (the WFD domain).

ECOMAR has provided high-quality data sets, methods and cross-cutting analyses in support of evidence-based implementation of the Maritime Spatial Planning Directive. Further, ECOMAR demonstrates that methods and tools are at hand and ready for use. Thus, the ECOMAR partnership hopes that this work will be useful and encourages relevant authorities and other potential end-users to make use of data sets, tools and results in the context of evidence-based management or in projects following up on ECOMAR.

Sammenfatning

ØKOMAR-projektet blev udført fra foråret 2018 frem til efteråret 2020 og blev finansieret af VELUX Fonden. Projektets hovedformål var at i) kortlægge alle relevante presfaktorer og menneskelige aktiviteter samt en række økosystemkomponenter i de danske farvande, ii) estimere potentielle akkumulerede effekter (på engelsk "Cumulative Effect Assessement" (CEA)) fra forskellige menneskelige presfaktorer, for derefter at rangordne disse og undersøge effekter af mulige fremtidige ændringer i presfaktorernes intensitet og iii) kortlægge eksisterende menneskelige aktiviteter med henblik på at identificere potentielle konflikter mellem aktiviteter og for at undersøge hvordan en såkaldt 'zonering' kan udføres.

ØKOMAR har samlet state-of-the-art datalag af den rumlige fordeling af menneskelige aktiviteter, presfaktorer og økosystemkomponenter i danske havområder. En bred vifte af relevante presfaktorer (n = 42) er inkluderet såvel som økosystemkomponenter (n = 56), der dækker pelagiske habitater, bentiske habitater, fisk, havfugle og havpattedyr. ØKOMAR har anvendt eksisterende værktøjer såsom SeaSketch og EcoImpactMapper, men har også udviklet specifikke koder til efterbehandling af resultater.

ØKOMAR har desuden demonstreret, hvordan data og værktøjer kan bruges, både som analytiske værktøjer og som beslutningsstøtteværktøjer, ikke kun i forhold til Havplandirektivet (MSPD), men også Havstrategidirektivet (MSFD) og Vandrammedirektivet (WFD). Således peges der med denne synteserapport på, at det samlede pres på havets ressourcer, herunder natur- og miljøforholdene, sandsynligvis vil stige mod 2030 og 2050, og at der ikke er noget, der tyder på, at den danske implementering af Havplandirektivet vil støtte implementeringen af Havstrategidirektivet og Vandrammedirektivet og dermed føre til bedre miljø- og naturforhold.

Analyse af metoderne til bestemmelse af usikkerhed for de enkelte datalag har vist, at der anvendes vidt forskellige metoder, og i mange tilfælde medtages ikke alle relevante usikkerhedskomponenter. Dette kan påvirke resultaterne i ØKOMAR. Der er derfor udviklet en ny metodik for bestemmelse af usikkerheden i datalag som er estimeret på basis af diskrete datapunkter, ofte indsamlet uensartet i tid og rum.

Implementering af økosystembaseret maarin arealforvaltning, ofiicielt benævnt 'maritim fysisk planlægning', i Danmark står over for to forhindringer. For det første starter implementaringen næsten fra bunden efter årtiers fokus på forurening fra næringsstoffer og farlige stoffer. For det andet skal den ikke kun omfatte alle sektorer og presfaktorer, herunder interaktioner mellem land og hav, men det skal tage højde for, at miljøforholdene svækkes, hvilket efterlader begrænset eller potentielt ingen plads til bæredygtig blå vækst. Faktisk kan øget pres på havmiljøet føre til manglende opfyldelse af miljøstatusmålene både for de åbne farvande (under Havstrategidirektivet) og kystområderne (under Vandrammedirektivet).

Med ØKOMAR er der nu etableret data, metoder og resultater som nu og fremadrettet kan understøtte en evidens-baseret gennemførelse af EU's Havplandirektiv. Det er således ØKOMAR-partnernes håb at data, metoder og eksempler i fremtiden vil blive inddraget i forskellige processer, først og fremmet i arbejde for at gennemføre evidens-baseret forvaltning (MSPD, MSFD, WFD), men også i andre relevante forsknings- og udviklingsprojekter.

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1 Introduction

Denmark is in the process of implementing Maritime Spatial Planning in Danish law and to develop the first national Maritime Spatial Plan. This process is embedded in the 2014 EU Maritime Spatial Planning Directive, which follows from the 2002 Council Recommendation on Integrated Coastal Zone Management. For decades, national strategies for the protection of Danish marine waters have focused on inputs of pollutants (nutrients and contaminants) and to a lesser degree on how space is utilized and the effects caused by multiple human activities.

1.1 What is Maritime Spatial Planning?

Maritime Spatial Planning refers to a process established in the EU Integrated Maritime Policy (Anon. 2007) and regulated by the EU Maritime Spatial Planning Directive (MSPD), adopted 23 July 2014 (Anon. 2014).

MSP aims to reduce potential conflicts between sectors and activities competing for marine space. At the same time, MSP also intends to protect the marine environment. Further, MSP seeks to encourage investment by creating a level playing field between sectors and interests. MSP is by the UN Intergovernmental Oceanographic Commission (2020) defined as:

- *MSP is a public process of analysing and allocating the spatial and temporal distribution of human activities in marine areas to achieve ecological, economic, and social objectives that have usually been specified through a political process. Characteristics of marine spatial planning include ecosystem-based, area-based, integrated, adaptive, strategic and participatory.*
- *MSP is not an end in itself, but a practical way to create and establish a more rational use of marine space and to manage the interactions between its uses, to balance demands for development with the need to protect the environment, and to deliver social and economic outcomes in an open and planned way.*

Ecosystem-based MSP works across borders and sectors. Therefore, land-sea interactions should also be considered because human activities in upstream catchments may have significant impacts on environmental condition in downstream coastal and marine waters. For MSP implementation to be ecosystem-based, the planning process should include all ecologically relevant features and the human activities and pressures impacting these.

In Denmark, the MSPD is implemented in 'Lov om maritim fysisk planlægning' (Anon. 2016). In accordance with the MSPD, this law will establish a basis for national coordination of sea use and support sustainable Blue Growth in Danish marine areas. The law *shall* contribute to sustainable development of the off-shore energy sector (oil and gas as well as offshore wind farms), shipping, transport infrastructure, fisheries and aquaculture, extraction of marine raw materials, and environmental protection and improvements including the resilience towards climate change.

However, other sectors such as tourism and recreation are mentioned as *optional* in the marine spatial plan while underwater cultural heritage is not mentioned. Areas will be designated for specific uses, e.g. for offshore energy production (oil and gas as well as well as offshore wind farms), shipping, fisheries, aquaculture, deep sea mining and environmental protection towards 2030. This upcoming national MSP plan is sometimes referred to as 'Havplan Danmark' and will enter into force in 2021. 'Havplan Danmark' will, according to the Danish Maritime Authority (2020), establish not only predictable circumstances for maritime activities but also predictable provisions regarding the use of sea space. In a Danish context, implementtation of spatial planning at sea has to start virtually from scratch (see **section 1.2**). Thus, there is a need for compilation of spatial data sets and development and testing of MSP tools.

1.2 Where are we now?

In a Danish context, MSP is a new activity. This may sound unexpected, but this current state-of-play is justified to some extent and can be explained.

For decades, the key environmental problem in Danish marine waters, especially in coastal waters and the Danish Straits, has been nutrient inputs and eutrophication, i.e. the effects of elevated nutrient concentration stimulating excessive growth of algae in surface water, leading to reduced transparency of waters and subsequent loss of submerged aquatic vegetation, low oxygen concentrations in bottom water due to sedimentation and mineralisation of organic matter from surface water causing fish kills due to the low concentrations or even absence of oxygen (Ærtebjerg *et al*. 2003).

The problem of eutrophication has received considerable attention and other problematic pressures have been addressed to a limited extent or not at all. Discharges and emission of contaminants, dumping of dredged material and physical modification have been addressed nationally sector by sector (e.g. shipping, industries) or case by case (i.e. the Great Belt fixed link and the Øresund fixed link). Fishing activities have been dealt with through the EU Common Fisheries Policy. For an overview of national environmental policies, please confer with Miljø- og Energiministeriet (1999).

The problems with excessive algal blooms, oxygen depletion and occasional fish kills have been overwhelming and therefore at the top of the political agenda, leaving other issues with less attention. However, with the adoption of the Marine Strategy Framework Directive (MSFD) in 2008, the focus has been widened and evidence has emerged that pressures other than nutrient inputs also impact Danish marine waters (Miljøministeriet 2012, Petersen *et al*. 2018, Andersen *et al*. 2019, Miljø- og Fødevareministeriet 2019).

The concept of the human activities and pressures in Danish marine water has evolved from a state with a single dominant pressure (nutrient inputs) and a relatively low number of pressures of concern to today's situation with a few dominating pressures (nutrient inputs, fishing, contaminants, and climate change) and more than a dozen of other ecologically relevant pressures. Further, the MSFD has put focus on new emerging threats such as introduction of non-indigenous species and inputs of marine litter as well as noise leading to increased awareness on the political agenda.

Climate change is an important pressure affecting marine ecosystems, but it is not included in the MSFD, which may seem peculiar as the MSFD is anchored in an ecosystem-based approach for managing human activities. However, climate change is addressed in many other ways, nationally and internationally (i.e., IPPC and EU). The reasons for *not* including climate change in the MSFD, are somewhat obscure and this deficiency contradicts the definition of the ecosystem-based approach and how it is supposed to be implemented.

In Denmark, land-sea interactions are the main pressures in coastal waters (i.e. nutrient inputs from upstream catchments). Accordingly, it is important to include this key pressure to ensure a genuine ecosystem-based Danish implementation of the MSPD.

1.3 Where should we be going?

Evidence-based decision support is a prerequisite for ecosystem-based MSP and ultimately for attaining sustainable Blue Growth and clean, healthy, and productive seas with a good environmental status (EEA 2019a).

With the adoption of the MSPD in 2014 and the subsequent enactment in Danish law in 2016, Denmark is committed to developing and adopting a national maritime plan for the Danish EEZ by 2021. Despite the current uncertainties regarding the probable focus and context of 'Havplan Danmark', currently being developed by the Danish Maritime Authority, it could seem from those parts of the plan that have been presented to key stakeholders in the autumn 2020, that the plan most likely will focus on the minimum requirements of the MSPD and to a lesser degree on a full range of features vital for ecosystem-based management.

Marine ecosystem-based management (EBM) has according to Long **et al**. (2015) been defined as:

- *Ecosystem-based management is an interdisciplinary approach that balances ecological, social and governance principles at appropriate temporal and spatial scales in a distinct geographical area to achieve sustainable resource use. Scientific knowledge and effective monitoring are used to acknowledge the connections, integrity and biodiversity within an ecosystem along with its dynamic nature and associated uncertainties. EBM recognizes coupled social-ecological systems with stakeholders involved in an integrated and adaptive management process where decisions reflect societal choice.*

It follows from the definition that prerequisites for genuinely ecosystem-based management of human activities will have to include, as a minimum, the following features:

- Detailed information on the occurrence of all ecologically relevant ecosystem components ranging from planktonic organisms over benthic communities to fish, seabirds and marine mammals.
- Data on the occurrence of all human pressures, either as distribution maps of the intensity or presence/absence of specific pressures.
- Information on the effect distances, i.e. how far from the point a specific pressure takes place to where it can be expected to have an impact.
- Information on the sensitivity of a specific ecosystem component to a specific pressure.

With the above information at hand, it is possible to map, analyse and plan a broad range of human activities as well as their interactions within Danish marine waters and thereby support the decision-making process and ultimately ecosystem-based MSP.

Reflecting the many facets and interests covered by the MSPD process, ECOMAR has been an interdisciplinary project covering a broad knowledge-base, including biology, geology, chemistry as well as social sciences. Further, ECOMAR has not only focused on establishing state-of-the-art data sets but has also demonstrated the use of data and relevant tools. These data and tools, as well as key synthesis results, are presented in this synthesis report. We hope the report can enable a data-driven ecosystem-based MSP and that relevant end users, for example national agencies and NGO's, will utilise the ECOMAR outputs in the same manner as they have been demonstrated in this report.

ECOMAR alone will not improve environmental status of Danish marine waters, but it can support ecosystem-based MSP, if three key conditions are met:

- Firstly, a paradigm shift is required – it should be recognized that MSP is a data-driven process where the best available data is turned into knowledge, which again is fed into decision-making processes.
- Secondly, it should be acknowledged that the MSPD and MSFD are closely connected and that MSP should *not* be used to increase pressures, but to decrease or restrict pressures.
- Thirdly, all relevant sectors should be included.

1.4 ECOMAR objectives

The overarching purpose of the ECOMAR project has been to develop, test and demonstrate the use of ecologically relevant data sets and tools for data-driven and ecosystem-based maritime spatial planning in Danish marine waters.

In order to achieve this, we defined several concrete objectives to be achieved. A key objective of ECOMAR has been to gather and organize the best possible data sets describing human pressures and ecosystem components within the Danish EEZ. A second, but no less important, objective has been to map human activities and pressures and analyse both pressures and their potential combined effects on a broad range of ecosystem components, and the relative importance of individual groups of pressures on different scales (nationally, regionally and locally).

Further, it has been an objective to demonstrate the concept of zoning in Danish marine waters through the following process:

- Establish a baseline for activities, pressures and combined effects.
- Identify potential conflicts between activities within the same areas.
- Group and categorize existing and planned activities in different categories, ranging from multi-purpose zone (zone level 1) where permits are not mandatory to a restricted access zone (zone level 4).

An additional objective of ECOMAR has been to carry out a broad range of scenario analyses aiming to showcase potential consequences of increasing or decreasing intensity of human activities and pressures. ECOMAR has also analysed ways to combine the demands of the MSPD, MSFD and WFD regarding pressure analyses into a streamlined and cost-effective process.

ECOMAR also aims to communicate the results of the development and demonstrations to a wider audience. For this reason, a list of abbreviation and acronyms used is shown in **Table 1**.

Table 1: *Abbreviations and acronyms used in this report.*

BITS	Baltic International trawling Survey
CEA	Combined effect assessment (see CIA)
CIA	Cumulative impact assessment (see CEA)
DEA	Danish Energy Agency (Energistyrelsen)
DMA	Danish Maritime Authority (Søfartsstyrelsen)
EA	Ecosystem Approach
EBA	Ecosystem-based Approach
EBM	Ecosystem-based Management
EEA	European Environment Agency
EEZ	Exclusive Economic Zone
EMODnet	European Monitoring and Observation Data Network
EU	European Union
GES	Good Ecological/Environmental Status
HD	Habitats Directive
HELCOM	Helsinki Commission. See www.HELCOM.fi
IPCC	Intergovernmental Panel on Climate Change
MPA	Marine Protected Area
IBTS	International Baltic Trawling Survey
MFVM	Miljø- og Fødevareministeriet (Ministry of Environment and Food of Denmark)
MSFD	Marine Strategy Framework Directive
MSP	Maritime/Marine Spatial Planning
MSPD	Maritime Spatial Planning Directive
MST	Miljøstyrelsen (Danish Environmental Protection Agency)
MSY	Maximum Sustainable Yield
N2000	Natura 2000
NIS	Non-indigenous species
NOVANA	National Monitoring Programme for Water and Nature
OSPAR	OSPAR Commission. See www.ospar.org
POPs	Persistent organic pollutants
SAR	Swept Area Ratio
SwAM	Swedish Agency for Water and Marine Management
VME	Vulnerable Marine Ecosystem
VMS	Vessel Monitoring System
WFD	Water Framework Directive

2 Methods

This chapter describes the study area of the Danish Exclusive Economic Zone (EEZ) and introduces the data sets used. The Danish marine waters are often divided into three sub-regions: i) the North Sea/Skagerrak area, ii) the Kattegat, and iii) parts of the western Baltic Sea including the Danish Straits. Most parts of the Danish EEZ are well studied and monitored, especially regarding eutrophication, contaminants and biodiversity. Further, the methods, concepts and models for analyses, mapping and uncertainty, developed or applied in the context of the ECOMAR project are introduced.

2.1 Study area

The Danish Exclusive Economic Zone (EEZ) covers eastern parts of the North Sea, southern parts of the Skagerrak, western and central parts of the Kattegat, the Little Belt, the Great Belt, the western parts of the Sound, parts of the western Baltic Sea and also the marine waters around Bornholm and the Ertholmene archipelago.

Together with the Swedish parts of the Kattegat and Sound, the Danish EEZ forms the transition zone between the North Sea and Baltic Sea (see **Fig. 1**).

The environmental conditions of the Danish marine waters have been consistently monitored since the mid-70's, mostly via the national monitoring program, see Svendsen *et al*. (2005) and Andersen *et al*. (2017) for details.

Most coastal waters in Denmark are classified as eutrophication problem areas (EEA 2019b), meaning that nutrient levels are elevated and primary effects, such as high concentrations of chlorophyll, or secondary effects, such as loss of submerged aquatic vegetation or benthic invertebrates, are common. Offshore parts of the North Sea and Skagerrak are classified as non-problem areas indicating that inputs of nutrients, i.e. nitrogen and phosphorus, are not an issue. Over the past three decades, eutrophication status has improved, both in coastal waters (Riemann *et al.* 2016), but especially in the open parts of the North Sea (Andersen *et al*. 2016 and OSPAR 2017).

Classification of eutrophication status in Danish marine waters has been done as part of the Danish MSFD implementation (Naturstyrelsen 2012) and for the OSPAR Common Procedure (Andersen *et al*. 2016) as well as part of the HELCOM second holistic assessment (HELCOM 2018). An up-to-date overview can be found in EEA (2019b), where 'problem areas' and 'non-problem areas' have been mapped (see **Fig. 2A** - please note that although large parts of the Danish waters are classified as 'problem areas', the off-shore part of the North Sea and Skagerrak are classified as 'non-problem areas'). For more information on nutrient inputs and eutrophication in Danish marine waters, please see Ærtebjerg *et al*. (2003), Riemann *et al*. (2016), HELCOM (2018), OSPAR (2017), Miljø- og Fødevareministeriet (2019) and EEA (2019b).

Biodiversity in Danish waters is threatened and there is no evidence for areas with a good biodiversity status. The key pressures causing an impaired biodiversity status are nutrient inputs, especially in coastal waters, and fishing activities, mostly in offshore waters of the North Sea, Skagerrak and Kattegat. Biodiversity status of Danish marine water was assessed as part of the Danish MSFD implementation (Miljøstyrelsen 2012) and in recent HELCOM and OSPAR assessments (HELCOM 2018, OSPAR 2017). An up-to-date assessment of biodiversity status can be found in EEA (2019c) and **Fig. 2B** provides an overview for the Danish EEZ. For more information on status of the biodiversity in Danish marine waters, please see Andersen *et al*. (2015), OSPAR (2017b), HELCOM (2018), MFVM (2019) and EEA (2019c).

Figure 1: *Map of the Danish Exclusive Economic Zone (EEZ). The total area of the Danish EEZ is 105,000 km^2, where internal marine waters make up 3,500 km^2, the Territorial Zone (12 nautical miles) 40,000 km^2 and the remainder 61,500 km^2. The Danish EEZ can be divided into three sub-regions: i) the Danish parts of the North Sea and Skagerrak, ii) the Danish parts of the Kattegat, and iii) the Danish parts of the western Baltic Sea including the marine waters around Bornholm.*

Contamination by hazardous substances is also a challenge in Danish waters, and most parts are classified as 'problem areas' , i.e. with an impaired environmental status. Substances of concern are many, especially some heavy metals, e.g., mercury (Hg), cadmium (Ca), copper(Cu) and lead (Pb), selected groups of persistent organic pollutants (POP's), e.g., polybrominated diphenyl ethers (PBDEs) from flame-retardant chemicals, pest controls, leaded petrol, PCBs and polycyclic aromatic hydrocarbons (PAHs) from burning wood and fossil fuel.

Assessment of contamination status has also been carried out in connection with the Danish MSFD implementation (Miljøstyrelsen 2012) and in recent HELCOM and OSPAR assessments (see HELCOM 2018 and OSPAR 2017).

Recently, the EEA carried out an integrated assessment and mapped 'problem areas' and 'non-problem areas' with respect to contaminants and **Fig. 2C** shows the results for the Danish EEZ. For more information on contaminants in Danish marine waters, please see HELCOM (2010a), OSPAR (2017b), Miljø- og Fødevareministeriet (2019) and EEA (2019d).

In summary, environmental conditions in most parts of the Danish marine waters are impaired compared to the objectives and goals for the MSFD, WFD and HD (e.g. MFVM 2019). For Danish marine waters, 'ecosystem health' was assessed as part of Naturstyrelsen (2012), which concluded that a good status (= GES) could only be found in the western-most parts of the Danish sector of the North Sea, whilst the status in all other parts of the North Sea, Skagerrak, Kattegat and the western Baltic Sea was not good (sub-GES).

The latest EEA assessment of ecosystem health in Europe's seas is based on an unprecedented data set including a broad set of indicators. For the Danish marine waters, no evidence could be found for identification and subsequent classification of so-called 'non-problem areas' having a good status (EEA 2019a). This can also be concluded from **Fig. 2**, showing that when all assessments are overlaid using a 'one out, all out' principle, not a single one of the combined assessment units is in a high or good status.

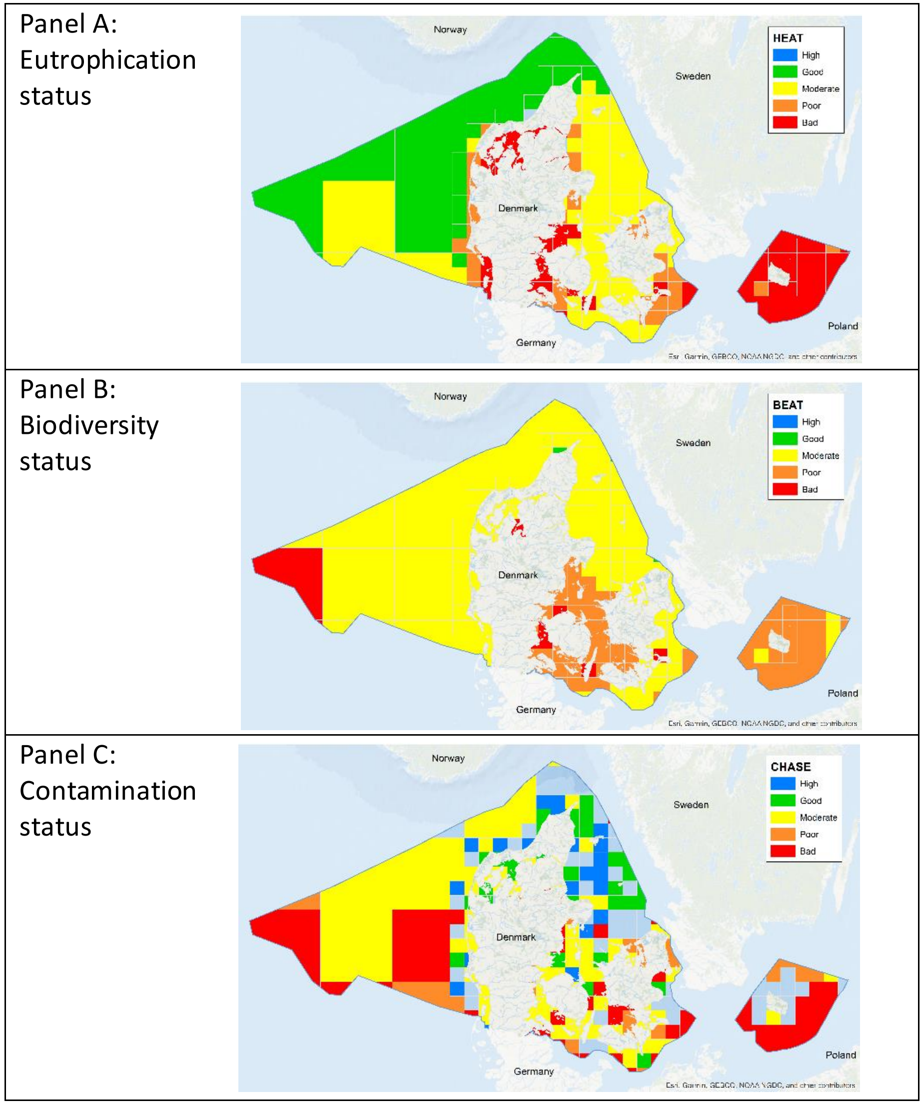

Figure 2: *Results of mapping of 'eutrophication status' (panel A), 'biodiversity status' (panel B), and 'contamination status' (panel C) in Danish marine waters, extracted from Europe-wide classifications of 'problem areas' and non-problem areas' using established assessment tools (i.e. HEAT+, BEAT+ and CHASE+; see EEA 2019b, 2019c and 2019d for details).*

2.2 Data layers

A key objective of ECOMAR has been to establish state-of-the-art data sets representing i) human pressures and activities, ii) ecosystem components and iii) a selection of societal interests, including recreational interests and marine protected areas. Given the goal of MSP, to allocate space for human activities, it is imperative to have high quality data sets for a variety of human activities and pressures. Hence, considerable effort has been spent by the ECOMAR partnership to establish the best possible data sets for all ecologically relevant human activities and pressures. Similarly, with ECOMAR aiming to develop and test tools and concepts for ecosystem-based MSP, it is also imperative to gather the best possible data sets for the ecosystem components.

2.2.1 Pressures and activities

The starting point for establishing the nation-wide data set on pressures and activities is the EU MSFD (Anon 2008), especially Annex III, Table 1 'Pressures and impacts' which focuses on 8 themes and 19 individual pressures. In ECOMAR, focus has been broadened in comparison with the MSFD and previous studies (e.g. HELCOM 2010b, Korpinen *et al*. 2012, Andersen & Stock 2013, Riemann *et al*. 2019, Andersen *et al*. 2020). Hence, a total of 13 themes, 42 groups and 98 distinct pressures and activities (see overview in **Table 2**) are included in ECOMAR:

1. **Aquaculture:** Data on the location of marine aquaculture plants are taken from The Danish Food Administration Agency (2020) and applied.
2. **Climate change**: Two existing data sets on sea surface temperature anomalies and sea level increase have been adapted and applied.
3. **Industry, energy and infrastructure**: Georeferencing of the variety of activities is based on multiple sources cf. the Supplementary Material, Annex A.
4. **Marine litter**: Data is collected under IBTS and BITS fish surveys, where several stations are trawled in a standardized procedure and where each ICES rectangle is swept representatively. In addition to the fish caught, all litter is collected.
5. **Noise and cooling water:** Noise is included as pulse-block days (from ICES impulsive noise register, 2016-2018) and continuous noise (ship noise levels exceeding ambient noise).
6. **Non-indigenous species**: An existing index developed for MSFD reporting (Andersen *et al*. 2020) has been used for ECOMAR purposes.
7. **Physical disturbance of the sea floor**: Data set on this pressure group is based on multiple sources cf. the **Supplementary Material, Annex A**.
8. **Pollution, contaminants**: A recent assessment of contaminants in Europe's seas (EEA 2019d) has been rescaled and used as a proxy of inputs of contaminants.
9. **Pollution, nutrients**: Concentrations of nutrients, i.e. nitrogen and phosphorus, are used as proxies for nutrient inputs.
10. **Selective extraction of species: commercial fishing**: International landings in tons by the gear groups pelagic trawl, mobile bottom contacting gears for industrial purposes, mobile bottom contacting gears for human consumption, longlines and set gillnets as a yearly average based on the period 2015-2017. In ECOMAR, it is used as a pressure layer. VMS is mandatory on vessels longer than 12 meters, so for those vessels, all fishing activity is represented in the data layers.
11. **Selective extraction of species: recreational fishing and bird hunting**: Two data layers based on an extract from two nation-wide recreation and tourism surveys (Kaae *et al*. 2018), and activities including three types of hunting and nine types of fishing, as well as mapping of tour boats in Øresund (Angantyr & Holm-Hansen 2017).
12. **Shipping and transportation**: Data on the spatial distribution and intensity of shipping intensities is taken from EMODnet (2020).
13. **Recreation and tourism**: Data come from two nation-wide surveys of 92 coastal and marine recreation activities grouped in 16 main types (Kaae *et al*. 2018). Use frequencies are added to the approx. 16,000 mapped recreation sites and data combined with AIS data for recreational boating. Data represents the annual participation by Danish citizens including domestic tourists, but not international tourists.

Description of all individual data sets and their origin can be found in the **Supplementary Material (Annex A)** to this report.

Table 2: *Overview of pressures and activities and the groups of pressures. A so-called 'Pressure map' illustrating the spatial distribution of pressures can be found in* ***section 3.1****. For detailed information about individual data layers, please confer with the* ***Supplementary Material (Annex A)****.*

Pressures and activities	
1. Aquaculture	**8. Pollution - contaminants**
Fish farms	Contaminants
Shellfish farms	Dumped chemical munitions
2. Climate change	Oil spills
Sea surface temperature anomalies	**9. Pollution - nutrients**
Sea level rise trend	Nitrogen winter concentrations (DIN)
3. Industry, energy and infrastructures	Phosphorus winter concentrations (DIP)
Coastal habitat modification	**10. Selective extraction of species:** ***Commercial fishing – effort by gear group***
Bridges and coastal constructions	Set gillnet
Dredging	Longlines
Disposal sites for construction, garbage and dredged material	Mobile bottom contacting gears, for industrial purposes (small mesh sizes)
Offshore oil and gas installations	Mobile bottom contacting gears, for human consumption (large mesh sizes)
Oil and gas pipelines	Pelagic trawl
Wind farms	Mussel dredging
Sea cables	**11. Selective extraction of species:** ***Recreational fishing and hunting***
Lighthouses	Recreational fishing
Military areas	Bird hunting
4. Marine litter	**12. Shipping and transportation**
Marine litter	Shipping
5. Noise and energy	Industrial ports
Continuous noise (ship sound 125 Hz)	Harbours
Impulsive noise	**13. Recreational activities**
Energy production	Recreational boating
6. Non-indigenous species	Non-motorised water craft
Non-indigenous species	Coastal recreation sites
7. Physical disturbance to the sea floor	Scuba-diving recreational
Swept area ratio (SAR) from bottom trawling: Surface SAR	
Swept area ratio (SAR) from bottom trawling: Sub-surface SAR	
Extraction of material from the seafloor	

2.2.2 Ecosystem components

Inclusion of all ecologically relevant groups of organisms is a prerequisite for ecosystem-based MSP. Hence, ECOMAR focuses on a substantial range of organisms ranging from primary producers, i.e. from phytoplankton over a broad range of benthic habitats to fish, seabirds and top predators such as seals and harbour porpoise.

The data includes a total of five groups and 56 individual ecosystem components cf. **Table 3**:

1. **Pelagic habitats**: This ecosystem component group consist of two data layers: Chlorophyll *a* concentrations in surface water and oxygen depletion, expressed as areas with low oxygen concentrations in bottom waters (two thresholds). The data layer on phytoplankton is produced based on data from ODA and ICES, while the data layer on areas depleted of oxygen is based on the official reporting from the Danish Centre for Environment and Energy (DCE).
2. **Benthic habitats**: This group of ecosystem components includes two types of data layers, one for broad-scale benthic habitats and one for the distribution of Eelgrass (*Zostera marina*). Information and maps on the distribution of broad-scale benthic habitats originates from EMODnet covering Europe's seas. In ECOMAR, we have combined the original maps in eight groups, each constituting a separate map. The map of the potential distribution of eelgrass in Danish coastal waters is based on Stæhr *et al*. (2019).
3. **Fish**: Data from two sources show the distribution of fish species: one dataset shows the yearly average Catch Per Unit Effort (CPUE) per species for commercial MSFD species for the period 2015-2017. It is based on VMS data, which is only available for vessels longer than 12 meters, so species caught by smaller vessels cannot be presented using this method (e.g. eel, blue mussels and cockles). Another dataset shows Catch Per Unit Effort (CPUE) or presence derived from scientific trawl surveys for the period 2009-2018, used as a proxy for abundance of commercial MSFD species. This dataset shows the CPUE (number caught per trawl haul, standardized with respect to haul duration, year, time of the year and gear used) or presence (probability of catching at least one individual in a standardized trawl haul). Spatial abundance indices are derived from analysis of the data from the International scientific trawl surveys, IBTS, BITS, BTS available from ICES and data from the Danish Cod and Sole surveys.
4. **Seabirds**: The following bird abundance data layers are included in our work: Razorbill/Guillemot (Alk/Lomvie: *Alca torda*/*Uria aalge*), Red-throated Diver/Black-throated Diver (Rødstrubet Lom/Sortstrubet Lom: *Gavia stellate*/*Gavia arctica*), Common Eider (Edderfugl: *Somateria mollissima*), Long-tailed duck (Havlit: *Clangula hyemalis*), Red-breasted Merganser (Toppet skallesluger: *Mergus serrator*), and Common Scoter (Sortand: *Melanitta nigra*).
5. **Marine mammals**: There are data layers for three species: harbour porpoise (Marsvin: *Phocoena phocoena*), grey seal (Gråsæl: *Halichoerus grypus*), and harbour seal (Spættet sæl: *Phoca vitulina*) in the western part of the study area. However, in the North Sea and Skagerrak spatial distribution layers only exists for harbour porpoises.

Description of all individual data sets and their origin can be found in the **Supplementary Material (Annex B)** to this report.

Table 3: *Overview of ecosystem component data and the groups. A so-called 'Ecosystem Map' illustrating the spatial distribution of the amount of ecosystem components can be found in* ***section 3.2****. For detailed information about individual data layers, please see the* ***Supplementary Material (Annex B)****.*

Ecosystem component	
1. Pelagic habitats	**3.2 Commercial fish species**
Productive surface waters- chlorophyll *a*	***Pelagic fish species***
Oxygen depletion	Herring, *Clupea harengus*
2. Benthic habitats	Mackerel, *Scomber scombrus*
Broad scale benthic habitats: Infralittoral sand and muddy sand	Norway pout, *Trisopterus esmarki*
Broad scale benthic habitats: Infralittoral mud	Saithe, *Pollachius virens*
Broad scale benthic habitats: Infralittoral coarse sediments	Sprat, *Sprattus sprattus*
Broad scale benthic habitats: Infralittoral rocks and biogenic reefs	***Demercial/benthic fish species***
Broad scale benthic habitats: Infralittoral mixed sediments	Plaice, *Pleuronectes platessa*
Broad scale benthic habitats: Circalittoral sand and muddy sand	Sole, *Solea solea*
Broad scale benthic habitats: Circalittoral mud	Cod, *Gadus morhua*
Broad scale benthic habitats: Circalittoral coarse sediments	Haddock, *Melanogrammus aeglefinus*
Broad scale benthic habitats: Circalittoral rocks and biogenic reefs	Hake, *Merluccius merluccius*
Broad scale benthic habitats: Circalittoral mixed sediments	Sandeel, *Ammodytes spp.*
Broad scale benthic habitats: Upper bathyal sediments	Turbot, *Psetta maxima*
Eelgrass potential distribution, *Zostera marina*	***Crustaceans***
Stone reefs within 'Natura2000' areas	Shrimp, *Crangon crangon*
3.1 Sensitive fish species	Norwegian lobster, *Nephrops norvegicus*
Cartilaginous fish species	Pandalus, *Pandalus borealis*
School Shark, *Galeorhinus galeus*	**4. Seabirds**
Skates, *Dipturus spp.*	Auks, *Alcidae* (Razorbill/Guillemot)
Smooth-hound sharks, *Mustelus spp.*	Common scoter, *Melanitta nigra*
Spotted Ray, *Raja montagui*	Eider, *Somateria mollissima*
Starry ray, *Amblyraja radiata*	Fulmar, *Fulmar spp.*
Thornback Ray, *Raja clavate*	Red-breasted Merganser, *Mergus serrator*
Bony fish species	Red-throated/Black-throated diver, *Gavia spp.*
Atlantic wolffish, *Anarhichas lupus*	Long-tailed Duck, *Clangula hyemalis*
Atlantic Halibut, *Hippoglossus hippoglossus*	**5. Marine mammals**
Greater forkbeard, *Phycis blennoides*	Grey Seal, *Halichoerus grypus*
Ling, *Molva molva*	Harbour Seal, *Phoca vitulina*
Monkfish, *Lophius piscatorius*	Harbour Porpoise, *Phocoena phocoena*
Rabbit fish, *Chimaera monstrosa*	

2.2.3 Societal interests

A number of societal interests are also impacted by marine activities and are included in the project as equivalent to ecosystem components. This enables a variety of novel analyses, e.g.:

- To analyse which pressures (such as trawling, dredging, or construction) may potentially disturb or destroy ancient shipwrecks and/or archaeological sites or findings.
- To estimate how coastal and marine recreation and tourism areas may be impacted by factors such as low water quality, noise, and aesthetic disturbances from large constructions.
- To highly to which extent marine protected areas may be impacted by pressures from marine activities.

Data layers treated as ecosystem compentents are:

1. **Archaeological sites, findings and ancient shipwrecks**: These were downloaded from the Danish Agency for Culture and Palaces (Slots- og Kulturstyrelsen 2020) and comprise information about the location, the type of the artefact, the name of the location, the archaeological date as well as the approximate age manifested as a range of years it can fall into. The dataset was first filtered for age for all findings and ancient wrecks, the findings and ancient shipwercks which are from the Stone Age (ca. 12,800 – ca. 3.500 BC), the Bronze Age (ca. 3500 – ca. 500 BC), the Iron Age (ca. 500 BC – ca. 800 AD), the Viking Age (ca. 800 AD – 1047 AD), and the Middle Age (1047 AD – 1536 AD) were taken into consideration.
2. **Shipwrecks**: Data was obtained from the Danish Agency for Culture and Palaces (Slots- og Kulturstyrelsen 2020). Data includes the actual shipwrecks of historical importance including parts of the wreck and/or the anchor. The metadata contains information about the location coordinates, the name of the location, the type of the artefact, the archaeological date as well as the approximate range of years it can fall into.
3. **Recreational interests**: National coastal and marine recreation data was collected by the University of Copenhagen (Kaae *at al*. 2018) through two studies: A crowdsource-based study using an online public participation GIS (PPGIS) mapping tool allowing respondents to map places of marine recreation and identify key facts about their activity and the site. Secondly, a national representative survey of the Danish adult population with 10,291 valid responses and combined with mapping. These studies provide new in-depth knowledge of 92 water-oriented recreation activities grouped in 16 main types as well as nation-wide spatial mapping. In total approx. 16,000 recreation sites were mapped, and the two studies supplement each other. Recreation and tourism are interlinked, as participation in activities outside the local municipality is regarded as day-visits by one-day tourists. Danish residents undertaking recreation activities while staying overnight outside their municipality are classified as domestic tourists (25 % of the data). Results show that marine recreation is very widespread, and 77.6 percent of the adult population has participated in water-oriented recreation within the past year. Triangulation of data with AIS data on recreational boating has shown to provide a solid documentation and mapping at national level.
4. **Marine Protected Areas (MPAs)**: Data comprises four types of marine protected areas designated under i) the Habitats Directive (Anon. 1992), ii) the Birds Directive (Anon. 2009), and iii) the Ramsar Conventions (2020) plus iv) national offshore biodiversity protection areas under the MSFD (Naturstyrelsen 2016).

2.3 Combined effects of human activities

Applying the Ecosystem Approach or an Ecosystem-based Approach to management of human activities and pressures in Danish marine waters implies that all ecologically relevant activities and pressures should be addressed. A truly ecosystem-based MSP, or an MSP plan claiming to be ecosystem-based, must accordingly address not only all relevant pressures but also their potential combined effects. Otherwise, resulting policies and management strategies cannot claim to be ecosystem-based.

Potential combined effects are estimated using a concept developed by Halpern *et al*. (2008) and subsequently applied in northern Europe by Korpinen *et al*. (2012) and Andersen & Stock (2013). To estimate the potential combined effects, four types of information are required cf. **Fig. 3**: i) data on the spatial distribution of pressures, ii) data on spatial distribution of all relevant ecosystem components, iii) information on the effect distances, i.e. how far from a point source the effect of a pressure can be expected, and iv) information on how sensitive or susceptible a specific ecosystem component is to impact from a specific pressure.

Using the EcoImpactMapper software developed by Stock (2016) in combination with the data sets compiled by ECOMAR, including effects distances and sensitivity scores, we have not only mapped the potential combined effects of multiple human pressures in Danish marine waters but also ranked pressures and carried out a wide range of downstream analyses on different scales ranging from national to local (see **section 2.6**).

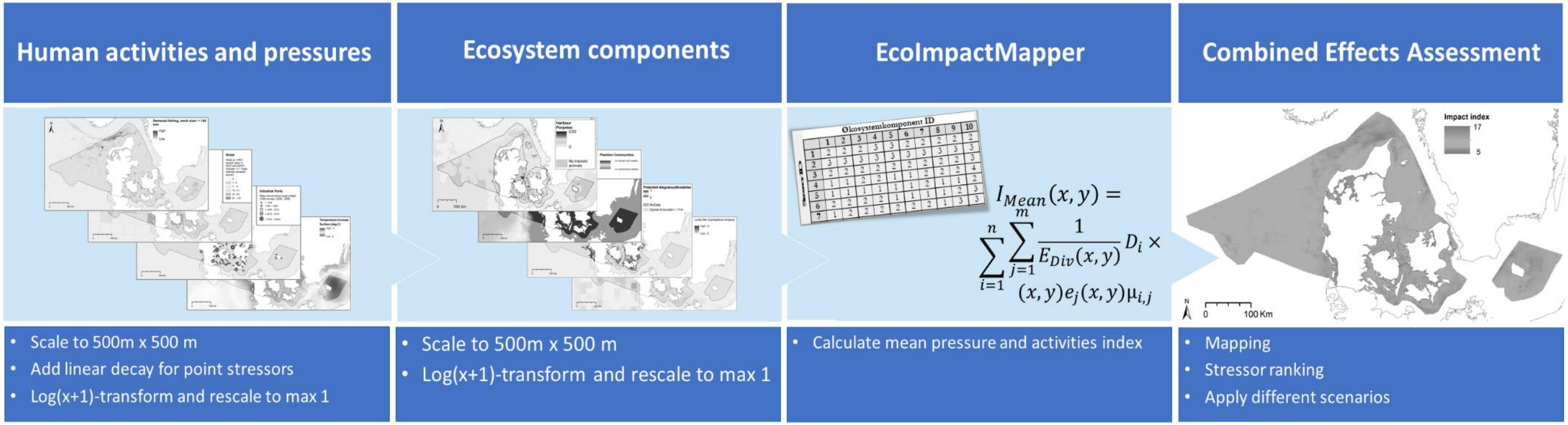

Figure 3: *Conceptual illustration of the steps in mapping of combined effects of multiple human pressures. Step 1a: Scaling and log-transformation of individual pressure data layers including addition of effect distances for point data; Step 1b: Scaling and log-transformation of individual ecosystem component data layers; Step 2: Calculation of mean impact; Step 3: Mapping and subsequent post-processing of results. Data sets, effects distances and sensitivity scores are described in detail in the* **Supplementary Material (Annex A-C)** *to this report. Based on Andersen* et al. *(2019).*

The methods developed by Halpern *et al.* (2008) and further by Halpern *et al.* (2009 and 2015) and Stock (2016) for an additive human impact index have been used to calulate the combined effects of human activities as a 'pressures index'. Stock (2016) has developed the software 'EcoImpactMapper', an open-source Java program that implements the Halpern model. EcoImpactMapper has, although the method is rather simple (Halpern & Fujita 2013), been used used widley in marine ecosystems for assessment of cumulative human impacts (Korpinen & Andersen 2016) and now also in the ECOMAR project.

EcoImpactMapper and the Halpern model require three kinds of input data:

- **D_i**, pressures and activities *i*, represented by its spatial distribution in a regular grid; for example, fishing intensity with a given gear type.
- **e_j**, ecosystem component *j*, represented by its spatial distribution in a regular grid; for example, different kinds of broad-scale habitats, eelgrass or fish species, either as presence-absence or continuous data.
- **$\mu_{i,j}$**, sensitivity scores, a numerical representation of the sensitivity of ecosystem component *j* to pressure or activity *i*, based on surveys.

The intensities of the pressures and activities and the ecosystem component data were all normalized by log(x + 1)-transformation and rescaling to maximum 1. The reason for this was to enable comparisions between different units for the layers, e.g. presence/absence, probabilities of presence, population densities or concentrations (see **Supplementary Material, Annex A and B**) for details of the data units for each layer).

For pressures or activities with a point distribution or decay from a restricted area, effect distances were also estimated based on expert surveys, and those data layers were pre-processed by adding this effect. A simple linear decay function from the source and to the limit of the effect distance was used.

Based on these data, we calculated the dimensionless combined effects of multiple human pressures index for each cell in the regular grid (x,y) estimated for n pressures/activities and m ecosystem components; I_{Mean}:

$$I_{Mean}(x,y) = \sum_{i=1}^{n} \sum_{j=1}^{m} \frac{1}{E_{Div}(x,y)} D_i(x,y) e_j(x,y) \mu_{ij}$$

where

$$E_{Div}(x,y) = \sum_{j=1}^{m} e_j(x,y)$$

In ECOMAR, the combined effects are estimated as the mean of the impact over all present ecosystem components, rather than the sum, because some ecosystem component datasets did not cover the whole study area. This mean model is also more applied in more recent publications, e.g. Halpern *et al*. (2015) and Andersen *et al.* (2020). The mean model is used to avoid conflating the effects of high-intensity pressures/activities with the number of ecosystem components in a given grid cell. Besides the combined effects indices, the contribution of each of the stressors to the total effect was also calculated.

Sensitivity scores linking specific pressures with specific ecosystem components as well as effect distances for specific point sources/activities have been set through surveys with relevant experts. See the **Supplementary Material (Annex C1)** for detailed information about the sensitivity scores and **Annex C2** for the effect distances used.

Mapping of combined effects of multiple human pressures and ranking of pressures are reported in **section 3.3** and **3.4**, respectively.

2.4 Analysis and scenarios

An important objective of ECOMAR has been to analyse the potential effects and consequences of changes in human activities and the management of these. The analyses have focused on increases or decreases in pressure intensities, as well as on the introduction of new activities, and have been demonstrated on relevant scales, i.e. national, regional or local scale. Whenever possible, the assumed changes are anchored in existing predictions and scenarios. In some cases the levels of change have been set together with the experts within the ECOMAR partnership. Nevertheless, the scenarios should be looked upon as hypothetical and demonstrational.

2.4.1 SeaSketch

The analyses and scenarios are done using SeaSketch, a widely used MSP tool developed by the National Centre for Ecological Analyses and Synthesis (NCEAS) at University of California Santa Barbara (UCSB), USA.

SeaSketch is an online participatory mapping tool designed to allow planners and stakeholders to interact with data related to MSP processes (please confer with https://www.seasketch.org/home.html).

The ECOMAR SeaSketch project (http://ecomar.seasketch.org) allows users to visualize > 100 interactive maps depicting the distribution of ecosystem components (e.g., habitats and species), human activities and pressures (e.g., pollution, extraction, physical disturbance, climate change, etc.) and other reference layers. Within the ECOMAR SeaSketch project, these layers have been modified according to set up analyses and scenarios (described in section 2.4.2 and 2.4.3), by icreasing or decreasing the pressures or by sketching new activities (in SeaSketch called 'sketches') within the Danish EEZ. The existing pressures within the new sketches was either modified or new pressures were added to simulate future management scenarios. SeaSketch provides analytical feedback about your sketched zone within seconds. These reports identified if and where the combined human effects had increased or decreased and which pressures that was contributing most as well as which ecosystem components that were most affected. These types of analyses can be used to e.g. inform the development of broadly supported marine spatial plans.

The analyses and scenarios were analysed individually or as collections, simulating a comprehensive marine spatial plan with a variety of sketches including different human activities. The combined effects of all human activities within the sketch was compared to the baseline state, pointing to the differences between the current state and the scenarios. One might, for example, calculate whether increasing shipping activities while removing oil and gas installations within zones ultimately increases or decreases cumulative effects.

The ECOMAR partners could share the designs (including any modified stressors) within map-based discussion forums including commentary on the justifications for their designs. Others with access to the forums could then copy the designs, modify boundaries and stressors, and contribute their own design concepts. In this way, users may collaboratively develop scenarios with a quantitative understanding of how they impact ocean ecosystems.

2.4.2 Description of analyses and scenarios

Analyses were done for the 13 pressure groups (see **section 2.2.1**) and specific new activities were included. Predicted changes were combined for two future scenarios, one for 2030 and one for 2050. In addition, a scenario anchored in the ecosystem components and an improved conservation regime in accordance with the MSFD will be undertaken (MSFD GES scenario). Most of the scenarios are directly linked to the Blue Growth strategy from the European Commission or National Danish plans and strategies, aiming to support a sustainable growth in the marine and maritime sectors. Others are more general, based on the current intensities of pressures.

Pressure group 1: Aquaculture
Marine aquaculture for fish meat production in net cages is a small industry in Denmark. However, this industry gives rise to environmental concerns and has consequently been on the political agenda for decades, as it releases excess nutrients and organic matter to the ecosystem and thus increasing the problems with eutrophication. According to the national aquaculture strategy production is expected to increase, mostly for land-based systems. However, increases in marine shellfish and kelp farms are also expected, which does not add but instead remove nutrients from the water column. Several estuaries have been identified as suitable for potential new shellfish farms to be established: Roskilde Fjord, Gamborg Fjord, Limfjorden, Mariager Fjord, Vejle Fjord, Kolding Fjord, Åbenrå Fjord, Augustenborg Fjord and Flensborg Fjord (Altinget 2020). Marine fish farms can expect a decrease in nutrient losses due to improved technologies and environmental concerns (Miljøstyrelsen 2020). Therefore, the 2030 scenario includes a decrease for marine aquaculture by 10% relative to present levels, but an increase in the shellfish farm area by 5% placed within the estuaries mentioned. In 2050, the increase in shellfish farm areas is 10%. Kelp farms are not considered.

Pressure group 2: Climate change
Sea Surface Temperature (SST) and marine heat waves are foreseen to rise in the future if CO_2 emissions are not lowered significantly (IPCC 2019). Future scenarios of SST in the North Sea (Schrum *et al*. 2016) and the Baltic Sea (Meier 2015) suggest an increase of about 2°C by the end of century, with some variation between the various scenarios. The rate of SST anomalies is therefore assumed to be 0.2°C per decade, which will lead to anomalies of about 0.33-0.37°C in 2030 and 0.73-0.77°C in 2050. These temperature anomalies correspond to increases of 54% in the North Sea/Skagerrak, 59% in the Kattegat and 60% in the Western Baltic in 2030, relative to baseline. In 2050, the SST anomalies will have increased by 0.6°C, which corresponds to an increase of 78% increase in the North Sea/Skagerrak, 81% in the Kattegat and 82% in the Western Baltic. The global rate of sea level rise is 3.3 mm per year (EEA 2019e, IPCC 2019) which means 3.3 cm over a decade and thus 9.9 cm increase in 2050. The change in the sea level rise trend over 10 years (2030) is assumed to be at least the same as the global rate, which then gives an increase compared the current rate of 47% in the North Sea/Skagerrak, 86% in the Kattegat and 55% in the Western Baltic. In 2050, the rate is expected to be even steeper and we used the current global rate of 3.3 mm/year times 1.5, resulting in a rate of 4.65 mm/year. For 2050 the rate is thus expected to increase compared to the current rate by 64% in the North Sea/Skagerrak, 91% in the Kattegat and 70% in the Western Baltic.

Pressure group 3: Industry, energy and infrastructure
The long term forecast up to 2025 is that Denmark will be a net exporter of energy until 2035 (DEA 2018). According to this report the production will be about the same in 2030 as per today (2018), due to new findings and technical advancements, except for a temporary drop in 2020/21 due to rebuilding of a specific oil field. The wind power plants pressure is expected to increase by new areas being taken into use. The wind power parks that already are approved will be assumed to be implemented by 2030. In 2050, all areas that are “in pipeline” will be implemented (DEA 2018). An increase in wind power plants will lead to an extension of the sea cables and accordingly, dredging within the new areas will increase and disposal sites will increase by 5% each year, which also will be implemented. An increase in shipping will also lead to an increase in coastal protections and piers with 10% in 2030 and 20% in 2050 and dredging and disposal of material will both increase by 5% in 2030 and 10% in 2050.

Pressure group 4: Marine litter
Despite huge media attention and expression of political will to develop European and national plastic management strategies, there is currently no evidence supporting a decrease in the amount of plastic entering Europe's seas and Danish marine waters. On the contrary, we have assumed future trends to be increasing with 10% by 2030 and 20% in 2050.

Pressure group 5: Noise and cooling water
If shipping intensity increases up to 2030, the continuous noise from shipping will also increase. Noise is measured in a log10 scale (dB) and a direct calculation of the increased noise is not possible. The 20% increase in shipping is therefore estimated to give an increase by 2.3% on average for the noise index used (based on an increase of the median level of 0.8 dB). Assuming new technologies, we estimate that by 2050 the sound pollution will decrease again and be of the same magnitude as per today. The average impulsive noise of impulse-block days per year will increase, especially in the areas where new wind power plants will be constructed, thus an increase by 20% in the new areas of wind power parks will be used for both 2030 and 2050. As no changes in inputs of cooling water to coastal waters is expected, no modelling focusing on this specific input has been undertaken.

Pressure group 6: Non-indigenous species
There is no evidence for any reduction in the number in new introductions of non-indigenous species to Danish marine waters (Stæhr *et al*. 2016). In European Seas an average of 28 new species per year were recorded between 2006-2011 (EEA 2019f). This number is hard to directly translate to the NIS index used in the model. A reasonable and likely increase of the index by 25% over a decade and 50% for 2050, will be applied.

Pressure group 7: Physical disturbance of the sea floor
Due to the expected growth in the building industry and the increased need for sand for coastal protection, the production of marine resources is expected to increase in the existing resource areas as well as in new developed areas (NIRAS, 2018). The pressure intensity is in 2030 expected to increase by 20% relative to current levels. In 2050, the areas currently designated as approved, but not active, are included in the pressure layer.

Pressure group 8: Pollution - Contaminants
Oils spills are mainly from shipping and oil platforms. The risk of oil spills is proportional to shipping so their intensity is assumed to increase correspondingly with 20% in 2030 and 40% in 2050. Oil spills from oil platforms are expected to remain the same (DEA 2018). Contaminant levels will remain the same in 2030 and be reduced by 5% in 2050. It should however be noted, that there is some uncertainty regarding whether the degree of contamination is increasing or decreasing. Discharges of some substances have been reduced significantly, but at the same time, new substances are being introduced at a high rate. The data layer represents many present substances which are degraded slowly in nature. They will therefore tend to persist, even given a reduction in releases to the sea. No change in the levels of dumped chemical munitions is forseen.

Pressure group 9: Nutrients
The most important pressure in Danish marine waters, especially estuaries and coastal waters, is nutrient input from land and atmosphere. Dedicated efforts have for decades focused on reducing losses from agriculture, discharges from urban wastewater treatment plants and industries with separate discharge. Since the late 1980s, significant reductions have been obtained for both nitrogen (appr. 50%) and phosphorus (appr. 90%). However, inputs to coastal waters have levelled out since 2001/2002 (Andersen *et al.* 2019) and nitrogen inputs may even have increased in the past decade. Climate change with increased rain leading to more run-off and changes in animal production in combination with less area used for agriculture might have large impacts in the future. We assume a 10% decrease in 2030, according to the current political goals, and a slightly more ambitious goal of a decrease by 20% in 2050.

Pressure group 10: Selective extraction of species - commercial fishing
Assuming that more fish species will be sustainably managed in European Seas based on the maximum sustainable yield (MSY) concept, it is expected that intensity of fishing with bottom trawl for human consumption in the Baltic Sea in 2030 will be 40% lower than at present and pelagic trawl in the same area 30% lower. Bottom trawling for industrial use remains the same.

In the North Sea and Kattegat, the fishing pressure by bottom trawl for human consumption and industry are decreased by 30% each and pelagic trawl by 20%. In the 2050 scenario, the pressures are reduced with an additional 10%. The reduction of the fishing quotas for cod and sprat in 2020 and with further reductions expected in the coming years the pressure from bottom trawling will also decrease; in the Baltic Sea by 30% in 2030 and 40% in 2050; in the North Sea and Kattegat, the reduction in bottom trawling pressure is analyzed with a decrease of 20% in 2030 and 30% in 2050. The pressure from other fishing methods are also reduced by 10% in 2030 and 20% in 2050. Mussel dredging occurs only in a few areas and is assumed to remain unchanged in future scenarios.

Pressure group 11: Selective extraction of species - recreational fishing
In the Baltic Sea, we expect a slight reduction in the fishing of cod allowed, due to the critical condition of the population. A rise in recreational fishing in general is expected, so we have projected an increase in the order of 15% in general and a smaller increase of 10% in the Baltic Sea in 2030. For 2050 we anticipate increases of 25% and 20%, respectively. Bird hunting pressure will decrease by 10% in the western Baltic Sea due to the condition of some seabirds in 2030, in 2050 it will decrease by 20% in all regions.

Pressure group 12: Shipping and transportation
Overall shipping is expected to increase by 20% in 2030 and 40% in 2050, including all types of ships from container industrial to large international cruise ships. Denmark's blue maritime strategy is investing in maritime developments to facilitate, among other things, an increase in shipping capacity. The industrial ports pressure will be increased by an equivalent of 20% and 30%, coastal protections and piers with 10% and 20% and dredging and disposal of material will both increase by 5% and 10%.

Pressure group 13: Recreation and tourism
Future growth with respect to all types of tourism and recreational activities is anticipated, especially in the coastal zone. For 2030 we have increased the intensity in this pressure group with 20% for all categories and for 2050, we have increased the group with 40%.

Addition of new activities
New activities in Danish marine waters, such as new offshore wind farms and the construction of a bridge between Zealand and Jutland can be introduced and tentatively analysed using SeaSketch:

- Offshore wind farms: Based on information from the Danish Energy Agency (DEA 2020) we can introduce new offshore wind farms, e.g. in the North Sea and at Kriegers Flak east of the island Møn.
- Kattegat Bridge: This proposed link is introduced assuming the route will consist of two new bridges between Zealand (Røsnæs) and Samsø and between Samsø and Jutland (Hov) (Ingeniøren 2018).

Scenarios for 2030 and 2050
In addition to the above pressure group specific analyses, we have combined the results and established scenarios for the years 2030 and 2050:

- **2030 scenario:** We have combined what we consider being the most realistic scenarios for the year 2030 (see individual sections above) and rerun the model and thus estimated how the expected combined effects most likely will develop compared to the baseline in **section 3.1**.
- **2050 scenario:** Similarly, we have re-run the model and estimated the combined effects in year 2050 based on what we considered to be the most likely scenario for individual pressures or group of pressures.

Interactions between pressure groups and ecosystem components
In addition to the analyses and scenarios described above, we have grouped pressures and activities and ranked these with respect to the following key groups of ecosystem components:

- Pelagic habitats (Chlorophyll *a* and oxygen depletion).
- Benthic habitats (Broad-scale benthic habitats and eelgrass).
- Fish species.
- Seabirds.
- Marine mammals.

Further, treating societal interests such as recreation & tourism, ancient shipwrecks and stone-age dwellings as an analogue to ecosystem components, we analyse and rank the human activities and pressures with potential impacts on these.

MSFD GES scenario
Based on the identification of key pressures affecting the ecosystem component groups, a MSFD GES scenario was modelled. Here the environment was prioritised by hypothetically reducing the current pressure intensities from human activities with the aim of improving environmental status in accordance with the EU MSFD. The GES scenario should be considered as a theorethical 'what if' demonstration, not as a prediction of future conditions. The MSFD scenario was modelled in two versions: one with climate change remaining at current levels and one version with the increase as in the 2030.

- Pressure group 1: Aquaculture: 20% decrease in current farms, and a decrease in renewed permissions. No new aquaculture introduced.
- Pressure group 2: Climate change is not included.
- Pressure group 3: Industry, energy and infrastructure Wind power remain as in 2030. Some oil and gas installations can be demounted, and the areas can be restored, as well as the pipelines -> reduction 20%. Less material dumped at sea -> reduction 30%. Dredging decrease by 20% in accordance with less shipping. Military areas explosions are set to lower levels and outside the breeding periods - reduction 20%.
- Pressure group 4: Marine litter reduction of 20%, some of the litter can be collected and removed, better information and better control of polluters.
- Pressure group 5: Noise and cooling water: Continuous noise is reduced by 2.3% related to less shipping and technological developments.
- Pressure group 6: Non-indigenous species: Better control legislation and controls of ballast water can be implemented. No change as already introduced species are present.
- Pressure group 7: Physical disturbance of the sea floor: Sand dredging is reduced by 50%. No new areas are changing status to active.
- Pressure group 8: Contaminants: A decrease of 10%, oil spills reduced 5%. Areas with dumped chemical munitions can be sanitized and bombs can be removed, reduction of 5%.
- Pressure group 9: Nutrients: A decrease of 10% via changes of agricultural practices and land use.
- Pressure group 10: Commercial fishing: Impacts on fish species and impacts on the seafloor caused by bottom trawling decreases 30%, other fishing methods 20%. Mussel dredging reduced 10%.
- Pressure group 11: Recreational fishing: A decrease of 25%, seabird hunting by 30%.
- Pressure group 12: Shipping and transportation: Reduction in ship traffic by 20% as well as industrial ports by 15 %. Recreational harbours remain the same.
- Pressure group 13: Recreation and tourism: A decrease by 15% due to new regulations of restricted periods for human presence.

2.4.3 Linking MSPD, MSFD and WFD pressure analyses

A total of three EU directives require Member States to map and assess human pressures in marine waters; the MSPD, MSFD and WFD, where the latter focuses only on coastal and transitional water bodies. Despite some differences in the objectives and geographical coverage between these directives, there is both as demand and an overlap in mapping of human pressures.

All three directives require assessment of current pressures. These pressures can be either identical or overlapping between the three directives, but, importantly, the data requirements usually are the same. However, most EU Member States, including Denmark, carry out the prescribed assessments as directive-specific activities in a manner that is usually not coordinated with the activities of the other directives. The MSFD and WFD implementation processes are coordinated by the Ministry of Environment (MIM), while the MSPD is in the hands of the Danish Maritime Authority under the Ministry of Industry, Business and Financial Affairs (in Danish: Erhvervsministeriet) and coordination between these two ministries appears to be limited.

Within MFVM, the practical implementation of MSFD and WFD is further divided. The Danish Environmental Protection Agency produces 'WFD Initial Assessments' including pressure analyses, and the Department of the MFVM produces 'MSFD Initial Assessments', including mapping and assessment of combined/cumulative impacts. Even within the same ministry, coordination seems limited, cf. the recent Initial Assessments published in 2019 (MSFD; Miljø- og Fødevareministeriet 2019) and 2020 (WFD; Miljøstyrelsen, 2020).

ECOMAR demonstrates how the task ideally could be coordinated and carried out on the basis of the same data and methods. Our take on this has been straightforward and based on the data sets for pressures and ecosystem components available (see **Table 2 and 3**). Analyses have already been made in the context of the MSPD and MSFD (see **section 3.6**). For both the MSFD and WFD analyses, pressures from climate change are not included as it is considered an exogenic pressure and consequently not included.

In order to target the mapping and analyses for MSFD and WFD specific purposes, we have focused on relevant ecosystem components as outlined in **Table 4** and below:

- **WFD_{DIR}**: Only quality elements and indicators directly used for assessment of GES are considered, i.e. Chlorophyll-a and potential eelgrass distribution Eelgrass (used here as a proxy for depth limit).
- **$WFD_{DIR+INDIR}$**: In addition, quality elements and indicators indirectly related to WFD assessments of GES have also been included, i.e. oxygen depletion and benthic habitats.

Table 4: *Overview of ecosystem components in the analyses for i) MSFD, ii) WFD_{DIR} and iii) $WFD_{DIR+INDIR}$.*

Ecosystem component	MSFD[1]	WFD_{DIR}	$WFD_{DIR+INDIR}$
Pelagic habitats			
- Productive surface waters	X	X	X
- Oxygen depletion	X	–	X
Benthic habitats			
- Infralittoral coarse sediments	X	–	X
- Infralittoral rocks and biogenic reefs	X	–	X
- Infralittoral mixed sediments	X	–	X
- Infralittoral mud	X	–	X
- Infralittoral sand and muddy sand	X	–	X
- Circalittoral coarse sediments*	X	–	X
- Circalittoral rocks and biogenic reefs	X	–	X
- Circalittoral mixed sediments*	X	–	X
- Circalittoral mud*	X	–	X
- Circalittoral sand and muddy sand*	X	–	X
- Upper bathyal sediments	X	–	–
- Stone reefs within N2000 areas	X	–	X
- Eelgrass distribution	X	X	X
Fish[2]	X	–	–
Sea birds[2]	X	–	–
Marine mammals[2]	X	–	–

[1] *Includes offshore areas.* [2] *all ecosystem component data sets are considered.* * *Indicates that the circalittoral layer is merged with the corresponding deep circalittoral layer.*

2.5 Towards marine zoning – establishing building blocks for a future zoning plan

'Marine zoning' was originally developed in Australia and has played a key role in the adaptive management of human activities within the Great Barrier Reef Marine Park (Day *et al*. 2018) for more than 40 years. It is a concept for resource management through designation of zones for specific human activities and uses. A key element of the concept is the nesting of human activities into groups of similar types and subsequently a zoning matrix for a given area. In our case, the area in question is Danish marine waters. Benefits of zoning can include: i) licencing of specific activities, which can develop with certainty, ii) reduction of conflicts between users, and iii) protection of culturally important areas (e.g. archaeological sites) or environmentally important areas (e.g. Natura 2000 areas or Bird Protection Areas). Establishing a baseline for the development of a draft zoning plan in Danish waters is straightforward – ECOMAR has the information on activities and pressures and has used this for outling a so-called 'Zoning matrix', the perhaps single most important step in the making of zoning and a national data-driven 'Zoning plan'.

ECOMAR has thus developed a tentative zoning matrix opting for four different types of zones ranging from i) 'General Use Zone' over i) 'Targeted Management Zone', iii) 'Exclusive Use Zone', and iv) 'Restricted Access Zone' (based on Ekebom *et al.* 2008):

- Zone 1 'General Use' is the least restrictive of the four zones, and the largest, and covers all marine activities not covered by the other three zones – all types of human activites can take place, except those specifically prohibited by law. Activities that require permissioins or licences are only allowed after permissions and the same general rules within this zone are applied to all the three stricter zones.
- Zone 2 'Targeted Management' considers areas where there is a further restriction. This can be areas where a permission or a licence has been granted but it can also be nature protection areas which have certain regulations. Activities can be allowed as long as they are not in conflict with the targeted management within the zone.
- Zone 3 'Exclusive Use' are zones reserved for single use activites and most other activities should be prevented. Recreational or research activities can be allowed if it is allowed in the management plan. This can e.g. be fish farms, harbours, wind farms or vulnerable marine habitats.
- Zone 4 'Limited Access' is subject to rigorous regulations and restrictions allowing only limited access and specific activities. Entry to this zone should be prohibited, except in case of emergency or for scientific activities, e.g. research or environmental monitoring.

An important step towards a draft zoning plan is to find out where there could be spatial conflicts between activities. A conflict map was made based on a conflict matrix where the most likely conflicts could potentially occur, for example commercial fishing vs. harbour or aquaculture areas, or placement of disturbing industrial activities vs. areas used intensively for recreation or vice versa.

As another important step, we have estimated the sensitivity linkages of all ecosystem components based on their sensitivity scores and created a provisional vulnerability map showing the most and least vulnerable marine areas within the Dansish EEZ.

A fully-fledged data- and criteria-driven application of zoning in Danish marine water including all human activities and land-sea interaction will ensure space for all human uses, involvement of all interested stakeholders while taking care to minimise impacts and multiple pressures on the marine environment. Hence, zoning is a necessary tool for planning multiple use of sea areas in a way that balances human activities and sea use with environmental objectives.

Further, it should be noted, that a zoning plan must have a management plan, including the specific permissions and regulations etc. for each zone. But this is a task for Competent Authories, and also very complicated as visions and goals of at least MSPD, MSFD and WFD would have to be considered and aligned.

2.6 Confidence and uncertainty

An essential component of every scientific result is the quantification of its confidence and uncertainty. Whereas uncertainty expresses the random variability associated with scientific results and has the same unit as the result, the confidence expresses a probability that the result is within certain boundaries, i.e. typically the probability that the result is above/below a certain threshold or the boundaries of the result associated with a fixed confidence level (e.g. 95%). Quantifying the uncertainty of a given result is a prerequisite for quantifying the confidence. In practice, if regulatory limits are available for data layers or aggregates of these, then we can quantify the probability (confidence) of complying with these limits, provided that the uncertainty of data layers and their aggregates are known. Alternatively, we can fix the confidence level (typically to 95%) and then estimate the range of variability for that confidence level, provided that (again) the uncertainty of data layers and their aggregates are known.

2.6.1 Sources of uncertainty

Data layers are typically generated from some underlying data, which may be associated with uncertainty in their acquirement (e.g. measurement noise), but spatial and temporal variability may also influence the underlying data and add to the overall uncertainty of the data layer, when discrete observations are compiled. Data layers are typically generated using: i) full-coverage registrations, ii) simulation models, and iii) statistical models.

Full-coverage registrations cover the entire spatial domain and may or may not have a temporal component. For instance, the mapping of oil and gas pipelines in Danish waters can be considered complete and without temporal variability, as stone reefs are static features the location of which is considered known. Consequently, the uncertainty associated with such a data layer is zero. In other cases, full-coverage registrations may exist for all or a subset of years of the assessment period, which in the case of all years implies no temporal variability (the entire temporal population is known) and therefore zero uncertainty, and in the latter case implies that interannual variability will contribute with uncertainty to the data layer because the spatial distribution is not known and has to be estimated for those years without data.

Simulation models can be used to produce spatial distributions that cover the entire spatial domain for the entire assessment period. However, this does not mean that model output can be equated with full-coverage registrations and similarly be associated with zero uncertainty. Instead, model output is influenced by uncertainties deriving from model input, model parameters, boundary conditions and inadequacy of the model structure (i.e. all models are approximations). The uncertainty of the model output can be quantified if the magnitude of these sources of uncertainty is known, but this is seldom the case and consequently, the uncertainty of data layers based on simulation models is generally not quantified.

Statistical models are typically used for data layers, where simulation models do not exist or are not considered sufficiently precise for describing spatial and temporal variations. Statistical models are typically employed on discrete observations that are heterogeneously distributed in time and space and in many cases, the temporal dimension of the data is overlooked when the objective is to describe spatial variability. For example, a data layer produced from a single year's data will only represent that given year and not the mean spatial distribution for the entire assessment period. In addition to the temporal variability, predictions from the statistical models are also associated with uncertainty, typically increasing with distance from the observations. Statistical models handle random variations differently and some methods are better at describing uncertainty than others (see below). In this respect, it should be noted that methods such as linear interpolation, inverse distance weighting and nearest neighbour are mathematical methods and do not incorporate any terms for the random variability.

An important question for correctly addressing the temporal variability in the compilations of data layers is to delineate the relevant period. First, data layers should preferably represent the same period before aggregation, as artefacts may appear from combinations of pressure and ecosystem layers covering different periods, when temporal variability is large. Second, the uncertainty associated with a data layer may be underestimated if based on temporally limited data without considering the random temporal variation. However, this temporal random component cannot be truly assessed if the temporal limits of the assessment period are not defined. Consequently, it is of outmost importance that the temporal limits are clearly defined and harmonised across data layers.

ECOMAR has addressed confidence and uncertainty in the data input in two ways. Firstly, we have assessed uncertainty in individual data layers and evaluated the overall uncertainty in the aggregated product, (see **section 3.8**). Secondly, we outline and demonstrate, based on a case study, how a data-driven methodology could be developed and implemented in the future (see **section 3.8.2**).

Other sources of uncertainty can arise from the inherent model assumptions for the CEA method (Stock & Micheli 2016, Stock *et al*. 2018). To assess the model uncertainty we have applied the Monte Carlo simulations inbedded in EcoImpactMapper described by Stock *et al*. (2018) and the Morris analyses (so called 'Elementary effects', i.e. sensitivity and uncertainty estimations) according to Stock & Micheli (2016) (see **section 3.8.1**).

2.6.2 Assessing uncertainty in layers made from discrete data

Data layers used in planning tools are typically generated from discrete observations ($z(s_i, t_i)$) that have been sampled more or less irregularly in time (t) and space (s). These discrete observations are integrated over the spatial domain using different methods such as natural neighbors, inverse distance weighting, splines and kriging. Common to all integration methods is that we are interested in predicting the value of the spatio-temporal process ($Z(s, t)$) in each point in time and space from the observations, i.e.:

$$\hat{Z}(s_0, t_0) = f(z(s_i, t_i); i = 1, \dots, n)$$

implying that the true spatio-temporal process can be described as:

$$Z(s_0, t_0) = f(z(s_i, t_i); i = 1, \dots, n) + e(s_0, t_0)$$

where $e(s_0, t_0)$ is a spatio-temporal process describing the uncertainty of the prediction at the point (s_0, t_0). The prediction error may comprise both observation error and model error, i.e. the latter describing the inadequacy of the spatial interpolation function ($f()$). For many of the commonly applied integration methods $e(s_0, t_0)$ has the following properties:

$$E[e(s_0, t_0)] = 0$$

$$V[e(s_0, t_0)] = R(s_0, t_0)$$

which means that $\hat{Z}(s_0, t_0)$ is a central estimator (unbiased) with a variance described by $R(s_0, t_0)$. Variance of the prediction error may exhibit both spatially and temporally dependent variations. For a treatment of spatial and spatio-temporal processes, see Cressie (1993) and Diggle (2013).

The two most common methods for integrating point observations into data layer are ordinary kriging and splines. In short, ordinary kriging assumes a constant mean field ($\hat{Z}(s_0, t_0) = \mu$) and that the variance of the prediction error depends on the distances to the observations ($z(s_i, t_i)$) used for predicting $\hat{Z}(s_0, t_0)$. The variance structure is described through a variogram model, normally based on the assumption that observations are spatially correlated up to a certain range (r). Ordinary kriging is useful when the observation network is dense (distances less than r), utilizing that observations are spatially correlated. Essentially, the prediction function ($f(z(s_i, t_i); i = 1, \dots, n)$) of ordinary kriging is a weighted average of the observations ($z(s_i, t_i)$), where the weights are determined based on the variogram model. However, ordinary kriging is less suitable when the observation grid is less dense, with internal distances extending beyond the range r. In such cases, the predicted mean field will be constant. Therefore, a trend function can be used to describe the mean field ($\mu(s)$ for stationary processes or $\mu(s, t)$ when the mean field changes with time) and this mean field is formulated as a parametric function of different co-variates, including geographic position, depth, salinity or temperature fields, for which there are data layers covering the entire spatial domain. In such cases, the method is termed universal kriging. However, universal kriging assumes that there is a parametric relationship between observations ($z(s_i, t_i)$) and the explanatory variables. Nevertheless, both ordinary kriging and universal kriging build on a spatial correlation structure, which can be useful for prediction purposes, but these methods may also overestimate the prediction uncertainty if the correlation structure, formulated as a random model, is governed by underlying mechanisms that are better described with a fixed model. Hence, although ordinary kriging can indeed be useful and readily applied to dense observation grids, this method may also overestimate the prediction variance for prediction points that are located further away from observation points.

Splines (2-dimensional, here referred to as splines) are also commonly used to model data layers from discrete observations in time and space, where there is no prior knowledge for parametric relationships between drivers and the observations. In practice, splines are estimated within the framework of generalized additive models (GAM). Splines are non-parametric functions that aim at capturing an underlying spatial pattern in data through smooth functions, which appropriately balance the spline's goodness-of-fit against the spline's curvature (wiggliness), i.e. selecting smooth non-parametric functions that describe data reasonably well without overfitting the observations. Typically, the mean field is described as a smooth function of the coordinates ($\mu(s) = S(x, y)$), but the spline model can also include covariates and time-dependencies. Although it is possible to formulate more complex covariance structures as Generalized Additive Mixed Models (GAMM), this is seldom done in practice due to the impracticability of estimating both fixed and random model structures for the same data, unless these models are very simple. Consequently, the spatial random variation may not be adequately described using splines to model data layers.

Combining kriging and spline approaches could be advantageous, utilizing the advantages of one method to accommodate the shortcomings of the other. In short, splines are good in capturing variations attributable to underlying but unknown relationships, whereas kriging is better at describing small-scale random variations. In fact, both approaches are inadequate if spatial variations are a combination of both large-scale fixed and small-scale random. Therefore, the potential for combining the two approaches has been investigated using oxygen depletion maps as an example.

2.6.3 Combining kriging and splines for oxygen depletion

Oxygen depletion maps are produced every month (August to October/November) as part of the Danish environmental reporting. The spatial distribution of oxygen depleted bottom waters is estimated from CTD casts (see Carstensen & Erichsen 2003). In short, for each CTD profile the depths of 2 mg L^{-1} and 4 mg L^{-1} are found or predicted by regression analyses, in case these thresholds are not observed in the profile (i.e. oxygen concentrations are expected to fall below these thresholds at depths deeper than the profile). The depths for the observed or expected occurrences of the two oxygen thresholds are interpolated using ordinary kriging with a linear variogram model, and the predicted oxyclines are combined with the bathymetry to assess if oxygen concentrations below the thresholds are to be expected in each grid point over the entire spatial domain. Maps from September, the month when hypoxia peaks, were produced for the threshold of 2 mg L^{-1} based on the current approach using a linear variogram model as well as an exponential variogram model fitted from empirical variograms for 13 years. The latter was used to produce 95% confidence layers for the extent of oxygen depletion with the ordinary kriging approach.

However, as stated above ordinary kriging assumes that the oxycline is constant over the entire spatial domain, although it is locally adjusted to the observed profiles. Therefore, the mean field of the oxycline was estimated on data from multiple years (2002-2014) using a spline ($S(x, y)$) to describe the mean spatial variability across all years and an additive yearly factor (y_t) allowing the oxycline mean field to move up and down for individual years (denoted t). Hence, for the oxycline depth

$$Z(x, y, t) = S(x, y) + y_t + e(x, y, t)$$

where $e(x, y, t)$ is the prediction error in a given grid point and year. For each individual year, the spatial variation of the residuals was modelled using ordinary kriging. This means that for a given year (t_0), the oxycline depth is distributed with a mean of $S(x, y) + y_t$ and a variance of $V[e(x, y, t = t_0)] = R(x, y, t = t_0)$. The residuals from the GAM were analyzed with ordinary kriging for each year, and the oxycline mean field was predicted by combining the mean field with the ordinary kriging predictions.

2.6.4 Uncertainty assessment of aggregated products

If all data layers are described with spatial distributions ($Z_i(x, y)$; $i = 1, \dots, n$) then the resulting data layer following from an aggregation scheme ($g(Z_i(x, y))$) will similarly be described as a spatial distribution. There are several approaches to calculate the resulting spatial distribution from the aggregation scheme, but the main three are: i) if the aggregation scheme is linear then the distribution can be calculated in each grid point following standard algebraic calculus, ii) if the aggregation scheme is non-linear, but can be linearly approximated by a Taylor expansion then the same algebraic calculations apply, and iii) otherwise determine the distribution by numerical integration using Monte Carlo simulations.

2.6.5 Initial uncertainty and data coverage assessment

All data are associated with some form of uncertainty and the more than 100 data layers within ECOMAR are very variable. Transforming 3-dimensional information based on the actual existence into 2-dimensional maps requires assumptions and may introduce biases. This is the case for all 2-dimensional maps but are assumptions that we accept.

Some of the ECOMAR data layers are based on direct observations, for example stone reefs within Natura 2000 areas, archaeological sites and findings, and recreational use. Other data layers are initially based on observations that have been used for further modelling of e.g. distributions of sea birds, marine mammals, fish species, eelgrass distribution, broad scale benthic habitat distributions and areas of oxygen depletion. The models are based on a combination of observations and other explanatory factors, such as seabed slope, currents, bathymetry, photic depth, salinity and sediments. Within ECOMAR we have also assessed the overall uncertainty and data coverage for the ecosystem components. The overall combined uncertainty of the data layers was estimated using the different uncertainty variables of the layers. In some cases the model error variables were used, such as the coefficient of variation, standard deviations or the model exploratory percentage (derived from the r^2 values). Uncertainty based on the amount of fishing hauls, percent and landings of fish correlated to areas fished per year (WMS data) were applied to the fish distribution maps. A categorical uncertainty estimation was applied for the broad scale habitats, with 3 categories, based on the uncertainty of the underlying models.

In other cases, where model estimates were not available categorical classification of the uncertainty was made from a scale of 0 = Observed data, 0.25 = Very good/validated model, 0.5 = Good model, 0.75 = Weak model/best guess/extrapolation and 1 = No data.

Ideally, one should be able to provide a sufficient estimation of the associated uncertainty while creating a data layer, but this is not the present situation. Hence, the initial overall uncertainty assessment made in ECOMAR is a first attempt of mapping the areas with high and low uncertainty and data coverage, based on the uncertainty estimations available and the data coverage maps, within the Danish EEZ. By this we are able to give a first indication of where to find areas with high quality data and where the data coverage is good, as well as to identify where more effort in collecting ecosystem data should be undertaken.

Details regarding the models and uncertainties for each data layer are found in the **Supplementary Material (Annex A and B).**

3 Results

Using spatial data sets of the distributions of both human activities and pressures and ecosystem components, we have mapped and analysed the potential combined effects in relation to the MSPD, MSFD and WFD. Subsequently, we have ranked pressures and identified potential key pressures per group of ecosystem components. Based on comprehensive analyses of changes in the pressure groups as well as re-allocation or introduction of new activities, we set up three scenarios for tentatively estimate the combined effects in 2030, 2050 and in a scenario aiming to improve environmental status according to the MSFD goals of GES. There has been special focus on data coverage and uncertainty including a future framework for assessment of uncertainty in spatial distribution maps. Last we have made a draft zoning matrix.

3.1 Pressure map

Calculated pressure intensities range between 1.3 and 12.8. The scale is arbitrary, but important information about the spatial distribution of pressures in Danish marine waters can be taken from **Fig. 4.** Areas without pressures do not exist. However, areas with low pressure intensities can be found in the central offshore parts of the Kattegat south of the island Læsø and north and west of the island Anholt. Another offshore area with low pressure intensity is located southwest of the island of Bornholm. Low pressure intensities can also be found in some coastal waters, e.g. Hjelm Bay, Jammer Bay and Sejerø Bay.

High pressure intensities are found mostly in coastal waters, e.g. areas in the vicinity of major ports, coastal waters receiving discharges from cities, industries or upstream catchments, areas with high shipping intensity. Other areas with increased pressure intensities are also found where coastlines force human activities to congregate – for example in entrances to the Limfjorden (both east and west), Isefjorden, Ringkøbing Fjord and in the areas between the island of Funen and the Jutland peninsula and between Elsinore and Helsingborg in the Sound. Most of the shallow estuarine systems in Denmark have high pressure intensities, e.g. Horsens Fjord, Limfjorden, Mariager Fjord, Odense Fjord, Randers Fjord, Roskilde Fjord and Vejle Fjord. Further, the Sound, the strait between Denmark and Sweden, and the southern parts of the Little Belt and the Great Belt also have high pressure intensities.

3.2 Ecosystem map

Mapping the ecological components index illustrates a large spatial variation in the number of ecosystem components in the different parts of Danish marine waters (**Fig. 5**). Based on a total of 56 data sets representing a broad range of ecosystem components), we identify areas with high ecological value (high index values) as well as areas with lower ecological values or missing data (low index values).

Areas with high index values are characterized by occurrence of many different species, habitats and communities and are in Danish marine waters found in the northern parts of the North Sea, Skagerrak and northern and central parts of the Kattegat.

Areas with low index values are found in the Danish parts of the Baltic Sea, especially in the water around the island of Bornholm and in the coastal water south of the Little Belt, the Great Belt and the Sound.

Given the natural variability in salinity in Danish marine waters, and in the Baltic Sea, we would expect to find low values in the Danish parts of the southwestern Baltic Sea and to identify areas with high values in frontal areas in saline waters. This is also the case, as can bee seen in **Fig. 5** – lowest values are found around Bornholm and in the Arkona Basin, whilst the highest values are found in the Skagerrak area.

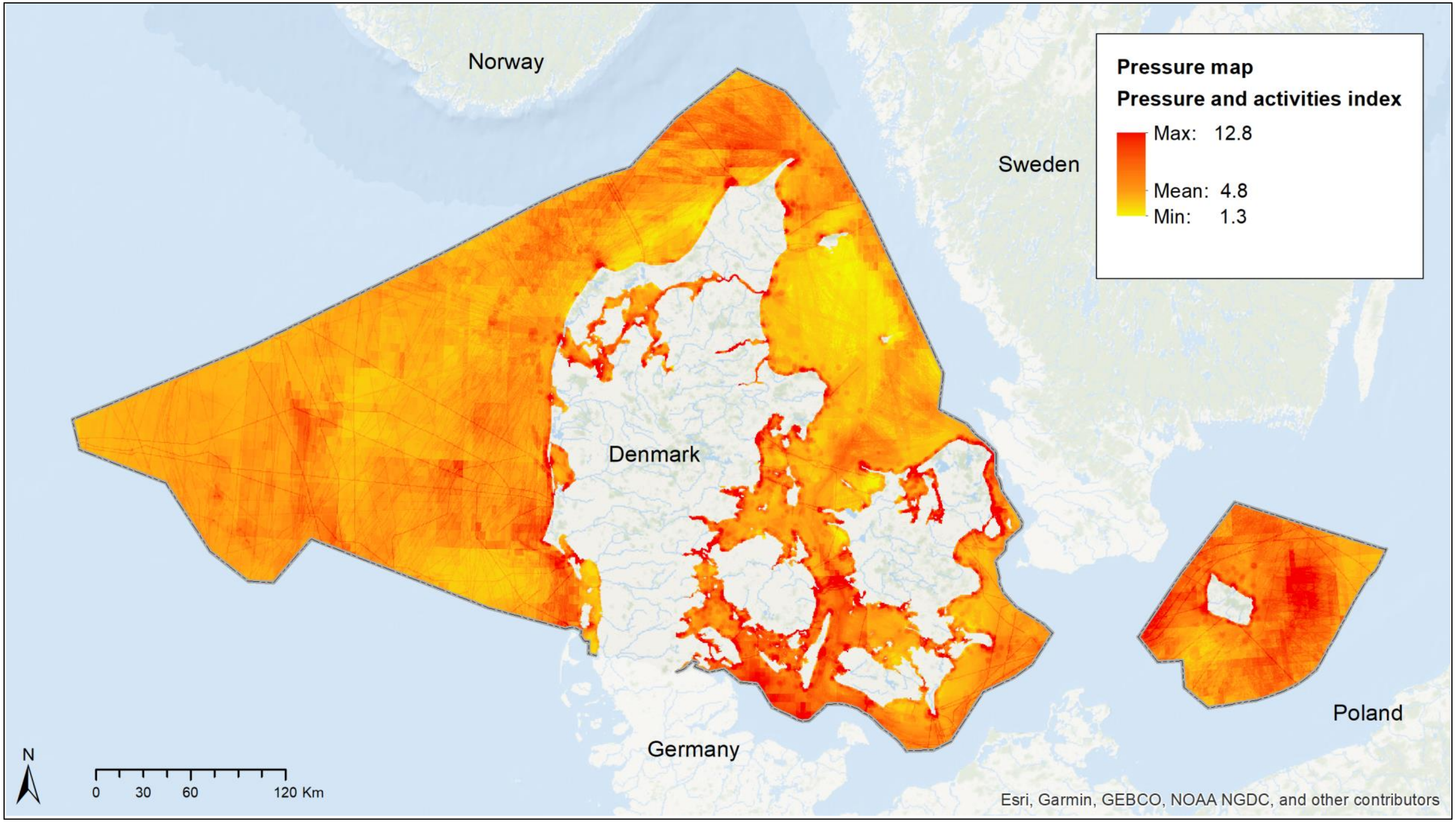

Figure 4: *ECOMAR Pressure map – a mapping of the current pressure and activities data sets. The colour scale shows the stretch for 2.5 standard deviations from the mean, where the darker colour indicates a greater intensity/presence of pressure data sets.*

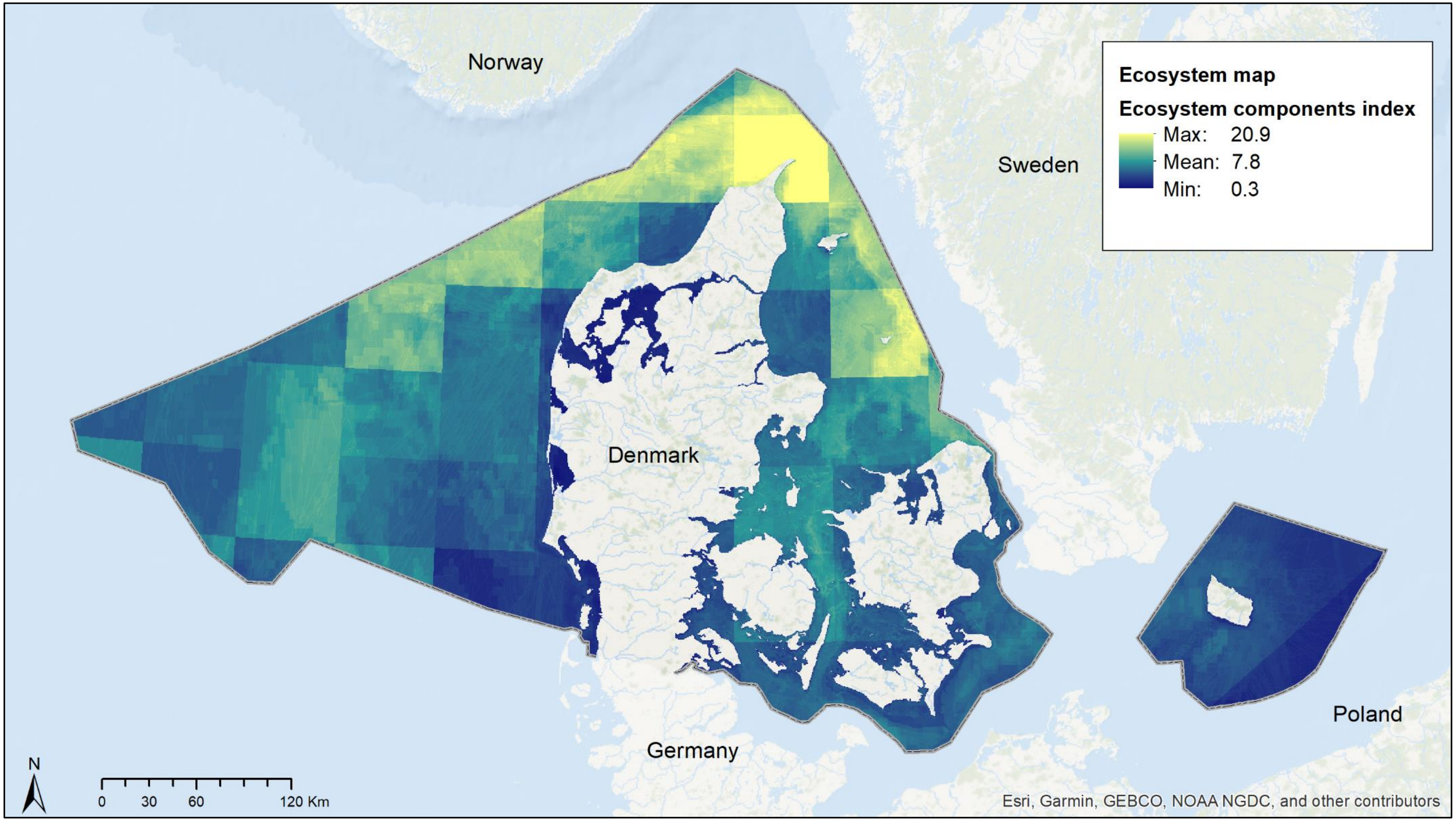

Figure 5: *ECOMAR Ecosystem map – mapping of the current ecosystem component data sets. The colour scale shows the stretch for 2.5 standard deviations from the mean where the yellow colour indicates a greater intensity/presence of ecosystem component data sets.*

3.3 Mapping of combined effects

Potential combined effects of multiple human pressures, earlier denoted 'cumulative impacts', have been mapped in Danish marine water areas previously (Korpinen *et al*. 2012, Andersen & Stock 2013 and Andersen *et al*. 2020). ECOMAR builds on these studies but is based on broader data sets.

ECOMAR has established new sensitivity scores specifically for the pressures and ecosystem components available. The median sensitivity scores provided by the expert survey ranged from 0 to 2 (**see Supplementary Material**, **Annex C1**). This demonstrates that, according to the experts, some activities and pressures may have no effects or insignificant effects upon specific ecosystem components whilst other pressures can potentially have much larger effects on specific ecosystem components. By using the medians instead of the means of the survey replies, we were able to avoid any possible large biases driven by either a few low or high replies.

The expert-derived effect distances are listed in **Table 5** (see **Supplementary Material, Annex C2** for details). In general, pressures will have effects in the precise location where they take place and also in their vicinity. The effect distances applied do not indicate any long-range effects of pressures and is assumed to be linear.

When combining information on pressures, ecosystem component, sensitivity scores and effect distances using the EcoImpacMapper software, we have mapped the potential effects of multiple human pressures in relation to the MSPD including climate change. Areas with high index values were found both offshore and in coastal water (**Fig. 6,** an index map without climate change is found in **Supplementary Material, Annex C3**).

Offshore areas with high index values are found in parts of the North Sea, in the northern parts of the Skagerrak, in the southwestern parts of the Kattegat and around the island of Bornholm, both to the west and east. The background for these is often a combination of high intensities of shipping, fishing and contaminants.

Offshore areas with low index values are found in some parts of the North Sea, in the southwestern parts of the Skagerrak, in the central parts of the Kattegat and south of the island Bornholm. These are attributable to low intensities of offshore activities (fishing and oil and gas).

Coastal areas with high index values are widespread and found from west to east, e.g. in the Wadden Sea, along the west coast of Jutland, in almost all estuaries, and in large parts of the Little Belt, the Great Belt and the Sound. The causes are in general inputs of polluting substances from land.

Coastal waters with low index values are areas without major discharges from land and are found in the Jammer Bay, Tannis Bay, Sejerø Bay, Musholm Bay, north of Zealand, south of Læsø and around Anholt.

Table 5: *Effect distances (medians in km) used in the calculations of the potential combined effect index within the Danish EEZ.*

Pressure	Effect distance
Dumped chemical munitions	5
Aquacultures: fish and shellfish farms	5
Sea cables	0
Offshore oil and gas installations	1
Oil and gas pipelines	0
Heat and power plants	1
Disposal sites for construction and dredged material	5
Dredging in harbours and shipping lanes	5
Dredging sites in production	1
Offshore wind turbines	1
Bridges and costal constructions	1
Coastal habitat modification (coastal protection, piers)	1
Lighthouses	0
Military areas	7.5
Marine ports: industrial	5
Marine ports and marinas: recreational	3
Mussel dredging	1
Dumped chemical munitions	5

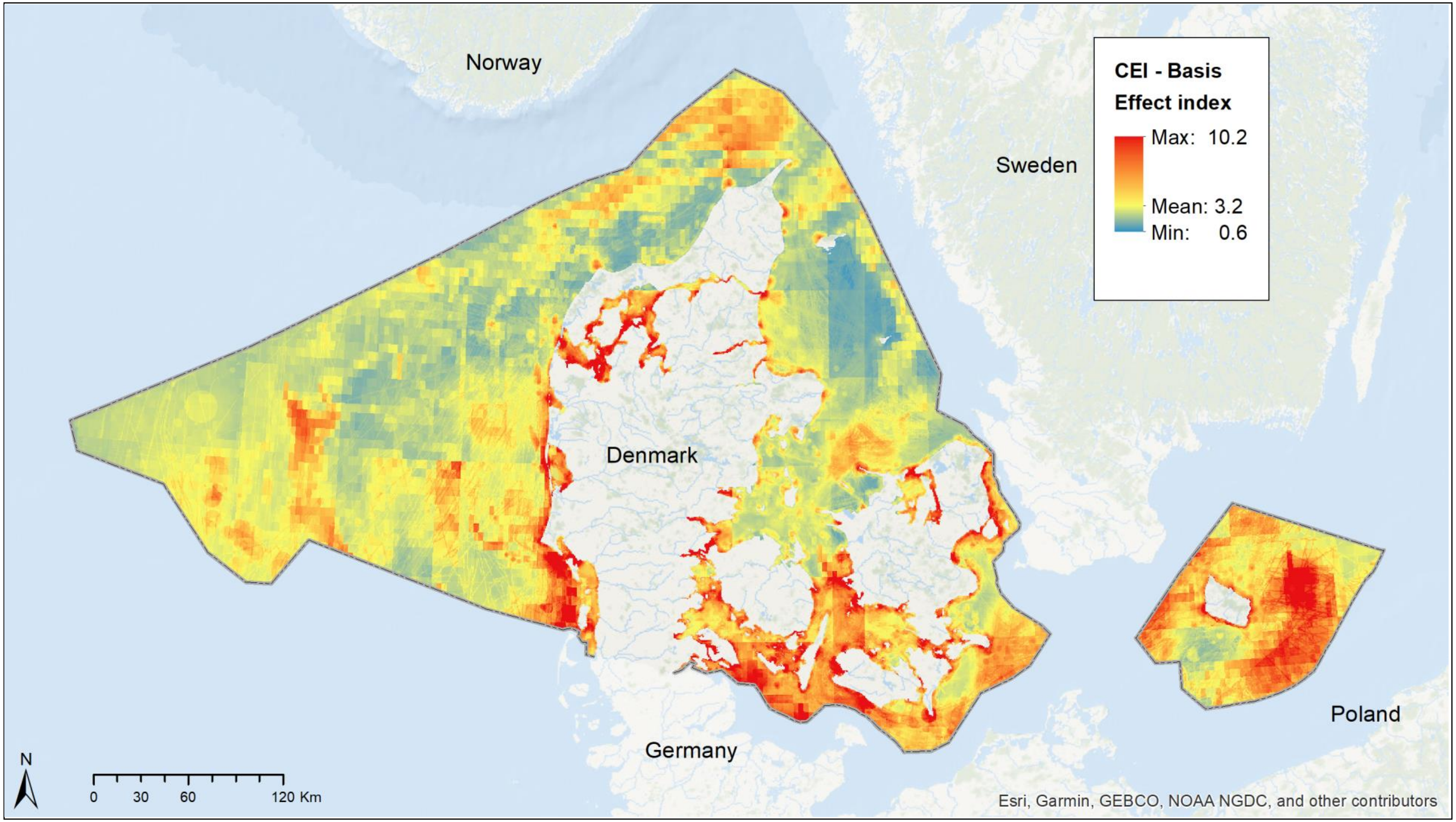

Figure 6: *Map of intensities and spatial variations in the estimated combined effects of human pressures and activities including climate change. The colour scale shows the stretch for 2.5 standard deviations from the mean, where red indicates a higher effect impact and blue lower. Please note that the values are unit less and that the magnitude is defined by the models data inputs, which here are normalised between 0-1. The index is calculated using EcoImpactMapper developed by Stock (2016).*

3.4 Ranking of pressure groups

Based on the mapping of combined effects in Danish marine waters, we have ranked and grouped pressures both nationally and regionally as well as for coastal waters (the WFD domain) and offshore waters (the Danish EEZ minus WFD coastal waters).

The analyses are based on 42 individual pressures and activities, which have been combined in 13 pressure groups, similarly to what was done in the context of HELCOM (Korpinen *et al*. 2012), the HARMONY project (Andersen & Stock 2013), the two published Danish MSFD Initial Assessments (Naturstyrelsen 2012 and Miljø- og Fødevareministeriet 2019) and the Havplan Øresund project (Riemann *et al*. 2019). The climate change pressure group is included in the results shown in **Fig. 6**, the results without climate change can be found in **Supplementary Material (Annex C3).**

On a national scale, ranking of pressures within the Danish EEZ (**Fig. 7A**) reveals that the potential governing pressures are: i) commercial fishing, ii) nutrient enrichment, iii) contaminants, iv) climate change and v) marine litter. Other pressures, which are important, are vi) noise and energy, and vii) recreational activities. Pressures, which may have local importance are iix) non-indigenous species, ix) shipping, x) industry including energy production, xi) recreational fishing and hunting, xii) physical disturbance and xiiv) aquaculture.

In the North Sea/Skagerrak region (**Fig. 7B**), the main pressures groups are: i) commercial fishing, ii) nutrients enrichment, iii) climate change, iv) contaminants, and v) marine litter. Other pressures, which are important on a regional level, are vi) noise and energy, and vii) non-indigenous species. Pressures, which may have local importance are iix) recreational activities, ix) industry incl. energy production (the latter not entailing losses of contaminants), x) shipping and transportation, xi) physical disturbance, and xii) recreational fishing and hunting.

For the Danish parts of the Kattegat (**Fig. 7C**), potential dominant pressure groups are: i) nutrients enrichment, ii) recreational activities, iii) climate change, iv) contaminants, and v) marine litter. Other pressures, which are important on a regional level, are vi) commercial fishing and vii) noise and energy. Pressures, which may have local importance, are iix) shipping, ix) non-indigenous species, x) industry including energy production, xi) recreational fishing and hunting, xii) aquaculture, and xiiv) physical disturbance.

In the Danish parts of the western Baltic Sea (**Fig. 7D**), potential dominant pressure groups are: i) contaminants, ii) nutrient enrichment, iii) marine litter, iv) climate change and v) recreational activities. Other pressures, which are important on a regional level are vi) commercial fishing, and vii) noise and energy. Pressures, which may have local importance are iix) non-indigenous species, ix) shipping and transportation, x) industries including energy production xi) recreational fishing and hunting, xii) aquaculture, and xiiv) physical disturbance.

By only including the ecosystem components relevant for the MSFD (See **Table 4**) and excluding the pressures of climate change (**Fig. 8A**) , the dominant pressure groups are: i) commercial fishing, ii) nutrients enrichment, iii) contaminants, iv) marine litter and v) noise and energy. Other pressures, which are important are vi) recreational activities, vii) non-indigenous species and iix) shipping and transportation. Pressures, which may have local importance are ix) industry including energy production, x) recreational fishing, xi) physical disturbance, and xii) aquaculture.

Focusing on coastal waters under the WFD domain (see **Table 4** and **Fig. 8B and C**), the ranking of the pressure groups differs depending on the ecosystem components included. Common is that nutrient enrichment has the potential largest impact together with contaminants, commercial fishing and marine litter. Recreational activities may have a larger impact when assessing the direct ecosystem components within the WFD, whearas non- indigenous species seems to be of higher importance for the assessment of indirect ecosystem components.

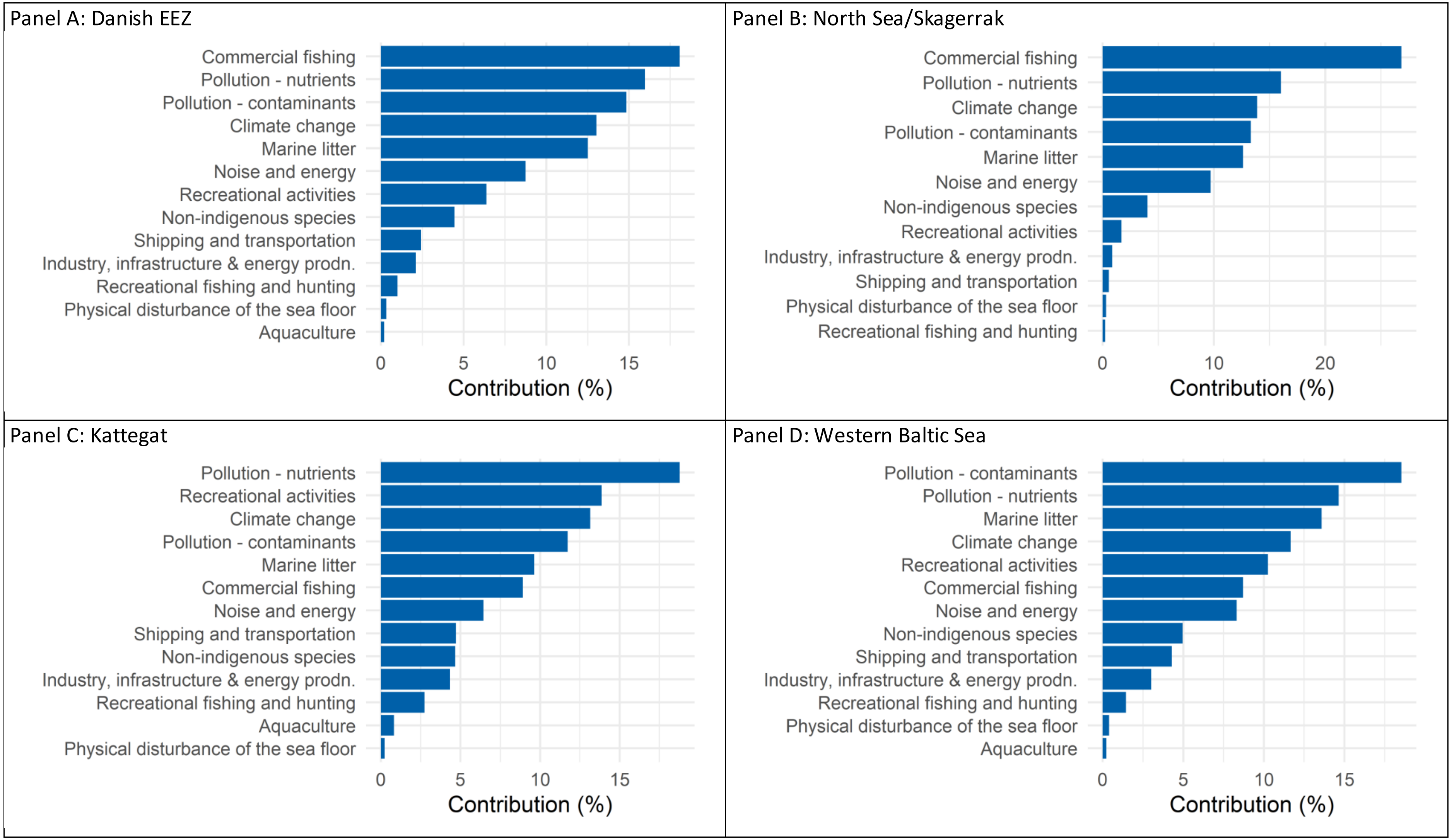

Figure 7: *Ranking of pressures in the Danish EEZ (panel A). Results for sub-divisions, i.e. the Danish parts of the North Sea and Skagerrak, the Kattegat and the western Baltic Sea, are shown in panels B, C and D, respectively. Results of the same analyses but without the pressure group 'climate change', can be found in the* ***Supplementary Material (Annex C3).***

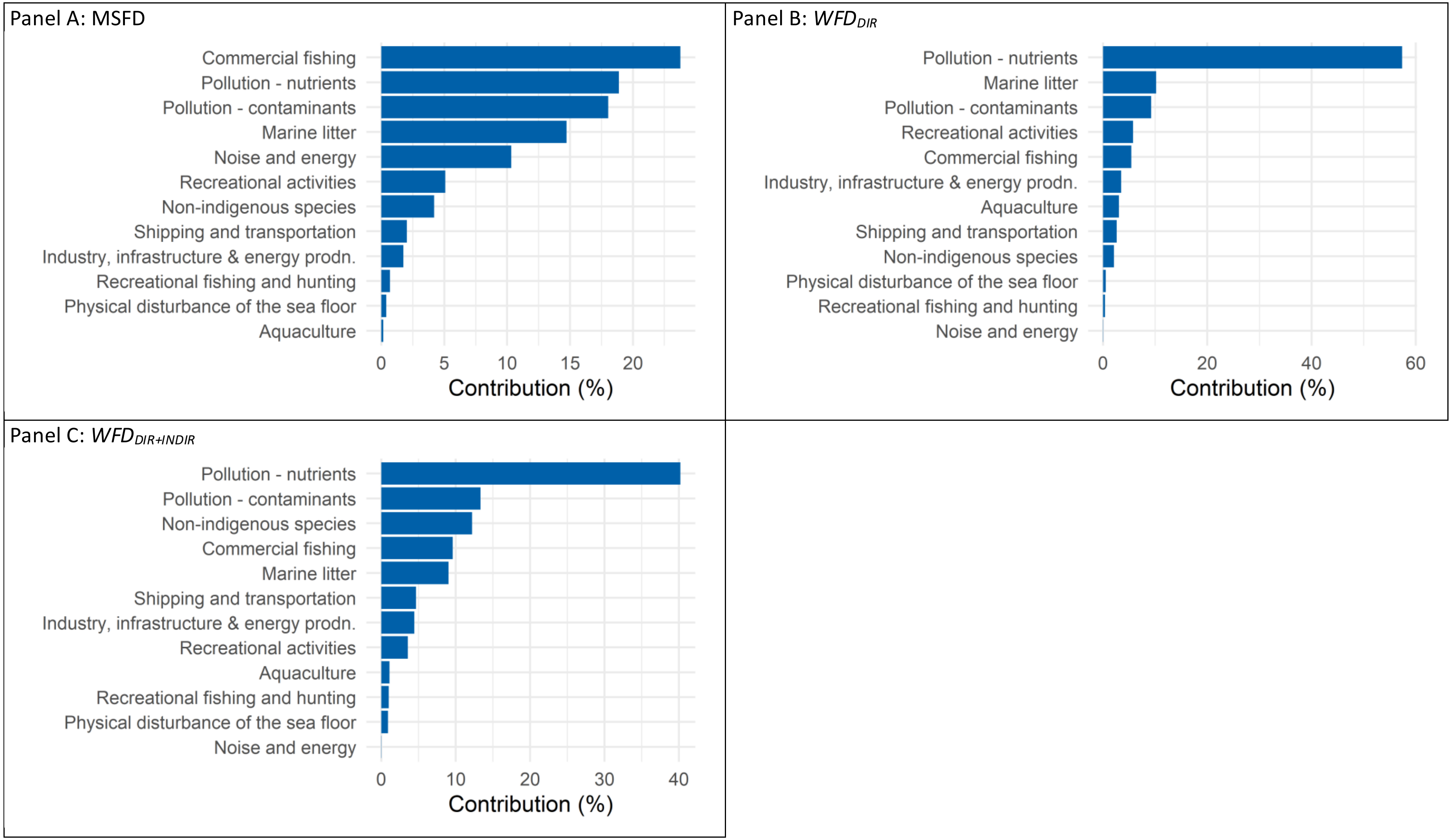

Figure 8: *Ranking of pressures in the Danish EEZ for the MSFD (panel A) and the WFD. For WFD, panel B shows 'direct ecosystem components', whilst panel C shows 'direct and indirect ecosystem components'. See Table 4 for details on the ecosystem components included. Note that climate change is not included for the MSFD and WFD analyses.*

3.5 Analysis and scenarios

A key objective for ECOMAR has been to analyse how changes in pressure intensities may potentially change the combined effects and subsequently lead to improvements or worsening of the environmental status in Danish marine waters.

3.5.1 Increase/decrease in existing activities and pressures

In the following section, we describe the possible consequences of modifying the pressure intensities of the 13 groups of pressures that have been altered, i.e. reduced or increased according to the considerations and descriptions in section **2.4.2**.

Pressure group 1: Aquaculture
The ecosystem groups most likely to be affected by aquaculture farms are pelagic habitats (in ECOMAR: phytoplankton and oxygen concentration in bottom waters), benthic habitats and recreational interests. Other ecosystem components potentially affected are various species of fish and birds. The estimated impacts in the 2030 and 2050 scenarios are as follows: In 2030 and 2050 and in the MSFD scenario, improved condition may be expected regarding pelagic habitats, i.e. chlorophyll *a* concentration and to a lesser degree for benthic habitats and recreational interests (**Fig. 9A**). The MSFD scenario indicates that significant declines in impacts could be within reach. The relation between aquaculture and plankton is well known, but it is interesting to find a relation with recreational interests as well. In the MSFD scenario, improvement could be up to three to five times greater, probably even more pronounced on a regional or local scale.

Pressure group 2: Climate change
Based on the results of the mapping of combined effects and ranking of stressors, the ecosystem components likely to be affected most by climate change are pelagic habitats (increased phytoplankton biomass and lower oxygen concentration in bottom waters) and benthic habitats (e.g. submer-ged aquatic vegetation, biogenic reefs, and the composition of benthic invertebrates).

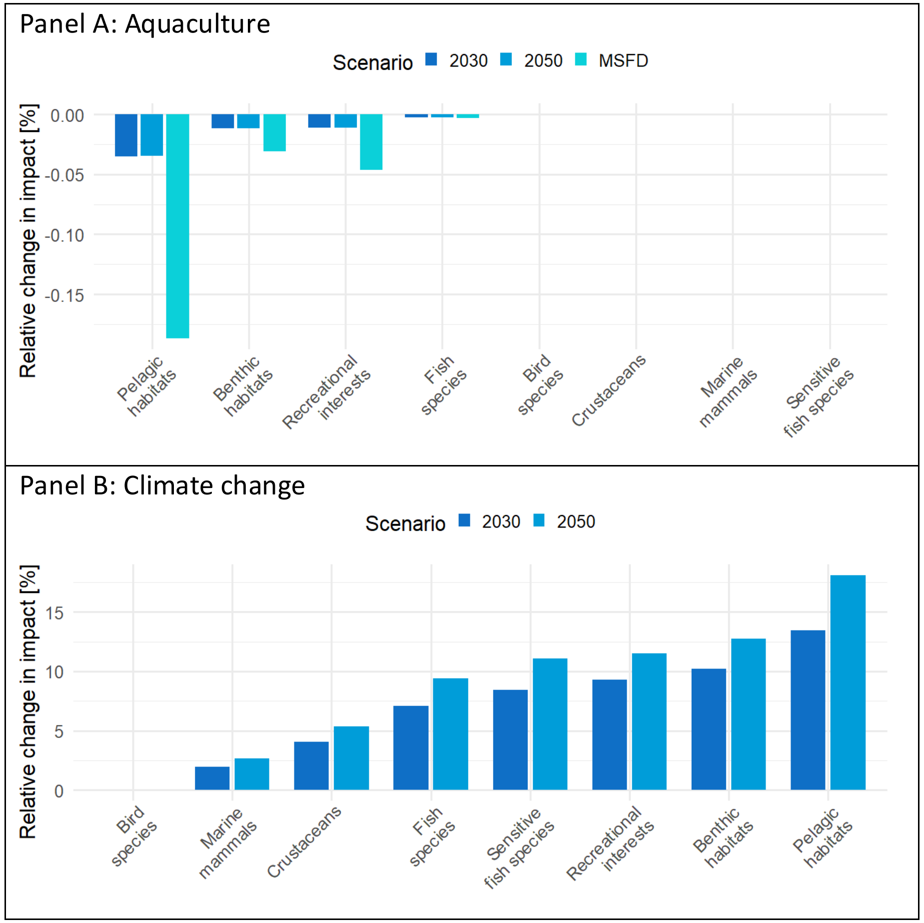

Figure 9: *Differences in impacts on key ecosystem components cf. the baseline and the 2030, 2050 and MSFD scenarios. Panel A: Aquaculture. Panel B: Climate change. Please note the differences in ecosystem components and the scale on the y-axises.*

Both the 2030 and 2050 scenarios (**Fig. 9B**) show that climate change will lead to an increase in impact on marine ecosystems in Danish waters. This may jeopardize potential improvements likely to be obtained through reductions of other pressures. Within the **MSFD GES scenario, climate** change is considered as an exogenic pressure and included (see **section 2.4.3**).

Pressure group 3: Industry, energy and infrastructure

The ecosystem components and cultural interests most impacted by pressures anchored in industries, energy production and infrastructure are recreational interests, birds and benthic habitats. In the 2030 scenario, an increase in impacts can be expected due to an increase in the intensity of these activities (**Fig. 10A**). Groups of ecosystem components and societal interests most affected are recreational interests and benthic habitats. Other ecosystem groups to be affected are fish and crustaceans, birds and pelagic habitats. In the 2050 scenario, the most impacted groups are recreational interests, benthic habitats and birds. Even in the MSFD scenario, negative effects are envisaged, mostly regarding marine mammals, benthic habitats, birds and recreational interests. Hence, the planned activities in 2030 and 2050 and in the MSFD scenario, will result in increased impacts on marine ecosystems and most likely contribute to a further deterioration, directly or indirectly, of environmental status in Danish marine waters.

Pressure group 4: Marine litter

The ecosystem groups most likely to be impacted by marine litter are birds and fish, while recreational interests, marine mammals and both benthic and pelagic communities may also be impacted. For the 2030 and 2050 scenarios (**Fig. 10B**), the difference between the years is directly related to the expected increase in pressure intensity. However, the MSFD reveals that reduction in pressure intensity would probably reduce the effects and subsequently lead to improvements in environmental status.

It should be noted that marine litter is a rather diverse group spanning several types of litter, e.g. microplastic, plastic of different sizes and ghost nets. These sub-groups may impact different ecosystem groups in different ways – macrolitter is known to be eaten by animals, e.g. birds, while microplastic may be by eaten by filter feeders or deposited at the seafloor. Knowledge about the effects for the various types of marine litter is scarce for the moment and more research on this is required to not only better understand the relationships between the effects but also to estimate potential impacts.

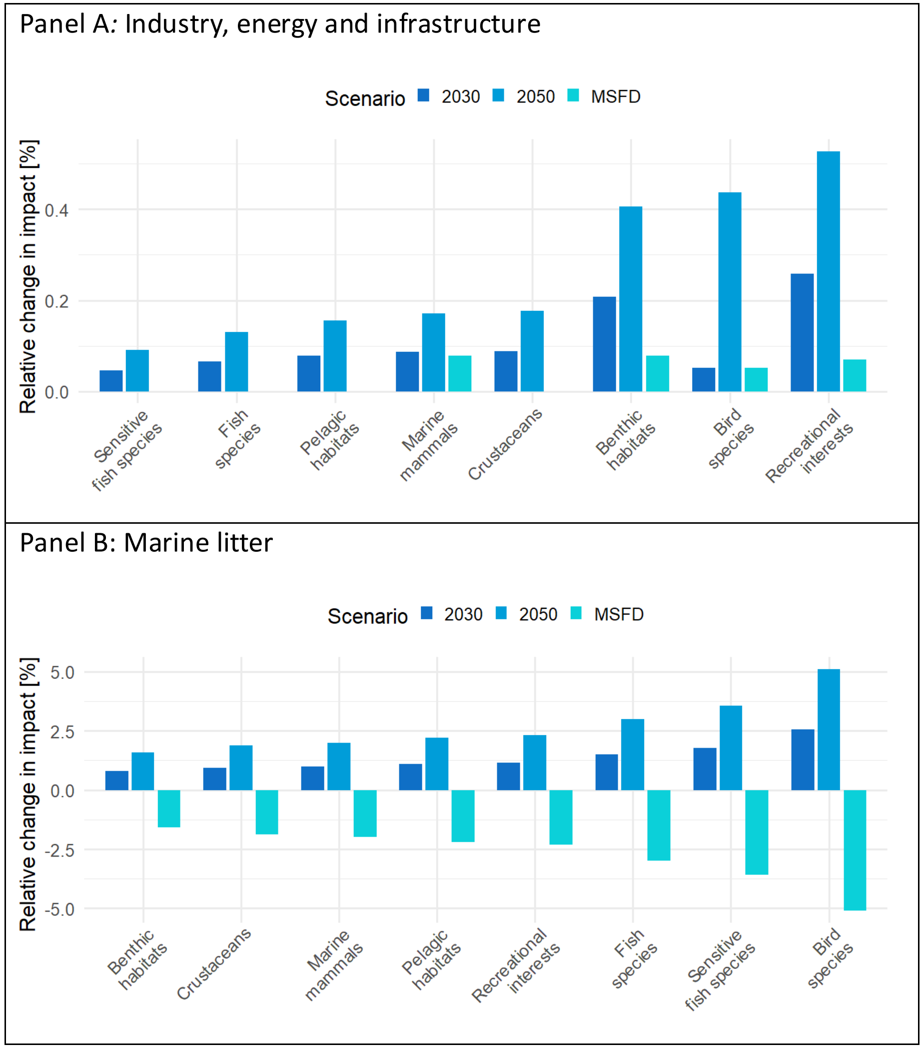

Figure 10: *Differences in impacts on key ecosystem components cf. the baseline and the 2030, 2050 and MSFD scenarios. Panel A: Industry, energy and infrastructure. Panel B: Marine litter. Please note the differences in ecosystem components and the scale on the y-axises.*

Pressure group 5: Noise and cooling water
Reduction in noise levels is mostly linked to the reduction of local impulsive noise and will lead to reductions in the impacts on marine mammals, seabirds, and recreational interests. Minor reductions in impacts can be found for fish and benthic communities.The highest increase in impacts in the 2030 scenario is found for marine mammals, while some increase is also found for birds and recreational interests (**Fig. 11A**). In the 2050 scenario, only minor increases from today's levels are expected. However, the MSFD scenario indicates potentially large reductions in impacts, especially for marine mammals, fish, birds and also recreational interests. These results should be seen as provisional and require more detailed analyses and studies – if proven correct, there is an untapped potential for measures, for regulation the impulsive noise, that may ultimately improve environmental conditions for higher trophic levels, in particular marine mammals and fish. Further, the relations between reduced levels of noise and recreational interests should be scrutinized at a variety of spatial scales, e.g. sub-regionally and locally, as this pressure group may have a large influence.

Pressure group 6: Non-indigenous species
The introduction of non-indigenous species (NIS) to the Danish marine environment may potentially have a large influence on its structure and functioning, as well as its species, communities and populations. In some cases, NIS can become invasive thereby acting as a significant pressure on endemic species. Substantial impacts from NIS in some parts of Danish marine waters are well-known and considered an emerging risk as the rate of newly introduced species is relatively constant (Stæhr *et al.* 2016).

The key ecosystem components expected to be impacted by NIS are benthic habitats (including crustaceans) and recreational interests. Assuming an unchanged rate of new introductions (**Fig. 11B**), the 2030 scenario reveals increased impacts, while the 2050 scenario, being based on improved management practises and at the same level as today, the impacts are not surprisingly matching today's estimated impacts. No changes are seen in the MSFD scenario where already introduced species are present, and the pressure was not altered.

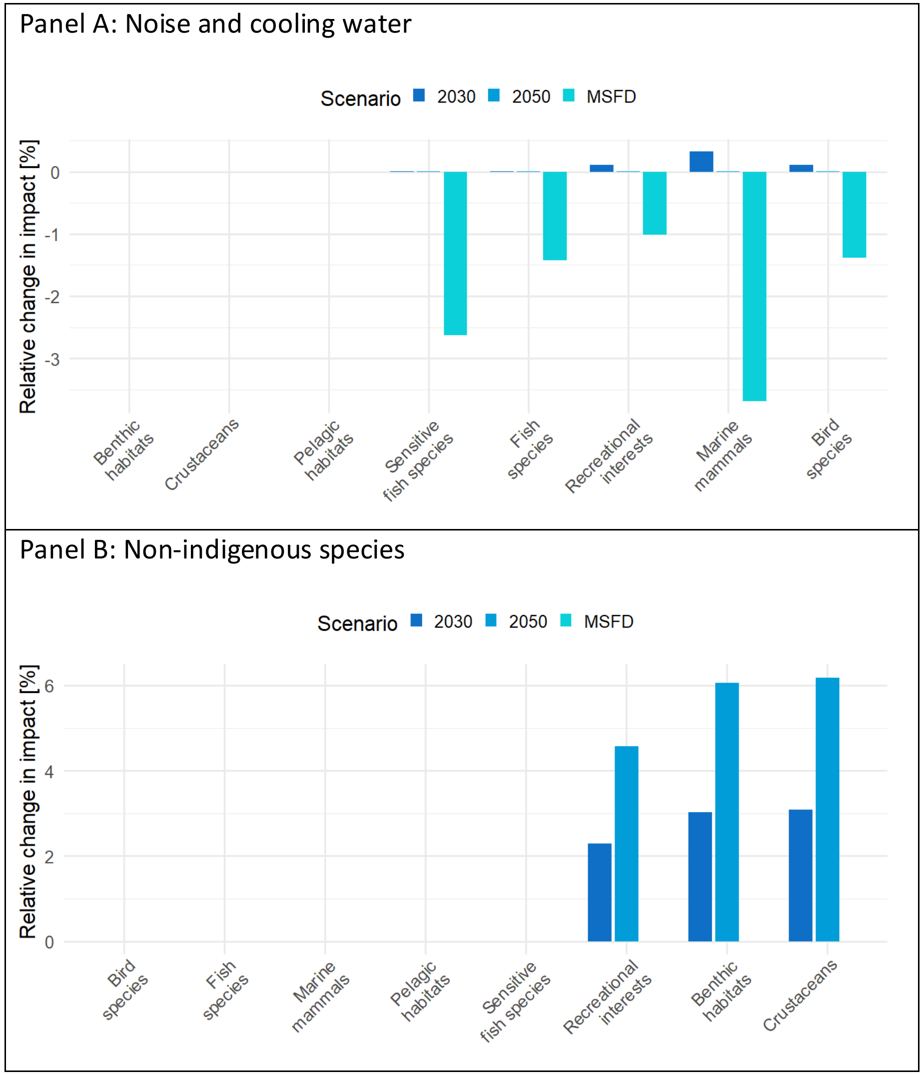

Figure 11: *Differences in impacts on key ecosystem components cf. the baseline and the 2030, 2050 and MSFD scenarios. Panel A: noise and cooling water. Panel B: Non-indigenous species. Please note the differences in ecosystem components and the scale on the y-axes.*

Pressure group 7: Physical disturbance of the sea floor
Physical disturbance from a broad range of human activities is widespread in Danish marine waters, e.g. from dredging and maintance of shipping lanes in shallow waters, exploitatation of natural resources such as sand and gravel or from smothering from activities such as dumping of dredged materials from harbous and shipping lanes. With a reduction in dredging of sand and gravel in 2030 compared to today activities, a significant decrease in impacts can be expected (**Fig. 12A**), especially for the following ecosystem components: fish and benthic habitats including crustaceans. Some reduction in impacts are likely for pelagic habitats (reduced resuspension) as well as recreational interests. The 2050 scenario indicates a slight increase in pressure intensities impacting the ecosystem components in question almost equally, except the sensitive fish species.

Given that significant improvement are attained in a short term perspective and not in a long term, both political focus and more research on the environmental consequences of dredging of sand and gravel as well as smothering is urgently required.

Pressure group 8: Contaminants
Discharges and losses of contaminants from Danish sources in combination with long-range transport and deposition constitute important pressures for the Danish marine environment (see **section 3.3** and **Fig. 8A**). Multiple strategies and action plans have been adopted and implemented, presumably with a variety of successes (Dahlöf & Andersen 2009). In the 2030 scenario, where the pressure intensity is assumed to increase slightly, the impact will increase with regard to fish and crustaceans, but also marine mammals. The 2050 scenario may, however, lead to reductions in the pressure intensity and thus a lower impact on marine mammals, fish, benthic habitats and birds. The MSFD scenario, focusing on attaining a better environmental status through a major reduction of pressure intensity, indicates lower impacts on the following ecosystem component groups: fish, marine mammals, benthic habitats, and seabirds (**Fig. 12B**). The latter indicates that reductions of inputs of contaminants are essential for higher trophic levels to improve the currently impaired conditions and to meet both the objectives of the MSFD and WFD as well as the so-called Generation Target.

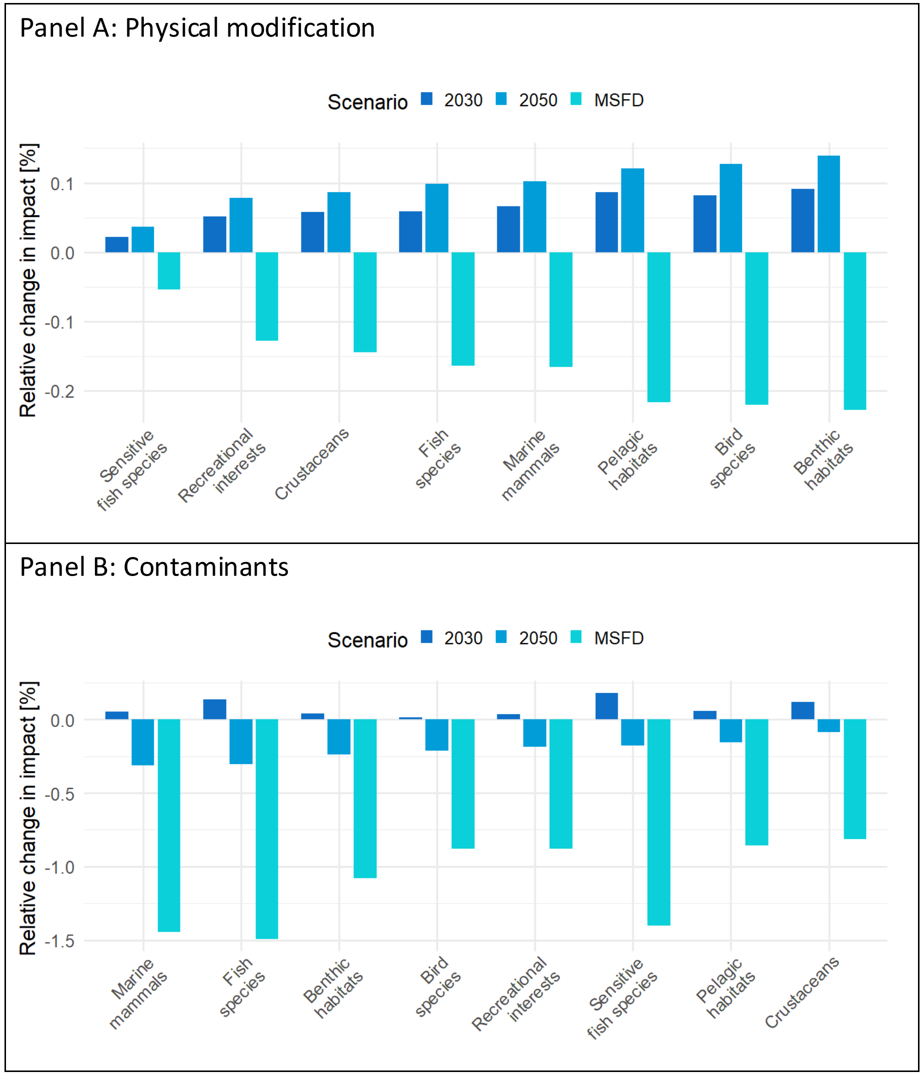

Figure 12: *Differences in impacts on key ecosystem components cf. the baseline and the 2030, 2050 and MSFD scenarios. Panel A: Physical modification. Panel B: Contaminants. Please note the differences in ecosystem components and the scale on the y-axises.*

Pressure group 9: Nutrients
Nutrient inputs resulting in elevated nutrient concentration and eutrophication effects have for decades been a crucial pressure in Danish marine waters, especially in estuaries and coastal waters (see also **section 3.3** and **Fig. 8A**). Significant efforts have been made to reduce nutrient inputs from agriculture, urban wastewater treatment plants and from industries with separate discharge (see Andersen 2012 and Riemann *et al.* 2016).

The 2030 and MSFD scenarios are identical and the groups of ecosystem components most likely to face reduced impacts are pelagic habitats (i.e. chlorophyll *a* concentration in surface water and oxygen concentrations in bottom waters) and benthic habitats including the key species eelgrass. In the 2050 scenario is based in reduction in nutrient inputs and thus lower nutrient levels is surface waters, highlights that significant reduction in pressure intensity and subsequently impacts on pelagic and benthic habitats (**Fig. 13A**). This indicates that improvement in both coastal waters (WFD domain) and offshore water (MSFD domain) can be expected – this should support implementation of additional measures and reduction in nutrient inputs. Follow up analyses focusing on specific coastal waterbodies, specific ecosystem components groups (related to WFD biological quality elements or the MSFD D5 descriptor) are urgently needed.

Pressure group 10: Selective extraction of species: commercial fishing
A growing number of studies and reports on human activities and pressures in Danish marine waters have indicated that fishing, especially bottom trawling, is an significant pressure (Miljø- og Fødevareministeriet 2019, HELCOM 2018, Andersen *et al*. 2020, EEA 2020). These results are confirmed by the analyses done in the context of ECOMAR. In 2030, assuming a reduction in fishing intensity, reduction in impact may be expected for the following ecosystem groups: fish, crustaceans and benthic habitats. Some effects, but to a lesser extend, are foreseen for pelagic habitats, marine mammals (due to bycatch) and recreational interests. The 2050 scenario is parallel to the 2030 scenarion with slightly higher reduction in pressure intensity, whilst the MSFD scenario indicate that significant rediction in pressure intensity (**Fig. 13B**).

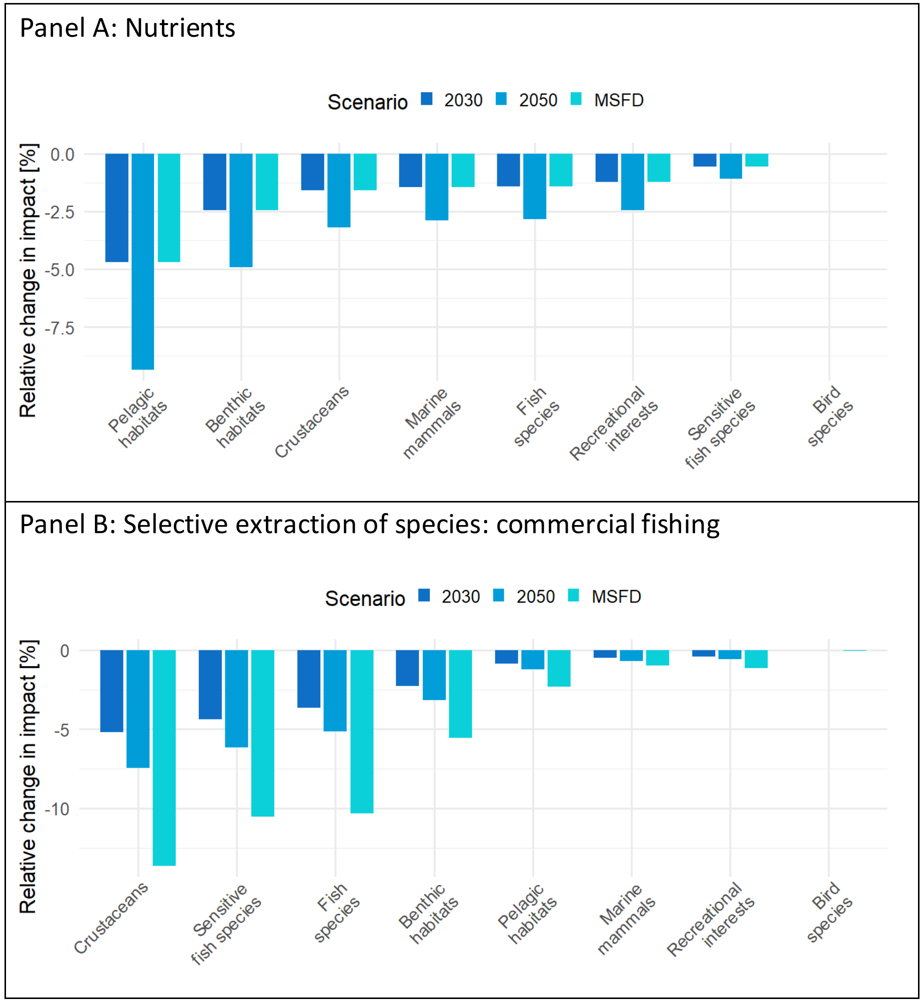

Figure 13: *Differences in impacts on key ecosystem components cf. the baseline and the 2030, 2050 and MSFD scenarios. Panel A: Nutrients. Panel B: Selective extraction of species: commercial fishing. Please note the differences in ecosystem components and the scale on the y-axises.*

Pressure group 11: Selective extraction of species: recreational fishing
Given the availability of information on recreational fishing, we have tentatively estimated the potential effects of changes in the intensity of this specific activity. Assuming a slight increase in recreational fishing in 2030, an increased impact is seen on fish populations, in bentich habitats and for recreational interests. In the 2050 scenario, the ecosystem components estimated to encounter reduced impacts are fish and crustaceans as well as sea birds, mammals and bentic habitats. The MSFD scenario indicates reductions in the pressures on the following ecosystem components: seabirds and fish as well as recreational interests (**Fig. 14A**).

Although being a pressure of restricted importance on a national scale, recreation can be of significant importance locally, for example in Øresund. There is a need for more detailed studies, also linking the status and pressures of target fish species to environmental conditions.

Pressure group 12: Shipping and transportation
Shipping can impact a broad range of ecosystem components through presence, resuspension of material at the seafloor or by generating waves etc. Accordingly, the key ecosystem component groups impacted are seabirds, marine mammals and benthic habitats. Recreational interest can also be affected.

The 2030 scenario indicates elevated levels of impacts for seabirds, recreational interests, marine mammals and benthic habitats, the latter probably through phycisal effects. In the 2050 scenario, the same ecosystem component groups will be even more impacted. In the MSFD scenarios, the ecosystem groups assumed to face a reduction in the impacts are the same (**Fig. 14B**).

Pressure group 13: Recreation and tourism
Recrational activities and tourism primarily have impacts on seabirds, marine mammals, benthic habits, and other recreational interests. In the 2030 and 2050 scenarios, the pressures are assumed to increase and so are the potential impacts on the ecosystem groups and recreational interests (**Fig. 15**). Reductions of recreational activities and tourism, and envisage in the MSFD scenario, will lower the impacts on seabirds, marine mammals, recreational interests and benthic habitats.

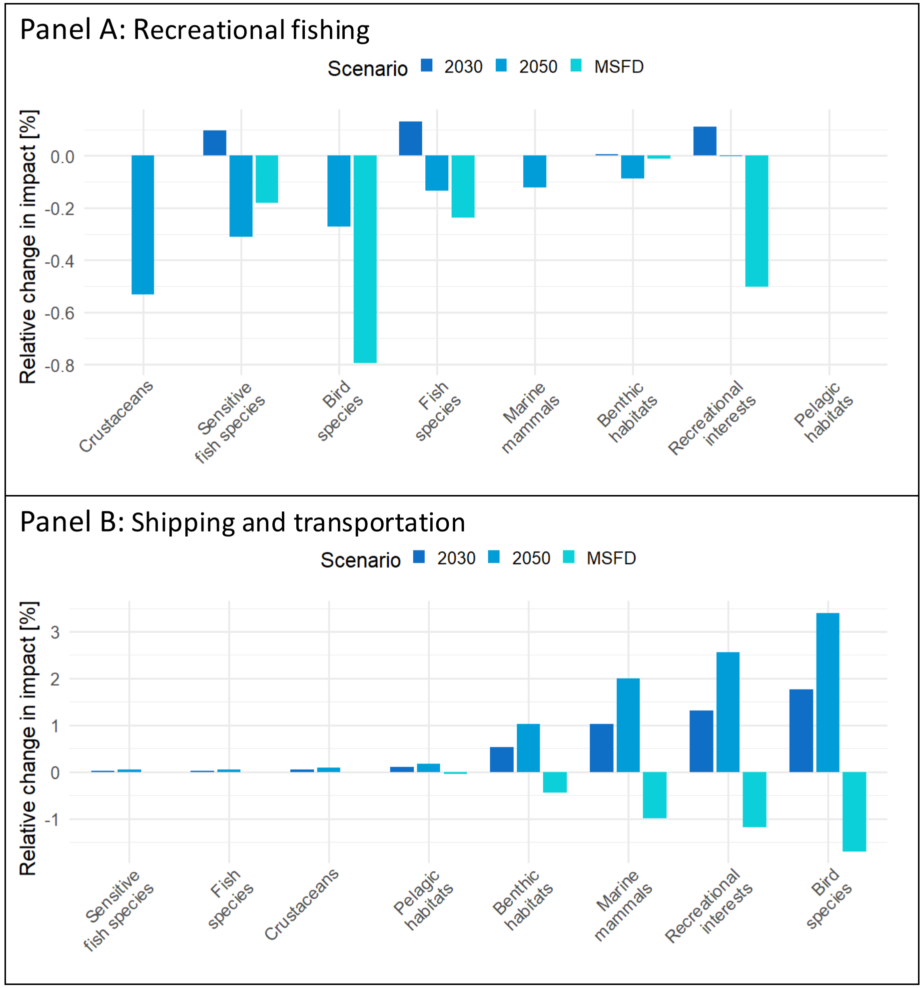

Figure 14: *Differences in impacts on key ecosystem components cf. the baseline and the 2030, 2050 and MSFD scenarios. Panel A: Recreational fishing. Panel B: Shipping and transportation. Please note the differences in ecosystem components and the scale on the y-axises.*

A key lesson learned from this straightforward analysis is that follow up studies on the interlinkages between recreation and tourism and marine ecosystem components (including other recreational interests) and *vice versa* is required is order to achieve a better understanding as well as basis for decision-making, e.g. in the context of MSPD, MSFD and WFD.

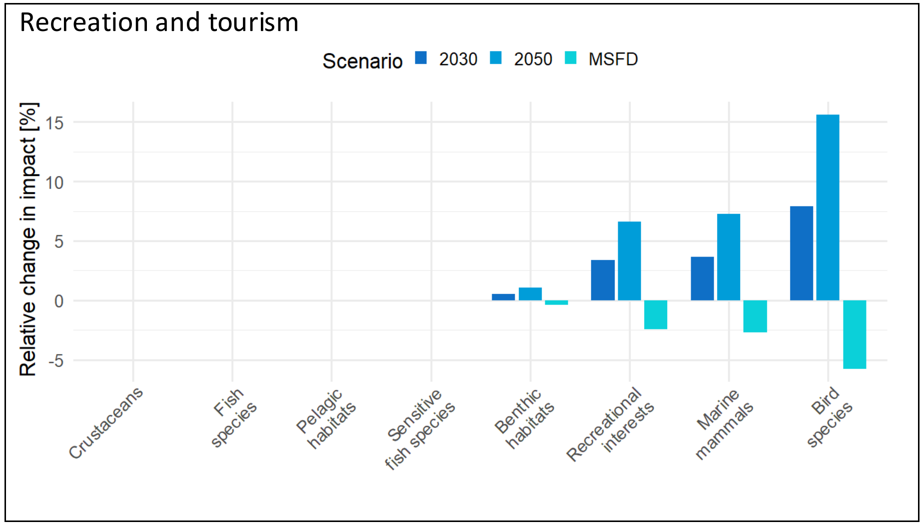

Figure 15: *Differences in impacts from recreation and tourism on key ecosystem components cf. the baseline and the 2030, 2050 and MSFD scenarios.*

3.5.2 Placement of activities and pressures

SeaSketch can be used to analyse the implication of reallocation of existing activities to other areas. A real-life example of this is from the late 80s and early 1990s, where several medium sized fish farms were reallocated from shallow coastal waters, often inside fjord systems to more open waters. One of the better examples was the fish farm in Nordby Bay, which previously was located within Stavns Fjord, northeast of the island Samsø.

We are using the placement of two hypothetical aquaculture farms as a demonstration example. Here, we show the consequences and differences between two locations of a fish farm near Horsens Fjord, where one of the selected locations is within an existing Natura 2000 area and the other outside (**Fig. 16**). When the aquaculture is placed within the Natura 2000 area (alternative 1), and where there is a high potential of eelgrass coverage, the impacts on the ecosystem components are higher compared to when the aquaculture is placed outside the MPA (alternative 2). In alternative 2 the relative impact on bentic habitats is less than half the impact in alternative 1 (~45%). This would mean that a placement of the aquaculture outside the Natura 2000 area would be more beneficial from an ecosystem-based management perspective.

Other case studies of relevance could be: i) Natura 2000 areas, of which some probably could be more suitable located, to ensure a higher ecological protection, and ii) some shipping lanes could probably also be modified for safety reasons. These issues are not considered in the ECOMAR project, but thay are examples that it would be relevant to consider, as well as other cases, at a later stage.

It should be mentioned that the aquaculture example used here is for demonstration of the tool's suitability. For undertaking a tangible environmental impact assessment in a defined local assessment, higher spatial resolution of ecological data and qualitative relationships between pressures and ecosystem components (if present), would be more legitimate to use.

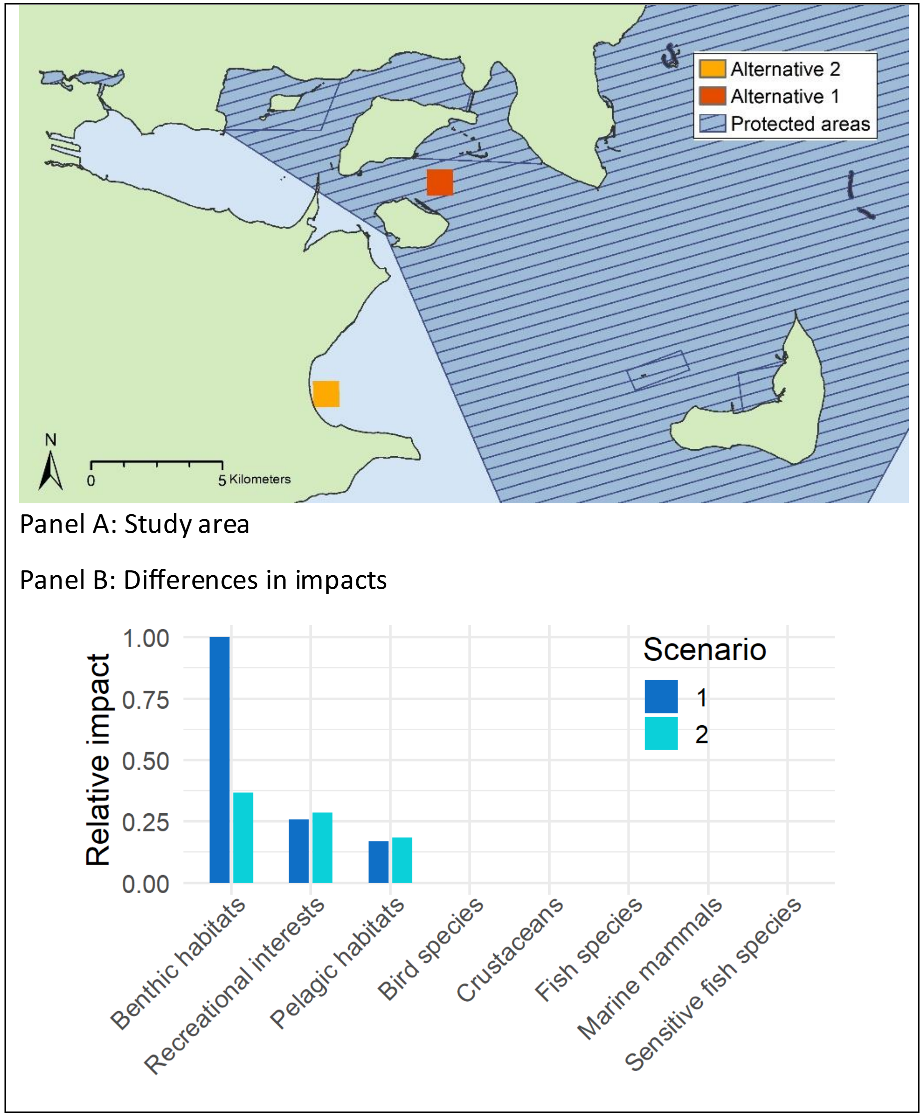

Figure 16: *Map (panel A) showing the example of the two alternative placements of an aquaculture farm. Panel B shows the difference in the relative impacts when placing the aquaculture within a protected area with sensitive ecosystem components like eelgrass compared to in a less sensitive area.*

3.5.3 Introductions of new activities

As with reallocation of existing activities, SeaSketch can analyse the impacts of introducing new activities. To demonstrate this, we present two case studies: i) introduction of new offshore wind farms in the North Sea and ii) introduction of the planned Kattegat Bridge in the northern parts of the Great Belt between Røsnæs on the west coast of Zealand and Hou on the eastcoast of Jutland.

Denmark plans to expand the number and capacity of offshore winds parks (DEA 2020). Thus, we have analysed the potential increase in impact for the example of a new wind power park at Kriegers Flak, which is approved and will be in place in a couple of years. When adding a wind park it means that several ecosystem components will be affected (**Fig. 17**). There will be an increase in the impulsive noise (affecting marine mammals) during the construction as well as habitat loss for benthic species. Both recreational interests and birds species may be affected: i) birds as they have problems avoiding the rotor blades and ii) recreational interests as there will be restrictions in the access to the area for e.g. fishing, sailing etc, as well as an often perceived negative impact on the scenery.

Another example is the addition of the planned Kattegat bridge between Zealand over Samsø to Jutland (Ingeniøren 2018) (**Fig. 18**). Though the ferry routes to and from Samsø are reduced, continuous noise remain the same as there are many other ferry routes crossing the area. The pressure from harbours decreases whereas all recreational activities will increase as the area will be more accessible by the bridge. Commercial fishing is not a large activity within the area but will decrease. Coastal constructions and disposal of material will increase but dredging in relation to the ferry routes will decrease.

Other case studies of potential interest could be introduction of the so-called 'energy island', additional Natura 2000 or MSFD areas, or new fish farms, mussel farms or areas for production of macroalgae. These and many other relevant cases could be explored and analysed.

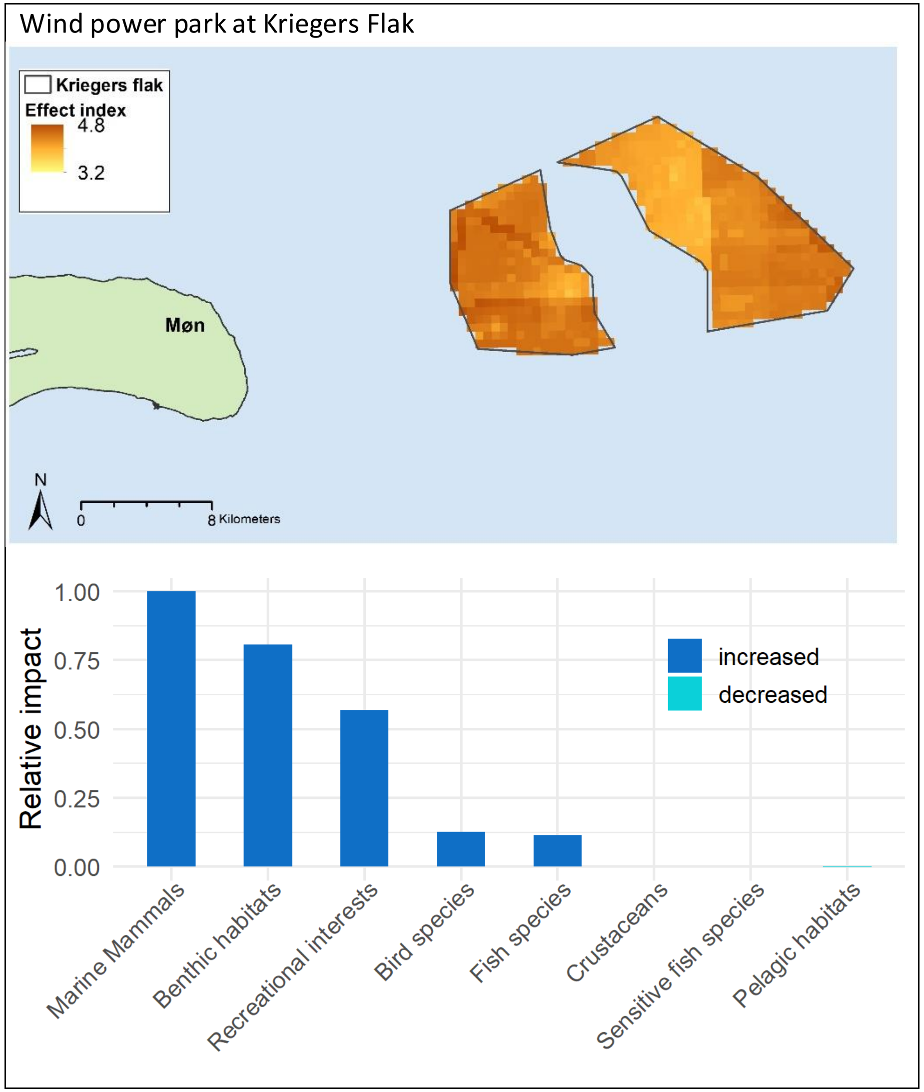

Figure 17: *Placement of the newly installed wind park at Kriegers Flak, east of the island Møn. The graph shows the relative potential change in % (increase or decrease) of the effects upon the ecosystem component groups. The graph shows the relative change in % impact for adding an offshore wind farm at Kriegers Flak, east of the island Møn.*

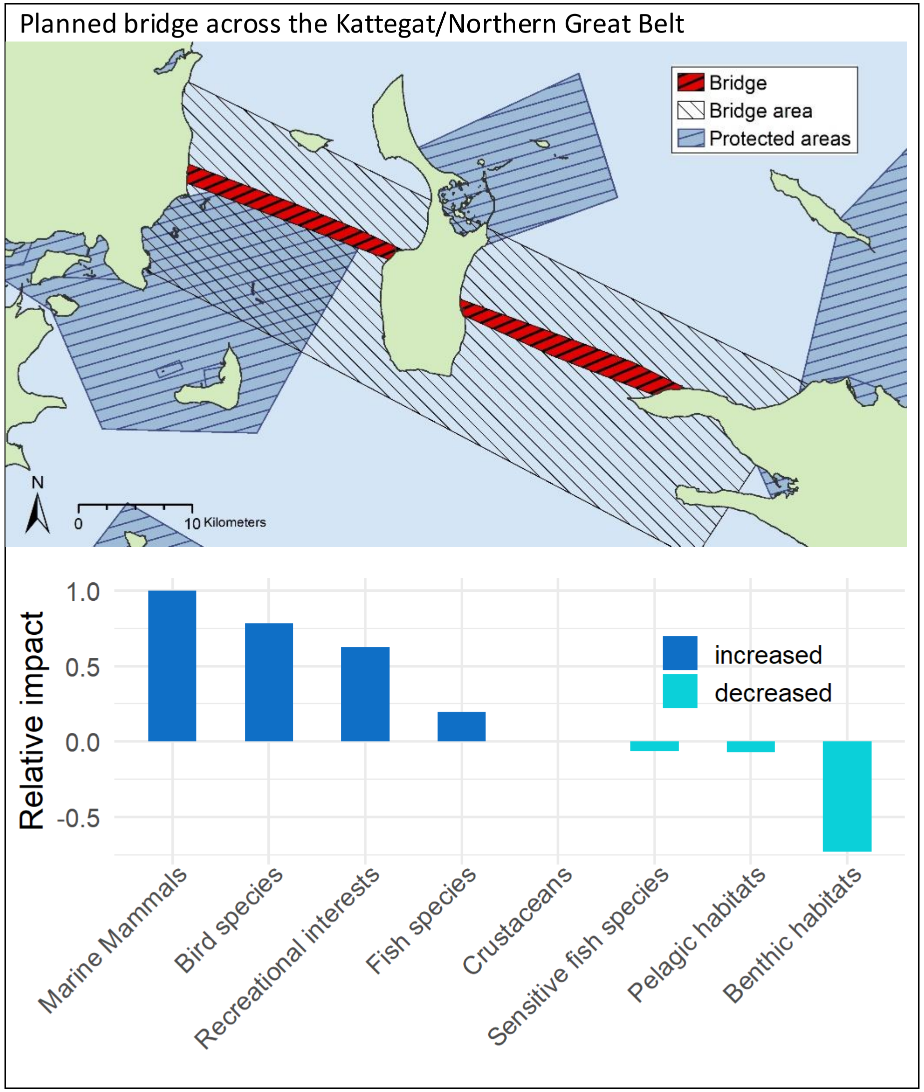

Figure 18: *Location of the proposed Kattegat Bridge between Zealand (east) and Jutland (west) the areas that potentially will be affected around it. The graph shows the relative potential change in % (increase or decrease) of the effects upon the ecosystem component groups.*

3.6 Combining MSPD, MSFD and WFD pressures analyses into a coherent process

EU's marine directives, i.e. the MSPD, the MSFD, both covering all marine waters within the EEZ, and the WFD, covering coastal waters, all require that pressures are assessed and reported as part of either a national maritime spatial plan cf. the MSPD or Initial Assessments cf. the MSFD and WFD.

Given the quality and broad extent of the ECOMAR data sets, we demonstrate that the above pressure assessments can be combined into a joint process using the same data but with outputs targeted by addressing the directive-specific requirements of the MSFD and WFD.

From running the EcoImpactMapper in combination with ECOMAR data sets, we have produced the following four analyses: i) based on all pressures including climate change and ecosystem components representing direct WFD quality elements (**Fig. 20A**), ii) same as i), but without climate change (**Fig. 20B**), iii) based on all ecosystem components representing both direct WFD quality elements such as oxygen depletion and benthic habitats and indirect elements (see **Table 4**) in coastal waters (**Fig. 20C**), and iv) same as iii), but without climate change (**Fig. 20D**). All four maps demonstrate that mapping of pressures in coastal waters is achievable with the EcoImpact-Mapper software or similar tools. The map for the MSFD relevant ecosystem components are presented in the **Supplementary Material** (**Annex C4**).

Previous studies (Korpinen *et al*. 2013, Andersen *et al*. 2020 and many more cf. Korpinen & Andersen (2018) and ECOMAR have documented that the methodology is applicable and widely used for open waters. The maps, despite the variations in data on which they are based on, all identify areas with high, intermediate and low potential pressure effects. Although the maps can be a useful prioritization tool and identify which areas are prone to high levels of pressures and identify the potential dominating pressure groups in these areas, they cannot be used to quantify reductions in individual pressures. It can be argued that climate change should be disregarded when mapping pressures in coastal waters as it is an exogenic pressure and that the management of that takes place at a global scale. If so, the scenarios to consider are those presented in **Fig. 22B & D**.

Determining which of the analyses that would be most useful, 'WFD direct' (using only the ecosystem components equivalent to WFD biological quality elements) or 'WFD direct + indirect' (using also ecosystem component indirectly linked to the WFD biological quality elements), is difficult. In practice, it relates to the confidence required and what the acceptable uncertainty is. The analysis being broadest in terms of ecosystem components is therefore regarded as the most reliable and should be a demonstration of the applicability of CEA mapping in support of WFD pressure analyses.

The CEA method is widely used today by both researchers and authorities (e.g. MFVM, MST, SwAM, HELCOM, and EEA), probably because correlations between environmental status and pressures are well-documented, e.g. for 'ecosystem health' and 'ecological status' (**Fig. 19**). For more information about validation of the CEA method, please see EEA (2019a) and Korpinen *et al*. (submitted).

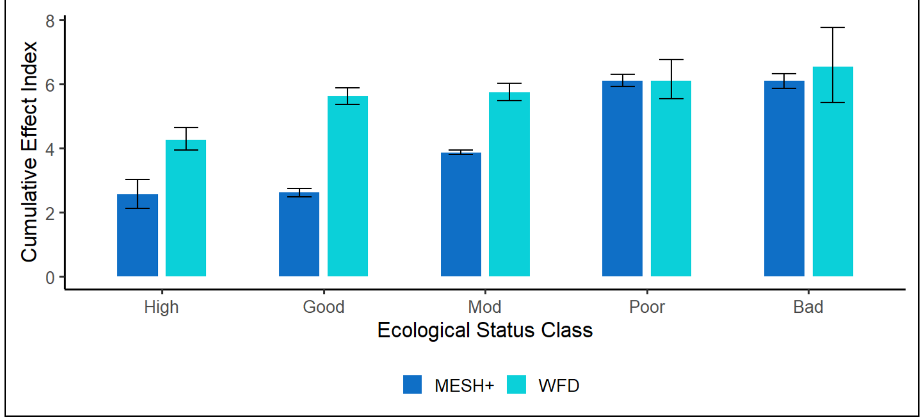

Figure 19: *Validation of the CEA index. The example correlates the cumulative effects index to two different Ecological Status Classes of marine ecosystems within European seas (EEA 2019a, Korpinen* et al. *submitted)).*

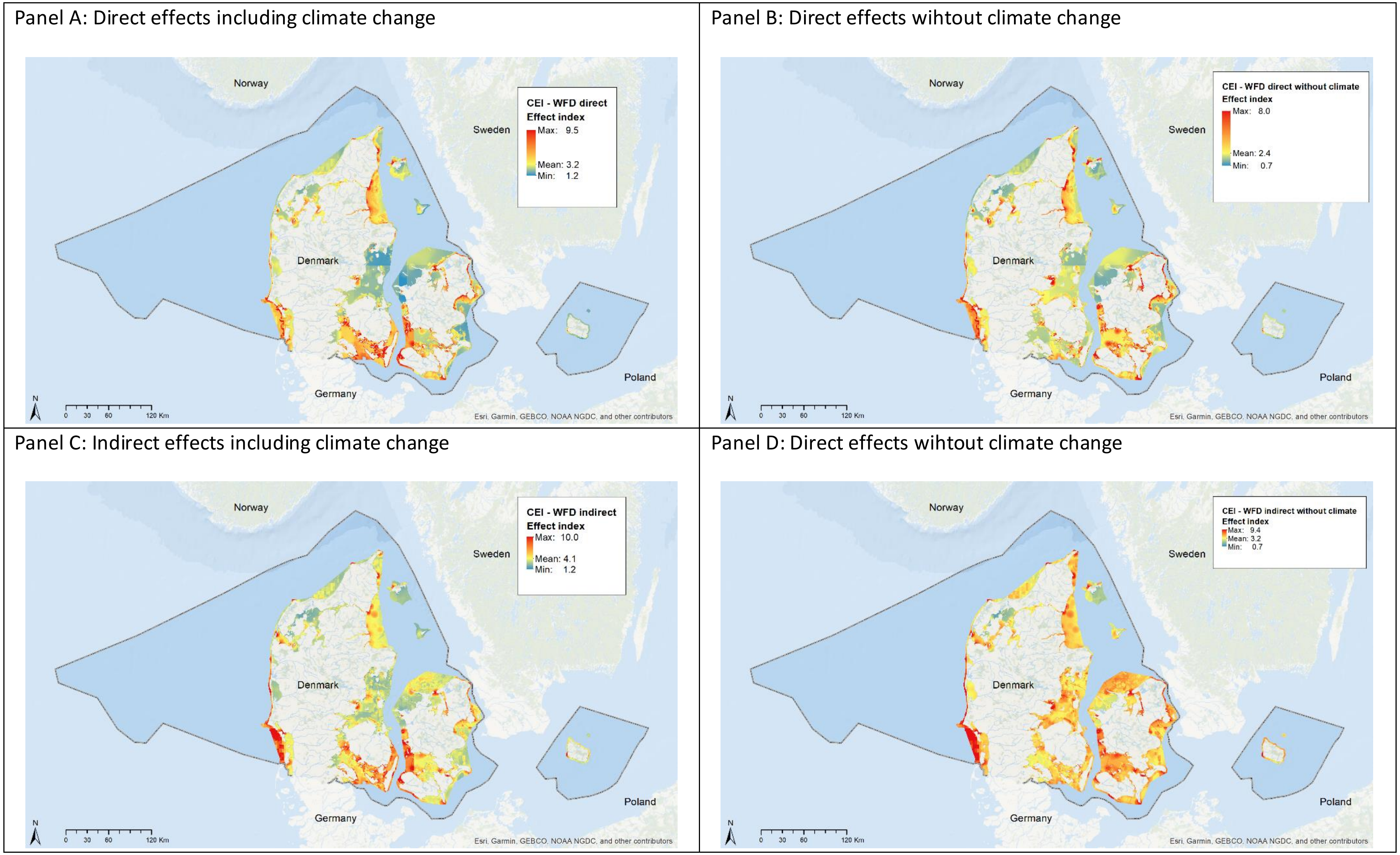

Figure 20: *Mapping of potential combined effects of multiple human pressures within the WFD domain, i.e. coastal waters defined as the baseline plus one nautical mile. Effect index map based on WFD biological quality element only (WFD direct), including pressure group 'climate change' (Panel A) and without 'climate change' (Panel B). Effect index map based on WFD biological quality element and associated indicators (WFDin direct), including pressure group 'climate change' (Panel C) and without'climate change' (Panel D). Note that the max and min impact changes with the model, which is reflected in the scales.*

3.7 Combining analyses and scenarios

Based on the analyses described in **section 3.5** as well as the introduction of specific new activities, we have combined these into two theoretical future scenarios for 2030 and 2050 as well as a hypothetical "MSFD" scenario with focus on improvements in environmental status through reduction of key pressures.

The 2030 scenario represents the most likely expected developments in pressures in Danish marine waters based on the present knowledge and agreed policies, strategies, plans and measures. Similarly, the 2050 scenario represents most likely changes in pressure intensities according to available information.

However, the MSFD GES scenario differs from the above 2030 and 2050 scenarios as it is anchored in a hypothetical reduction in a broad range of pressures assumed to be needed to achieve a good environmental status.

An overview of the changes in pressure intensities is given in **Fig. 21** and the consequential ecosystem responses are summarized in **Fig. 22**.

3.7.1 2030 scenario

Comparing the pressure-specific effects in the 2030 scenario reveals changes in the relative impacts on the national level and shows that some pressure groups have reduced contributions while other have increased contributions (**Fig. 22**).

Pressures groups where the changes in effects are numerically negative, and thus appear to contribute to improved environmental conditions are: i) commercial fishing (-8.2%), ii) nutrients (-3.4%) and iii) aquaculture (-1.9%).

For the following 10 pressure groups, we see numerically positive responses to changes in pressure intensity and may therefore expect a negative impact on the environmental conditions and status: i) climate change (20.1%), ii) non-indigenous species (8.4%), iii) societal and recreational interests (6.7%), iv) shipping and transportation (6.2%), v) physical disturbance (6.6%), vi) marine litter (3.4%), vii) industry, energy and infrastructure (2.3%), viii) recreational fishing and hunting (3.3%), ix) noise and energy (0.2%) and x) contaminants (0.3%).

These changes are relative to the baseline impact estimated for each pressure group. Since 'Commercial fishing' accounts for 18% of the combined impact (**Fig. 9A**), an 8.2% change in the impact due to this pressure group is approximately four times larger in absolute terms than the 8.4% change in impact attributable to non-indegenous species, which accounts for 4.4% of the baseline impact (**Fig. 9A**). Overall, the scenario for 2030 shows an increase in impact of 8%.

When comparing the spatial differences (**Supplementary Material, Annex C5, Fig. C5.1**) between the CEA baseline map and the changes of the 2030 scenario (**Fig. 22)**, areas that potentially might be more affected can be identified. Only some small scattered areas in the North Sea and outside the west coast of Denmark show a small decrease of up to 10% in the potential cumulative pressure index when the changes in the 2030 scenario are implemented. More generally, for the off-shore areas there is no change or a small increase of up to 5% as the dominant change.

The exceptions are in the western and southern North Sea as well as south of Bornholm, where there is an increase of 5-15% in the CEA index. Areas with a more pronounced increase in the CEA index of 15% to above 20 % are found within the fjords, the Kattegat, southern Baltic Sea as well as in all the coastal areas. The large difference in the Kattegat is found in an area where the current CEA index is relatively low. This means that in the future there will only be a limited possibility to increase the pressures and that some of the largest negative differences according to the changes in the 2030 senario will happen in areas which today show a relatively low CEA index.

Pressure	2030	2050	MSFD
Aquaculture: Fish farms	-	-	-
Aquaculture: Shellfish farms	+	++	-
Sea surface temperature anomalies	+	++	-
Sea level rise trend	+	++	-
Mobile contacting gear (large mesh size)	-	--	---
Mobile contacting gear (small mesh size)	-	--	---
Pelagic trawl	-	-	--
Gillnets	-	-	--
Longlines	-	-	--
Mussel dredging	na	na	--
Recreational fishing	+	++	--
Recreational bird hunting	-	-	--
Marine litter	+	++	-
Non-indigenous species	+	+	--

Pressure	2030	2050	MSFD
Disposal sites for construction, garbage and dredged material	+	++	-
Dredging	+	++	-
Sea cables	+	++	na
Military areas	na	na	na
Coastal habitat modification	+	++	na
Pipelines (oil and gas)	na	na	-
Wind farms	+	++	na
Lighthouses	na	na	na
Bridges and costal constructions	+	+	na
Offshore oil and gas installations	na	na	-
Continuous noise (ship sound 125 Hz)	+	++	--
Impulsive noise	+	++	--
Heat and power plants	na	na	-
Excavation sites in production	+	++	---

Pressure	2030	2050	MSFD
Surface swept area ratio (SAR)	-	--	---
Sub-surface swept area ratio (SAR)	-	--	---
Dumped chemical munitions	na	na	-
Contaminants	na	-	-
Oil spills	+	++	-
Phosphorous background winter concentrations	-	--	--
Nitrogen background winter concentrations	-	--	--
Shipping intensity	+	++	---
Industrial ports	+	++	---
Harbors	+	++	--
Recreational boating	+	++	--
Coastal recreation sites	+	++	--
Recreational scuba-diving	+	++	--
Non- motorized watercrafts	+	++	--

Figure 21: Overview of *changes in pressure intensities. The plusses indicate '+' = small increase, '++' = moderate increase and '+++' = large increase, while the minusses indicate '-' = small decrease, '- -' = moderate decrease, and '---' = large decrease. 'na' = not applicable/ no change.*

3.7.2 2050 scenario

Adding another 20 years to the 2030 scenario and taking into account planned developments and expected changes in human activities (summarised in **Fig. 21**), reveals a further increase in pressure intensities compared to the present baseline (**Fig. 22**).

Pressure groups contributing to the increase in pressure intensities encompass the following groups: i) climate change (25.8 %), ii) non-indigenous species (16.8 %), iii) societal and recreational interests (13.3 %), iv) shipping and transportation (12.0%), v) physical disturbance (10.2%), vi) marine litter (6.7%), vii) industry, energy and infrastructure (4.6%) and viii) recreational fishing and hunting (4.4 %). There is no change for ix) noise and energy. Pressures groups where the effects are numerically negative, and thus tend to contribute to improved environmental conditions are: i) commercial fishing (-11.5 %), ii) nutrients (-6.7 %), iii) aquaculture (-1.9 %) and iv) contaminants (-1.1 %).

The changes revealed in the 2050 scenario provide a total negative impact of 10.7%. The spatial differences between the baseline map and the 2050 scenario changes are shown in **Supplementary Material, Annex C5, Fig. C5.2.**

Similar to the 2030 scenario there is a general low increase with 0-5% difference for the off-shore areas. However, the areas with a decrease (although low at 0-10%) are relatively larger and are found spread across the North Sea and again outside the Danish west coast. The difference in the CEA index is larger and increasing with 10 to 20% or above in the same areas as in the 2030 sceario, but with larger extent and higher intensities. The largest difference is found in the southwestern Baltic Sea and the Kattegat with dominating differences by an increase above 20%. As seen in the 2030 scenario, areas with relatively low combined human pressures (low CEA index) can potentially be disturbed, so these areas could be given extra attention in the MSP plan, in addition to already intensively affected areas (with high CEA index), which might not be able to sustain more disturbance by different human pressures.

3.7.3 MSFD GES scenario

The MSFD GES scenario is, as mentioned, a hypothetical scenario but it does however demonstrate the potential effects of reducing pressure intensities across the board in order to improve environmental status of Danish marine waters and thus fulfil the overarching objective of the MSFD, i.e. attaining a good environmental status (GES) or at least move closer to fulfilling this objective.

Pressure groups with reduced effects on ecosystem component are: i) physical disturbance (-49.7%), ii) commercial fishing (-29.4%), iii) recreational fishing and hunting (-26.1%), iv) aquaculture (-20%), v) marine litter (-19.9%), vi) noise and energy (-18.5%), vii) shipping and transportation (-18.0%), viii) industry, energy and infrastructure (-17.7%), ix) societal and recreational interests (-14.9%), x) nutrients (-10%) and xi) contaminants (-9.6%).

The pressure groups 'Non-indigenous species' and 'Climate change' and the contribution to the pressure intensites are cf. **Fig. 22** assumed to be at the same levels as today. With all these effects in combination, the MSFD GES scenario results in a reduced impact of 14.7% overall (cf. the summary in **Table 8**).

The spatial differences between the baseline and the MSFD GES scenario is shown in **Supplementary Material (Annex C5, Fig. C5.3I).** A general decrease in the CEA index values in the order of 10%-20% is seen over the full EEZ with large areas in the North Sea showing a difference by more than a 20% decrease.

In the MSFD GES scenario, the only areas with an increase in CEA index are the areas where new wind power farms are currently being implemented or will be in in the coming years.

The MSFD GES scenario shows that there is room for improvement and that a potential decrease in the combined effects of human pressures can be achived by reduction of pressure levels.

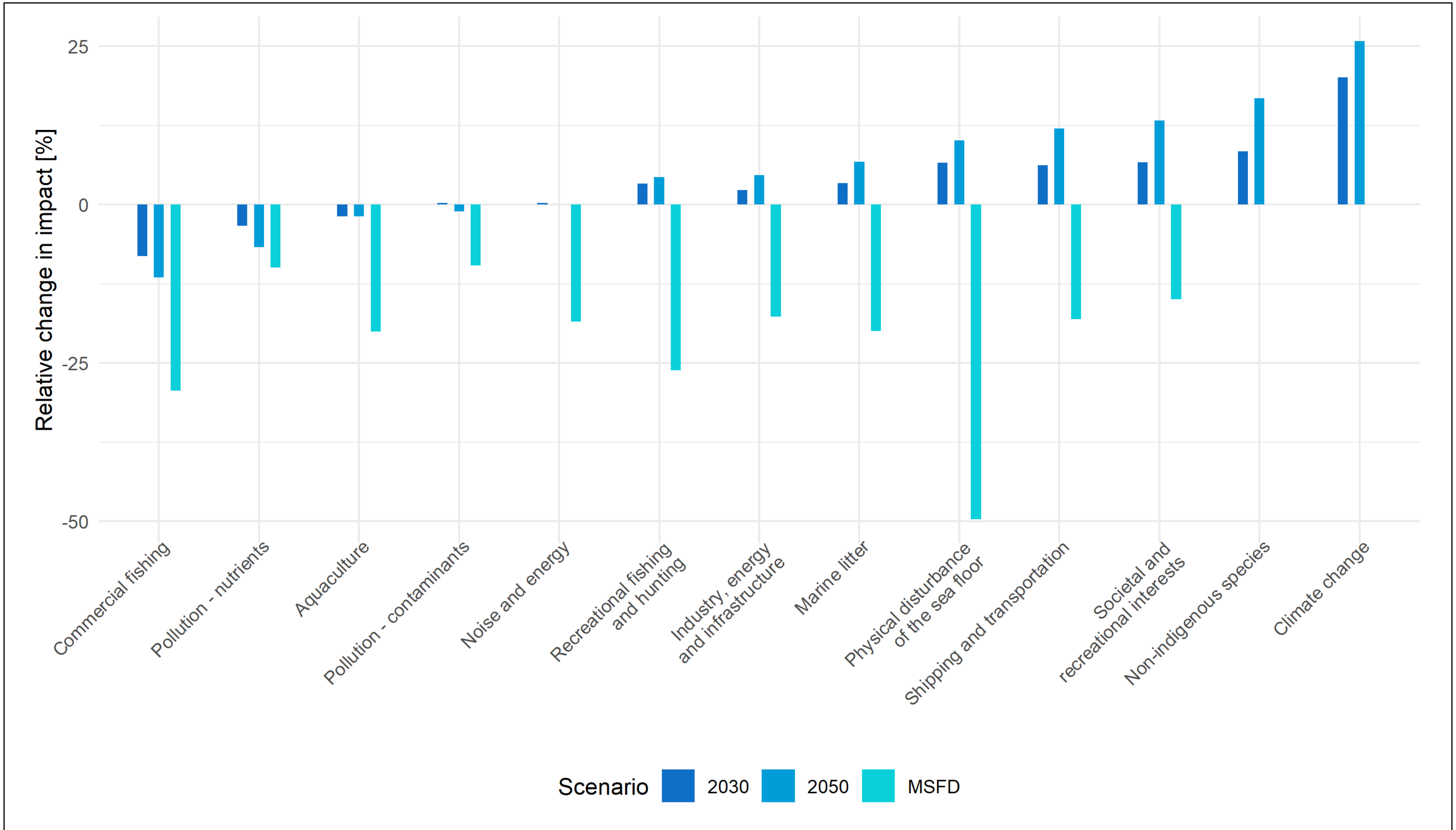

Figure 22: *Differences between the baseline and the 2030, 2050 and MSFD GES scenarios, where O indicates no change, positive values an increase in CEA per pressure group and a negative values indicates a decrease in CEA per pressure group. See* ***section 2.4*** *and* ***Fig. 23*** *for description of the pressure group specific changes for each scenario.*

3.8 Assessing data coverage, uncertainty of data layers and sensitivity of the CEA model

The results for two evaluations are presented below: i) an initial estimate of the data coverage of the ecosystem components and the overall uncertainty of the data layers, and ii) a case study on the quantitative estimation of uncertainty in the oxygen depletion data layer.

The ecosystem component layers form the basis of the cumulative effect assessment. The assessment of data coverage shows the variation in the data availability for ecosystem components within the Danish EEZ and gives a measure of the quantity of ecosystem component data available for the CEA assessment.

The initial uncertainty assessment shows the result of combining the different uncertainty estimates, qualitative, categorical or quantitative, associated with each ecosystem component and pressure data layer, to give a simple measure of the quality of all data layers used in the CEA assesment.

The spatial coverage of the ecosystem component data layers was assessed by calculating an index showing the fraction of ecosystem component layers having data within a grid cell (**Supplementary Material, Annex C6**). It should be noted that it is not an index of presence or absence of the ecosystem component itself, rather an index of availability of data describing the ecosystem component. In this respect, data indicating the absence of an ecosystem component is as valuable as data indicating its presence.

A high coverage index means that the ecosystem components are well assessed within the area and a low index shows that it there is less information forming the basis for the assessment. In the map it is seen that there is a large difference between the eastern parts of the Danish EEZ (the Skagerrak/Kattegat and the southwestern Baltic regions) and the North Sea region and east of Bornholm area, the latter having a lower data coverage.

The extensive coastal area along the west coast of Jutland is also very much underrepresented by data on ecosystem components. The inner Danish waters have the best coverage of ecosystem component data layers. This can can be explained by the boundary limits imposed by many of the models used to describe species distributions (e.g. marine mammals and sea birds). These limits are either based on the lack of *in situ* observations or defining habitats not considered relevant for investigation for species. National monitoring also tends to revisit the same spots to ensure high quality time series. However, areas with few observations may be important for other species.

The uncertainty of the assessment was estimated by aggregating the uncertainty data of all the individual data layers (pressures and ecosystem components), giving a spatially varying indicator of assessment uncertainty. The spatial uncertainty is based on normalised data layers varying from 0 and 1, where 0 represents the lowest uncertainty and 1 the highest. The results are shown in **Fig. 23**. The variation in aggregated uncertainty follows the same pattern as data coverage, with the best assessments found in the inner Danish waters.

The maps indicate that the robustness of the assessment varies spatially when evaluating the results of the CEA models and scenarios. Areas with low data coverage might be underestimated in the CEA models as data on several ecosystem components are missing. In the same manner the uncertainty map provides an indication of areas with less confidence on the distribution of data layers and thus assessment result.

Overall, the uncertainty map reflects a well-known bias, where mapping and monitoring in the inner Danish waters (i.e. Kattegat and western Baltic Sea, the latter including the water around the island of Bornholm) and in the coastal waters along the west coast of Jutland have, in general, a high quality and an adequate spatial coverage. In contrast, mapping and monitoring of the Danish parts of the North Sea and Skagerrak have had relatively low priority for decades, both in terms of spatial and temporal coverage.

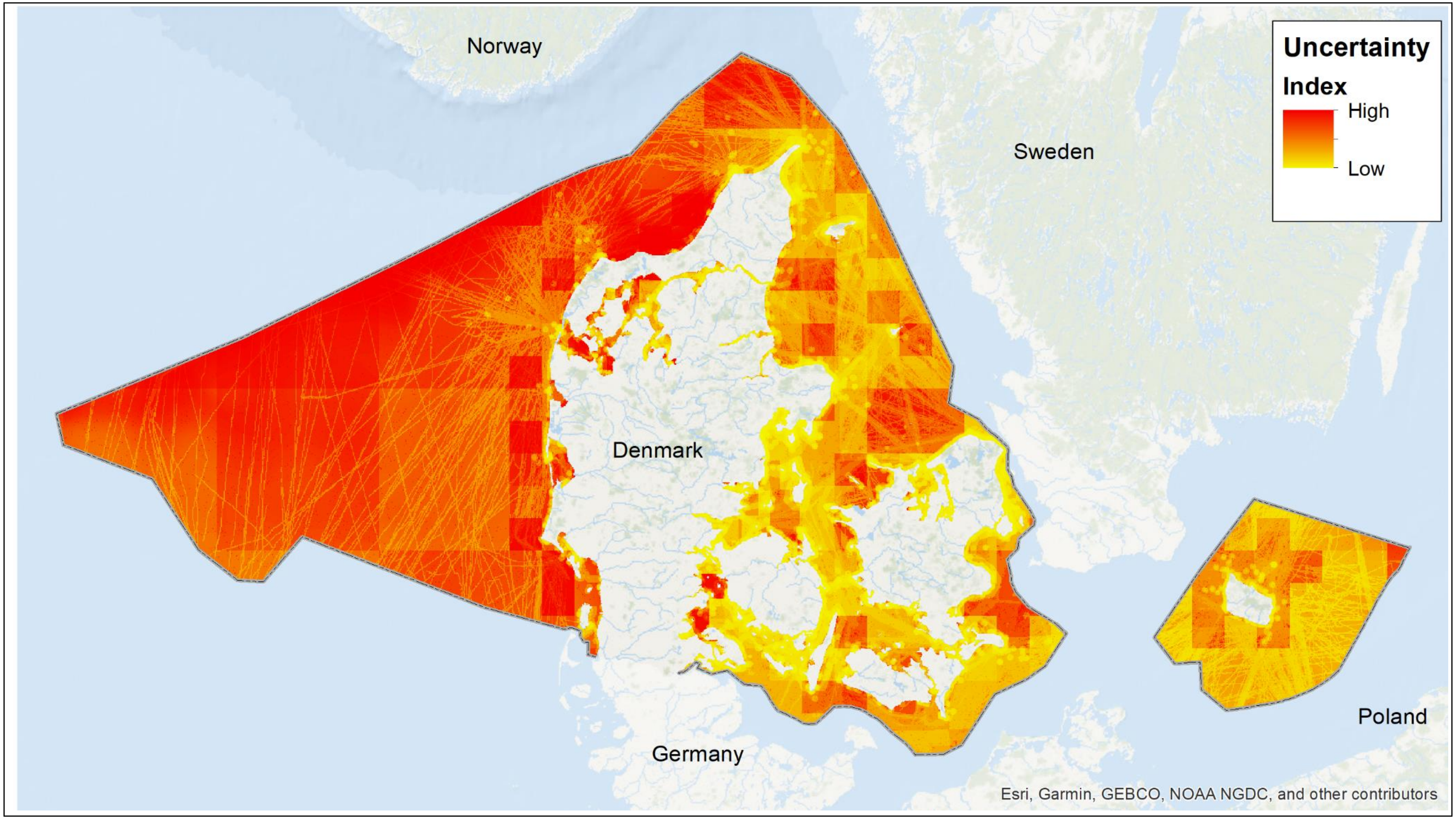

Figure 23: *Mapping uncertainty for the ECOMAR data layers. Red indicates a higher level of uncertainty of the data layers and the yellow a lower uncertainty.*

3.8.1 Uncertainty and sensitivity of the CEA model

Like all models, the Halpern CEA model also has assumptions that may affect the model results in different ways. To address the uncertainty and the sensitivity of the CEA model, alternative model assumptions and data quality problems were tested in two ways: i) Monte Carlo (MC) simulations based on 1000 runs and ii) Elementary Effect model (EE) with 500 simulations conducted according to the methods and method adjustments (of the EE model) described in Stock & Micheli (2016) and Stock *et al*. (2018). In the simulations for both of the tests seven different factors/model assumptions were tested: F1) Missing pressure data, F2) Data quality/errors of sensitivity scores, F3) Linearity/Ecological thresholds, F4) Reduced analysis resolution, F5) Impact model (mean or sum of impacts), F6) Transformation type, and F7) Multiple stressor effects model (Additive, Dominant pressure or Antagonistic model). The factors were randomly selected for each MC run or EE simulation. The factors Linear decay and Reduced stressor resolution were not tested due to the pre-transformations of the input layers.

The uncertainty of the CEA model results were tested by the 1000 MC runs, and showed that the three pressure groups that were ranked in the top 3 as being the potentially most important pressures affecting the ecosystem components are: 'Commercial fishing', 'Pollution – nutrients', and 'Pollution – contaminants'. The three pressures grops that consistently were ranked in the bottom are: 'Aquaculture', 'Physical disturbance of the sea floor', and 'Recreational fishing and hunting' (**Table. 6**).

The sensitivity of the model was tested by the EE model and it showed that the three factors that had the most overall effect on the ranking of pressures, denoted μ* in Stock & Micheli (2016), were F6, F1 and F2. The factors that had the least impact on the pressure ranks were F4 and F5. The factors that were most and least influenced by interactions with other factors and random components in the model, denoted σ* in Stock & Micheli (2016), were the same as for μ*.

Factors affecting the rank of the ecostytem components (μ*) were primarily F7, F5 and F2. The interaction and stochasticity measure σ* was dominated by F7 followed by F1 and F3. The least influential factors affecting the model results (μ*) and interaction and stochastisity (σ*) for the ecosystem components were F4 and F6.

The results show that the uncertainty of the ranking is low and that the model results are robust. The MC simulated runs showed that the top three and bottom three pressure groups corresponds exactly with the ranking of the pressures for the baseline presented in **Fig. 6**. The areas that are consistently under potential high and low CEA index were also robust showing the same pattern as the spatial distribution of the CEA in **Fig. 6.** The EE model results indicates that there is a combination of the assumptions in the factors affecting the model that influence the results and not just a single factor, although some factors have a larger influence than others. The ones with large influence in our model are all known and some solution to address those in coming models are presented in **section 3.8.2,** like e.g., which transformation type to use on the data layers. There are also more sophisticated ways to conduct the expert interviews that can be used for collecting the sensitivity scores (see e.g. Doubleday *et al.* 2017, Gissi *et al.* 2017 and Jones *et al.* 2018), which can be considered in other studies. One of the most influential factors was 'Missing pressure data'.

Table 6: *Results of the rankings of pressure groups from the the model assumptions and factors applied randomly in the 1000 Monte Carlo simulations. Adopted from Stock & Micheli (2016). For detailed descriptions see Stock & Micheli (2016) and Stock* et al. *(2018).*

Pressure group	Top 3	Bottom 3
Commercial fishing	89.1%	0%
Pollution - nutrients	66.3%	0%
Pollution - contaminants	62.1%	0%
Aquaculture	0%	99.9%
Physical disturbance of the sea floor	0%	97.5%
Recreational fishing and hunting	0%	75.3%

3.8.2 Uncertainty of oxygen depletion maps

The current approach to describe the areal extent of oxygen depletion in the Danish Straits does not consider the uncertainty or confidence associated with the maps. However, this uncertainty can be assessed by estimating the variograms for the depth location of the oxyclines, computed from oxygen profiles in a number of discrete monitoring positions scattered around the spatial domain. The variogram describes the variation between two points in space as function of their inter-distance. The empirical variograms for all the years (2002-2014) showed the same tendency of increasing variance up to around 100 km, where it reached a maximum plateau (**Fig. 24**). An exponential variogram model was found suitable to describe these empirical variograms, with a nugget parameter of 0.05 (intercept), a scale parameter of 0.35 and range parameter of 40 km. The nugget effect of 0.05 indicates that the estimated depth location of the oxycline itself was associated with uncertainty (±25%). Although the uncertainty of the oxygen sensor is probably less, the measured profile is essentially a single snapshot that should represent a period of approximately 10 days. Furthermore, changes in water levels may also add to this 'observation error' in the pycnocline depth. The maximum variance (0.4; nugget+scale) was attained at distances beyond 120 km, implying that no spatial correlation remains for profiles that are more than 120 km apart and that the prediction uncertainty of a grid point more than 120 km away from the nearest measurement point is approximately ±88%.

The current algorithm for mapping the oxygen depletion uses ordinary kriging with a linear variogram without a nugget effect, which implies that the mean field has a trend (**Fig. 25A**). Using the exponential variogram model (**Fig. 24**) produces a similar mean field by ordinary kriging (**Fig. 25B**), although it should be noted that there is no trend with this model, i.e. predictions at far distances will all tend to the same constant value ("global mean"). The relative uncertainty of the predictions strongly depended on distances to monitoring points, ranging from ±25% near monitoring stations (nugget effect) up to ±88% when all monitoring points were more than 120 km away (**Fig. 25C**). Using the prediction error of the ordinary kriging to calculate a 95% confidence interval for the oxycline depth and combining these with the bathymetry provides upper and lower confidence maps for the areal extent of oxygen depletion (**Fig. 25D**).

In September 2005, the estimated area and volume with hypoxia (ordinary kriging with exponential variogram) were 493 km^2 and 2.2 km^3, respectively (**Fig. 26**). However, the confidence intervals were extremely broad, ranging from 0.6 to 19400 km^2 for the areal extent. This high degree of uncertainty would lead to quite different interpretations on the spread of hypoxia in the Danish Straits, whether you consider the lower, mean or upper extent (**Fig. 25D**). The reason for broad confidence intervals is because the ordinary kriging approach does not attempt to model the underlying mean field, and therefore overestimates the magnitude of the random variation.

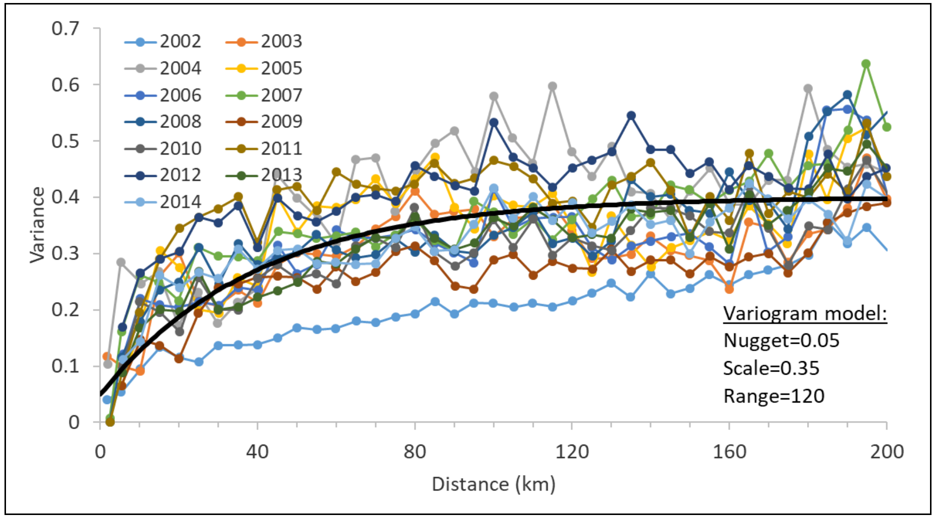

Figure 24: *Empirical variograms estimated for each year in the study period and the fitted exponential variogram model with parameters inserted.*

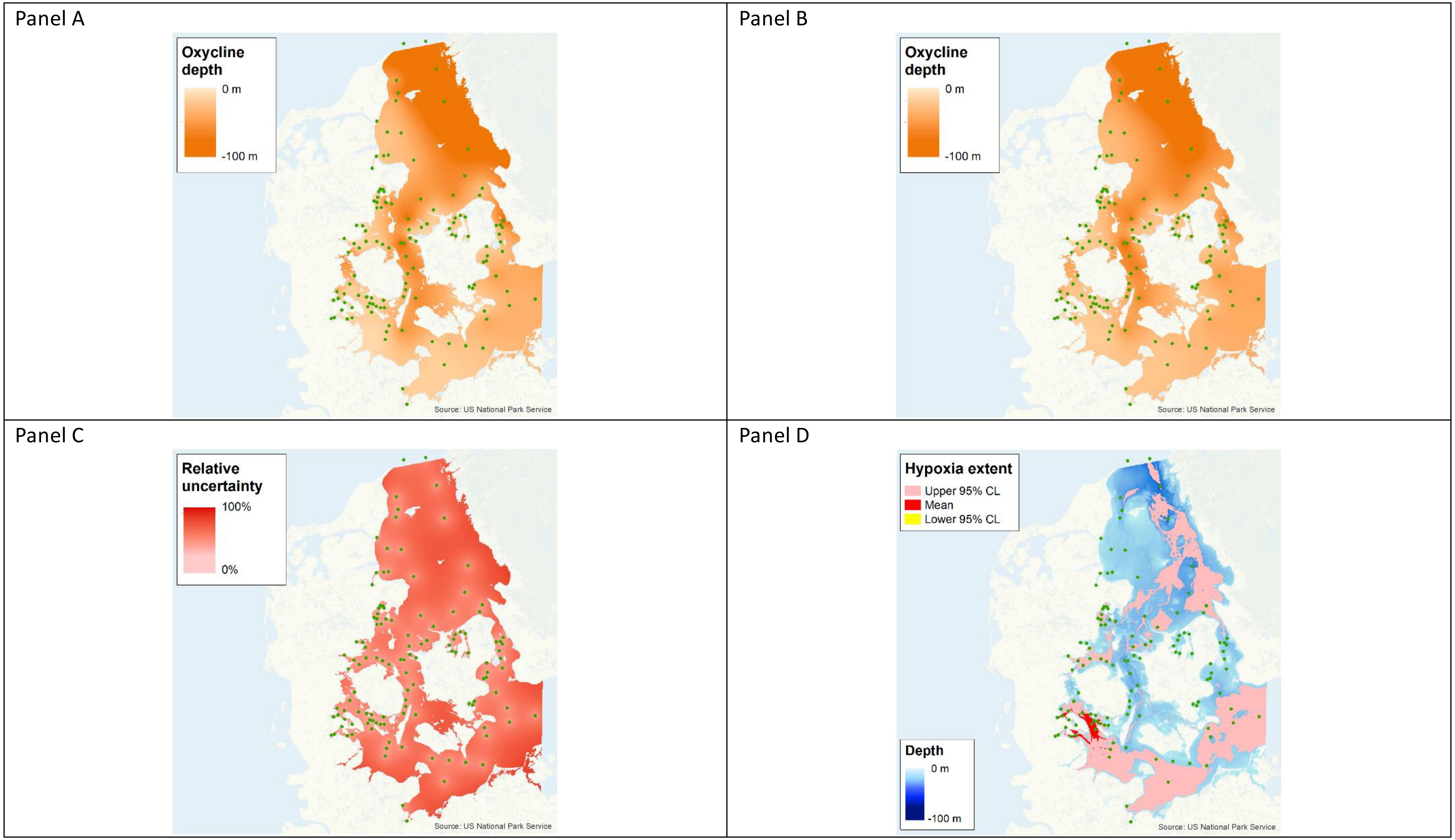

Figure 25: *The mean field for the oxycline depth using a linear variogram model (panel A) and the estimated exponential variogram model (panel B). The relative uncertainty of the oxycline depth from the exponential variogram model (panel C). The resulting 95% confidence mappings of oxygen depletion (panel D). Monitoring stations used for spatial interpolations are shown as green dots. The maps represent September 2005.*

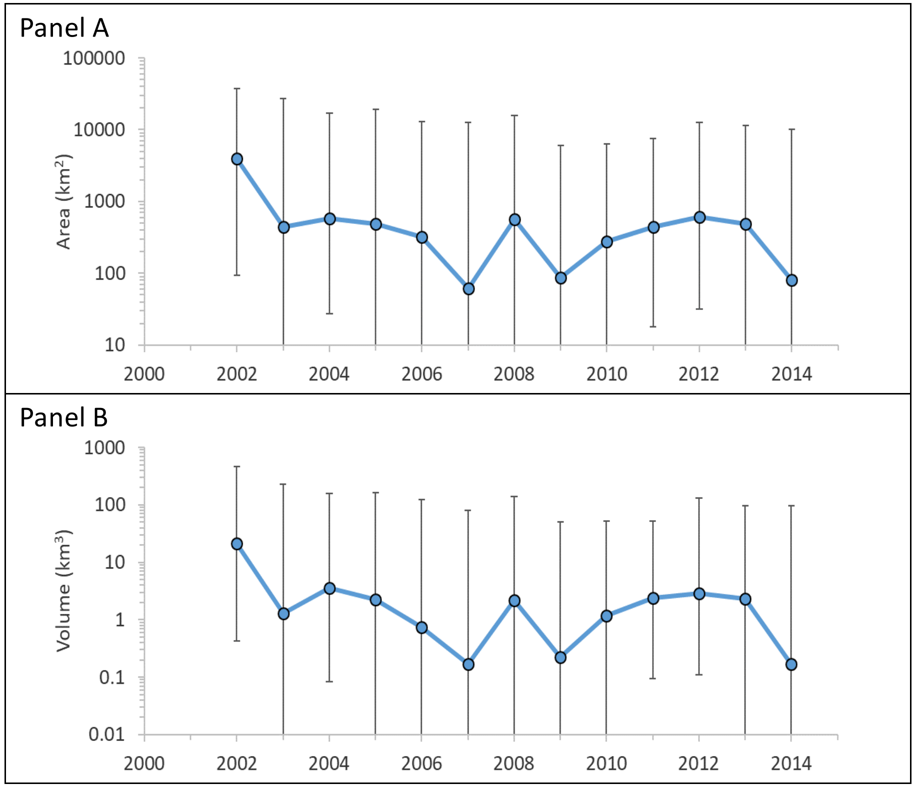

Figure 26: *Interannual variation in the area and volume of bottom water with oxygen concentration below 2 mg L^{-1}. Data represent September. Estimating the mean field of the oxycline depth for all years combined with the GAM produces slightly smoother contours (**Fig. 29**) compared to those obtained with ordinary kriging (**Fig. 25A+B**), because the spline is generally smoother by nature and because it is based on data from 13 years.*

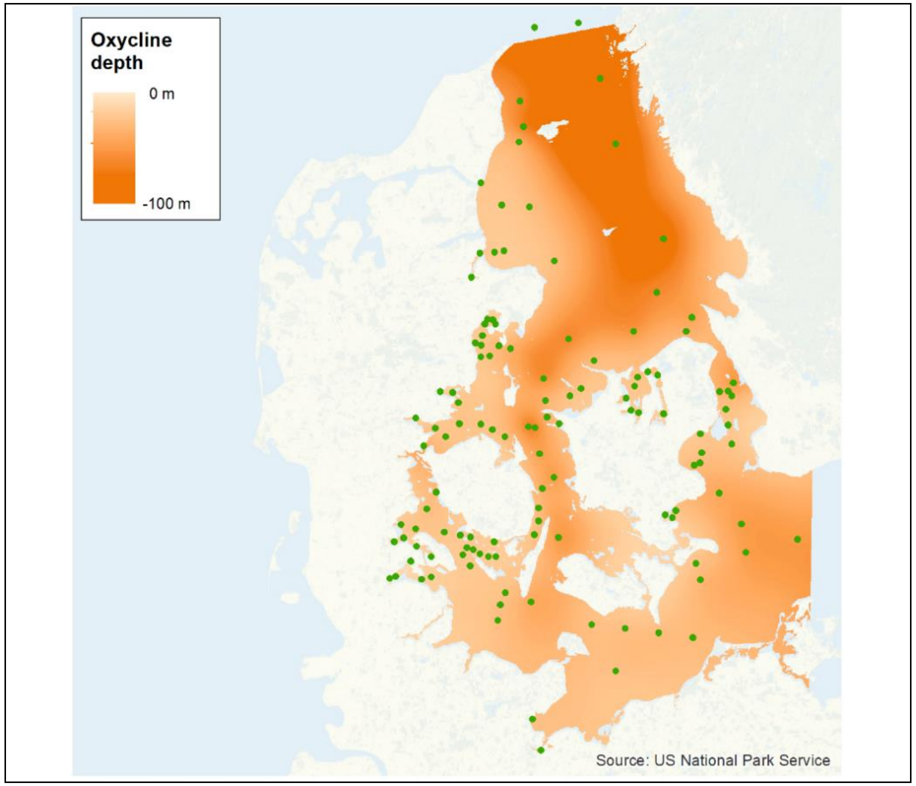

Figure 27: *The mean field estimated by a GAM with a 2-dimensional spline and a year factor based on all oxycline depths from monitoring stations (2002-2014).*

The residuals from the GAM exhibited substantially lower variation (**Fig. 28**) than the constant mean field model employed in ordinary kriging (**Fig. 24**). The nugget effect corresponded to an "observation error" of ±33% and spatial correlation only remained at distances less than 120 km. Obviously, variations interpreted as random correlated variability by ordinary kriging was converted into fixed variability by employing the GAM to describe the mean field of the pycnocline depth.

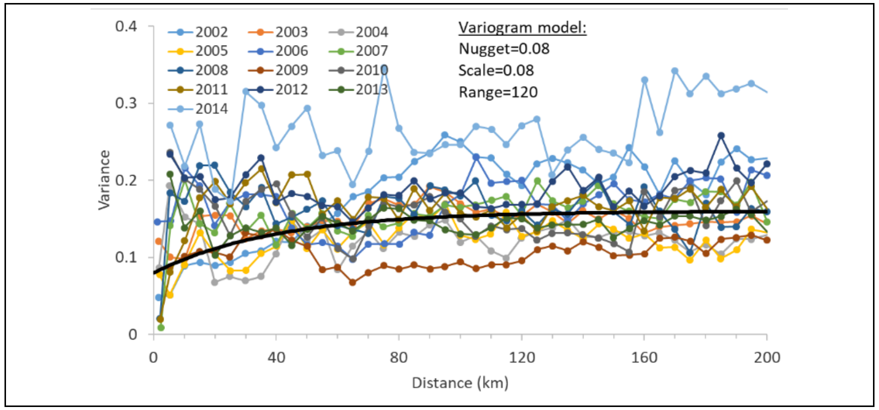

Figure 28: *Empirical variograms estimated on residuals from the GAM. The fitted exponential variogram model is shown with a solid black line and parameters inserted.*

Although the predicted oxycline depth from the combined approach (**Fig. 30A**) did not appear much different from neither the ordinary kriging (**Fig. 25B**) nor the GAM mean field (**Fig. 27**), the predictions changed up to ±40% from the GAM mean field due to the ordinary kriging adaptation for the specific year (**Fig. 30B**). In September 2005, the oxycline was relatively higher in the water column in the western Kattegat, the Great Belt and the Sound, whereas it was relatively deeper in the northern Little Belt, Fehmarn Belt and Arkona Sea. The relative uncertainty of the predictions from the combined approach varied with distances to the nearest monitoring station, however noteworthy, with considerably lower uncertainty (**Fig. 30C**). Finally, the confidence mapping of the oxygen depletion was also less variable, displaying a more realistic range for oxygen depleted areas (**Fig. 30D**).

The reduced random variability was also apparent in the assessment of areal extent and volume of hypoxia (**Fig. 29**). According to the combined approach, the predicted areal extent of hypoxia was 836 km^2 in September 2005 with a 95% confidence interval of 208-6343 km^2.

The uncertainty of the oxygen depletion maps of individual years is still considerable, but this uncertainty is reduced if we consider the mean oxygen depletion in September for the entire period (2002-2014). The average oxycline for the 13 years (not shown) was similar to the mean field estimated with the GAM approach (**Fig. 27**), but the relative uncertainty was generally low, ranging up to 8.3% (**Fig. 30E**). The reduced uncertainty also had implications for the confidence interval of the oxygen depletion maps, which showed less variability for the mean oxygen depletion (**Fig. 30F**).

This example demonstrates that the standard ordinary kriging overestimates the uncertainty when predicting oxygen depletion maps. However, the uncertainty can be reduced, and narrower confidence intervals produced by incorporating more of the variability in the data into a model for the mean spatial field. It is possible that continued efforts to improve the mean field model may reduce the random variation even further, which will constrain the estimates of oxygen depletion area and volume.

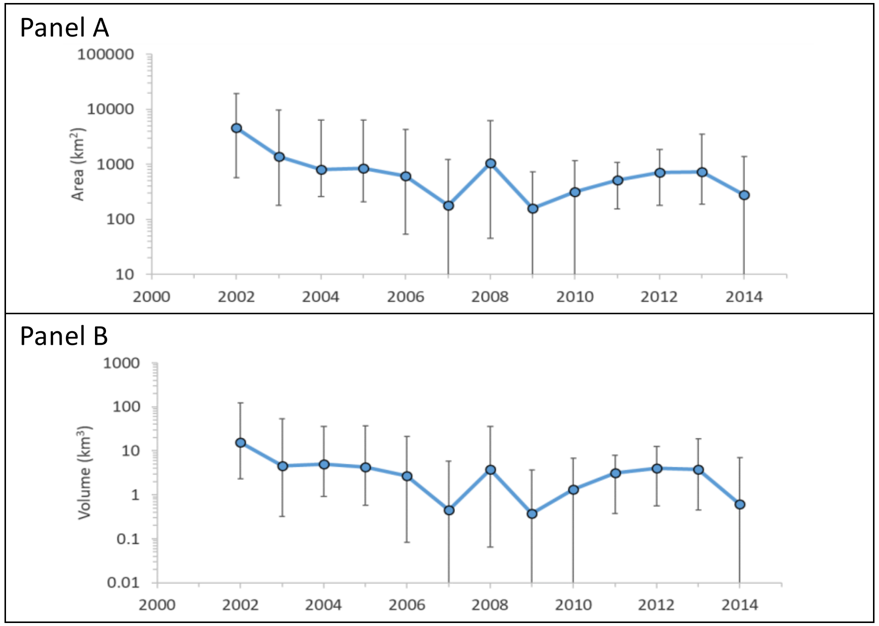

Figure 29: *Interannual variation in the area (A) and volume (B) of bottom water with oxygen concentration below 2 mg L^{-1} from the combined approach (GAM and ordinary kriging). Data represent September.*

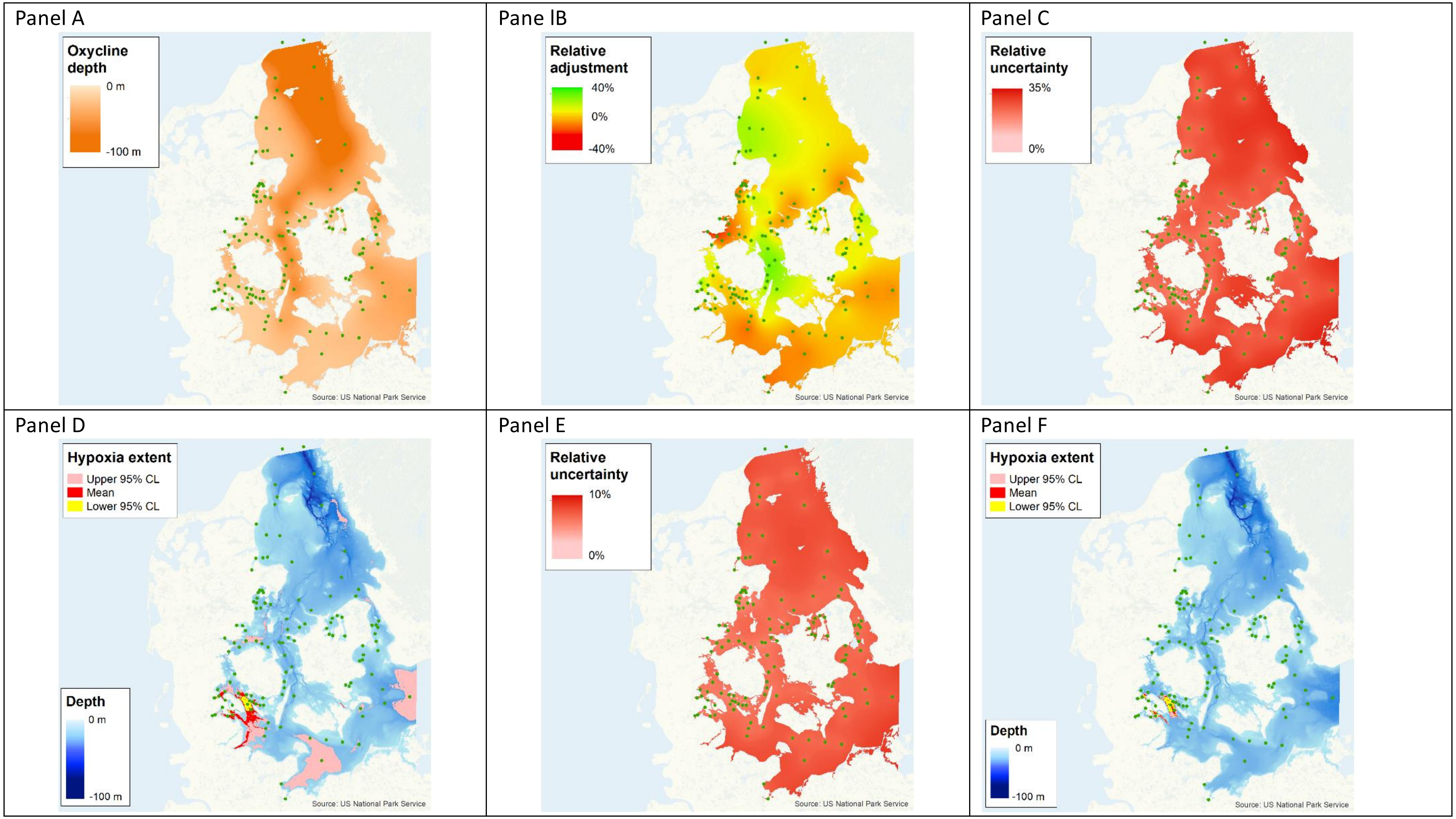

Figure 30: *The estimated oxycline depth using GAM and ordinary kriging (A) and the relative change of this to the GAM mean field (cf.* ***Fig. 27****) (B). The relative uncertainty of the oxycline depth from the exponential variogram model (cf.* ***Fig. 25****) (C). The resulting 95% confidence mappings of oxygen depletion (D). Maps in A-D represent September 2005. The relative uncertainty of the mean oxycline depth (E) and the 95% confidence mappings of oxygen depletion (F). Maps in E and F represent September for the years 2002-2014. Monitoring stations used for spatial interpolations are shown as green dots.*

3.9 Zoning – steps toward a roadmap

The first step toward zoning in Danish marine waters has been a baseline mapping of existing activities and pressures. This mapping is probably as good as it gets, given the spatial coverage of monitoring and mapping activities. However, coexistence is not the same as a lack of conflict, but rather the lack of principles for marine spatial planning. Hence, ECOMAR has carried out a criteria-based evaluation of potential conflicts between activites and subsequently mapped conflict zones (**Fig. 31**, page 69). Most of these are to be considered hard conflicts and detrimental to both activities – for example the dumping of dredged material nearby an aquaculture plant or dredging of sand within an important fishing area. Although the analysis is preliminary, it is also an eye-opener in a MSP context, and can be used to guide decision making on how to avoid or reduce the number of conflicting activities within an area. To improve the values of these analyses, a revision of the conflict criteria and considerations of not only spatial but also temporal conflicts is recommended.

An important step toward production of a national zoning plan is the definetion of different types of zones ranging from a general use zone, where a lot of activities can take place without any specific permit, over various intermediate zones to a top zone type, where human activities are reducted to a minimum. For ECOMAR, we have opted for four types of zones: zone 1 is a ‘general use zone’, zone 2 is a ‘targeted management zone’, zone 3 is an ‘exclusive use zone’ and zone 4 is a ‘restricted access zone’. This approach is adopted from Ekebom *et al*. (2007). A so-called zoning matrix, where human activites are allocated to the four different use zones, together with indication whether a permit is required or not, has tentatively been developed (**Table 7**). Such matrix enable a data-driven approach to zoning but further consideration regarding the number of zone types and which activites allowed to take place in the different zones is beyond the scope of ECOMAR.

Finally, we have ventured into creating a provisional ecological vulnerability map (**Fig. 32**, page 70) which shows spatial variations in the vulnerability of the ecosystem components in Danish marine waters. This vulnerability map is calculated by EcoImpactMapper tool, based on the weighted mean sensitivity scores of the ecosystem components present in each model point. The areas tentatively identified as vulnerable should be regarded not only as ecological ‘hot spots’ with high number of species, but as areas, where the ecosystem components tend to be more sensitive to human pressures.

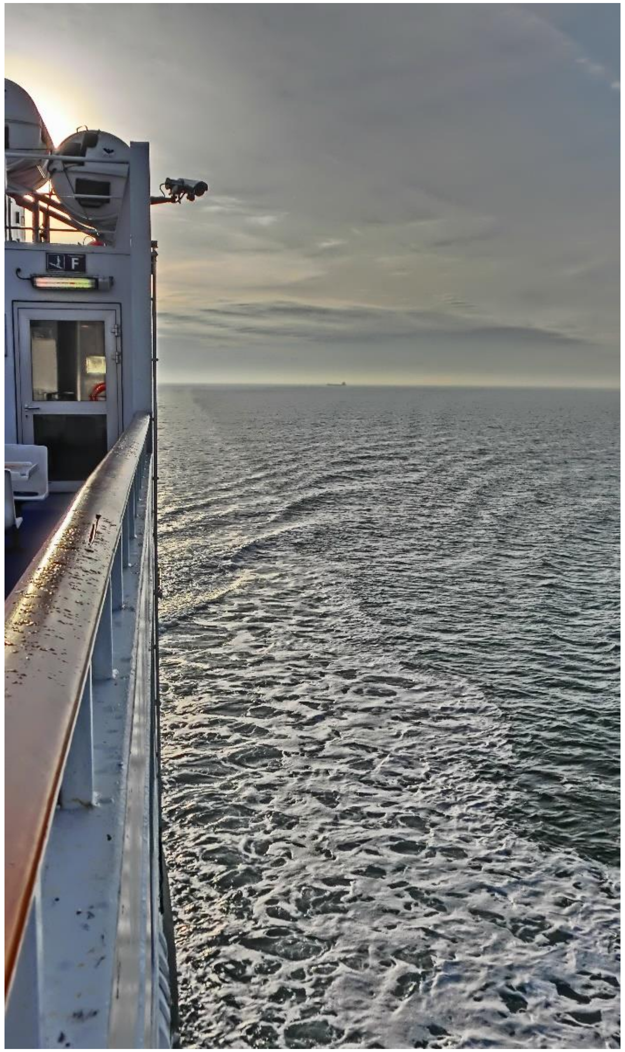

Table 7: *Zoning matrix for the Danish EEZ. Human activities are allocated to the four zones suggested, i.e. Zone 1: General Use, Zone 2: Targeted Management, Zone 3: Exclusive Use, and Zone 4: Restricted Access. Based on Ekebom* et al. *(2008), but adapted according to ECOMAR data layers.*

Human activities	**Impacts**								**Zones**			
	1: Physical loss	**2: Physical damage**	**3: Other physical disturbance**	**4: Interference with hydrological processes**	**5: Contamination by hazardous substances**	**6: Systematic and/or intentional release of substances**	**7: Nutrient and organic matter enrichment**	**8: Biological disturbance**	**Zone 1: General Use**	**Zone 2: Targeted Management**	**Zone 3: Exclusive Use**	**Zone 4: Restricted Access**
Land-sea interactions												
UWWTP discharge (point source)**	-	-	x	-	x	x	x	x	Permit	Permit, if no conflict	NO, except when in agreement (then YES or Restricted)	NO
Discharges from industries***	-	-	-	-	x	x	x	-	Permit	Permit, if no conflict	NO, except when in agreement (then YES or Restricted)	NO
Pollution - Contaminants												
Dumped chemical munitions**	-	x	x	-	x	-	-	-	NO	NO	Contracted if this is the exclusive use	NO, Contracted if this is the exclusive use
Maritime traffic/ Shipping and transportation												
Large vessel traffic*	-	x	x	-	x	-	x	x	YES	YES, if no conflict	NO or Restricted	NO
Small vessel traffic*	-	x	x	-	x	-	x	x	YES	YES, if no conflict	Restricted	NO
Industrial ports**	x	x	x	-	x	x	-	x	YES	YES, if no conflict	NO, except when in agreement (then YES or Restricted)	NO
Harbours**	x	x	x	-	x	x	-	x	YES	YES, if no conflict	NO, except when in agreement (then YES or Restricted)	NO
Seaplane traffic***	-	-	-	-	x	-	x	-	YES	YES, if no conflict	NO, except when in agreement (then YES or Restricted)	NO
Industry, energy and infrastructure												
Coastal habitat modification**	x	x	-	x	-	-	-	-	Permit	Restricted + Permit	NO, except when part of the exclusive use (Permit)	NO, unless part of the agreed use (Permit)
Jetties, breakwaters*	x	x	-	x	-	-	-	-	YES	YES	NO, except when part of the exclusive use (Permit)	NO, unless part of the agreed use (Permit)

Human activities	Impacts								Zones			
Shoreline buildings*	x	x	-	x	-	-	-	-	Permit	Restricted + Permit	NO, except when part of the exclusive use (Permit)	NO
Bridges & coastal constructions**	x	x	-	x	-	-	-	-	Permit	Restricted + Permit	NO, except when part of the exclusive use (Permit)	NO
Dredging**	x	x	-	-	x	-	-	-	Permit	Restricted + Permit	NO, except when part of the exclusive use (Permit)	NO
Disposal sites for construction, garbage & dredged material**	x	x	-	x	x	-	-	-	Permit	Restricted + Permit	NO, except when part of the exclusive use (Permit)	NO
Extraction of material from the seafloor**	x	x	-	-	x	-	-	-	Permit	Restricted + Permit	NO	NO
Mining***	x	x	-	-	x	-	-	-	Permit	Restricted + Permit	NO, except when part of the exclusive use (Permit)	NO
Offshore oil & gas installations**	x	x	x	-	x	x	-	-	Permit	Restricted + Permit	NO, except when part of the exclusive use (Permit)	NO
Oil and gas pipelines**	-	x	-	-	x	-	-	-	Permit	Permit	NO, except when part of the exclusive use (Permit)	NO
Power and heat plants**	x	x	-	x	-	-	-	-	Permit	Restricted + Permit	NO, except when part of the exclusive use (Permit)	NO
Wind farms**	x	x	x	-	-	-	-	-	Permit	Restricted + Permit	NO, except when part of the exclusive use (Permit)	NO
Sea cables**	-	x	-	-	-	-	-	-	Permit	Permit	NO, except when part of the exclusive use (Permit)	NO
Lighthouses**	x	x	-	-	-	-	-	-	YES	YES	YES	YES, but can be restricted
Other nautical support structures***	x	x	-	x	-	-	-	-	YES	YES	YES	YES, but can be restricted
Selective extraction of species - Commercial and recrestional fishing, recreational hunting												
Bottom trawling (small mesh size)**	-	x	x	-	-	-	-	x	Permit	Permit, if no conflict	NO, except when in agreement (then YES or Restricted)	NO
Bottom trawling (large mesh size)**	-	x	x	-	-	-	-	x	Permit	Permit, if no conflict	NO, except when in agreement (then YES or Restricted)	NO
Pelagic trawl**	-	-	x	-	-	-	-	x	Permit	Permit, if no conflict	NO, except when in agreement (then YES or Restricted)	NO
Longlines**	-	x	x	-	-	-	-	x	Permit	Permit, if no conflict	NO, except when in agreement (then YES or Restricted)	NO
Set gillnets**	-	x	x	-	-	-	-	x	Permit	Permit, if no conflict	NO, except when in agreement (then YES or Restricted)	NO
Driftnet fishing***	-	-	x	-	-	-	-	x	Permit	Permit, if no conflict	NO, except when in agreement (then YES or Restricted)	NO

Human activities	Impacts								Zones			
Mussel dredging**	-	x	x	-	-	-	-	x	Permit	Permit, if no conflict	NO, except when in agree-ment (then YES or Restricted)	NO
Recreational net fishing*	-	x	x	-	-	-	-	x	YES + Permit	YES + Permit	NO, except when in agree-ment (then YES or Restricted)	NO
Recreational angling/spinning*	-	x	x	-	-	-	-	x	YES + Permit	YES	NO, except when in agree-ment (then YES or Restricted)	NO
Recreational fishing tour boats*	-	x	x	-	-	-	-	x	YES + Permit	YES + Permit	NO, except when in agree-ment (then YES or Restricted)	NO
Bird recreational hunting**	-	-	-	-	-	-	-	x	Permit	Permit, if no conflict	NO, except when in agree-ment (then YES or Restricted)	NO
Seal hunting***	-	-	-	-	-	-	-	x	NO	NO	NO	NO
Aquaculture												
Fish farms**	-	x	-	x	x	x	x	x	NO	NO	Permit	NO
Shellfish farms**	-	x	-	x	x	x	x	x	NO	NO	Permit	NO
Military activities												
Military practice areas*	x	x	x	-	x	x	-	-	NO	NO	Contracted if this is the exclu-sive use	Contracted, if it is the reason for protection
Military base areas*	x	x	x	-	x	x	-	-	NO	NO	Contracted if this is the exclu-sive use	Contracted, if it is the reason for protection
Recreation and leisure activities												
Kayaking*	-	-	x	-	-	-	-	-	YES	YES, if no conflict	YES, unless in disagreement with the exclusive use (then NO or Restricted)	NO
Surfing*	-	-	x	-	-	-	-	-	YES	YES, if no conflict	YES, unless in disagreement with the exclusive use (then NO or Restricted)	NO
Rowing*	-	x	x	-	-	-	-	-	YES	YES, if no conflict	YES, unless in disagreement with the exclusive use (then NO or Restricted)	NO
Walking, visiting*	-	-	x	-	-	-	-	-	YES	YES, if no conflict	YES, unless in disagreement with the exclusive use (then NO or Restricted)	NO
Observing nature*	-	-	x	-	-	-	-	-	YES	YES, if no conflict	YES, unless in disagreement with the exclusive use (then NO or Restricted)	NO
Collecting*	-	x	x	-	-	-	-	x	YES	YES, if no conflict	YES, unless in disagreement with the exclusive use (then NO or Restricted)	NO

Human activities	Impacts								Zones			
Swimming/Bathing*	-	-	x	-	-	-	x	-	YES	YES, if no conflict	YES, unless in disagreement with the exclusive use (then NO or Restricted)	NO
Bathing sites**	x	x	x	-	-	-	x	-	YES	YES, if no conflict	YES, unless in disagreement with the exclusive use (then NO or Restricted)	NO
Coastal recreation sites**	x	-	x	-	-	-	x	-	YES	YES, if no conflict	YES, unless in disagreement with the exclusive use (then NO or Restricted)	NO
Boating**	-	x	x	-	x	-	-	-	YES	YES, if no conflict	YES, unless in disagreement with the exclusive use (then NO or Restricted)	NO
Jetskiing*	-	x	x	-	x	-	-	-	YES	YES, if no conflict	YES, unless in disagreement with the exclusive use (then NO or Restricted)	NO
Scuba diving**	-	x	x	-	x	-	-	x	YES	YES, if no conflict	YES, unless in disagreement with the exclusive use (then NO or Restricted)	NO
Other												
Research***	x	x	x	x	x	-	-	x	YES	YES if no conflict, NO/Permit if conflict	YES if no conflict, NO/Permit if conflict	NO, if not contracted
Public arrangements (museum, guided tours)*	-	x	x	-	-	-	-	x	YES	YES if no conflict, NO/Permit if conflict	YES if no conflict, NO/Permit if conflict	NO, if not contracted
Upsteream management activi-ties***	-	x	x	x	x	x	x	x	YES	YES if no conflict, NO/Permit if conflict	YES if no conflict, NO/Permit if conflict	YES, if no conflict, NO if conflict
Marine protection												
Natura 2000 sites, HD*	-	-	-	-	-	-	-	-	NO	YES	YES	YES
Natura 2000 sites, BD*	-	-	-	-	-	-	-	-	NO	YES	YES	YES
Nature 2000 sites, Ramsar sites*	-	-	-	-	-	-	-	-	NO	YES	YES	YES
MSFD MPA*	-	-	-	-	-	-	-	-	NO	NO	YES	YES
Stone reefs within N2000 areas**	-	-	-	-	-	-	-	-	NO	NO	YES	YES

** Part of an ECOMAR data layer; ** A fully-fledged ECOMAR data layer, *** Not included in ECOMAR.*

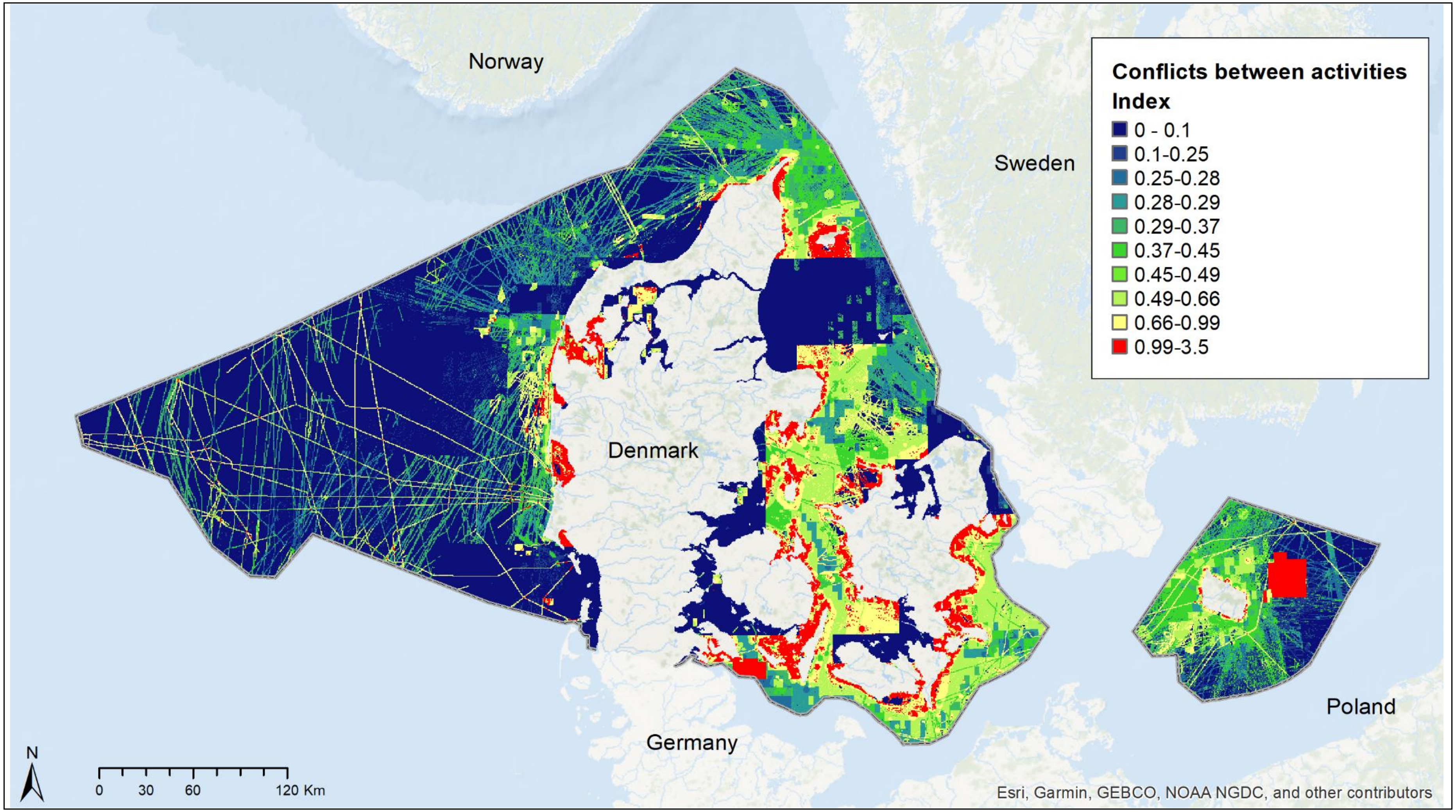

Figure 31: *Current conflict zones identified on the basis of provisional conflict criteria. Red areas indicates the highest 10th percent quantile and where there are most potential conflicts. Blue areas indicate low potential for conflicts between pressures and activities.*

The map of conflict zones is tentative and should be seen as a demonstration of the power of data and how data can support the development of evidence-based MSP. If implemented, conflict criteria should be critically reassessed and adapted for the marine region or sub-region in question. If so, a criteria-based identification of conflicts and subsequent analysis of how to avoid conflicts would potentially lead to few conflict, lower combined pressures and finally improvement of ecological status in coastal waters (WFD domain) and environmental status in offshore waters (MSFD domain)

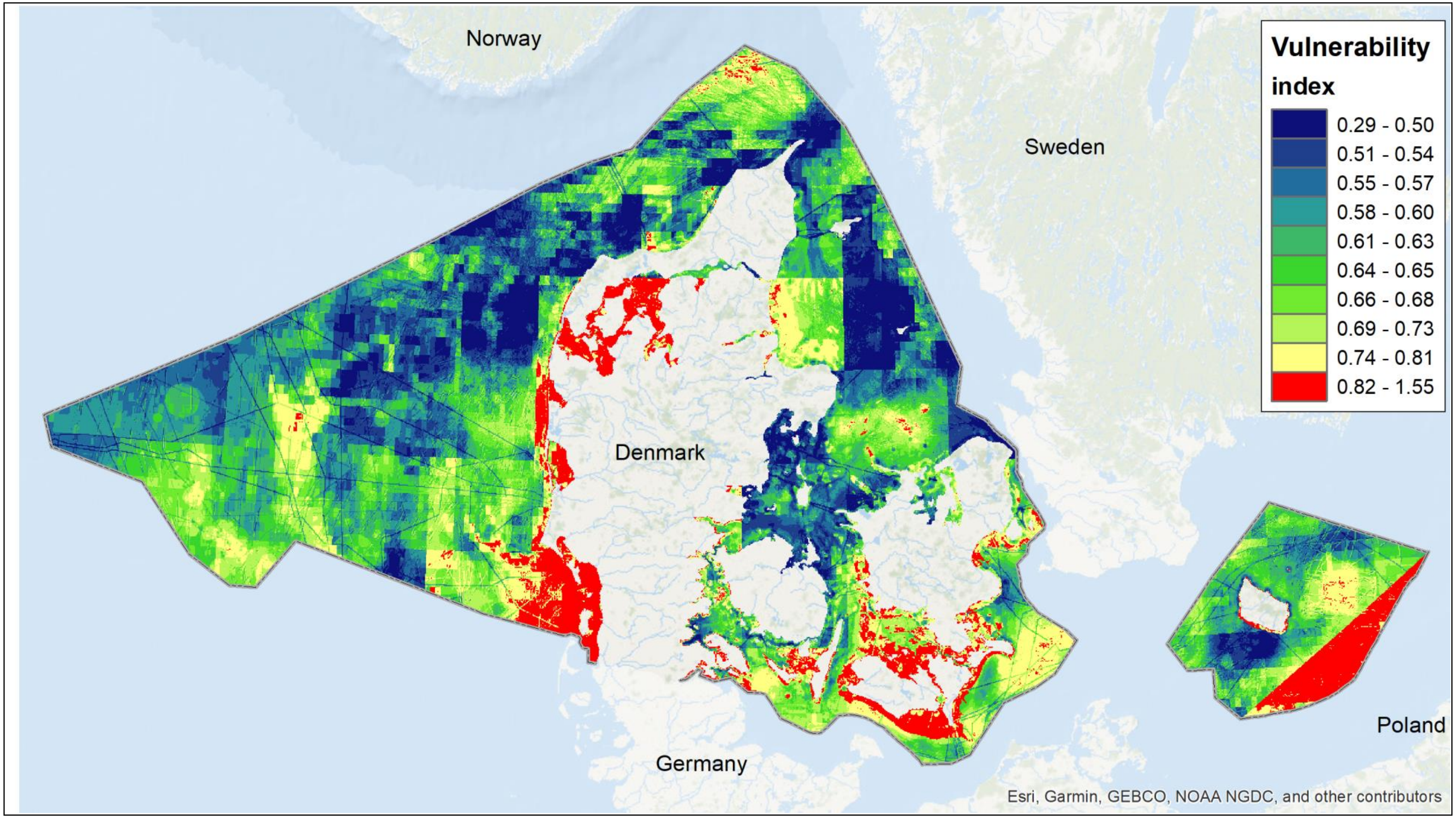

Figure 32: *Provisional vulnerability mapping of the Danish marine waters. Red areas indicates the highest 10th percent quantile and where the ecosystem components have the highest mean vulnerability and the blue areas indicate where there is a lower mean vulnerability.*

The vulnerability map shows that specific areas, especially coastal, are more prone to disturbance than most offshore areas. Given the relationship between biodiversity status (Andersen *et al*. 2015) and ecological status (EEA 2019a) on the one hand and human pressures on the other, the addition of more human pressure is not in accordance with the overall visions and goals of the MSFD and the MSPD.

4 Discussion and conclusions

Based on the analyses and scenarios presented in Chapter 3, we discuss these as well as the strengths, weakness and potential implications of the results. Special focus is put on the combined effects analyses and on the 2030, 2050 and MSFD scenarios, since these indicate that pressures may neither be reduced in a short term (2030) or long-term perspective (2050). We also conclude that a better coordination between 'marine' authorities is needed and that it is imperative to make use of data-driven approaches, to consider uncertainty and to consider all activities and pressures, including land-based, and to include all ecosystem components.

4.1 Data layers

The data sets and maps compiled by ECOMAR represent a leap forward towards a more complete spatial analysis based on more extensive data sets, especially with regard to the activity and pressure layers. All sectors, activities, and pressures mentioned in the MSPD, MSFD and WFD are covered, and are supplemented with data representing climate change, recreational activities and tourism. The data sets and maps representing ecosystem components cover all key ecosystem groups, e.g. pelagic habitats, benthic habitats, fish, birds and marine mammals. In addition, data layers representing societal interests, i.e. areas important for recreation, shipwrecks and archeological sites (e.g. stone age dwellings), are included and analysed. Although ECOMAR has made significant progress and developed comprehensive state-of-the-art data sets (see **Supplementary material**, **Annex A** and **B**), we have also identified weaknesses in some of the data sets with room for improvement.

The following themes are of key relevance, when it comes to improving the data layers, especially those related to ecosystem components: i) spatial coverage (all data sets and model should cover the entire Danish EEZ), ii) confidence (data sets with low confidence should be improved and made more accurate and precise), and iii) updating (all data should be up-to-date). This important task is evidently an assignment for relevant competent authorities, i.e. the Danish Maritime Agency (regarding the MSPD) and the Danish Ministry for the Enviroment (regarding the MSFD and WFD).

4.2 Mapping of combined effects

The estimation and mapping of potential combined effects of multiple human pressures in Danish marine waters is based on a well-documented (Halpern *et al.* 2008, Stock 2013) and widely used method (Korpinen & Andersen 2016, HELCOM 2018, Miljø- og Fødevareministeriet 2019, EEA 2020).

Given the data availability in ECOMAR, we have been able to demonstrate the power of combining data and demonstrate how CEA can support ecosystem-based management in the context of multiple directives, e.g. MSPD, MSFD and WFD. A key result is the map of potential combined effects of human pressures in Danish marine waters (see **Fig. 6**). It significantly advances the performance of previous studies by Miljø- og Fødevareministeriet (2019), HELCOM (2018), Andersen *et al.* (2020), EEA (2020) and the Swedish Agency for Water Management (Hammar *et al*. 2018 and 2020).

The CEA method is admittedly simple but it provides a good overview of where hot spots are located and also enables a broad range of analyses. Weaknesses of the CEA method, e.g. the setting of sensitivity scores and effect distances as well as the assumption of linear responses between the pressure and ecosystem components, normalization of data layers and the assumed additive nature of the pressures are well known (Halpern & Fujita 2013). Other methods for assessing cumulative impacts exist and many of them include some of these assumptions whereas others, such as mechanistic, Bayesian models or marchine learning methods, can include both interactions and non-linear reponses between pressures and ecosystem components (Petersen *et al.* 2020). These other types of models are usually heavy to run and can demand a high quality of quantified relationships between the data layers. The models are therefore not an alternative and useful for MSP applications, but can be used on smaller scales or to a limited amount of data layers. As in the CEA model used by ECOMAR, they can also include expert knowledge when data or knowledge about the relationships are missing, which can in some situations be problematic (Halpern & Fujita 2013). There are other ways of including an uncertainty estimate of the sensitivity scores gathered from expert studies described by e.g. Doubleday *et al*. (2017), Gissi *et al*. (2017) and Jones *et al*. (2018). Unfortunately, this comprehensive type of study was beyond the scope of the ECOMAR project, as the setting of the sensitivity scores was planned for the early phase of ECOMAR. An *ad hoc* solution for testing of alternative model assumptions and as well as data quality problems are presented by Stock & Micheli (2016) and Sock *et al*. (2018) and have been applied in several previous studies, like Andersen *et al*. (2020) and also within the ECOMAR project (see **section 3.8.1**).

Although the various assumptions can affect the model results, it has also been shown that they are robust (Stock & Micheli 2016, Stock *et al*. 2018, Andersen *et al*. 2020). This is also the case for ECOMAR as seen from the results of the Monte Carlo simulations and the elementary effects model described in **section 3.8.1**. These model results show that ECOMAR estimates are robust and the factors affecting the model output are known restrictions and in line with previous studies. The results from ECOMAR can therefore with confidence be used in a Danish MSP context but can also be relevant to others, e.g. neighbouring countries as well as HELCOM and OSPAR.

4.3 Confidence and uncertainty

At the beginning of ECOMAR, data layer providers were asked to deliver an uncertainty estimate with their data layer. Due to the diversity of different approaches and the lack of a general framework for assessing uncertainty, a multitude of different uncertainty layers were produced. The experiences gained from ECOMAR on assessing uncertainty in data layers will be useful for further development of tools such as EcoImpactMapper and SeaSketch.

For aggregating data layers and their associated uncertainties, it is important that these use the same 'currency' before aggregation. This can be achieved through transformation to a common scale, as was done for the data layers in EcoImpactMapper. Essentially, the same transformation can be applied to the uncertainty of the data layers, if the uncertainty is represented on the same scale as the data layer, i.e. as absolute uncertainty of the value in the grid cell. In case the uncertainty is expressed relative to the value of the grid cell, the absolute uncertainty can be computed by scaling with the grid cell value. However, uncertainty expressed qualitatively using different confidence classes or using a scale (e.g. 0-100) that is not directly related to the grid cell value do not conform to the "common currency" approach that enables aggregation of uncertainties in a similar manner to aggregation of data layers. Consequently, there is a strong need for harmonizing the reporting of uncertainty in absolute values, using the same unit as the data layer itself. Therefore, a first key lesson from ECOMAR is that uncertainty reporting should be done in the same unit as the data layer.

Quantification of uncertainty in data layers is a difficult task and therefore it is often overlooked or sometimes even ignored. ECOMAR is one of the first projects to emphasize confidence assessments in marine spatial planning, which has led to the realisation that a general statistical method should be developed to quantify the uncertainty. ECOMAR has contributed to this by demonstrating the usefulness of combining two commonly used statistical methods for obtaining realistic uncertainty estimates. Therefore, a second key lesson from ECOMAR is that statistical methods, capable of quantifying uncertainty, should be employed generically.

However, the background data for compiling data layers are associated with multiple sources of uncertainty (e.g. observational, model, parameter errors), which are not all relevant for expressing the uncertainty of the data layer. Whereas model and parameter errors express uncertainty with the approach used for compiling the data layer and should be included, observational errors pertain to uncertainty associated with the measurements and thus not relevant for the data layer.

Furthermore, data layers are mostly dynamic and should, preferably, represent the same assessment period before aggregation, but in reality they are more likely based on data from different years. This adds another source of variability; temporal variation, which should be quantified and included in the data layer uncertainty, provided that the data layer is not based on data from all years of the assessment period. For example, if the data layer is compiled on a single year's survey of a data type exhibiting larger interannual variability, then that data layer is an uncertain representation of a longer assessment period. Therefore, a third key lesson from ECOMAR is that a standard assessment period should be chosen and the multiple sources of uncertainty affecting the data layer estimate representing that period should be quantified and included in the uncertainty of the data layer.

4.4 Analysis and scenarios

With ECOMAR, it has been demonstrated that reductions or increases in individual pressure intensity also affects the intensity of the combined pressure and ultimately on the ecosystem components. All pressure groups have been addressed and the potential impacts on a national level has been estimated. All in all, ECOMAR has demonstrated the use of SeaSketch and EcoImpactMapper directly and indirectly, the latter through postprocessing, on a national or sub-regional scale.

In addition, scenarios showing reallocation of existing pressures or introduction of new activities and pressure have been shown. The analyses have, however, been done on a local scale, for demonstration purposes. Despite this we have shown that SeaSketch can be used for a broad range of analyses and scenario calculations (see **sections 3.5** and **3.7**) and the complete potential is yet to be proven.

Of particular interest for follow up studies are:

- Cumulative or combined effects of the planned construction of multiple offshore wind farms.
- Down-scaling of analyses/scenarios from national and regional level to sub-regional and/or local level.
- Testing of the applicability of CEA in the context of strategic environmental assessment (SEA) and evironmental impact assessments (EIA).

This specific types of environmental assessments (SEA and EIA) are nowadays carried out regularly and do, but at a superficial level, address potential cumulative effects. With ECOMAR and the lessons learned, this type of assessments could be improved from being short generic narratives to become data- and tool-based.

Combining individual analyses into scenarios specific for 2030 and 2050 and also estimating the potential effects of a GES focused reduction in pressures have revealed two important messages:

- Firstly, the combined effects of pressure are likely to increase in 2030 and 2050 (see **Table 8**).
- Secondly, the MSFD GES scenario indicates a reduction in combined impacts and thus potentially an improvement in environmental status.

We believe this is an important result of ECOMAR. However, there is no evidence, based on the analyses and scenarios carried out, that 'Havplan Danmark', being the Danish implementation of the MSPD, will lead to any significant improvements in 'environmental status', cf. the MSFD. The above conclusion may be considered premature, but ECOMAR documents that i) the combined effects in 2030 are estimated to be 8.4 % higher compared to the levels in the baseline established by ECOMAR, and ii) the combined effects in 2050 are estimated to be 10.7 % higher compared to the levels in the baseline.

Table 8. *Estimate pressure sums for all CEA assessment unit in Danish marine waters in the baseline and in the 2030, 2050 and MSFD scenarios.*

	Denmark	North Sea	Kattegat	Baltic Sea
Baseline	1,324,871	685,144	194,070	445,657
2030	1,435,961	723,243	221,680	491,038
2050	1,466,422	731,304	228,109	507,009
MSFD GES	1,130,123	579,019	168,940	382,164

4.5 From data to zoning and beyond

ECOMAR has established a baseline mapping of human activities and pressures based on an unprecedented dataset in terms of data layers representting activities and pressures on the one hand and ecosystem components on the other. The data layers on activities and pressure include all those relevant under the MSPD, MSFD and WFD plus a few additional (i.e. recreational activities and tourism). There is, however, room for improvement as inclusion of some additional data layers would be helpful, e.g. locations of discharges from urban wastewater treatment plants and industries, harbours and well as information on riverine inputs.

This baseline mapping has been used for identification of spatial overlap of potentially conflicting activities, for example shipping lanes vs. offshore wind farms, or aquaculture farms vs. Natura 2000 areas. Even when excluding soft conflicts and only focusing on hard conflicts, we document a large overlap of potentially conflicting activities (**Fig. 31**). These conflicts will have to be addressed by competent authorities and by inclusion of relevant stakeholders in the process, for example through 'Havplan Danmark', and resolved to the extent possible. An added value of avoiding conflicting activities within an area, should be either a separation of activities or a reduction in pressures.

An important element to be taken into account when doing a zoning plan is the vulnerability of species, habitats and communities. This has been addressed indirectly through the setting of pressure- and ecosystem component-specific sensitivity scores. ECOMAR has in addition carried out the first attempt of mapping of vulnerability of ecosystem components in Danish marine waters and identified 'hot spots' as well as the 'cold spots'. Though preliminary, the work represents a potentially important source of information in the zoning process, although the setting of sensitivity scores within ECOMAR is based on expert judgment.

ECOMAR has developed a provisional zoning matrix for the Danish EEZ and based this on the following four zones: zone 1 'general use', zone 2 'targeted management', zone 3 'exclusive use', and zone 4 'restricted access', the latter with the highest feasible level of protection. Additional zones are vunerable marine ecosystems and cultural heritage locations. What separates these zones can of course be discussed and revised. The same is the case regarding the number of zone types - some could be further subdivided, for example zone four which could be split into a zone with 'restricted access and a zone for vulnerable marine ecosystems, with 'no go, not take' restrictions.

The so-called 100:30:10 plan proposed by WWF Denmark (2020) suggests that 10% of the Danish EEZ is designated for scientific reference areas, 30% as marine protected areas and that 100% will be managed according to an ecocosystem-based approach cf. the MSFD. The suggested 100:30:10 plan may at a glance seem well justified, but the actual numbers should be discussed and linked to and also part of a future official zoning plan for the Danish EEZ.

All in all, the demonstrations by ECOMAR should be seen as a first step toward a fully fledged Danish zoning plan based on a zoning matrix more or less similar to the example given in **section 3.9** and **Table 7**.

4.6 How to use ECOMAR's data, tools and results

All data sets originating from ECOMAR are described and documented in the **Supplementary Material**. These products (sometimes named 'foreground') of the project, in contrast to the background products (the data sets, codes and models, that existed before ECOMAR), can be used by others for specific purposed and acquired from the data authoring institutions (see **Supplementary Material** and information about data hosts).

Any ecosystem-based management plan or environmental assessment should, as a principle, be based on the best available data sets regarding both pressures and ecosystem components – if not, it can hardly claim to be ecosystem-based or to apply an ecosystem-based approach. The ECOMAR partnership thus encourages competent authorities, both local and national, as well as consulting companies and NGOs to study the data sets in the **Supplementary Material**. We encourage interested institutions and organisations to utilise the results in support of ecosystem-based managent plans, e.g. the MSPD, MSFD, WFD as well as specific environmental (impact) assessments.

EcoImpactMapper is an Open Source software, but SeaSketch is not. The original version of EcoImpactMapper is available via Stock (2016) and constitutes in our view a useful tool for those interested in mapping of combined effect of multiple human pressures. The current version of SeaSketch requires a license, but this will change within a few years once the open source version SeaSketch NEXT is made available in 2022.

Based on a combination of key results from ECOMAR, in particular the mapping of combined effects and the identification of 'hot spot' areas (**Fig. 8**) and the tentative mapping of ecosystem vulnerability (**Fig. 32**), and the fact that a good environmental status is nowhere present in Danish marine waters today, provides a starting point for designation of additional marine protected areas, either as Natura 2000 areas or as MSFD areas.

We believe theres is a large potential in ECOMAR regarding analyses and scenarios. Data sets and tools can be used to analyse both i) the potential risks associated with higher impact values resulting from changes in pressure intensities of existing activities and ii) the risk of higher effects caused by addition of new activities. Scenarios could be refined and updated if needed, especially if focus is on identification of a broad range of pressures that can be diminished in order to improve environmental status.

With the provisional zoning matrix for Danish marine waters developed by ECOMAR, we demonstrate how competent authorithies could develop data- and criteria-based zoning plans in five steps: i) definition of zone types, ii) allocation of existing activities to zone types, iii) identification of mismatches between existing and potentially conflicting activities based on ECOMAR's conflict map, iv) reductions in the number of conflicting activities, and v) development of the first ever national zoning plan for the Danish EEZ. One could assume that the upcoming 'Havplan Danmark' perhaps would constitue a zoning plan, but this will only be the case if it addresses a broad range of zone types, including all sea-based human activities and land-sea interactions.

With ECOMAR, we have demonstrated that mapping of pressures could be carried out under several EU directives, i.e. MSPD, MSFD and WFD, as a coordinated and joint activity. Not only has ECOMAR mapped combined effects cf. MSPD and MSFD (see **Fig. 6** and **Supplementary Material, Annex C4**), we have also mapped pressures in coastal water bodies (see **Fig. 20**), these being within the WFD domain, using the same data and methods. We have demonstrated that it can be done in the context of ECOMAR and we hope that this will initiate a process, that may ultimately result in a better coordination between the MSPD, MSFD and WFD implementation and reporting processes.

Competent authorities working with pressure analyses, for example under the MSPD, MSFD or WFD, should ideally base their work on the same data sets and validated methods. If so, there would be a potential for a more harmonized, but also cost-effective process compared to current practices.

4.7 Synthesis and outlook

In addition to establishment of the comprehensive compilation of data sets representing pressures and ecosystem components. ECOMAR has carried out an array of analyses and scenarios in order to demonstrate what is sometimes referred to as 'the power of data'.

In terms of analyses, initial focus has been on mapping and assessment of combined effects of multiple human activities. Due to the improvements in data quality and cover, the results represent state-of-the-art and are significantly broader and probably more robust that what has been reported previously in Denmark (Miljø- og Fødevareministeriet 2019), the Baltic Sea (HELCOM 2018) and North Sea regions (Andersen *et al.* 2013) as well as in Europe (Korpinen *et al.* 2020).

ECOMAR has barely scratched the surface in terms of what can be achieved – there are numerous analyses, especially with a sub-regional or local focus which have not yet been made. Thus, ECOMAR has established data and a first set of tools which are useful in the process related to implementation of the MSPD, MSFD and WFD. We hope that this potential will be fully exploited and developed in the coming years.

In terms of scenarios, ECOMAR has addressed planned developments (2030 and 2050 scenarios) as well as a hypothetical MSFD GES scenario. There is, based on the analyses and scenarios carried out, no evidence that 'Havplan Danmark', being the Danish implementation of the MSPD, will lead to any significant improvements in 'environmental status' as required by the MSFD.

Another lesson learned is that climate change presents a key pressure in all parts of Danish marine waters and thus a backdrop which must always be incorporated in strategies and plans, if these are to be ecosystem-based.

To develop fully-fledged ecosystem-based management strategies and plans for marine waters in Denmark, especially under the MSPD and MSFD but also in relation to the the WFD, the Natura 2000 directives and for environmental impacts assessments, it is imperative to make use of data-driven approaches, to consider uncertainty and to consider all activities and pressures, including land-based, and to include all ecosystem components. If the resulting plan – for example the final version of 'Havplan Danmark' or the Programmes of Measures in relation to the WFD and MSFD – does not include all ecologically important pressures including land-sea interactions and all ecosystem components, it will not meet the criteria for being ecosystem-based.

For a successful management plan that will ensure a sutainable use of the marine resources and ecosystem services the MSP process should be well anchored through stakeholder involvements. This has not been done within ECOMAR but it would of course be crucial for a successful and ecosystem-based implementation of 'Havplan Danmark'.

ECOMAR has been more than a project with fixed start and end dates. ECOMAR has evolved into a partnership and, perhaps most important, an innovative platform for carrying out analyses and scenarios that potentially can support reporting and decision making in the context of multiple processes and directives, in particular the MSPD and but also the MSFD, WFD and N2000 directives.

Recovery from decades of over-exploitation and pollution can be reversed and a better environmental status is within reach. Achieving this requires not only coordination but also streamlining and cross-institutional collaboration. If this is not done, the MSPD could potentially lead to a reversal in some of the improvements already achieved under the MSFD and WFD as well as regional and national action plans, first of all the substantial progress achieved via the Danish Action Plans on the Aquatic Environment.

In conclusion, perhaps the most important result of ECOMAR is the identification of the need for a significantly better coordination between the implementation of EU's marine directives, in particular the MSPD and MSFD, but also the WFD.

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6 Author contributions

The chapters in this ECOMAR synthesis report have been developed, written and edited by:

Preface	Jesper H. Andersen.
Introduction	Jesper H. Andersen, E. Therese Harvey and Ciaran Murray.
Methods	Jesper H. Andersen, E. Therese Harvey, Ciaran Murray, Will McClintock and Jacob Carstensen.
Results	JesperH. Andersen, Katherine Hammer, E.Therese Harvey, Ciaran Murray, Jacob Carstensen, Ib Krag Petersen, Jakob Tougaard, Signe Sveegaard, Karen Edelvang, Josefine Egekvist, Jeppe Olsen, Zyad Al-Hamdani, Jørn Bo Jensen, Jørgen O. Leth, Anton S. Olafsson, Berit C. Kaae, Will McClintock, Chad Burt and Dan Yokum.
Discussion and conclusions	Jesper H. Andersen, E.Therese Harvey, Ciaran Murray, Steen W. Knudsen, Jørgen Bendtsen, Jacob Carstensen, Ib Krag Petersen, Jakob Tougaard, Signe Sveegaard, Karen Edelvang, Josefine Egekvist, Jeppe Olsen, Zyad Al-Hamdani, Jørn Bo Jensen, Jørgen O. Leth, Anton S. Olafsson, Berit C. Kaae and Will McClintock.
References	All

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List of annexes

The full list of annexes comprises:

A. Pressures and human activities
B. Ecosystem components
C. Other annexes
   - C1 Sensitivity scores
   - C2 Effect distances
   - C3 Results without climate
     - C3.1 CEI spatial results without climate
     - C3.2 Ranking of pressures without climate
   - C4 MSFD analyses CEI maps
   - C5 Spatial differences between baseline and scenarios
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     - C5.3 Baseline and MSFD GES
   - C6 Data coverage
   - C7 Descriptions of pressure and activity layers
   - C8 Descriptions of ecosystem and societal component layers

The above annexes are published as a separate report, which can be downloaded from: https://niva.brage.unit.no/niva-xmlui/handle/11250/2678968.

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