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Under the surface: A gradient study of human impacts in Danish marine waters

NIVA Denmark Water Research

REPORT

Main Office
Gaustadalléen 21
NO-0349 Oslo, Norway
Phone (47) 22 18 51 00
Telefax (47) 22 18 52 00
Internet: www.niva.no

NIVA Region South
Jon Lilletuns vei 3
NO-4879 Grimstad, Norway
Phone (47) 22 18 51 00
Telefax (47) 37 04 45 13

NIVA Region East
Sandvikaveien 59
NO-2312 Ottestad, Norway
Phone (47) 22 18 51 00
Telefax (47) 62 57 66 53

NIVA Region West
Thormøhlensgate 53 D
NO-5006 Bergen Norway
Phone (47) 22 18 51 00
Telefax (47) 55 31 22 14

NIVA Denmark
Ørestads Boulevard 73
DK-2300 Copenhagen, Denmark
Phone (45) 88 96 96 70
www.niva-danmark.dk

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Author(s)	Topic group	Distribution
Jesper H. Andersen, NIVA Denmark Therese Harvey, NIVA Denmark Emilie Kallenbach, NIVA Denmark Ciarán Murray, NIVA Denmark Zyad Al-Hamdani, Geologic Survey of Denmark and Greenland Andy Stock, Stanford University	Marine biology Geographical area Danish marine waters	Public Printed NIVA

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Summary

We report the first ever ranking of the relative importance of human stressors along land-sea gradients based on a cumulative impact assessment *sensu* the methodology developed and published by Halpern *et al.* in 2008 and 2015. The study is based on a comprehensive Danish data set, originating from a broad range of projects and activities and a subsequent mapping of potential cumulative impacts of multiple human stressors in the Danish marine environment. The study is based on 35 data layers representing human stressors and 47 data layers representing ecosystem components. Our results document that the Danish marine waters, which are impaired, are prone to a wide range of human stressors. When combining individual stressors into groups, the top 5 groups are: (1) nutrients, (2) climate anomalies, (3) non-indigenous species (NIS), 4) contaminants and (5) fisheries. Gradient studies have focused on 16 case studies (where estuarine/fjord systems are linked to coastal and open waters) and we document land-sea gradients for key groups of stressors and how the relative importance of these vary, in some cases substantially (e.g. for the stressors Nutrients, Contaminants, Fishing, Non-indigenous species, Noise and Shipping).

Four keywords	Fire emneord
1. Stressors	1. Presfaktorer
2. Ecosystem components	2. Økosystemkomponenter
3. Cumulative impacts	3. Kumulative påvirkninger
4. Gradient studies and ranking	4. Gradientstudier og rangordning

Jesper H. Andersen
Chief Scientist

Nikolai Friberg
Research Director

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Under the surface:
A gradient study of human impacts in Danish marine waters

Preface

The study is rooted in previous endeavours to map potential cumulative impacts of human activities in the Baltic Sea (HELCOM HOLAS, see HELCOM 2010 and Korpinen *et al.* 2012) as well as in the eastern parts of the North Sea (HARMONY, see Andersen *& Stock* 2013). Both studies mapped potential cumulative impacts and tentatively ranked human stressors within the study areas. However, no studies so far have focused on mapping the relative importance of human stressors along a land-sea gradient. To our knowledge, this study is the first attempt to analyse variations in the relative importance of human stressors from land to offshore waters.

This study has been funded by Danish Agriculture and Food Council. The work in relation to this study has been presented to and discussed in an informal working group and thank are thus due to Anders Panum Jensen (chair), Marie van Maarschalkerweerd, Karl-Iver Dahl Madsen and Flemming Gertz.

We are indebted to the following three projects (1) HELCOM HOLAS I, which spearheaded several studies of cumulative impact assessment in northern Europe, (2) HARMONY, from which we have directly used 5 data sets for stressors and ecosystem components, and (3) SYMBIOSE, from which we have made use of the maps in the report and reconstructed a suite of stressor- and ecosystem component-specific shapefiles. Thus, we would like to thank the people responsible for collating the data sets within various studies: Laura Addington, Karsten Dahl, Rune Dietz, Cordula Göke, Stefan Heinänen, Lars I. Iversen, Samuli Korpinen, Maria Laamanen, Laura Meski, Lonnie Mikkelsen, Christian Mohn, Ib Krag Petersen, Anna Rindorf, Jonas Koefoed Rømer, Jakob Strand, Peter Stæhr, Signe Sveegaard, Jonas Teilmann, Jakob Tougaard, Henrik Skov, Andy Stock, Thomas Kirk Sørensen, Karen Timmermann and Morten Vinther.

Further, we wold like to thank the following persons for filling in the questionnaire for the setting of sensitivity scores: Karen Edelvang, Anders Erichsen, Samuli Korpinen, Linus Hammar, Peter Rask Møller, Johnny Reker and Thomas Kirk Sørensen. Finally, thanks are also due to Ferdi Rizkiyanto for kind permission to make use of the 'What Lies Under' illustration, a graphical statement about marine pollution, on the cover of this report, to Laura Addington for helpful guidance on MiljøGIS and to Mathias B. Kjeldgaard for assisting with the editing.

Copenhagen, 29 June 2017

Jesper H. Andersen

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Summary

This report concerns mapping and ranking of potentially cumulative impacts of multiple human stressors in Danish marine waters. Earlier studies have assessed potential cumulative impacts of multiple human stressors in the Baltic Sea (HELCOM HOLAS project, see HELCOM 2010 and Korpinen *et al.* 2012) and in the eastern parts of the North Sea (HARMONY project, see Andersen & Stock 2013). However, these studies have only addressed ranking of pressures on a broad scale.

The study area covers the Danish marine waters in the transition zone between the North Sea and the Baltic Sea, from which we have collated a robust and unique data set from existing publicly available information including both human stressors (n = 35) and ecosystem components (n = 47).

Based on the above-mentioned data set, we have estimated potential cumulative impacts of multiple human stressors in Danish marine water and subsequently ranked the individual stressors. The results show that the most important groups of stressors are, in order with the most important first: (1) Nutrients, (2) Climate anomalies, (3) Non-indigenous species, (4) Contaminants, (5) Fisheries, (6) Microplastic in sediments, (7) Noise, (8) Shipping and (9) Physical modifications. Further, we have analysed the relative importance (without Climate anomalies) along a gradient from fjord to open sea in 16 case studies. Our results document large spatial variations along the transects. Some stressors (e.g. Nutrients, Non-indigenous species and Microplastic in sediments) have a greater relative importance in estuarine and coastal systems compared to open sea, whilst other stressors (e.g. Fisheries and Noise) have a relatively higher importance in offshore compared to coastal waters.

Sammenfatning

Denne rapport omhandler kortlægning og rangordning af potentielt kumulative effekter af menneskelige aktiviteter i de danske farvande. Tidligere studier har vurderet de potentielle kumulative effekter af multiple menneskelige aktiviteter i såvel Østersøen (HELCOM HOLAS-projektet; se HELCOM 2010 og Korpinen *et al.* 2012) som i de østlige dele af Nordsøen (HARMONY-projektet; se Andersen & Stock 2013), men har kun på et overordnet plan vurderet de forskellige aktiviteters indbyrdes betydning.

Undersøgelsesområdet er de danske farvande i overgangszonen mellem Nordsøen og Østersøen, hvorfra vi har indsamlet et robust datasæt baseret på eksisterende offentlig tilgængelig information hvad angår både presfaktorer (n = 35) og økosystem-komponenter (n = 47).

Med udgangspunkt i ovennævnte datasæt har vi beregnet de potentielt kumulative effekter af multiple menneskelige aktiviteter samt gjort rede for betydningen af de forskellige presfaktorer. En rangordning baseret på en gruppering af presfaktorer er som følger (1) næringsstoffer, (2) klimaændringer, (3) ikke-hjemmehørende arter, (4) miljøfarlige stoffer (5) fiskeri, (6) mikroplastik, (7) støj, (8) skibstrafik og (9) fysisk modifikation. Vi har desuden analyseret den relative betydning af menneskelige aktiviteter (eksklusiv klimaændringer) langs en gradient fra fjord til åbent hav i 16 case studies. Vi finder at den relative betydning varierer fra land til hav, og at nogle presfaktorer (bl.a. næringsstoffer, ikke-hjemme-hørende arter og mikroplastik i sediment) betyder relativt mere i fjorde og kystvande, mens andre (bl.a. fiskeri og støj) betyder relativt mere i åbne farvande.

Titel: Gradientstudier af menneskelige presfaktorer i danske havområder
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1 Introduction

The Danish marine waters have been systematically monitored since the late 1970's. The first nation-wide programme, Danish National Aquatic Monitoring and Assessment Programme (DNAMAP), was established in 1988 (Andersen 2012).

This programme has been evaluated and revised several times over the past decades (Miljøstyrelsen 1989, 1992 and 2000; Svendsen *et al.* 2005; Naturstyrelsen 2011 and Andersen 2012). The programmes have, in general, had a good temporal and spatial coverage enabling nation-wide annual reporting of the environmental status and of inputs of polluting substances to the aquatic environment.

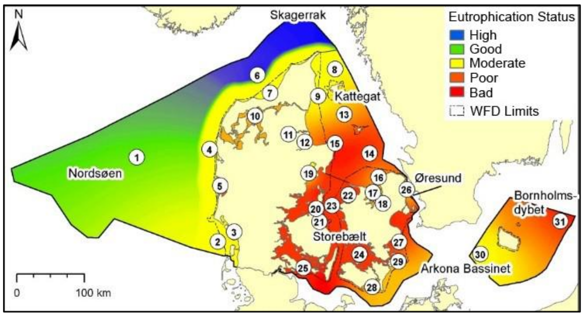
Data originating from DNAMAP has also been used in the context of EU directives, primarily the Marine Strategy Framework Directive (Anon. 2008) but also the Water Framework Directive (Anon. 2000) and in the so-called Initial Assessment required by these two directives.

1.1 Environmental status of Danish marine waters

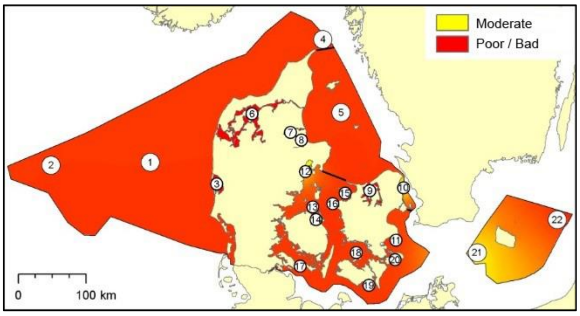
Assessments of environmental status in Danish marine waters are made on a regular basis, often with data sets of appropriate spatial coverage. Both the environmental status and the temporal trends are well understood and well documented (HELCOM 2010, OSPAR 2010 and Naturstyrelsen 2012).

Eutrophication - the effects of nutrient inputs and nutrient enrichment - is a nation-wide problem, where all coastal waters and fjords are classified as 'eutrophication problem areas' (Figure 1.1; panel A). The only non-problem areas with respect to eutrophication are the open parts of the North Sea and the Skagerrak. With respect to marine biodiversity, all Danish marine waters are classified as being moderately or significantly impaired (Figure 1.1; panel B). A key driver behind this impairment is fishing activities. Contamination due to inputs and presence of hazardous substances in sediments and biota has also been assessed in detail (Figure 1.1, panel C). Offshore waters in the North Sea, Skagerrak and Kattegat are generally classified as non-problem areas, while many of the fjords and coastal waters are contaminated.

A – 'eutrophication status'



B – 'biodiversity status'



C – 'chemical status'

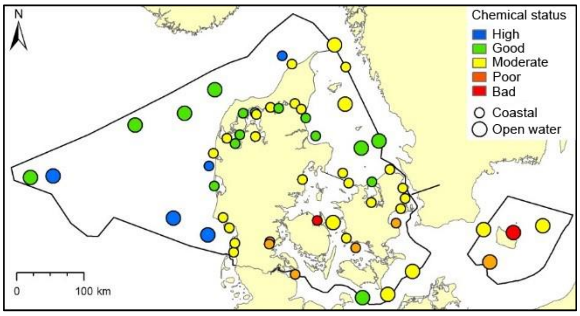


Figure 1.1 *Assessments of 'eutrophication status' (panel A), 'biodiversity status' (panel B) and 'chemical status' (panel C) in Danish marine waters. Panels A, B and C are based on Naturstyrelsen (2012) and Andersen et al. (2013).*

1.2 Human activities and stressors in Danish marine waters

The parts of DNAMAP related to stressors have for decades focused on direct and riverine inputs of polluting substances to marine waters (mostly nutrients, but also some hazardous substances) as well as atmospheric deposition of polluting substances (mostly nitrogen and heavy metals).

A first attempt to address key stressors was carried out in 2000 (Miljøstyrelsen 2000), but not all relevant stressors were included. The first comprehensive endeavours to assess the potential cumulative impact of multiple human stressors for Danish waters were made by HELCOM HOLAS (in the Kattegat, Danish Straits and south-western parts of the Baltic Sea; HELCOM 2010) and by HARMONY (in the North Sea, Skagerrak and Kattegat; Andersen & Stock 2013). Although the results of HOLAS and HARMONY have been merged (see Figure 1.2), the comprehensive study presented here, is in our understanding the first to produce a harmonized nation-wide mapping of the potential cumulative impact of multiple stressors.

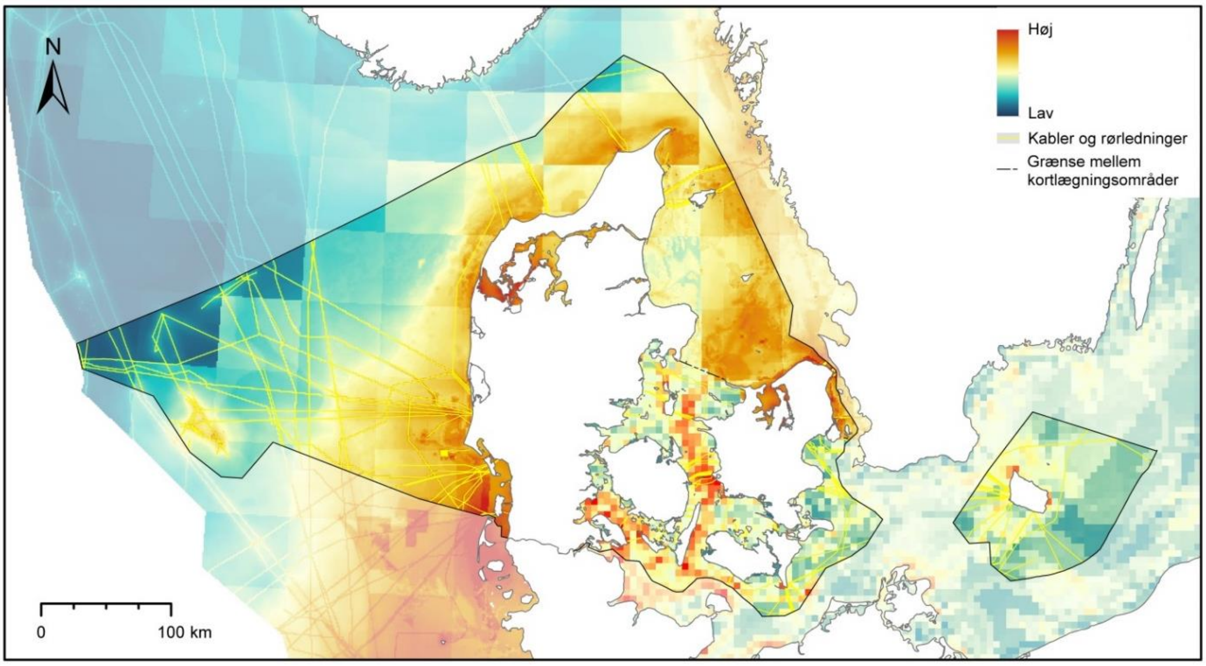


Figure 1.2 *Provisional map of cumulative impacts in Danish marine waters based on HOLAS I (HELCOM 2010) and HARMONY (from Hansen et al. 2013). Please note the difference is spatial resolution – the Danish parts of North Sea, Skagerrak and Kattegat are 1 km x 1 km, while the Danish parts of the Danish Straits and the south-western parts of the Baltic Sea are 5 x 5 km.*

From HOLAS and HARMONY, we learned that the top 4 stressors in Danish marine waters are inputs of nutrients, fishing activities, contaminants and physical modifications. The relative importance varies between sub-areas and basins. For more information, please see Naturstyrelsen (2012) and Hansen *et al.* (2013).

1.3 Objectives

The objectives of this study – building on existing studies of potential cumulative impacts of multiple human stressors in Danish marine waters – were:

- To estimate and map potential cumulative impacts in Danish marine waters
- To rank the relative importance of key human stressors along a land-sea gradient, to indicate the root causes of the impairment documented in the context of the MSFD and WFD.

2 Methodology

The methods for estimation of potential cumulative effects of multiple human stressors are in line with those applied in the HELCOM HOLAS I (HELCOM 2010), HARMONY (Andersen & Stock 2013), TACIA (Andersen *et al.* 2016a) and HELCOM HOLAS II projects, see Korpinen & Andersen (2016) for more information. In this study, we go a step further by estimating the relative importance of key human stressors along gradients from land to offshore marine waters. The cumulative impact assessment (CIA) is based on spatial data for human stressors and ecosystem components in Danish marine waters.

2.1 Study area

This study is carried out in Danish marine waters. The study area consists of the eastern parts of the North Sea, southern parts of the Skagerrak, the western parts of the Kattegat, the northern and central parts of the Danish Straits as well as the south-western parts of the Baltic Sea. Danish marine waters are parts of two larger neighbouring Seas; the North Sea to the north and west and the Baltic Sea to the south east.

The drainage basin of the brackish Baltic Sea is large (about 4 times) compared to the area of the sea. About 85 million people, from 14 countries, nine of which are riparian water states, inhabit the catchment area. As the Baltic Sea drains into the Kattegat (and further to the North Sea) via the Danish Straits, the eastern Danish marine waters are very much affected by the Baltic Sea. Hence, the central Danish marine waters are to a great extent affected by all the activities taking place, both on land and in the marine and coastal waters, for a considerable part of northern Europe. Consequently, the area receives large fractions of land-based pollution such as nutrients and hazardous substances. It is subject to pollution from marine activities e.g. oils spills, both in the North Sea as well as from the Baltic Sea.

The waters around Bornholm in the south-eastern Baltic Sea are situated in two basins: the Bornholm and Arkona Basins. The Bornholm Basin is bounded by a sill between Scania in southern Sweden and Poland and by the island of Bornholm. It has both shallow (20 m) and deep areas (105 m). The Arkona Basin extends from the Kiel Bight to the eastern Gotland Basin, and to the south Danish islands of Falster and Zealand. It is quite shallow with a maximum depth of 55 m.

North of the Arkona Basin are the Danish straits, which consist of the Sound, the Great Belt and the Little Belt areas. The sound is a narrow and shallow strait between Denmark and Scania with a mean depth of 11 m, where approximately 25 % of the water exchanges between Kattegat and the Baltic Sea take place. The primary flow direction is northerly at the surface, but the bottom current is reversed, bringing heavier more saline waters to the Baltic Sea.

The Kattegat area is bounded by the northern Danish peninsula of Jutland to the west, the islands of the Danish Straits to the south and western Sweden in the east.

The Skagerrak is a strait between the southeast coast of Norway, the west coast of Sweden, and the Jutland peninsula of Denmark, located at the threshold between the Kattegat and the North Sea. The depth increases toward the Norwegian coast, reaching over 700 m in the Norwegian Trench.

The North Sea receives freshwater from several European continental watersheds, as well as the British Isles. A large part of the European drainage basin empties into the North Sea, including water from the Baltic Sea. The largest and most important rivers flowing into the North Sea are the Elbe and the Rhine-Meuse.

2.2 Cumulative Impact Assessment

Estimates of potential cumulative impacts of multiple human stressors were calculated as originally described by Halpern at al. (2008 and updated 2015), but updated *sensu* Stock & Micheli (2016). The model was on spatial data for human stressors and ecosystem components.

2.2.1 EcoImpactMapper

EcoImpactMapper (Stock 2016), is an open-source software tool for cumulative assessments of human impacts on ecosystems. It is user-friendly, transparent and relatively easy to learn for someone working routinely with advanced data analyses. Moreover, the analyses can easily be reproduced, if needed (Stock 2016). The program implements the additive model developed by Halpern *et al.* (2008 & 2015), which is a well-established model for human impact assessments of marine ecosystems (Stock & Micheli 2016, Stock 2016). EcoImpactMapper has been tested in Arctic marine waters west and south of Greenland, where results were comparable with those obtained by manual calculations (Stock 2016).

Three kinds of input data are needed for calculations by the CIA model, the first two are spatial data and the third is a table:

- $\boldsymbol{D_i}$ the spatial distribution of stressors. For example, fishing intensity or sea surface temperature anomalies. All stressors are normalized by log(x+1)-transformation and rescaled so that the maximum value is 1.
- $\boldsymbol{e_j}$ the spatial distribution of ecosystem components. For example, data for different kinds of soft-bottom habitats or fish species, either as binomial; presence or absence or continuous, e.g. probabilities of presence or species distribution. All ecosystem components were normalized in the program by log(x+1)-transformation and rescaled so that the maximum value is 1.
- $\boldsymbol{\mu_{i,j}}$ the sensitivity weights, a numerical representation of the sensitivity of ecosystem component *j* to stressor *i*. Setting of the sensitivity weights is described in detail below (2.2.2).

The main analysis incorporated in EcoImpactMapper and further developed by Stock & Micheli (2016) is the dimensionless additive human impact index, $\boldsymbol{I_{Sum}}$, for each cell in the regular grid (*x,y*) estimated for *n* stressors and *m* ecosystem components from Halpern *et al.* (2008):

$$I_{Sum}(x,y) = \sum_{i=1}^{n}\sum_{j=1}^{m} D_i\,(x,y)e_j(x,y)\mu_{i,j} \qquad \text{(Eq. 1)}$$

where D_i is the intensity of stressor *i*, log(x+1)-transformed and normalized to maximum 1, e_j is the value or presence (1) or absence (0) of ecosystem component j, and $\mu_{i,j}$ a the sensitivity weight of ecosystem component j to stressor i.

By log-transforming and normalizing data, the intensities of the stressors were made comparable. Stressors with a point distribution and which had an estimated effect distance of stress (i.e. spatial distribution from point source) were also pre-processed by adding this effect in km according to the values listed in Table 3.3. Stressors with coarse resolution were pre-processed by refining the resolution and in some cases using a smoothing function to eliminate sharp delineation (mainly fishery layers). The ecosystem components were also pre-processed by log(x+1)-transformation and rescaled to maximum 1 so that the response of the ecosystem components was comparable. Similarly, some of the ecosystem components were pre-processed by refining the resolution and smoothing sharp edges (mainly fish and shellfish layers).

For each model, a total impact index was calculated as well as the contribution of each of the stressors to the total index. The contribution of the stressors can be used to rank each stressor based on its contribution to the total CIA index (see also section 2.2.3). The mean human impact index, I_{Mean}, was calculated in a similar way to the additive impact index, I_{Sum} but with the ecological diversity index included, E_{Div}, as shown below:

$$E_{Div}(x,y) = \sum_{j=1}^{m} e_j(x,y) \qquad \text{(Eq. 2)}$$

$$I_{Mean}(x,y) = \sum_{i=1}^{n}\sum_{j=1}^{m}\frac{1}{E_{Div}(x,y)}D_i\,(x,y)e_j(x,y)\mu_{i,j} \qquad \text{(Eq. 3)}$$

For this study, the additive model was used, with the estimated mean impacts, I_{Mean}, calculated as the sum of the impacts divided by the summed ecosystem components present for each grid cell. The size of the grid cell was set to 1 km x 1 km and all input data were in csv table format. A conceptual model of the processing schemes modified from Stock & Micheli (2016) is shown in Figure 2.1. The diversity index can be mapped showing the areas of high and low ecosystem complexity (intensity of the ecosystem components in each grid cell). The areas with the highest stressor intensity can likewise be mapped by calculating the stressor index (sum of individual stressor intensities in each grid cell). The diversity and stressor index were calculated within the program according to Stock & Micheli (2016).

The robustness of the three models in relation to the assumptions and different factors influencing the CIA results have been systematically investigated in Stock & Micheli (2016), and the methods for evaluating the estimates of the cumulative human impact assessment are included in the program. For example, the interaction between factors and the calculation of the sum or mean of the impacts on the present system was found to be influential on the results. Hence, they recommend using the described uncertainty and sensitivity analyses included in the program and the developed models when conducting a cumulative impact assessment. In this study, the uncertainty of the CIA results was estimated by Monte Carlo simulation, described in more detail in section 3.2.

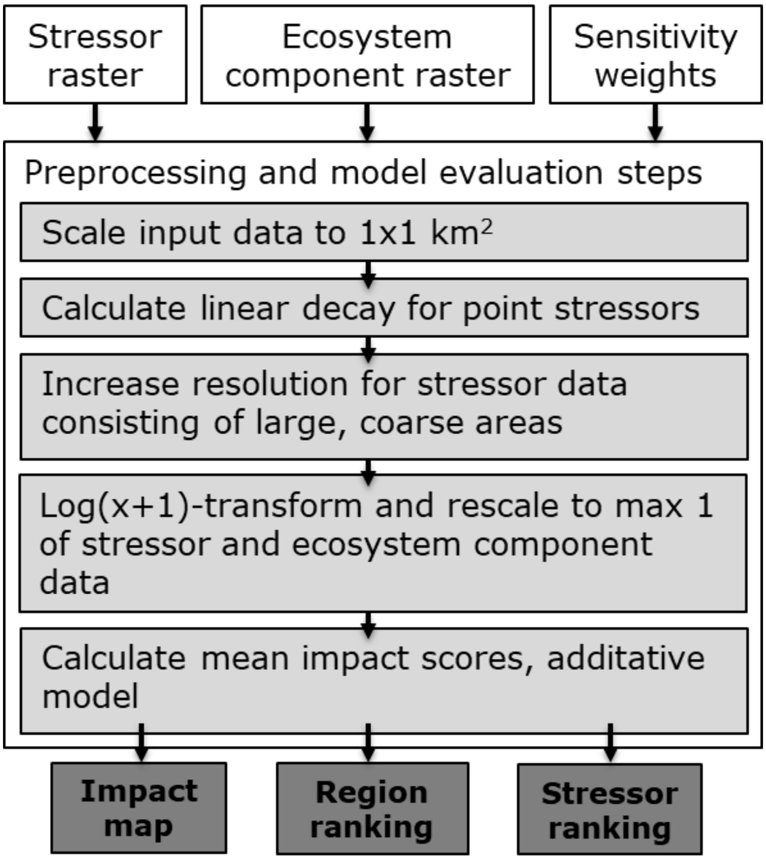


Figure 2.1 *Showing a conceptual model of data pre-processing steps for the human cumulative impact analyses in this study. Based on Stock & Micheli 2016.*

2.2.2 Setting of sensitivity weights and effect distances

As described above, the EcoImpactMapper requires two types of spatial data to calculate the potential cumulative impact within a grid cell: (1) Stressor data layers, and (2) ecosystem component data layers.

These two types of data layers are combined through the setting of stressor- and ecosystem component-specific sensitivity weights. The sensitivity weights represent the sensitivity of each ecosystem component to a specific stressor (Halpern *et al.* 2007 and Teck *et al.* 2010).

Hence, we have created a matrix of 35 stressors and 47 ecosystem component layers and have asked 12 experts to use their best judgement to provide a sensitivity score for each combination of stressor and ecosystem component (1 = very low (or zero); 2 = low; 3 = moderate; 4 = high; and 5 = very high). Further, the experts have been asked to estimate the 'effect distance', i.e. the maximum distance from where a stressor is located to where it potentially might have an effect (effect distance: local (< 1 km); > 1 km; > 5 km; > 10 km; > 25 km; and > 50 km).

Based on the replies received, we calculated the median sensitivity weight for each combination of stressor and ecosystem component as well as the median effect distance for each stressor (see Annex 3).

2.2.3 Ranking of stressors

The ranking of stressors was based on the contribution of each stressor to the total cumulative impact index for every grid cell. Hence, the impact from different stressors can be analysed for all Danish waters, regionally and for specific areas relative to the total CIA. The stressor ranks show the importance of their effects on all the ecological components, in relation to the total impacts from all stressors. Stressor ranks are indicated for each stressor. Stressor ranks have been calculated based on the CIA from EcoImpactMapper.

The ranking is made for Danish waters as a whole, for 3 regions (North Sea/Skagerrak, Kattegat and Baltic Sea) and for the following individual case studies with neighbouring coastal and offshore water indicated in parenthesis:

1. Aabenraa Fjord (southern parts of the Little Belt)
2. Augustenborg Fjord / Als Fjord (southern parts of the Little Belt)
3. Horsens Fjord (northern parts of the Great Belt)
4. Isefjord (southern parts of the Kattegat)
5. Kalundborg Fjord (northern parts of the Great Belt)
6. Karrebæk Fjord / Karrebæksminde Bay (Smålandsfarvandet, southern parts of the Great Belt)
7. Kolding Fjord (central parts of the Little Belt)
8. Limfjord, western parts (eastern parts of the North Sea)
9. Limfjord, eastern parts (Ålborg Bay, northern parts of the Kattegat)
10. Mariager Fjord (Ålborg Bay, central parts of the Kattegat)
11. Odense Fjord (northern parts of the Great Belt)
12. Præstø Fjord (Fakse Bay, Arkona Basin)
13. Randers Fjord (Hevring Bay, central parts of the Kattegat)
14. Ringkøbing Fjord (coastal parts of the eastern North Sea, open part of the North Sea)
15. Roskilde Fjord (northern part of Isefjord, southern parts of the Kattegat)
16. Vejle Fjord (northern parts of the Little Belt)

A map of the case studies can be found in Annex 4 showing the routes of fjord-coast-open water 'transects'.

2.3 Data sources and processing

This study is based primarily on pre-existing data sets for stressors and ecosystem components in Danish marine waters. Two key data sources are the HARMONY project (2009-2012; see Andersen & Stock 2013) and the SYMBIOSE project (2012-2013; see Mohn *et al.* 2015). However, some data set are generated by other projects and institutions, e.g. fish and fisheries (DTU Aqua, Dalskov *et al.* 2012 & Warnar *et al.* 2012), contaminants (EMODnet Chemistry project, see Andersen *et al.* 2016b), benthic habitats (EUSeaMap 2 project; data provided through Zyad Al-Hamdani, GEUS), winter DIN concentrations as a proxy for inputs of nitrogen (ICES Oceanographic database 2016) and winter DIP concentrations as a proxy for phosphorus inputs (ICES Oceanographic database 2016). The origin of the 82 data layers is outlined in Table 2.1.

Table 2.1 *Source of the stressor and ecosystem component layers used in the report.*

Source	Reference	Stressors	Ecosystem components	Total
DTU Aqua	Dahlskov *et al.* (2012) and Warnar *et al.* (2012)	12	21	33
HARMONY	Andersen & Stock (2013)	2	5	7
SYMBIOSE	Mohn *et al.* (2015)	11	11	22
EUSeaMap 2	Al-Hamdani (2016)	-	8	8
RALAHA	This study	10	2	12
Total		35	47	82

The processing of data from each source is described in the following section. Further, we list all individual data sets and document their origin with references to where they have been collated and/or published (stressors; Table 2.2 and ecosystem components; Table 2.3). A detailed description of the individual data sets can be found in Annex 2.

Stressor data from HARMONY (S: 17, 20) was updated with the latest available information. Thereby, data covering the entire Danish marine area was achieved. A few small estuaries and coastal embayments are not included due to poor data coverage (e.g. Kertinge Nor, Korsør Nor, Lindelse Nor, Norsminde Fjord, etc.). Data for ecosystem components (EC: 38-40 & 46-47) was used without any processing. This means that data for the modelled probability of these 5 ecosystem components covered only the North Sea.

Data from DTU Aqua was converted from raster data in grid format to a csv-file in ArcGIS. The same procedure was applied for fish data (EC: 13-33) as well as fishery data (S: 24-35)

Data from SYMBIOSE (EC:10, 12, 34-37, 41-45 & S: 1-2, 5, 8-9, 11-13, 18, 21, 23) was obtained by image analysis of pictures of data layers in the appendices of the report. The colour nuance of every grid cell was converted to a value, based on the colour scale and associated values given in the legends. Thereby, a map of every data layer was achieved. All data processing was carried out in the statistical software 'R' using the packages "dplyr", "png", "tidyr", "data.table" and "raster".

Data from EUSeaMap 2 was provided as shapefiles. The 37 habitat types were merged in ArcGIS to the 8 habitat types used in present study. Each habitat was converted to a specific layer (Table 2.3, EC 1-8). Since no estuary habitat existed, an estuary layer was generated (EC: 9) in ArcGIS containing selected fjords, estuaries, and semi-enclosed bays.

RALAHA layers were of varied origin. Some were downloaded from MiljøGIS as shapefiles (S: 4, 6, 15-16, 22), while others were produced from other data sources (S: 3, 7, 10, 14, 19 & EC: 9, 11). The data source and data processing for specific layers are stated in Annex 2.

All stressor and ecosystem component files were converted to csv format before being imported to the software EcoImpactMapper.

Table 2.2 *List of stressors (n = 35) used in this study and their origin. In the column 'source', we indicate the origin of the data used to establish the maps used in this study (see Annex 2 for details).*

No.	Stressors	Source	Reference
1.	Bridges and coastal dams	SYMBIOSE	Mohn *et al.* (2015)
2.	Climate anomalies	SYMBIOSE	Mohn *et al.* (2015)
3.	Contaminants	RALAHA	Andersen *et al.* (2016b)
4.	Dredged material disposal sites	RALAHA	MiljøGIS (2016)
5.	Dumped chemical munitions	SYMBIOSE	Mohn *et al.* (2015)
6.	Industrial ports	RALAHA	MiljøGIS (2016)
7.	Marine aquaculture sites	RALAHA	DVFA (2017)
8.	Microplastic in sediments	SYMBIOSE	Mohn *et al.* (2015)
9.	Military areas	SYMBIOSE	Mohn *et al.* (2015)
10.	Nitrogen winter concentrations (DIN)	RALAHA	-
11.	Noise (bang days)	SYMBIOSE	Mohn *et al.* (2015)
12.	Noise (ship sound 63 Hz)	SYMBIOSE	Mohn *et al.* (2015)
13.	Noise (ship sound 125 Hz)	SYMBIOSE	Mohn *et al.* (2015)
14.	Non-indigenous species	RALAHA	-
15.	Offshore oil and gas installations	RALAHA	DEA (2017)
16.	Offshore wind turbines	RALAHA	DEA (2017)
17.	Oil and gas pipelines	HARMONY	Andersen & Stock (2013)
18.	Oil spills	SYMBIOSE	Mohn *et al.* (2015)
19.	Phosphorus winter concentrations (DIP)	RALAHA	-
20.	Recreational shipping	HARMONY	Andersen & Stock (2013)
21.	Sea cables	SYMBIOSE	Mohn *et al.* (2015)
22.	Sediment extraction sites	RALAHA	Miljøportalen (2016)
23.	Shipping intensity (commercial shipping)	SYMBIOSE	Mohn *et al.* (2015)
24.	Beam trawls (mesh size <32 mm)	DTU Aqua	Dalskov *et al.* (2012)
25.	Beam trawls (mesh size ≥100 mm)	DTU Aqua	Dalskov *et al.* (2012)
26.	Demersal fishing (mesh size <16 mm)	DTU Aqua	Dalskov *et al.* (2012)
27.	Demersal fishing (mesh size 16-32 mm)	DTU Aqua	Dalskov *et al.* (2012)
28.	Demersal fishing (mesh size 33-69 mm)	DTU Aqua	Dalskov *et al.* (2012)
29.	Demersal fishing (mesh size 70-99 mm)	DTU Aqua	Dalskov *et al.* (2012)
30.	Demersal fishing (mesh size ≥ 100 mm)	DTU Aqua	Dalskov *et al.* (2012)
31.	Longlines	DTU Aqua	Dalskov *et al.* (2012)
32.	Mussel dredging	DTU Aqua	Dalskov *et al.* (2012)
33.	Pelagic fishing (mesh size 16-32 mm)	DTU Aqua	Dalskov *et al.* (2012)
34.	Pelagic fishing (mesh size 33-80 mm)	DTU Aqua	Dalskov *et al.* (2012)
35.	Set net (all mesh sizes)	DTU Aqua	Dalskov *et al.* (2012)

Table 2.3 *List of ecosystem components (n = 47) used in this study and their origin. In the column 'source', we indicate the origin of the data used to establish the maps used in this study (see Annex 2 for details).*

No.	Ecosystem component	Source	Reference
1.	Communities - infralittoral hard bottom	EUSeaMap 2	Al-Hamdani (2016)
2.	Communities - infralittoral sand	EUSeaMap 2	Al-Hamdani (2016)
3.	Communities - infralittoral mud	EUSeaMap 2	Al-Hamdani (2016)
4.	Communities - infralittoral mixed sediments	EUSeaMap 2	Al-Hamdani (2016)
5.	Communities - circalittoral hard bottom	EUSeaMap 2	Al-Hamdani (2016)
6.	Communities - circalittoral sand	EUSeaMap 2	Al-Hamdani (2016)
7.	Communities - circalittoral mud	EUSeaMap 2	Al-Hamdani (2016)
8.	Communities - circalittoral mixed sediments	EUSeaMap 2	Al-Hamdani (2016)
9.	Communities associated with estuaries	RALAHA	-
10.	Eelgrass distribution, *Zostera marina*	SYMBIOSE	Mohn *et al.* (2015)
11.	Oxygen deficit	RALAHA	-
12.	Plankton communities in sea water	SYMBIOSE	Mohn *et al.* (2015)
13.	Cod, *Gadus morhua*	DTU Aqua	Warnar *et al.* (2012)
14.	Coalfish, *Pollachius virens*	DTU Aqua	Warnar *et al.* (2012)
15.	Common Hooknose, *Agonus cataphractus* and monkfish, *Lophius piscatorius*	DTU Aqua	Warnar *et al.* (2012)
16.	Common Sole, *Solea solea*	DTU Aqua	Warnar *et al.* (2012)
17.	Dab, *Limanda limanda*	DTU Aqua	Warnar *et al.* (2012)
18.	Common Dogfish, *Scyliorhinus caniculus*	DTU Aqua	Warnar *et al.* (2012)
19.	Spiny Dogfish, *Squalus acanthias*	DTU Aqua	Warnar *et al.* (2012)
20.	Flounder, *Platichthys flesus*	DTU Aqua	Warnar *et al.* (2012)
21.	Haddock, *Melanogrammus aeglefinus*	DTU Aqua	Warnar *et al.* (2012)
22.	Herring, *Clupea harengus*	DTU Aqua	Warnar *et al.* (2012)
23.	Lumpfish, *Cyclopterus lumpus*	DTU Aqua	Warnar *et al.* (2012)
24.	Mackerel, *Scomber scombrus*	DTU Aqua	Warnar *et al.* (2012)
25.	Northern Prawn, *Pandalus borealis*	DTU Aqua	Warnar *et al.* (2012)
26.	Norway Lobster, *Nephrops norvegicus*	DTU Aqua	Warnar *et al.* (2012)
27.	Norway Pout, *Trisopterus esmarkii*	DTU Aqua	Warnar *et al.* (2012)
28.	Plaice, *Pleuronectes platessa*	DTU Aqua	Warnar *et al.* (2012)
29.	Shrimp, *Crangon crangon*	DTU Aqua	Warnar *et al.* (2012)
30.	Sprat, *Sprattus sprattus*	DTU Aqua	Warnar *et al.* (2012)
31.	Starry Ray, *Raja radiata*	DTU Aqua	Warnar *et al.* (2012)
32.	Turbot, *Psetta maxima*	DTU Aqua	Warnar *et al.* (2012)
33.	Whiting, *Merlangius merlangus*	DTU Aqua	Warnar *et al.* (2012)
34.	Auks, Alcidae	SYMBIOSE	Mohn *et al.* (2015)
35.	Common scoter, *Melanitta nigra*	SYMBIOSE	Mohn *et al.* (2015)
36.	Divers, Gavia	SYMBIOSE	Mohn *et al.* (2015)
37.	Eider, *Somateria mollissima*	SYMBIOSE	Mohn *et al.* (2015)
38.	Fulmar, *Fulmarus glacialis*	HARMONY	Andersen & Stock (2013)
39.	Gannet, *Morus bassanus*	HARMONY	Andersen & Stock (2013)
40.	Kittiwake, *Rissa tridactyla*	HARMONY	Andersen & Stock (2013)
41.	Long-tailed Duck, *Clangula hyemalis*	SYMBIOSE	Mohn *et al.* (2015)
42.	Red-breasted Merganser, *Mergus serrator*	SYMBIOSE	Mohn *et al.* (2015)
43.	Grey Seal, *Halichoerus grypus*	SYMBIOSE	Mohn *et al.* (2015)
44.	Harbour Seal, *Phoca vitulina*	SYMBIOSE	Mohn *et al.* (2015)
45.	Harbour Porpoise, *Phocoena phocoena*	SYMBIOSE	Mohn *et al.* (2015)
46.	Minke Whale, *Balaenoptera acutorostrata*	HARMONY	Andersen & Stock (2013)
47.	White-beaked Dolphin, *Lagenorhynchus albirostris*	HARMONY	Andersen & Stock (2013)

3 Results

The study covers Danish marine waters, excluding some small estuaries and coastal embayments. The analyses carried out are based on a comprehensive data set which includes 35 spatial data layers representing key stressors, and 47 data layers representing ecologically relevant ecosystem components.

The stressor index represents the sum of intensities of all processed stressor layers in each grid cell. The resulting map of the stressor index (Figure 3.1) shows the spatial distribution of human stressors.

Some stressors with point locations or local distributions have an effect outside the physical location of the stressor e.g. industrial harbours. In these cases (1, 4-7, 9, 11, 15-16, 20, 22, 32), an effect distance was applied. The effect distances are based on the answers from the expert survey. Median values in km, were applied to the stressors marked with a * in Table 3.3. For detailed results see Table 3.3.

The areas with the highest cumulative stressor intensities are found in the northern parts of the Danish parts of Skagerrak, eastern parts of the Kattegat and the north-western areas of the Danish parts of the Baltic Sea around Bornholm and the southern part and the western Baltic Sea (Figure 3.1). Many of the areas are located in coastal areas or areas with intense fishery or along the main shipping routes.

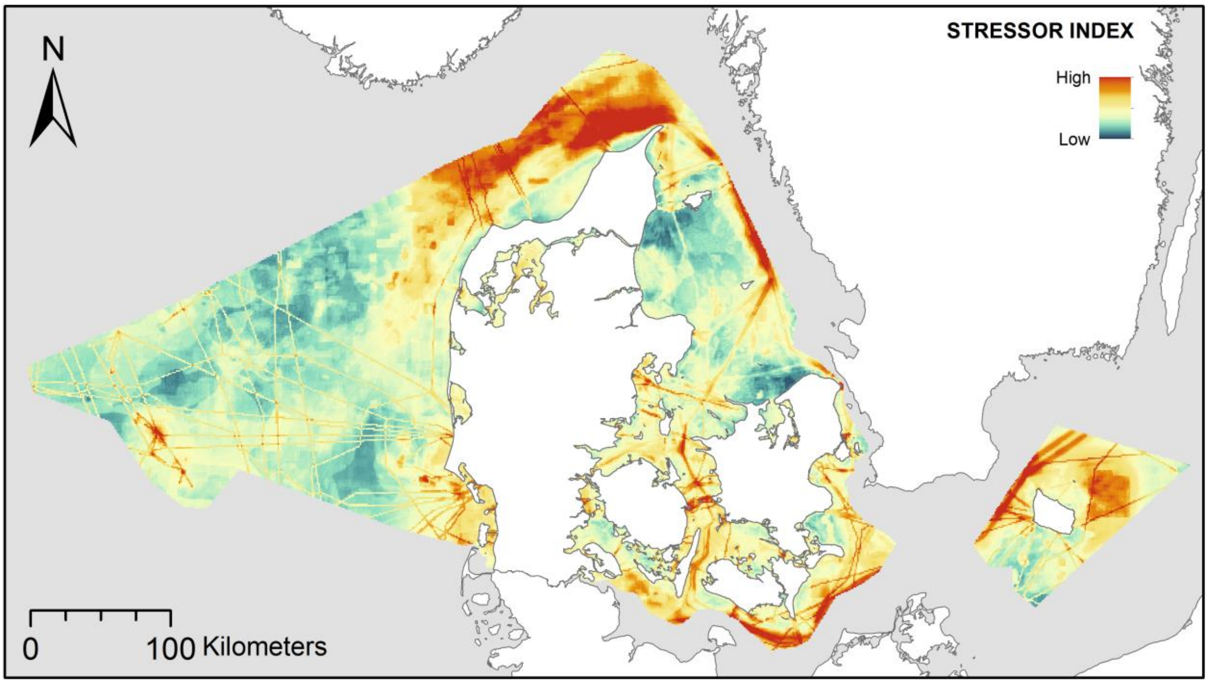


Figure 3.1 *Stressor index showing the areas with highest intensity of stressors from human activities (sum of individual stressor intensities). The results are based on all 35 stressor layers. Red areas indicate higher stressor intensity whereas blue areas indicate a lower stressor intensity.*

Similarly, a map of the Ecosystem Complexity Index can be produced, reflecting the spatial variation in the number of ecosystem components (Figure 3.2). The ecosystem complexity index is calculated as the sum of the ecosystem component data layers within each grid cell. The areas with the highest ecosystem complexity are mainly found in Kattegat and in the south-western parts of the Baltic sea (Great Belt and Little Belt).

The rectangular patterns in Figure 3.2 are due to the coarse resolution of the fish population density layers. The rectangular area of high complexity, shown with a red colour, on the west coast is due to high population density of some fish species (e.g. Common Hooknose (*Agonus cataphractus)* and Common Sole (*Solea solea)*).

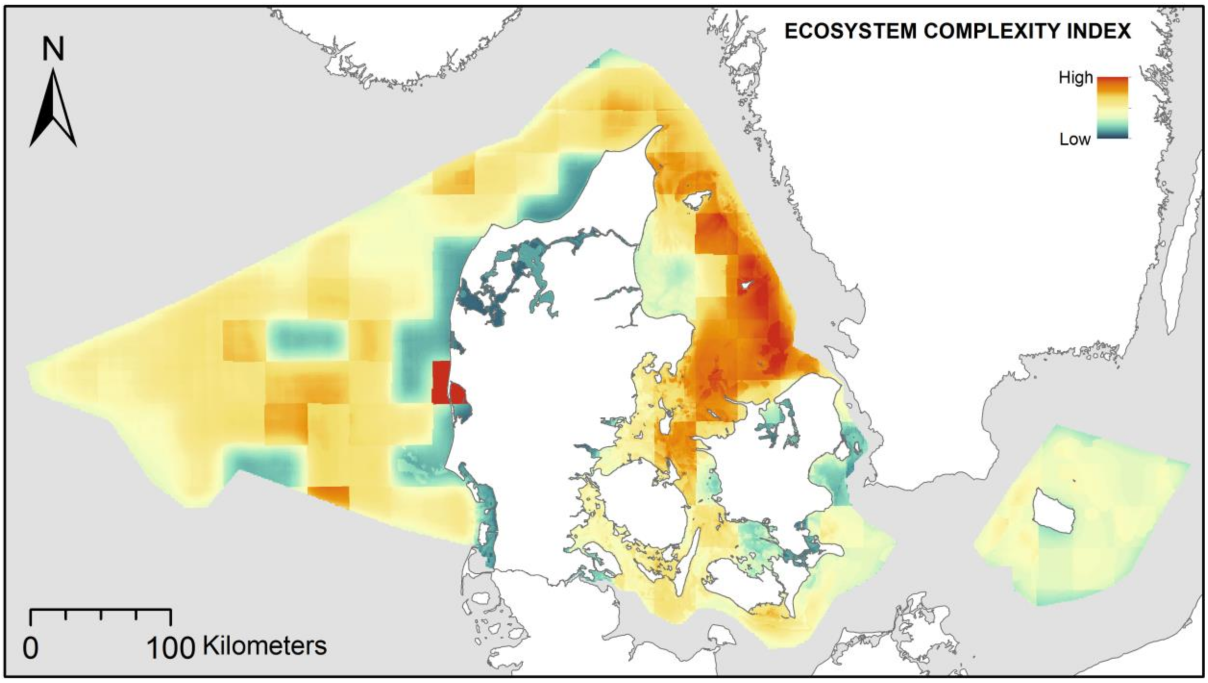


Figure 3.2 *Ecosystem complexity index showing the sum of the ecosystem components. Red areas indicate higher ecosystem complexity (more ecosystem components are present or higher abundances/ concentrations) whereas blue areas indicate a lower ecosystem complexity (less ecosystem components are present or lower abundances/concentrations). Please note that this map is based on data that has not been normalized or log(x+1)-transformed.*

The impact of stressors on ecosystems components is determined through the setting of sensitivity weights, where each weight represents the relative sensitivity of a single ecosystem component to a single stressor (see section 2.2.2). The average, minimum and maximum sensitivity to each stressor, averaged over all ecosystem components, is shown in Table 3.2. The average, min and max sensitivity of each ecosystem component, averaged over all stressor components, are presented in Table 3.3.

3.1 Mapping of potential cumulative impacts

All stressors and ecosystem layers together with the sensitivity weights were used to estimate the cumulative human impact based on the additive mean model (see section 2.2) and the results are presented in Figure 3.3 and Figure 3.4 and in section 3.3.

Climate anomalies, here represented by 'sea surface temperature anomalies', are an exogenic stressor acting on a spatial scale larger than the region in which the study area is located. Consequently, any abatement measures (e.g. reductions in CO_2 emissions) will have to take place on a scale greater than that of the study area. Therefore, we have mapped the potential cumulative impacts using two slightly different models, one including climate anomalies and one without.

For the model including Climate anomalies (Figure 3.3) the areas most affected by human pressures (i.e. areas with the highest impact index) cover most estuaries, fjords and coastal areas in Denmark. The more offshore areas with high impact are found in North Wadden Sea, eastern North Sea, Kattegat, the south-western parts of the Baltic Sea (Great Belt and Little Belt) as well as around Bornholm.

The model without climate anomalies (Figure 3.4) showed the same main patterns but with a lower overall impact in the off-shore areas of the North Sea as well as a substantially smaller impact in the areas around Bornholm.

Table 3.1 *Effect distance of stressors used in the study. Star (*) indicates that a spreading effect (distance, km) of the stressor has been implemented in the model. For the other stressors, the effect distances were either already accounted for in the input data layer or the median effects were 0 km.*

No.	Effect distance per stressor	Median	Max	Min
1.	Bridges and coastal dams *	1 km	25 km	0 km
2.	Climate anomalies	10 km	25 km	1 km
3.	Contaminants	5 km	50 km	0 km
4.	Dredged material disposal sites *	5 km	10 km	0 km
5.	Dumped chemical munitions *	1 km	5 km	0 km
6.	Industrial ports *	5 km	10 km	0 km
7.	Marine aquaculture sites *	5 km	5 km	0 km
8.	Microplastic in sediments	0 km	1 km	0 km
9.	Military areas *	10 km	50 km	0 km
10.	Nitrogen winter concentrations (DIN)	25 km	50 km	0 km
11.	Noise (bang days) *	10 km	50 km	0 km
12.	Noise (ship sound 63 Hz)	10 km	10 km	0 km
13.	Noise (ship sound 125 Hz)	10 km	50 km	0 km
14.	Non-indigenous species	10 km	50 km	0 km
15.	Offshore oil and gas installations *	1 km	5 km	0 km
16.	Offshore wind turbines *	1 km	5 km	0 km
17.	Oil and gas pipelines	0 km	1 km	0 km
18.	Oil spills	10 km	50 km	10 km
19.	Phosphorus winter concentrations (DIP)	0 km	25 km	0 km
20.	Recreational shipping *	1 km	1 km	0 km
21.	Sea cables	0 km	0 km	0 km
22.	Sediment extraction sites *	1 km	10 km	0 km
23.	Shipping intensity	5 km	10 km	0 km
24.	Beam trawls (mesh size <32 mm)	0 km	1 km	0 km
25.	Beam trawls (mesh size ≥100 mm)	0 km	1 km	0 km
26.	Demersal fishing (mesh size <16 mm)	0 km	1 km	0 km
27.	Demersal fishing (mesh size 16-32 mm)	0 km	1 km	0 km
28.	Demersal fishing (mesh size 33-69 mm)	0 km	1 km	0 km
29.	Demersal fishing (mesh size 70-99 mm)	0 km	1 km	0 km
30.	Demersal fishing (mesh size ≥ 100 mm)	0 km	1 km	0 km
31.	Longlines	0 km	25 km	0 km
32.	Mussel dredging *	1 km	25 km	0 km
33.	Pelagic fishing (mesh size 16-32 mm)	0 km	25 km	0 km
34.	Pelagic fishing (mesh size 33-80 mm)	0 km	25 km	0 km
35.	Set net (all mesh sizes)	0 km	25 km	0 km

Table 3.2 *Sensitivity to stressors, averaged over ecosystem components, based on the sensitivity weights.*

No.	Stressor	Average	Min	Max
1.	Bridges and coastal dams	1.9	1.3	3.0
2.	Climate anomalies	2.7	1.8	3.2
3.	Contaminants	2.5	1.9	3.2
4.	Dredged material disposal sites	2.1	1.5	3.3
5.	Dumped chemical munitions	1.6	1.3	2.8
6.	Industrial ports	1.9	1.5	3.0
7.	Marine aquaculture sites	2.0	1.5	3.5
8.	Microplastic in sediments	2.4	1.5	2.8
9.	Military areas	2.1	1.4	3.0
10.	Nitrogen winter concentrations (DIN)	3.0	2.4	4.3
11.	Noise (bang days)	2.4	1.6	3.9
12.	Noise (ship sound 63 Hz)	2.2	1.3	3.6
13.	Noise (ship sound 125 Hz)	2.1	1.2	3.6
14.	Non-indigenous species	2.4	1.6	3.6
15.	Offshore oil and gas installations	1.8	1.3	2.3
16.	Offshore wind turbines	2.0	1.5	2.6
17.	Oil and gas pipelines	2.0	1.5	2.5
18.	Oil spills	2.5	1.6	4.6
19.	Phosphorus winter concentrations (DIP)	2.5	1.6	4.3
20.	Recreational shipping	2.2	1.6	3.4
21.	Sea cables	1.9	1.5	2.5
22.	Sediment extraction sites	2.1	1.5	3.0
23.	Shipping intensity	2.4	1.6	6.8
24.	Beam trawls (mesh size <32 mm)	2.6	1.5	3.9
25.	Beam trawls (mesh size ≥100 mm)	2.6	1.5	3.9
26.	Demersal fishing (mesh size <16 mm)	2.7	1.5	3.9
27.	Demersal fishing (mesh size 16-32 mm)	2.7	1.5	3.9
28.	Demersal fishing (mesh size 33-69 mm)	2.6	1.5	3.9
29.	Demersal fishing (mesh size 70-99 mm)	2.6	1.5	3.9
30.	Demersal fishing (mesh size ≥ 100 mm)	2.6	1.5	3.9
31.	Longlines	2.7	1.7	4.2
32.	Mussel dredging	2.3	1.7	3.4
33.	Pelagic fishing (mesh size 16-32 mm)	2.7	1.8	3.5
34.	Pelagic fishing (mesh size 33-80 mm)	2.7	1.8	3.5
35.	Set net (all mesh sizes)	2.6	1.8	3.9

Table 3.3 *Average ecosystem sensitivity averaged over stressors, based on the sensitivity weights.*

No.	Ecosystem component	Average	Min	Max
1.	Plankton communities in sea water	2.5	1.7	3.9
2.	Communities - infralittoral hard bottom	2.4	1.6	4.0
3.	Communities - infralittoral sand	2.3	1.6	4.0
4.	Communities - infralittoral mud	2.5	1.6	4.1
5.	Communities - infralittoral mixed sediments	2.4	1.5	4.1
6.	Communities - circalittoral hard bottom	2.2	1.6	3.4
7.	Communities - circalittoral sand	2.3	1.7	3.4
8.	Communities - circalittoral mud	2.3	1.7	3.5
9.	Communities - circalittoral mixed sediments	2.3	1.6	4.0
10.	Communities associated with estuaries	2.2	1.7	3.4
11.	Eelgrass distribution, *Zostera marina*	2.4	1.5	4.2
12.	Oxygen deficit	2.1	1.5	4.3
13.	Cod, *Gadus morhua*	2.5	1.5	3.6
14.	Coalfish, *Pollachius virens*	2.5	1.4	3.8
15.	Common Hooknose, *Agonus cataphractus* and monkfish, *Lophius piscatorius*	2.4	1.2	3.8
16.	Common Sole, *Solea solea*	2.5	1.6	3.6
17.	Dab, *Limanda limanda*	2.5	1.6	3.6
18.	Common Dogfish, *Scyliorhinus caniculus*	2.3	1.3	3.6
19.	Spiny Dogfish, *Squalus acanthias*	2.3	1.3	3.8
20.	Flounder, *Platichthys flesus*	2.5	1.6	3.6
21.	Haddock, *Melanogrammus aeglefinus*	2.4	1.5	3.7
22.	Herring, *Clupea harengus*	2.5	1.4	3.6
23.	Lumpfish, *Cyclopterus lumpus*	2.4	1.2	4.2
24.	Mackerel, *Scomber scombrus*	2.5	1.5	3.7
25.	Northern Prawn, *Pandalus borealis*	2.2	1.3	3.2
26.	Norway Lobster, *Nephrops norvegicus*	2.4	1.3	6.8
27.	Norway Pout, *Trisopterus esmarkii*	2.5	1.6	3.4
28.	Plaice, *Pleuronectes platessa*	2.3	1.3	3.5
29.	Shrimp, *Crangon crangon*	2.5	1.2	3.9
30.	Sprat, *Sprattus sprattus*	2.5	1.4	3.9
31.	Starry Ray, *Raja radiata*	2.4	1.2	4.0
32.	Turbot, *Psetta maxima*	2.5	1.6	3.6
33.	Whiting, *Merlangius merlangus*	2.5	1.4	4.0
34.	Auks, Alcidae	2.2	1.3	4.6
35.	Common scoter, *Melanitta nigra*	2.2	1.5	4.6
36.	Divers, Gavia	2.2	1.5	4.6
37.	Eider, *Somateria mollissima*	2.2	1.5	4.6
38.	Fulmar, *Fulmarus glacialis*	2.2	1.3	4.6
39.	Gannet, *Morus bassanus*	2.2	1.5	4.6
40.	Kittiwake, *Rissa tridactyla*	2.2	1.5	4.6
41.	Long-tailed Duck, *Clangula hyemalis*	2.2	1.5	4.6
42.	Red-breasted Merganser, *Mergus serrator*	2.2	1.5	4.6
43.	Grey Seal, *Halichoerus grypus*	2.5	1.6	3.9
44.	Harbour Seal, *Phoca vitulina*	2.5	1.6	3.9
45.	Harbour Porpoise, *Phocoena phocoena*	2.4	1.6	3.5
46.	Minke Whale, *Balaenoptera acutorostrata*	2.1	1.4	3.9
47.	White-beaked Dolphin, *Lagenorhynchus albirostris*	2.1	1.4	3.9

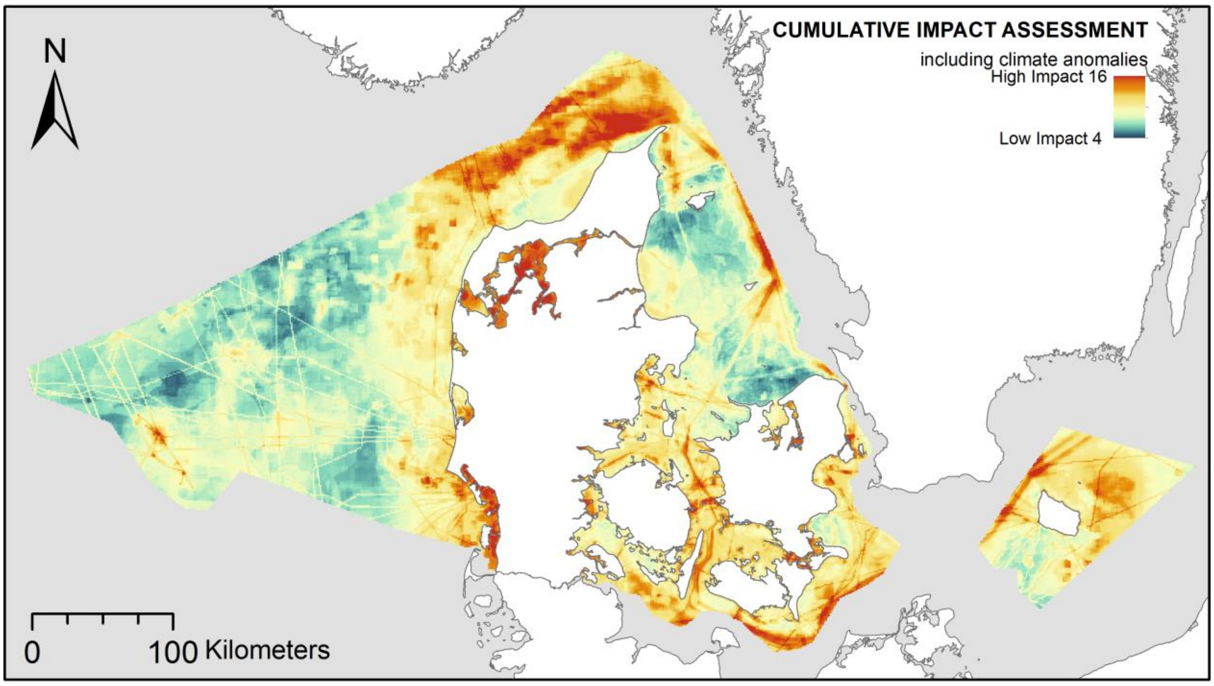


Figure 3.3 *Spatial variations in cumulative impacts in Danish marine waters, including climate anomalies. Red colours indicate areas of high impact and blue colours indicate areas with low impact.*

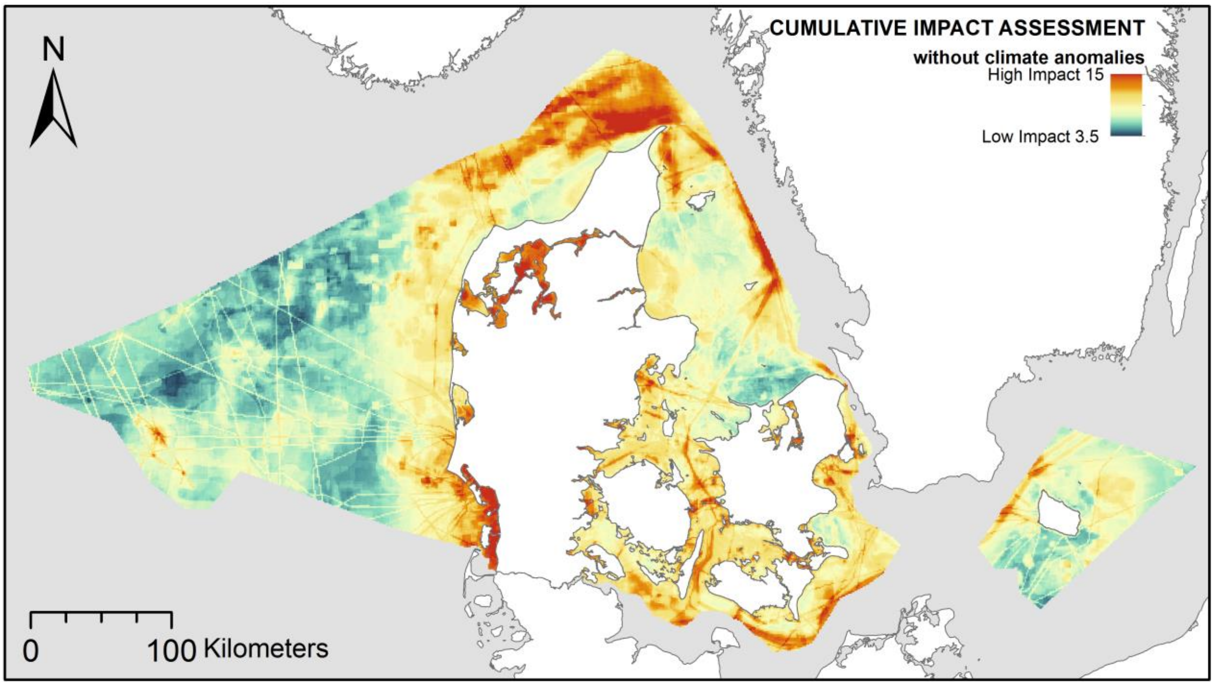


Figure 3.4 *Spatial variations in cumulative impacts in Danish marine waters, without the stressor climate anomalies. Red colours indicate areas of high impact and blue colours indicate areas with low impact. Please note that the scale differs from the scale used in Figure 3.3.*

The stressors were further analysed to determine their individual contributions to the total impact and to rank them, showing those having the highest impact. The results of this analysis are shown in Section 3.3.

3.2 Uncertainty analysis

In order to evaluate the robustness of the CIA analyses for Danish marine waters, 1000 randomly chosen Monte Carlo simulations were run to quantify the uncertainty of the results. These uncertainty analyses included possible problems in data quality (e.g. coarse resolution, missing input layers) and effects of model assumptions. The simulations were done in two threads, one including climate anomalies and one without. Within each simulation, different effects modifying the CIA calculation were randomly included:

- Randomly exclude up to 1/3 of stressor layers.
- Introduce a sensitivity weight error with a factor between 0 and 0.5, i.e. from 0 to half of the original weight.
- Vary effect distance of stress between 0 - 20 km (only applied to the stressors with an effect distance included).
- Vary model effects by using sum or mean of impacts.
- Reduce analyses resolution of the model grid from 1 to 2 km.
- Improved stressor resolution from original (varied among the stressor layers) by a 25 x 25 km low pass filter.

The results from the Monte Carlo simulations for the CIA model including Climate anomalies showed that the stressor layers Nitrogen winter concentrations (DIN), Non-indigenous species, Climate anomalies, Phosphorus winter concentrations (DIP) and Oils spills were the 5 most important stressors. They were placed in the top 25th percentile of stressors in 100% of the 1000 simulations. Other important stressors were Noise, Microplastic in sediments, Contaminants, Shipping intensity and different fishing activities. The stressors with the lowest simulated impact were various physical modifications and fishing by longlines. All results are presented in Table 3.4.

The results from the 1000 Monte Carlo simulations for the CIA model without Climate anomalies showed that the stressor layers Nitrogen winter concentrations (DIN), Non-indigenous species, Phosphorus winter concentrations (DIP), Noise (bang days), Microplastic in sediments and Oil spills were the 6 most important stressors, appearing in top 25th percentile of stressors in 100% of simulations. Other important stressors were Contaminants, Shipping intensity and Fisheries. The stressors with the lowest simulated impact were again connected to Physical modifications and Fishing by longlines. All results are presented in Table 3.5.

The results from the uncertainty analyses showed that the same two stressors having the greatest and the least impact in the simulations were consistent and in line with the results from our CIA model. Hence, our model for mapping the potential cumulative human impacts in Danish marine waters is robust and the results from the CIA are sound. Once the CIA model results were quality assured we moved on to rank the stressors and estimate the impact from each group of stressors (section 3.3) as well as to take the next step and analyse the changes in the relative spatial impact along gradients from land to offshore marine waters (section 3.4).

3.3 Ranking of cumulative impacts

The ranking of stressors indicates which ones have the most and least contribution to the total impact. We ranked all 35 stressor layers according to their contribution to the total cumulative impact for Danish waters (Table 3.2). Ranks are shown both including and excluding Climate anomalies. The stressors are also ranked within each of the three regions North Sea, Kattegat and Baltic Sea.

Table 3.4 *Results of uncertainty analyses for the CIA model including climate anomalies, where n sim is the number of times the stressor is included in the 1000 simulation runs, Highest and Lowest ranks are the normalised rank score amongst included stressors, Rank range is the difference between highest and lowest ranks, Top and Bottom 25p, % show the proportion of simulations in which the stressor was among the top or bottom 25th percentile of included stressors.*

Stressor	n sim	Highest rank	Lowest rank	Rank range	Top 25p, %	Bottom 25p, %
Nitrogen winter concentrations (DIN)	812	1.00	0.93	0.07	100	0
Non-indigenous species	831	1.00	0.90	0.10	100	0
Phosphorus winter concentrations (DIP)	836	1.00	0.77	0.23	100	0
Climate anomalies	842	1.00	0.77	0.23	100	0
Oil spills	835	0.97	0.79	0.17	100	0
Noise (bang days)	821	1.00	0.75	0.25	99	0
Microplastic in sediments	824	0.96	0.76	0.20	99	0
Shipping intensity	834	0.93	0.69	0.23	87	0
Noise (ship sound 125 Hz)	821	0.88	0.64	0.24	42	0
Contaminants	834	0.85	0.54	0.31	41	0
Demersal fishing (mesh size > 100 mm)	836	0.84	0.55	0.29	15	0
Sea cables	842	0.85	0.50	0.35	4	0
Noise (ship sound 63 Hz)	824	0.85	0.54	0.31	0	0
Military areas	825	0.81	0.38	0.44	2	0
Demersal fishing (mesh size 16-32 mm)	814	0.81	0.41	0.40	0	0
Demersal fishing (mesh size 70-99 mm)	844	0.79	0.48	0.31	2	0
Pelagic fishing (mesh size 16-32 mm)	818	0.75	0.42	0.33	0	0
Setnet (all mesh sizes)	843	0.38	0.24	0.14	0	0
Sediment extraction sites	823	0.58	0.17	0.41	0	1
Demersal fishing (mesh size <16 mm)	827	0.81	0.41	0.40	0	1
Beam trawls (mesh size >100 mm)	846	0.81	0.41	0.40	0	10
Demersal fishing (mesh size 33-69 mm)	849	0.58	0.17	0.41	0	12
Dumped chemical munitions	813	0.50	0.21	0.29	0	13
Oil and gas pipelines	841	0.61	0.03	0.57	0	38
Dredged material disposal sites	824	0.61	0.17	0.44	0	33
Pelagic fishing (mesh size 33-80 mm)	843	0.81	0.41	0.40	0	42
Mussel dredging	843	0.61	0.12	0.49	0	47
Beam trawls (mesh size <32 mm)	826	0.58	0.17	0.41	0	52
Bridges and coastal dams	831	0.50	0.17	0.33	0	52
Recreational shipping	831	0.50	0.17	0.33	0	79
Industrial ports	838	0.61	0.12	0.49	0	100
Marine aquaculture sites	858	0.50	0.03	0.47	0	100
Offshore wind turbines	843	0.18	0.08	0.10	0	100
Offshore oil and gas installations	851	0.18	0.03	0.15	0	100
Longlines	831	0.08	0.03	0.05	0	100

The results from the CIA showed that the Nitrogen winter concentrations (DIN), Climate anomalies, Non-indigenous species, Phosphorus winter concentrations (DIP), Microplastic in sediments and Oil spills made the greatest individual contributions to the total cumulative human impact (Figure 3.5). Noise, Fisheries, Contaminants and Shipping intensity also had large contributions. The ranking of stressors was also consistent with the model without Climate anomalies and within the different regions. Stressors having the least impact differed among the regions, as some of the stressor layers were not represented in all regions, e.g. certain fishing methods and Physical modifications. The stressors with high impact are in general widespread and have potential impacts on many of the ecosystems while the stressors with least impact are most often situated locally (e.g. Oil and gas pipelines) or are related to locally oriented activities (e.g. Longline fishing).

Table 3.5 *Results of uncertainty analyses for the CIA model without climate anomalies, where n sim is the number of times the stressor is included in the 1000 simulation runs, Highest and Lowest ranks are the normalised rank score amongst included stressors, Rank range is the difference between highest and lowest ranks, Top and Bottom 25p, % show the proportion of simulations in which the stressor was among the top or bottom 25th percentile of included stressors.*

Stressor	n sim	Highest rank	Lowest rank	Rank range	Top 25p, %	Bottom 25p, %
Nitrogen winter concentrations (DIN)	840	1.00	0.92	0.08	100	0
Phosphorus winter concentrations (DIP)	839	1.00	0.82	0.18	100	0
Non-indigenous species	841	1.00	0.82	0.18	100	0
Noise (bang days)	832	1.00	0.72	0.28	100	0
Oil spills	847	0.96	0.79	0.17	100	0
Microplastic in sediments	833	1.00	0.72	0.28	100	0
Shipping intensity	835	0.92	0.72	0.20	95	0
Noise (ship sound 125 Hz)	839	0.85	0.43	0.41	65	0
Contaminants	835	0.78	0.61	0.17	54	0
Demersal fishing (mesh size > 100 mm)	840	0.88	0.57	0.31	27	0
Military areas	839	0.90	0.85	0.06	3	0
Demersal fishing (mesh size 70-99 mm)	850	0.80	0.50	0.30	3	0
Noise (ship sound 63 Hz)	822	0.80	0.50	0.30	2	0
Sea cables	821	0.78	0.46	0.32	8	0
Pelagic fishing (mesh size 16-32 mm)	833	0.73	0.35	0.39	0	0
Demersal fishing (mesh size 16-32 mm)	842	0.67	0.38	0.28	0	0
Setnet (all mesh sizes)	818	0.67	0.38	0.28	0	0
Demersal fishing (mesh size <16 mm)	828	0.61	0.60	0.01	0	1
Sediment extraction sites	826	0.57	0.26	0.30	0	1
Beam trawls (mesh size >100 mm)	852	0.60	0.31	0.29	0	8
Demersal fishing (mesh size 33-69 mm)	836	0.57	0.21	0.36	0	11
Dumped chemical munitions	838	0.57	0.21	0.36	0	15
Dredged material disposal sites	821	0.60	0.31	0.29	0	32
Oil and gas pipelines	831	0.48	0.14	0.34	0	37
Pelagic fishing (mesh size 33-80 mm)	844	0.54	0.12	0.42	0	39
Bridges and coastal dams	828	0.48	0.17	0.31	0	47
Mussel dredging	824	0.48	0.04	0.44	0	49
Beam trawls (mesh size <32 mm)	820	0.48	0.12	0.37	0	51
Recreational shipping	847	0.48	0.04	0.44	0	79
Offshore wind turbines	829	0.60	0.04	0.56	0	99
Industrial ports	827	0.26	0.04	0.22	0	100
Longlines	815	0.24	0.03	0.21	0	100
Marine aquaculture sites	826	0.21	0.04	0.17	0	100
Offshore oil and gas installations	819	0.09	0.03	0.06	0	100

The cumulative impact on the ecosystems was driven by the top 5 stressors (rank 1-5) that together contributed with 70% of the total CIA for the model including all 35 stressors and 72% of the total for the model without Climate anomalies (34 stressors). The top 10 stressors account for as much as 88% and 89% of the cumulative impact on the ecosystems. Hence, a few key stressors are largely responsible for the cumulative human impact in Danish waters, although all are important. Within regions, there was a similar pattern with top 5 stressors accounting for a large fraction of the total impact (respectively 76%, 70% and 71% in the Baltic Sea, Kattegat and North Sea). In the North Sea and Baltic Sea, the top 5 stressors were identical to those for the Danish waters, whilst in the Kattegat, Noise was ranked higher than Oil spills.

All the top 5 stressors in Danish waters are widely distributed and affect many of the ecosystem components on a general scale whereas the stressors contributing the least to the total CIA act on very local scales e.g. specific fishery or Offshore wind turbines. Spatial variation in the relative importance of stressors has been investigated further in the case studies with transects from land towards open sea (see section 3.4).

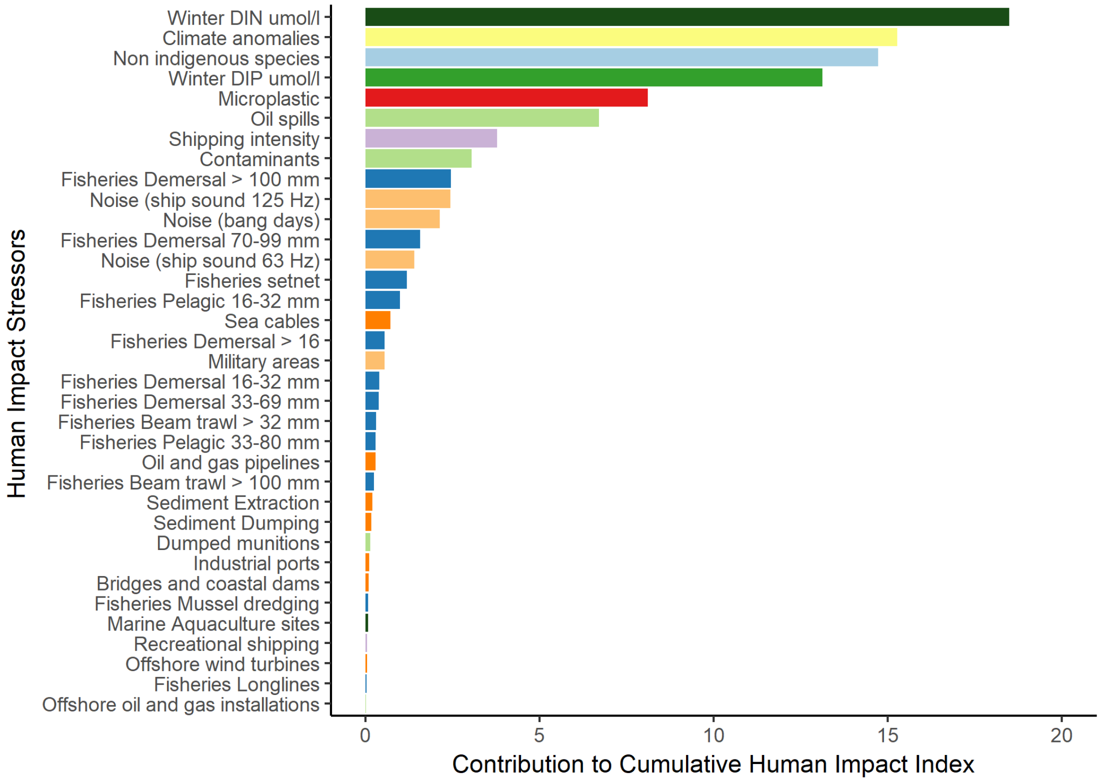


Figure 3.5 *Stressor contributions as percentage of total CIA (in descending order from most to least contribution to the total CIA) based on the human cumulative impact assessment for Danish waters.*

Since many of the stressors are similar or represent the same type of impact on the ecosystem, they were grouped together, as shown in the colour scheme in Table 3.6, with Climate anomalies, Non-indigenous species and Microplastic in sediments as separate groups of stressors. The impact and ranking for the respective groups are presented in Figure 3.6 and Table 3.7. The group with the greatest contribution to the impact was Nutrients making up about one third of the total CIA, followed by Climate anomalies and Non-indigenous species. When grouping the stressors, the impact from Fisheries are clearer, contributing with 8% to the total CIA. The group of stressors with the lowest combined impact was that associated with Physical modifications.

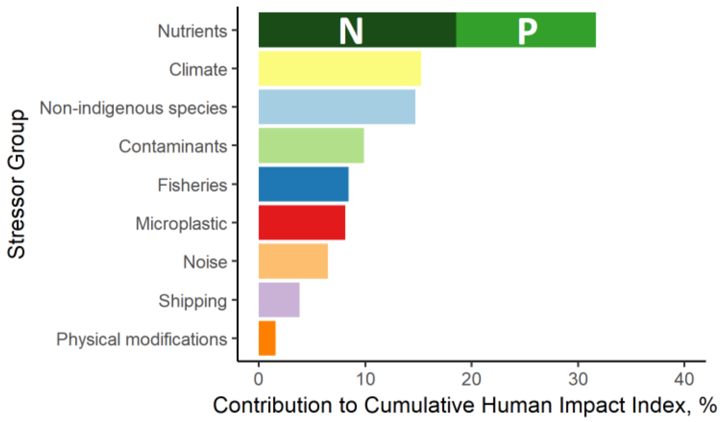


Figure 3.6 *Grouped stressor contributions in percentage of total cumulative impact. Additional figures with rankings in coastal and offshshore marine waters (excluding climate anormalies) are included in Annex 6.*

Table 3.6 *Ranking of stressors in Danish marine water and in three sub-divisions: (1) the Danish parts of the North Sea and Skagerrak, (2) the Danish parts of the Kattegat and northern and central parts of the Sound, and (3) the Danish parts of the south-western Baltic Sea. The stressors are divided in general groups by colours. The rank is represented by numbers and % is the stressor contribution to the total CIA. Light red markings indicates top 5 stressors with the highest ranks and light blue the lowest 5.*

Stressor	Denmark		Denmark no climate		North Sea		Kattegat		Baltic Sea	
	Rank	%	Rank	%	Rank	%	Rank	%	Rank	%
Bridges and coastal dams	29	<0.1	28	<0.1	26	<0.1	24	<0.5	22	<0.5
Climate anomalies	2	15	-	-	-	-	-	-	-	-
Contaminants	8	3	7	4	12	2	8	5	6	5
Dredged material disposal sites	26	<0.5	25	<0.5	25	<0.1	17	<0.5	19	<0.5
Dumped munitions	27	<0.5	26	<0.5	32	<0.1	28	<0.1	16	<1
Industrial ports	28	<0.1	27	<0.5	29	<0.1	22	<0.5	20	<0.5
Marine aquaculture sites	31	<0.1	30	<0.1	-	-	21	<0.5	26	<0.5
Microplastic in sediments	5	8	4	10	4	9	4	9	4	11
Military areas	18	1	17	<1	22	<0.5	13	<1	12	1
Nitrogen winter concentrations (DIN)	1	19	1	22	1	21	1	23	1	23
Noise (bang days)	11	2	10	3	13	1	5	8	11	1
Noise (ship sound 63 Hz)	10	2	9	3	8	4	11	2	9	2
Noise (ship sound 125 Hz)	13	1	12	2	11	2	12	<1	14	<1
Non-indigenous species	3	15	2	17	2	18	3	15	2	18
Offshore oil and gas installations	35	<0.1	34	<0.1	28	<0.1	-	-	-	-
Offshore wind turbines	33	<0.1	32	<0.1	27	<0.1	26	<0.1	30	<0.1
Oil and gas pipelines	23	<0.5	22	<0.5	19	<1	-	-	29	<0.1
Oil spills	6	7	5	8	5	8	6	8	5	7
Phosphorus winter concentrations (DIP)	4	13	3	16	3	15	2	17	3	17
Recreational shipping	32	<0.1	31	<0.1	31	<0.1	25	<0.5	27	<0.5
Sea cables	16	1	15	<1	16	<1	23	<0.5	13	1
Sediment extraction sites	25	<0.5	24	<0.5	24	<0.5	27	<0.1	15	<1
Shipping intensity	7	4	6	5	6	4	7	5	7	5
Beam trawls (mesh size <32 mm)	24	<0.5	23	<0.5	20	<1	-	-	31	<0.1
Beam trawls (mesh size ≥100 mm)	21	<0.5	20	<0.5	17	<1	29	<0.1	-	-
Demersal fishing (mesh size <16 mm)	17	<1	16	<1	14	1	-	-	32	<0.1
Demersal fishing (mesh size 16-32 mm)	19	<0.5	18	<0.5	21	<0.5	14	<1	18	<0.5
Demersal fishing (mesh size 33-69 mm)	20	<0.5	19	<0.5	18	<1	16	<0.5	21	<0.5
Demersal fishing (mesh size 70-99 mm)	12	2	11	2	10	2	9	3	28	<0.1
Demersal fishing (mesh size ≥ 100 mm)	9	3	8	3	7	4	18	<0.5	8	3
Longlines	34	<0.1	33	<0.1	30	<0.1	-	-	23	<0.5
Mussel dredging	30	<0.1	29	<0.1	-	-	20	<0.5	25	<0.5
Pelagic fishing (mesh size 16-32 mm)	15	<1	14	1	15	<1	10	2	10	1
Pelagic fishing (mesh size 33-80 mm)	22	<0.5	21	<0.5	23	<0.5	15	<0.5	17	<0.5
Set net (all mesh sizes)	14	1	13	1	9	2	19	<0.5	24	<0.5

Stressor: Fisheries, Non-indigenous species, Shipping, Noise, Physical modifications, Microplastic, Contaminants, Nutrients

Table 3.7 *Ranks and contributions to the total CIA by groups in %.*

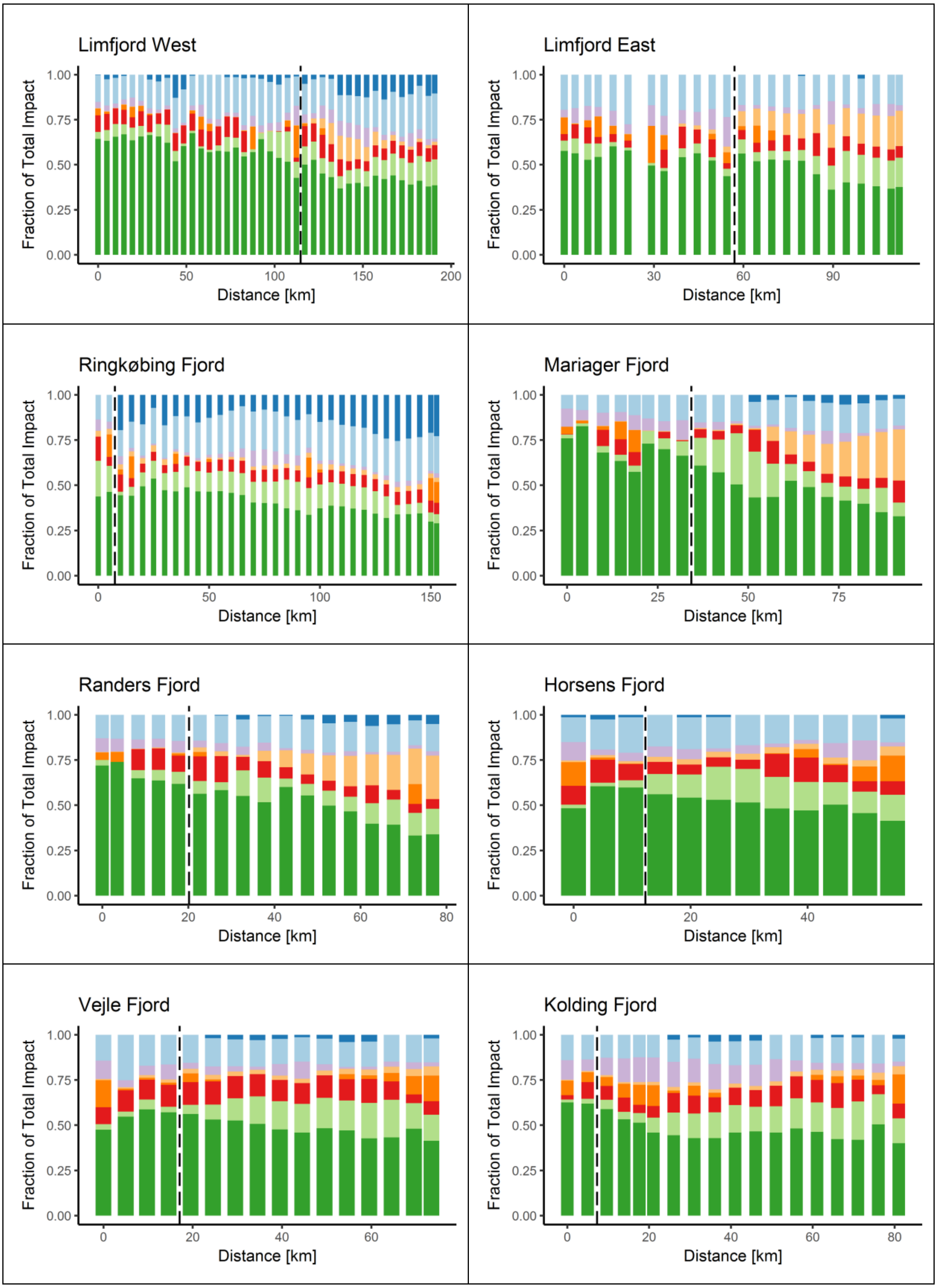
Stressor group	CIA including Climate		CIA without Climate	
	Rank	**%**	**Rank**	**%**
Nutrients	1	32	1	**37**
Climate anomalies	2	15	-	-
Non-indigenous Species (NIS)	3	14	2	17
Contaminants	4	10	3	12
Fisheries	5	8	4	10
Microplastic in sediments	6	8	5	9
Noise	7	7	6	8
Shipping	8	4	7	5
Physical Modifications	9	2	8	2

3.4 Gradients from land to open sea

The spatial variation in the importance of different stressors was considered by examining transects in 16 selected fjord or estuarine systems. The locations of the transects can be seen in Annex 4. Beginning at the end of the transect located furthest inside the fjord and continuing outwards to the open waters, data was extracted from the CIA results at intervals of approximately 5 km. The lengths of the transects vary from approximately 25 km for Kalundborg Fjord (which strictly speaking is a bay) to almost 200 km for the western Limfjord transect. At each point, the impact of each stressor was calculated as a percentage of the total cumulative impact. The relative contributions to the total impact were collected in the same groups used in Table 3.7 above (and seen also in Figure 3.6). The results are plotted in Figure 3.7, showing how the relative contribution of each stressor to the total cumulative impact varies along each of the transects from the inner parts of the fjord to open waters.

Direct comparison of the transects is difficult as they represent quite different ecosystems. However, there are some clear trends which can be observed with regard to the stressor groups Nutrients and Fisheries. The relative contribution of Nutrients in the innermost parts of the selected fjords varies from 40% (Kalundborg Fjord) to 75% (Mariager Fjord) of the total impact but there does appear to be a pattern showing that Nutrients account for a greater proportion of the total impact in the fjords than they do in open waters. As also might be expected, Fisheries have greater contribution to the total cumulative impact in transect sections of the open parts of the North Sea (e.g. Ringkøbing Fjord and Limfjord West transects) and Kattegat (e.g. Roskilde Fjord and Isefjord transects) than in the inner fjord or Belt Sea areas.

One noticeable feature related to fisheries is how mussel dredging causes a local increase in relative contribution to impact (12.8%) seen in the Limfjord west transect, approximately 45 km from the transect starting point.


Limfjord West
Fraction of Total Impact
Distance [km]
Limfjord East
Ringkøbing Fjord
Mariager Fjord
Randers Fjord
Horsens Fjord
Vejle Fjord
Kolding Fjord

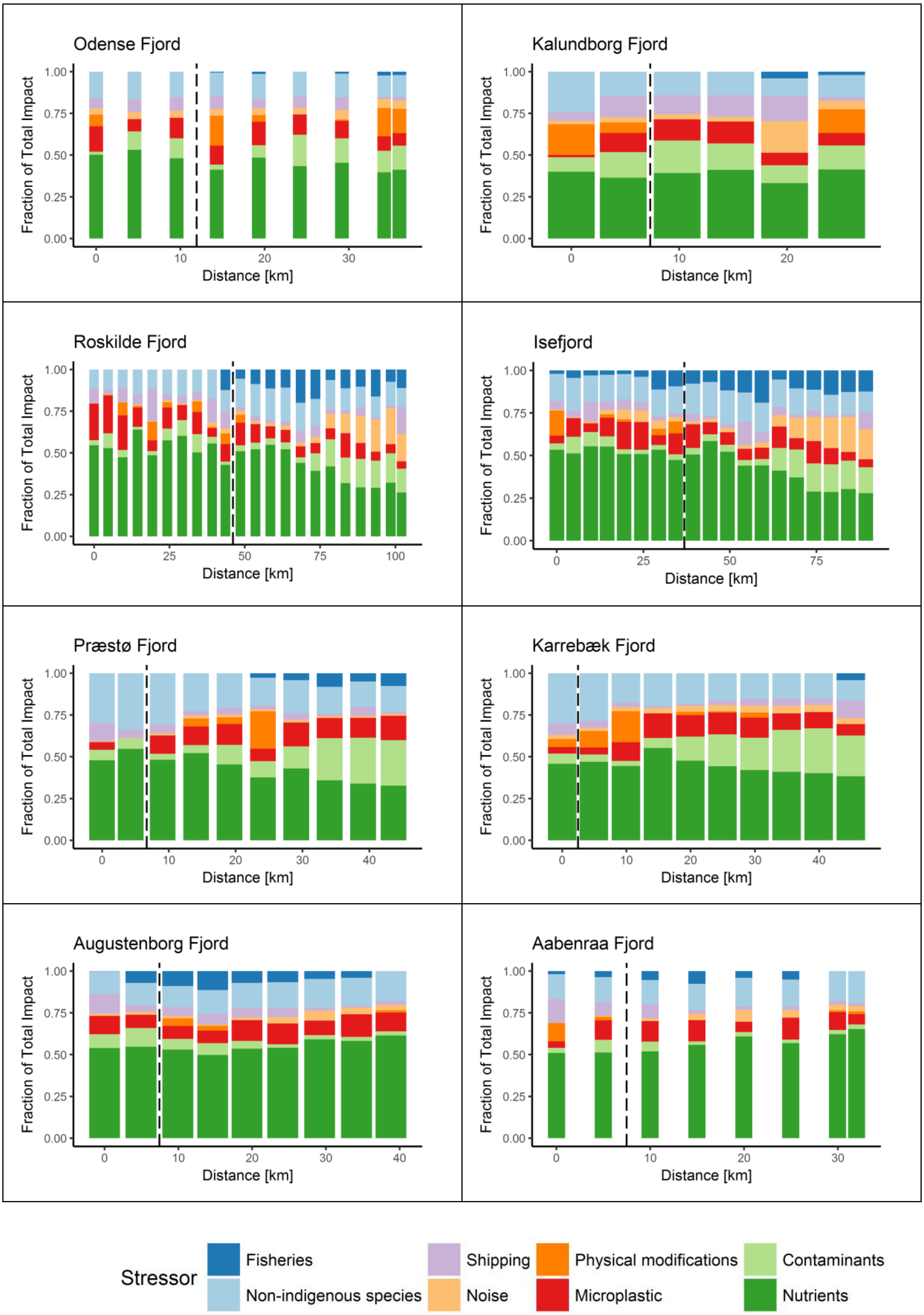


Figure 3.7 *Relative contribution of stressor groups to the total impact, along transects from inner fjord (0 km) to open water for 16 fjord systems in Denmark. A dashed line indicates the location of the mouth of the fjord system.*

4 Discussion

Assessment of human pressures in the marine area has, with the implementation of the EU Marine Strategy Framework Directive (MSFD), shifted from long-term temporal trends in individual pressures to integrated assessment of cumulative pressures. This is a big step forward, although the models applied at this stage are simple and do not consider synergistic or antagonistic effects. The most widely used models for assessing potential cumulative effects of multiple human stressors are based on Halpern *et al.* (2008) or derived additive models. This approach is perhaps not perfect and needs to be developed further (see Halpern & Fujita 2013), but has been considered not only useful but also fit-for-purpose (Korpinen & Andersen 2016).

The scope of stressors can be global (e.g. climate effects), regional (i.e. national) or local (e.g. bridges, ports, and mussel dredging). This study includes stressors at all of these spatial scales. We have, for the first time, included all ecologically relevant stressors *sensu* the MSFD including: (1) Microplastic in sediments, (2) a prototype stressor index for Non-indigenous species as well as (3) Climate anomalies.

The stressor data sets used in this study vary in quality and can be placed in one of three categories: some are very accurate (1), some have an acceptable quality that could potentially be improved (2), whilst a few should merely be regarded as provisional (3):

1. Most of the stressors data sets are considered accurate: Bridges and coastal dams (no. 1), Contaminants (no. 3), Dredged material disposal sites (no. 4), Dumped chemical munition (no. 5), industrial ports (no. 6), Marine aquaculture sites (no. 7), Military areas (no. 9), Nitrogen winter concentrations (no. 10), Noise (no. 11-13), Offshore oil and gas installations (no. 15), Offshore wind turbines (no. 16), Oil and gas pipelines (no. 17), Phosphorus winter concentrations (no. 19), Sea cables (no. 21), Sediment extraction sites (no. 22) and Commercial shipping intensity (no. 23).
2. Other data sets have been critically evaluated and assessed to hold an acceptable quality, given the objectives of this study: Climate anomalies (no. 2), Oil spills (no. 18) and all fishery-related stressors (no. 24-35).
3. A few of the stressor layers are based on the best available information, but should be considered provisional: Microplastic in sediments (no. 8), Non-indigenous species (no. 14) and Recreational shipping (no. 20). The microplastic stressor layer originates from Mohn *et al.* (2015) and is based on accurate count of microplastic particles in sediment samples. It can be discussed whether the interpolation of these counts is feasible, but at present, we find it the only way to establish a provisional nation-wide stressor layer. The stressor layer for Non-indigenous species is based on the best available information (Stæhr *et al.* 2016 and Carl *et al.* 2016), but should anyway be regarded as a prototype, which could be further developed once more accurate information of the distribution of Non-indigenous species becomes available.

The ecosystem component data sets (n = 47) represent a leap forward compared to earlier studies, e.g. the HELCOM HOLAS assessment (n = 13) (HELCOM 2010 and Korpinen *et al.* 2012), and the HARMONY project (n = 30) (Andersen *et al.* 2013). With this study, we cover all ecologically relevant ecosystem components from phytoplankton over benthic communities to top predators as fish, seabirds and marine mammals.

The ecosystem component data set also vary in quality, ranging from 1) very accurate through 2) acceptable quality that could potentially be improved to 3) provisional. The vast majority of the ecosystem components data are either accurate or acceptable, whilst a few should be regarded as provisional.

1. The data sets representing Plankton communities in water (no. 11), Oxygen deficit (no. 12), auks (Alcidae, no. 34), Common scoter (*Melangius nigra*, no. 35), Divers (Gavia, no. 36), Eider (*Somateria mollissima*, no. 37), Long-tailed Duck (*Clangula hyemalis*, no. 41), Red-breasted Merganser (*Mergus serrator*, no. 42), Grey Seal (*Halichoerus grypus*, no. 43), Harbour Seal (*Phoca vitulina*, no. 44) and Harbour Porpoise (*Phocoena phocoena*, no. 45) are all considered scientifically valid and robust.

2. The majority of the ecosystem component data sets (31 out of 47) are considered acceptable. These data sets related to benthic communities (no. 1-10) and fish (no. 13-33) have an acceptable quality given the objectives of this study. Some improvements to the data could be identified, but would probably not lead to different results or conclusions.
3. A few of the ecosystem components originating from the HARMONY project (Andersen & Stock 2013) should be considered provisional, i.e. Fulmar (*Fulmarus glacialis*, no. 38), Gannet (*Morus bassanus*, no. 39), Kittiwake (*Rissa tridactyla*, no. 40), Minke Whale (*Balaenoptera acutorostrata*, no. 46) and White-beaked dolphin (*Lagenorhynchus albirostris*, no. 47), but have been included as the information they contain is better than none.

The sensitivity weights are, as described, derived by expert judgement. Empirical data for the functional relations between stressors and ecosystem components only exist for very few of the 1645 combinations of stressors and ecosystem components included in this study. We must therefore rely on the available methodology (expert judgement, sometimes described as a Delphi technique), although changes or biased subjectivity in the weights may have an impact on the outputs cf. Halpern & Fujita (2013). This was also shown by Stock & Micheli (2016) in a study of the potential effects of different sources of uncertainty on spatial CIAs. Hence, one of the key assumptions in cumulative impact analyses is that the expert judgement is objective. In order to fulfil this criterion, the expert group used for this study was chosen to include an experienced and broad range of experts. The sensitivity weights used in the model were taken from the medians of the study results. Although the Delphi technique has been criticized, it is and will continue to be an important method for collecting information, with several applications and uses where scientists gather information from colleagues who are experts in the topic of interest (Rowe & Wright 1999, Hsu & Sandford 2007). Perhaps most importantly, no alternatives to the currently used CIA methodology (based on Halpern *et al.* 2008) have been developed, tested and applied.

The setting of effect distance of stressor layers covering a fixed area (ports, bridges, wind turbines, pipelines etc.) is accepted as a common procedure, which is applied in other CIA studies including the HARMONY project and the HELCOM HOLAS project.

It should be noted, that there are combinations of stressors and ecosystem components which do not overlap spatially. For example, the stressors Offshore oil and gas installations and Military areas do not occur in any estuarine and fjord systems and Industrial ports and Mussel dredging are not found in offshore parts of the North Sea, Skagerrak, Kattegat and south-western Baltic Sea. In fact, most grid cells only contain small subsets of stressors and ecosystem components.

It is perhaps trivial to state that ecosystem components respond differently to different stressors. The different responses are not generic but will in some cases be temporally or spatially distinct. For example, seabirds are more sensitive to disturbances (e.g. Noise and Shipping intensity) during the hatching period than the rest of the year. Also, seabirds might be more susceptible to Contaminants during periods with low food availability i.e. the winter period. These aspects are relevant and something that should be considered in future studies.

Another feature not included in the model is the potential for recovery of an ecosystem component. Some stressors may have long-term effect (damming a fjord system) while others may only have temporary effects (a military exercise or the construction of a wind farm). As these effects are not accounted for in the model, the results of this study should be looked upon as a snapshot of all possible stressors acting simultaneously on the ecosystem components.

Some of the stressors have multiple effects on the ecosystems, mostly having a negative impact, but some may have a positive impact. It is well documented that increases in nutrient loads lead to elevated nutrient concentrations and subsequently to a series of well-known eutrophication signals, e.g. accelerated growth of phytoplankton, increased sedimentation and in some areas decreased oxygen concentrations in bottom waters. This chain of effects is straightforward and is for most parts of the Baltic Sea and North Sea seen as a negative effect of nutrient inputs. However, the increased sedimentation can, in some areas, give increased food supply to mussels at the seafloor and thus an increase in food availability for seabirds which feed on these. Due to the simplicity of the model, we can only deal with a single effect, not the multiple effects such those illustrated in this mussel-seabird example.

The CIA method is transparent and objective and can be used and reproduced for both spatial mapping as well as quantitative analyses (Halpern & Fujita 2013). Further, the robustness of the results of this study were very consistent as shown in the uncertainty analyses developed by Stock & Micheli (2016). Application of the CIA methodology must, however, be accompanied by detailed descriptions of the data sets used, transparency in the setting of sensitivity scores and effects distances as well as cautious considerations of the added value of the estimates. We believe these criteria have been fulfilled for this study.

The ranking of stressors contributing to the cumulative impact in the Danish marine areas correspond to earlier studies, i.e. the HELCOM HOLAS project covering the Kattegat, Danish Straits and south-western Baltic Sea and the HARMONY project covering the Danish parts of the North Sea, Skagerrak and Kattegat. However, this study is the first to include the stressors 'Climate anomalies', 'Non-indigenous species' and 'Microplastic in sediment'. These stressors are shown to contribute significantly to the total cumulative impact.

It should be noted that the ranking is an overall national impact ranking (Figure 3.6) and that site-specific impact can vary between locations (Figure 3.7). Therefore, stressors covering large areas with non-zero values (e.g. climate anomalies) are likely to have a higher impact, than stressors present only in smaller isolated areas (e.g. wind turbines).

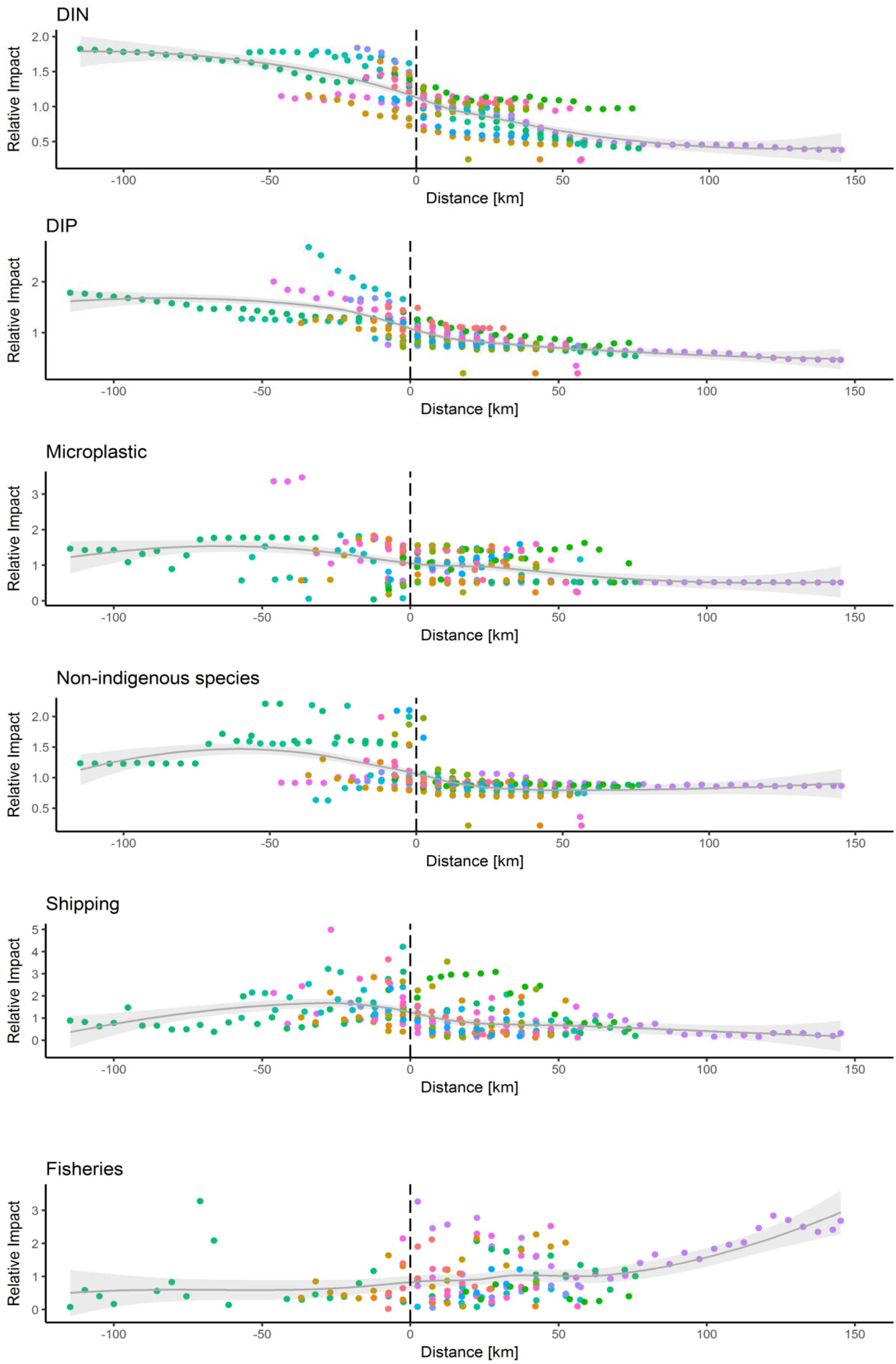
Plots of the "combined transects" for selected stressor groups are shown in Figure 4.1. Here, the results for percentage of total for a stressor group along a transect were collected for all 16 transects. Before plotting the combined transects, the results from section 3.4 above were adjusted in two ways. Firstly, the transect results were shifted in space so that distance is measured from the mouth of the fjord, rather than the end of the transect. This results in an alignment of the transects at the fjord mouths, with negative distances indicating movement into the fjord and positive distances outwards into open waters. Secondly, the mean value was calculated for all percentage contributions in all transects for the stressor group in question. The percentage contributions were normalised to this average value before being plotted. Additionally, the results for DIN and DIP are shown separately.

The trend in relative impact of nutrients seen along the individual transect becomes more obvious when the transects are grouped together. For both DIN and DIP, the results clearly match expectations that the impacts of nutrients are greater within fjords than in open waters (e.g. Carstensen *et al.* 2006). The general trend for Fisheries increasing from fjords to open waters is also clear.

Climate anomalies are excluded from the gradient studies because this stressor layer is an exogenic stressor and acts on a larger scale than that of the case studies (Elliot *et al.* 2015). Further, the exclusion is also justified by the Water Framework Directive and the Marine Strategy Framework Directive, which do not consider Climate anomalies, either in the specific Initial Assessments or in the Programmes of Measures. Both the above-mentioned Directives, the EU Water Framework Directive and the EU Marine Strategy Framework Directives are anchored in an Ecosystem-based Approach, which we will discuss briefly.

The Ecosystem-based Approach is EU terminology and considered a synonym for the Ecosystem Approach, which is defined by the Convention on Biological Diversity (CBD) and is a strategy for the integrated management of land, water and living resources that promotes conservation and sustainable use in an equitable way. HELCOM and OSPAR, the regional seas conventions in the Baltic Sea and North Sea, respectively, as well as the International Council for the Exploration of the Seas (ICES) apply the following definition:

- The comprehensive integrated management of human activities based on the best available scientific knowledge about the ecosystem and its dynamics, in order to identify and take action on influences which are critical to the health of marine ecosystems, thereby achieving sustainable use of ecosystem goods and services and maintenance of ecosystem integrity.


DIN
Relative Impact
Distance [km]
DIP
Relative Impact
Distance [km]
Microplastic
Relative Impact
Distance [km]
Non-indigenous species
Relative Impact
Distance [km]
Shipping
Relative Impact
Distance [km]
Fisheries
Relative Impact
Distance [km]

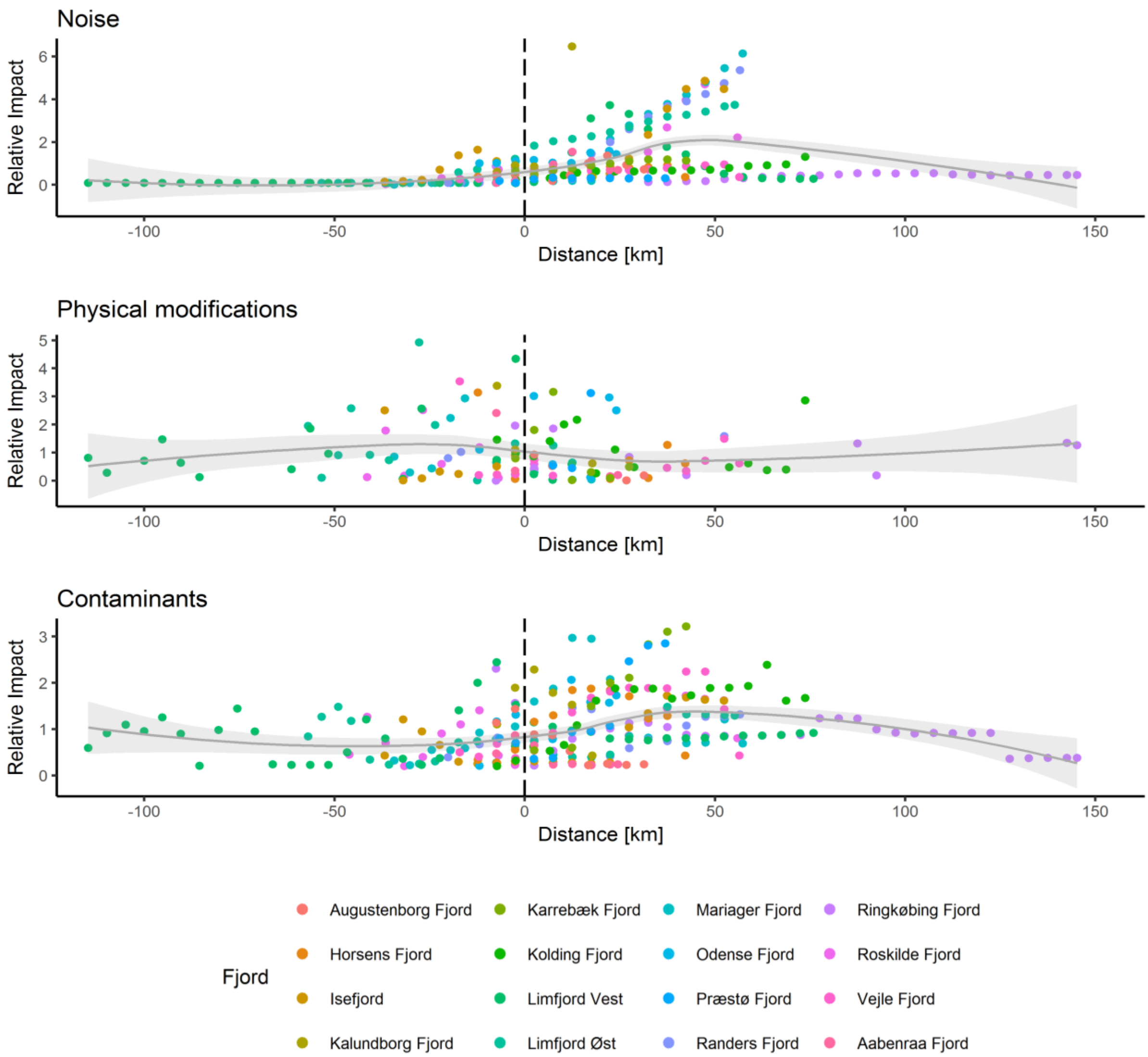


Figure 4.1 *Variation in relative impact of stressors DIN winter concentration, DIP winter concentration, Aquaculture sites, Microplastic concentration in sediment, Shipping intensity, Fisheries, Noise, Physical modifications and Contaminants along a transect from fjord to open water. A local polynomial regression fitting (LOESS) is shown by a dark grey line. The 95% confidence interval is shown by the light grey shading.*

An important implication is that the implementation of relevant policies and strategies such af the Marine Strategy Framework Directive and the Water Framework Directive – in order to fulfil an Ecosystem-based Approach – shall take into consideration the best scientific knowledge such as the CIA methodology and should base Programmes of Measure on the stressors that are critical to the structure and functioning of marine ecosystems. In practice, this implies that MSFD- and WFD-specific Programmes of Measures are to be considered as Ecosystem-based Management, defined as:

- EBM (noun) is an integrated approach to management of human activities that considers the entire ecosystem, including humans with the goal of maintaining an ecosystem in a healthy, productive and resilient condition so that it can provide the services humans want and need (McLeod *et al.* 2005).

EBM differs from approaches that focus on a single species, sector, activity or concern; it considers the cumulative impacts of different sectors. Specifically, EBM: (1) emphasizes the protection of ecosystem structure, functioning, and key processes; (2) focuses on a specific ecosystem and the range of activities affecting it; (3) explicitly accounts for the interconnectedness within systems, recognizing the importance of interactions between many target species or key services and other non-target species; (4) acknowledges interconnectivity among systems, such as between air, land and sea; and (5) integrates ecological, social, economic, and institutional perspectives, recognising their strong interdependences (Christensen *et al.* 1996, McLeod *et al.* 2005).

Hence, this study contributes to the implementation of the Ecosystem Approach and to the application of Ecosystem-based Management for Danish marine waters, especially in the context of the Marine Strategy Framework Directive. In addition, this study indicates that an Ecosystem-based Approach is not taken fully into consideration in the context of the Danish implementation of the Water Framework Directive as a number of ecologically-relevant stressors are currently not considered by this Directive, e.g. Fisheries, Mussel dredging, Physical modification, etc. If, as we suggest, there is an under-implementation of the Ecosystem-based Approach, then a potential way forward could be a closer coordination and harmonisation of the MSFD- and WFD-specific implementation processes. This would lead not only to synergies but also a more cost-effective implementation of both Directives.

5 Conclusions

Danish marine waters have an impaired status, an unfortunate situation documented by classifications of 'ecological status' of coastal waters *sensu* the EU Water Framework Directive (WFD) and 'environmental status' of marine waters *sensu* the EU Marine Strategy Framework Directive (MSFD). Why is this the case? Mostly because of a wide range of sea-based and upstream land-based human activities affecting coastal and marine ecosystems. This study has therefore been carried out in order to: (1) estimate and map potential cumulative impacts in Danish marine waters, and (2) to rank the relative importance of key human stressors along a land-sea gradient, to indicate the root causes of the impairments documented in the context of the MSFD and WFD. Based on the results of this nation-wide mapping of cumulative impacts of human activities in Danish marine waters, we conclude:

- There are large spatial variations in the number of stressors in different parts of the Danish marine waters (Figure 3.1).
- The ecosystem complexity also varies from high in the Kattegat to low along the west coast of Jutland (Figure 3.2).
- The estimated cumulative impacts, where the intensity of the stressors and the sensitivity of the ecosystem components are taken into account also varies greatly (Figure 3.3 and 3.4). Highly impacted areas are found in the Wadden Sea, open parts of the Skagerrak, Limfjorden and other estuarine systems, the Danish Straits and along shipping routes in the Kattegat and western Baltic Sea, while areas with estimated low impacts are found in some offshore parts of the North Sea and Kattegat.

Uncertainty analyses of the cumulative impact estimates have been addressed specifically by Monte Carlo simulations and we find the estimates robust and useful for subsequent analyses, i.e. ranking of impacts and gradient studies. With regard to ranking of the impacts, we conclude:

- Based on a grouping of individual stressor in 9 groups, the relative importance is as follows: (1) Nutrients, (2) Climate anomalies, (3) Non-indigenous species, (4) Contaminants, (5) Fisheries, (6) Microplastic in sediment, (7) Noise, (8) Shipping intensity, and (9) Physical modifications.

Based on 16 case studies in estuarine and fjord systems, we report the first ever analyses of the relative importance of stressors (Climate anomalies is as an exogenic stressor not included in these analyses) from land to open sea and conclude as follows:

- Relative importance of key groups of stressors varies along a land-sea gradient, as expected.
- Some groups of key stressors are important in estuarine systems and coastal waters (e.g. nutrients, Non-indigenous species, Contaminants and Microplastic in sediments), while others have a higher relative importance in offshore water (e.g. Fisheries and Noise).
- MSFD assessments are done according to an Ecosystem-based Approach, while this study indicates that the current WFD practices can hardly claim to be rooted in an ecosystem-based approach taking the best available information about human activities and coastal ecosystem into account.

The study and the analyses carried out represent a leap forward. The EcoImpactMapper can be used for mapping of the impacts of multiple human activities in the Danish marine wasters. The methodology has now been developed into an analytical tool for examining the spatial variation in these impacts.
We have identified a need for a closer coordination and harmonization of the implementation of the MSFD and WFD. Despite overlapping areas and threats, there are dichotomies in the implementation and reporting processes, especially with regard to Initial Assessment and analyses of predominant pressures. Therefore, as both the MSFD and WFD are supposed to follow an Ecosystem-based Approach, we suggest that future Initial Assessments under the MSFD and WFD should, where relevant, be based on the same data and methodologies, in particular the same approaches for mapping and assessing impacts of human activities in Danish marine waters.

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Annex 1: Acronyms and abbreviations

BSPI/BSII:	Baltic Sea Pressure Index / Baltic Sea Impact Index
CIA:	Cumulative Impact Assessment
COMP:	Comprehensive Procedure
DEA:	Danish Energy Agency
DNAMAP:	The Danish National Aquatic Monitoring and Assessment Program
DVFA:	Danish Veterinary and Food Administration
HEAT:	HELCOM Eutrophication Assessment Tool
BEAT:	Biodiversity Assessment Tool
CHASE:	Chemical Status Assessment Tool
HARMONY:	Development and demonstration of Marine Strategy Framework Directive tools for harmonization of the initial assessment in the eastern parts of the Greater North Sea subregion (A project funded by Denmark, Germany, Norway and Sweden)
HELCOM:	Baltic Marine Environment Protection Commission - Helsinki Commission
HOLAS:	HELCOM Initial Holistic Assessment
NOVA:	Nationale program for overvågning af vandmiljøet
NOVANA:	Det nationale overvågningsprogram for vandmiljøet og naturen
MSFD:	Marine Strategy Framework Directive
OSPAR:	Oslo/Paris convention (for the Protection of the Marine Environment of the North-East Atlantic)
SYMBIOSE:	Økosystem-baserede marine strategier: Udvikling af et værktøj for vurdering af kumulative belastninger og beslutningsstøtte [Ecosystem-based marine strategies: Development of a tool for cumulative effect assessments and decision support] (A DCE-AU funded project)
TACIA:	Towards assessment of cumulative stressors and impacts in Artic marine waters, a pilot project (A NMR-funded project)

Annex 2: Detailed description of data sets representing pressures and ecosystem components

Please note that all data were log-transformed and normalized to values between 0 and 1 (see section 2.2.1). Thus, the value "1" exists at all maps, even though the highest value in the original dataset varies quite a lot.

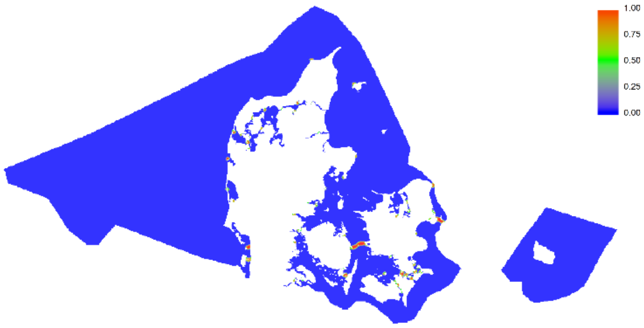
Please also note that the colour scale represents values from 0 to 1. The value "1" is shown by a red colour, the value "0" is indicated by a blue colour and the value 0.5 is shown with a green colour.

A2.1 Stressors

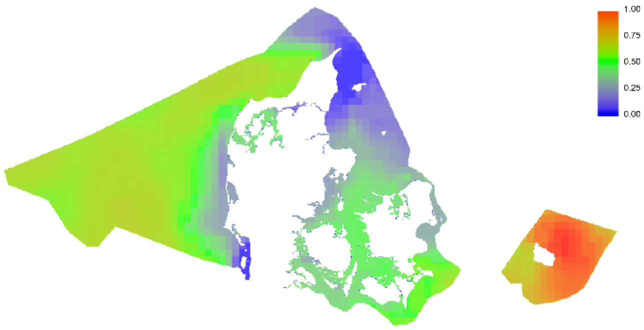
Please note that all stressor data were log(1+x)-transformed, normalized to values between 0 and 1 and added an effect distance (see section 2.2.1). Thus, the value "1" exists at all maps, even though the highest value in the original dataset varies quite a lot.

Please also note that the colour scale represents values from 0 to 1. The value "1" is shown by a red colour, the value "0" is indicated by a blue colour and the value 0.5 is shown with a green colour.

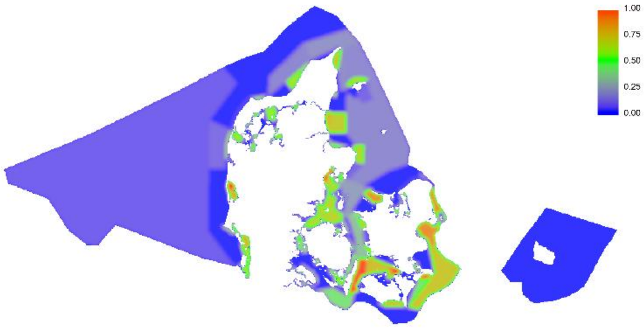
A2.1.1: Bridges and coastal dams

Description	Locations of major bridges and coastal dams.
Map	
Data source	Data originate from SYMBIOSE (Mohn *et al.* 2015).
Data processing	Data were achieved by image analysis of figure A1 in appendix A in the SYMBIOSE report.
Spatial coverage	Danish marine waters
Data resolution	n.i.
Unit	Presence/absence
Time period	2008

A2.1.2: Climate anomalies

Description	Change in Sea Surface Temperature (SST) in 2009-2010, compared to modelled data of mean Sea Surface temperature (SST) in the period 1900-1996.
Map	
Data source	Data originate from SYMBIOSE (Mohn *et al.* 2015).
Data processing	Data were achieved by image analysis of figure A2 in appendix A in the SYMBIOSE report.
Spatial coverage	Danish marine waters
Data resolution	1 x 1 km, smoothing factor 20 km.
Unit	°C
Time period	Average of 2009-2010

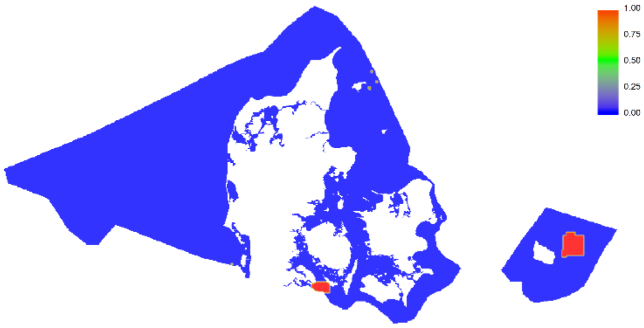
A2.1.3: Contaminants

Description	Integrated assessment of 'chemical status'.
Map	
Data source	EMODnet Chemistry (Andersen *et al.* 2016b)
Data processing	Integrated assessment of the combined effects of multiple chemical substances using a multi-metric indicator-based assessment tool (CHASE).
Spatial coverage	Danish marine waters
Data resolution	See Andersen *et al.* (2016b)
Unit	Contamination score
Time period	2009-2013

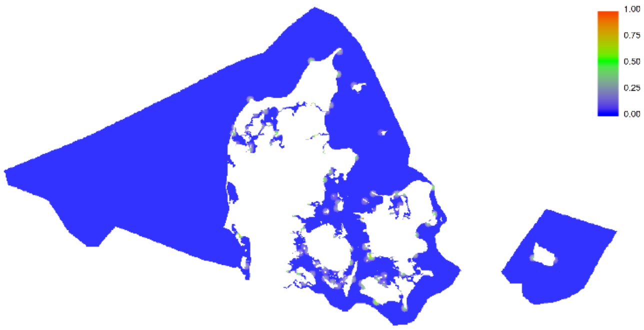
A2.1.4. Disposal sites for dredged material

Description	Sediment disposal sites and authorised landfill locations.
Map	
Data source	The Danish Environmental Protection Agency, (MiljøGIS, 2017a, http://miljoegis.mim.dk/cbkort?profile=miljoegis-raastofferhavet)
Data processing	Shapefile of "Fællesområder" was downloaded from miljøGIS.
Spatial coverage	Danish marine waters
Data resolution	n.i.
Unit	Presence/absence
Time period	2016

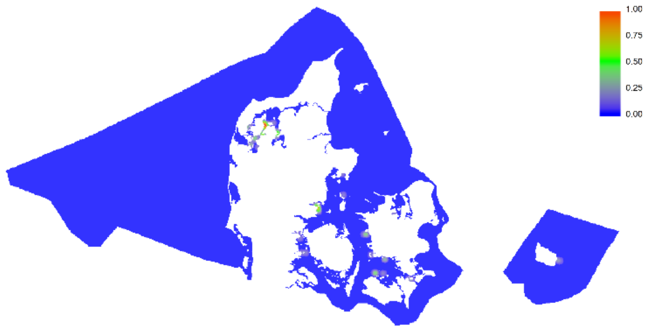
A2.1.5. Dumped chemical munitions

Description	Official munition dumping sites and encounters from other locations than the official dumping sites.
Map	
Data source	Data originate from SYMBIOSE (Mohn *et al.* 2015).
Data processing	Map was developed by image analysis of figure A6 in appendix A in the SYMBIOSE report.
Spatial coverage	Data covers all parts of Danish marine waters.
Data resolution	n.i.
Unit	Presence/absence
Time period	OSPAR: April 1999 – December 2011, HELCOM 2009-2011

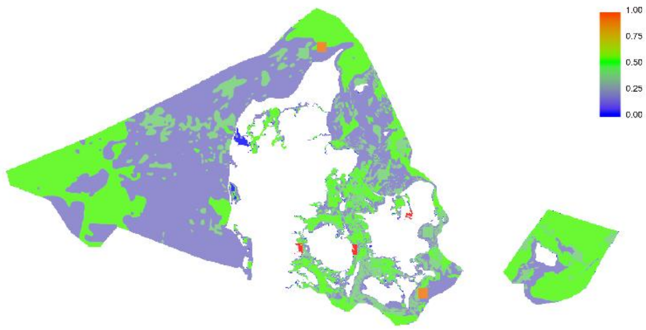
A2.1.6. Industrial Ports

Description	Danish industrial ports.
Map	
Data source	The Danish Environmental Protection Agency, (MiljøGIS, 2017b, http://miljoegis.mim.dk/cbkort?profile=vandrammedirektiv2-2016)
Data analysis	The coordinate system for industrial ports was downloaded and plotted in ArcGIS as points.
Spatial coverage	Danish marine waters
Data resolution	n.i.
Unit	Presence/absence

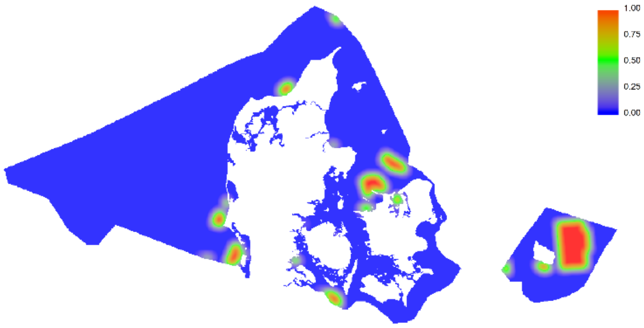
A2.1.7. Marine aquaculture sites (fish and shellfish)

Description	Production of fish and shellfish in farms in 2016.
Map	
Data source	Danish Veterinary and Food Administration, (Ministry of Environment and Food if Denmark, 2017, https://chr.fvst.dk/chri/faces/frontpage?_adf.ctrl-state=abx5hqhpe_3)
Data processing	All marine aquaculture sites were downloaded from webpage as a csv.file.
Spatial coverage	Danish marine waters.
Data resolution	n.i.
Unit	Presence/absence
Time period	2016

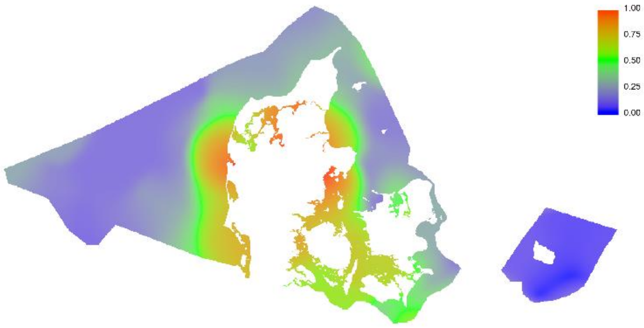
A2.1.8. Microplastic in sediments

Description	Amount of micro-plastic in sediment.
Map	
Data source	SYMBIOSE (Mohn *et al.* 2015).
Data processing	Map was developed by image analysis of figure A11 in appendix A in the SYMBIOSE report.
Spatial coverage	Danish marine waters
Data resolution	n.i.
Unit	Particles per 10 g dry weight
Time period	September 2012 – May 2013

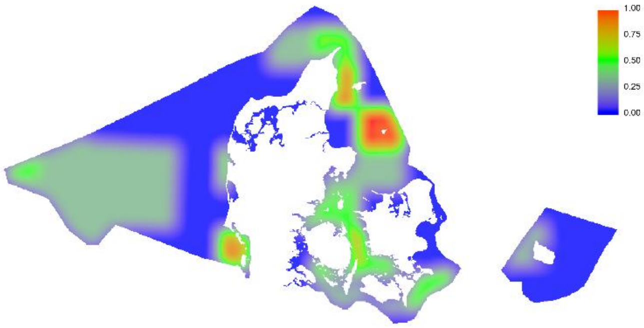
A2.1.9. Military areas

Description	Areas with military training activities.
Map	
Data source	SYMBIOSE (Mohn *et al.* 2015).
Data processing	Map was developed by image analysis of figure A10 in appendix A in the SYMBIOSE report.
Spatial coverage	Danish marine waters
Data resolution	n.i.
Unit	Presence/absence
Time period	2011

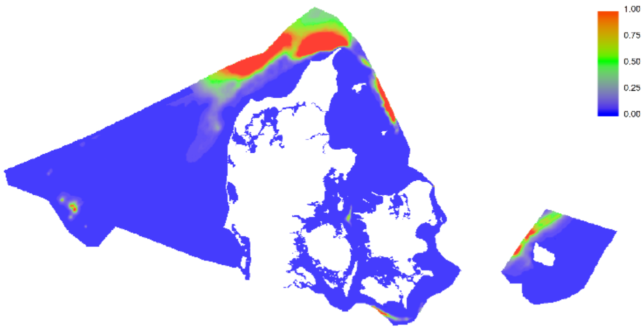
A2.1.10. Nitrogen winter concentrations (DIP)

Description	Concentration of dissolved inorganic nitrogen during winter.
Map	
Data source	ICES and The Danish Natural Environment Portal
Data processing	Point data of nitrogen winter concentrations were interpolated.
Spatial coverage	Danish marine waters
Data resolution	1 km x 1 km
Unit	µmol/l
Time period	2006-2013

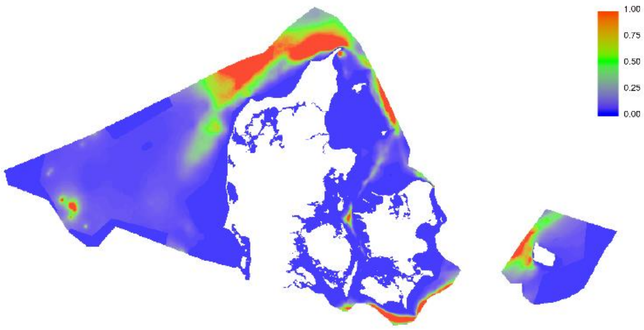
A2.1.11. Noise (bang days)

Description	Number of impulsive noise days in 2012.
Map	
Data source	SYMBIOSE (Mohn *et al.* 2015).
Data processing	Map was developed by image analysis of figure A12 in appendix A in the SYMBIOSE report.
Spatial coverage	Danish marine waters
Data resolution	ICES square (0,5-degree latitude x 1 degree longitude). Area pr. rectangle 3500 km^2
Unit	Number of days
Time period	2012

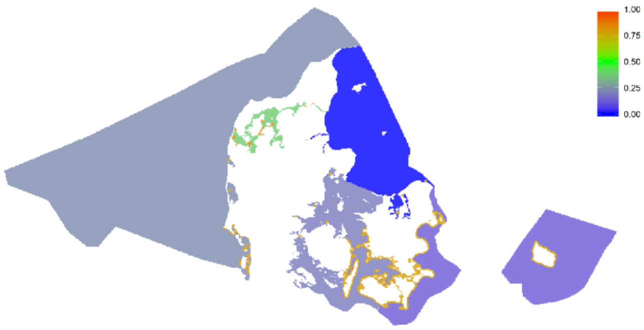
A2.1.12. Noise (63 Hz)

Description	Underwater noise (63 Hz 1/3 octave band)
Map	
Data source	SYMBIOSE (Mohn *et al.* 2015).
Data processing	Map was developed by image analysis of figure A13 in appendix A in the SYMBIOSE report.
Spatial coverage	Danish marine waters. Data are missing in the most eastern part of the Bornholm Basin.
Data resolution	n.i.
Unit	See SYMBIOSE (Mohn *et al.* 2015).
Time period	2012

A2.1.13. Noise (125 Hz)

Description	Underwater noise (125 Hz 1/3 octave band)
Map	
Data source	SYMBIOSE (Mohn *et al.* 2015).
Data processing	Map was developed by image analysis of figure A14 in appendix A in the SYMBIOSE report.
Spatial coverage	Danish marine waters. Data is missing in the most eastern part of the Bornholm basin.
Data resolution	n.i.
Unit	See SYMBIOSE (Mohn *et al.* 2015).
Time period	2012

A2.1.14. Non-indigenous species

Description	Interim index of presence of non-indigenous species
Map	
Data source	Pacific oyster (*Crassostrea gigas*): Fugleognatur.dk, (2017, http://www.fugleognatur.dk/artintro.asp?ID=7480) Round Goby (*Neogobius melanostomus*): Carl *et al***.** (2016) Phytoplankton, zooplankton, macroalgae, benthic invertebrates: Stæhr *et al.* (2016)
Data processing	Pacific Oyster (*Crassostrea gigas*): coordinates where the pacific oyster has been found, where transferred to ArcGIS as points. A buffer around each point of 2000 meters were used, as a proxy of the distribution. Values within the buffer zones were given the value “100”. Round Goby (*Neogobius melanostomus*): a buffer of 2000 meter from the coast of Denmark in areas where the Round Goby was found was used as a proxy of the distribution. Values within the buffer zone were given the value “100”. Phytoplankton, zooplankton, macroalgae, benthic invertebrates: For each marine area, the similarity value of the four groups were summed, and the sum was given as value to each marine area. The three data layers were combined and the summed value of each grid cell, was used as an index value of non-indigenous species.
Spatial coverage	Danish marine waters
Data resolution	1 km x 1 km
Unit	Interim non-indigenous species index
Time period	Pacific Oyster (*Crassostrea gigas*): 2017 Round Goby (*Neogobius melanostomus*): 2016 Phytoplankton, zooplankton, macroalgae, benthic invertebrates: 2006-2014

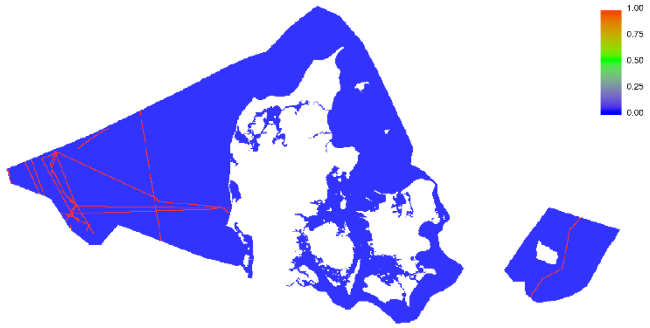
A2.1.15. Offshore oil and gas installations

Description	Oil and gas installations in the Danish marine areas.
Map	
Data source	Danish Energy Agency (Danish Energy Agency, 2016, https://ens.dk/en/our-services/oil-and-gas-related-data/shape-files-maps)
Data processing	The shapefile was used without any further data processing.
Spatial coverage	Danish marine waters
Data resolution	n.i.
Unit	Presence/absence
Time period	2017

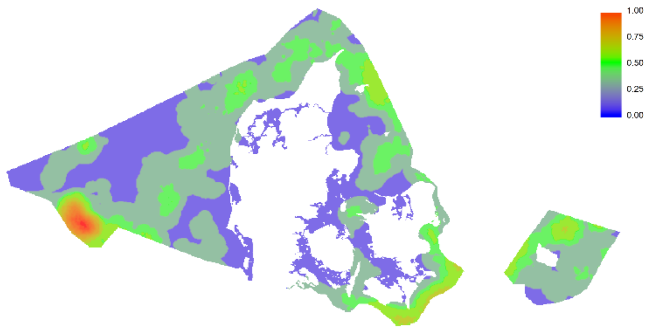
A2.1.16. Offshore wind turbines

Description	Marine wind turbines.
Map	
Data source	HARMONY (Andersen & Stock, 2013) and Danish Energy Agency (ArcGIS, 2017, http://www.arcgis.com/home/webmap/viewer.html?webmap=4398142262974c4b9b41ac477d423dcd&extent=7.4005,54.9737,15.514,57.524).
Data processing	Shapefile was downloaded from DEA.
Spatial coverage	Danish Marine areas.
Data resolution	n.i.
Unit	Presence/absence
Time period	2011-2017

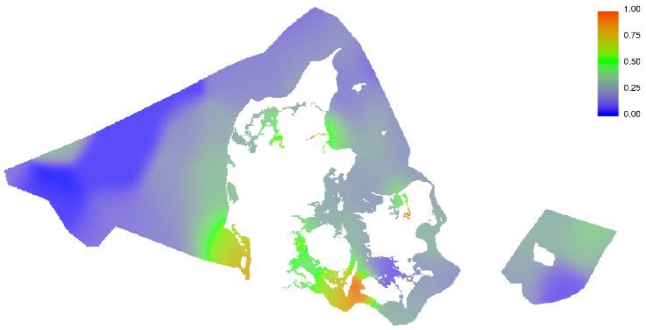
A2.1.17. Oil and gas pipelines

Description	Oil and gas pipelines in the Danish marine waters.
Map	
Data source	Harmony (Andersen & Stock, 2013) and Danish Energy Agency (2014) HARMONY data was updated based on the report: 'Oil and gas production in Denmark 2014' https://ens.dk/sites/ens.dk/files/OlieGas/oil_and_gas_in_denmark_2014_.pdf and http://factpages.npd.no/factpages/default.aspx?culture=en&nav1=tuf&nav2=PageView%7cPetReg and https://www.nord-stream.com/press-info/library/?q=&type=4&category=&country=
Data processing	The shapefile from HARMONY was updated based on the latest information on oil and gas pipelines from the Danish Energy Agency. Two extra pipelines, Nord Stream in the Baltic Sea and a pipeline in the North Sea, were added.
Spatial coverage	Danish marine waters
Data resolution	n.i.
Unit	Presence/absence
Time period	2016

A2.1.18. Oil spills

Description	Calculated oil spill risk index, based on the detected oil spill locations.
Map	
Data source	SYMBIOSE (Mohn *et al.* 2015)
Data processing	Map was developed by image analysis of figure A19 in appendix A in the SYMBIOSE report.
Spatial coverage	Danish marine waters
Data resolution	n.i.
Unit	Distance-weighted number of oil spills within a 25 km radius.
Time period	2003-2009

A2.1.19. Phosphorus winter concentrations (DIP)

Description	Interpolated concentration of dissolved inorganic phosphorus during winter.
Map	
Data source	ICES and The Danish Natural Environment Portal
Data processing	Point data of phosphorus winter concentrations was interpolated.
Spatial coverage	Danish marine waters
Data resolution	1 km x 1 km
Unit	µmol/l
Time period	2006-2013

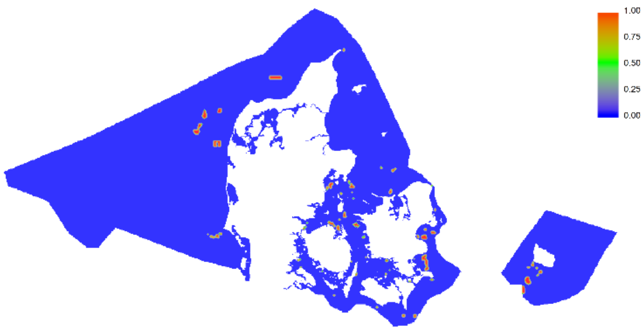
A2.1.20. Recreational shipping

Description	Estimated intensity of recreational shipping.
Map	
Data source	The Danish Environmental Protection Agency (MiljøGIS, 2017c, http://miljoegis.mim.dk/cbkort?profile=miljoegis_vandrammedirektiv2011)
Data processing	Danish recreational harbours (provided by Danish EPA), were used to estimate intensity of recreational shipping. The method was based on SYMBIOSE.
Spatial coverage	Danish marine waters
Data resolution	1 km x 1 km
Unit	Intensity index
Time period	2009-2011

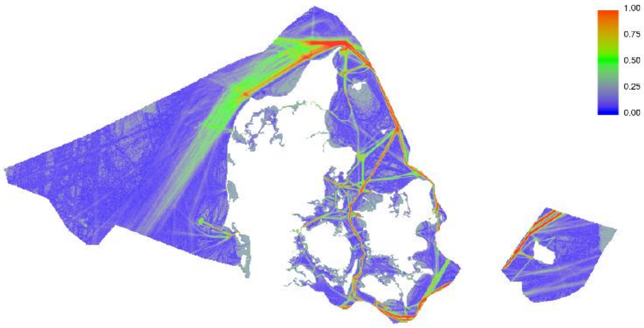
A2.1.21. Sea cables

Description	Sea cable locations in Danish marine waters.
Map	
Data source	SYMBIOSE (Mohn *et al.* 2015).
Data processing	Map was developed by image analysis of figure A24 in appendix A in the SYMBIOSE report.
Spatial coverage	Danish marine waters
Data resolution	n.i.
Unit	Presence/absence
Time period	Norway, Denmark and Sweden: 2011. OSPAR data are older.

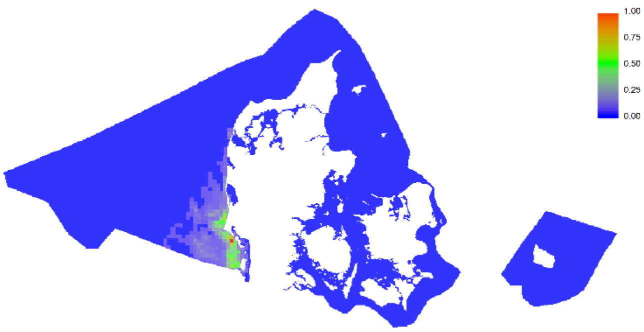
A2.1.22. Sediment extraction sites

Description	Sediment extraction sites in the Danish marine waters.
Map	
Data source	The Danish Environmental Protection Agency (MiljøGIS, 2017a, http://miljoegis.mim.dk/cbkort?profile=miljoegis-raastofferhavet)
Data processing	Shapefiles of "Fællesområder" was downloaded from MiljøGIS
Spatial coverage	Danish marine waters
Data resolution	n.i.
Unit	Presence/absence
Time period	2016

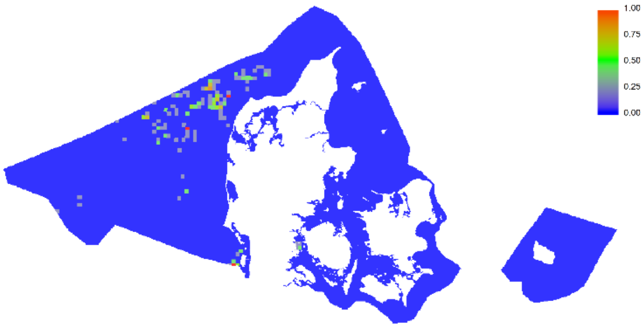
A2.1.23. Shipping intensity (commercial shipping)

Description	Commercial shipping intensity in Danish marine waters, as registered in AIS for 2009.
Map	
Data source	SYMBIOSE (Mohn *et al.* 2015)
Data processing	Map was developed by image analysis of figure A26 in appendix A in the SYMBIOSE report.
Spatial coverage	Danish marine waters.
Data resolution	1 km x 1 km
Unit	Intensity index
Time period	2009

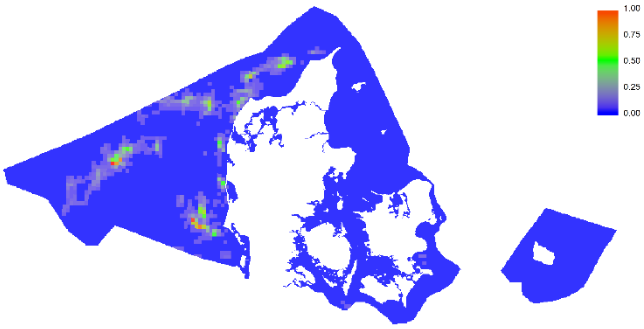
A2.1.24. Beam trawls (mesh size < 32 mm)

Description	VMS effort of beam trawls (mesh size < 32 mm) in Danish marine waters.
Map	
Data source	DTU Aqua (Dalskov *et al.* 2012)
Data processing	See Dalskov *et al.* (2012).
Spatial coverage	Danish marine waters
Data resolution	5 x 5 km
Unit	Time, see Dalskov *et al.* (2012).
Time period	2010

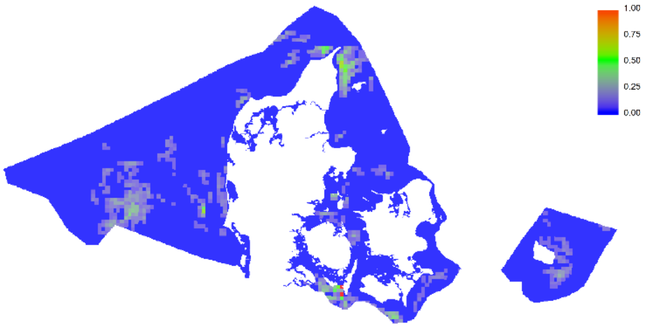
A2.1.25. Beam trawls (mesh size ≥ 100 mm)

Description	VMS effort of beam trawls (mesh size ≥ 100mm) in Danish marine waters.
Map	
Data source	DTU Aqua (Dalskov *et al.* 2012)
Data processing	See Dalskov *et al.* (2012).
Spatial coverage	Danish marine waters.
Data resolution	5 x 5 km
Unit	Time, see Dalskov *et al.* (2012).
Time period	2010

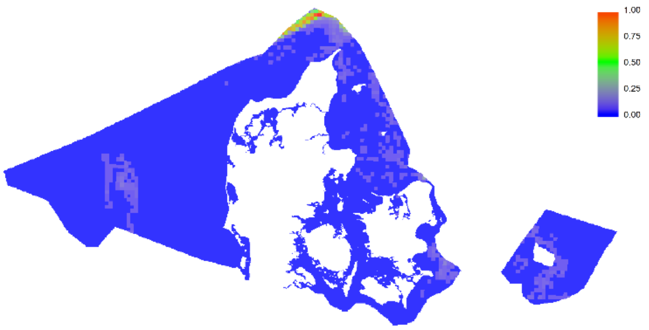
A2.1.26. Demersal fishing (mesh size < 16 mm)

Description	VMS effort of demersal fishing (mesh size < 16 mm) in Danish marine waters.
Map	
Data source	DTU Aqua (Dalskov *et al.* 2012)
Data processing	See Dalskov *et al.* (2012).
Spatial coverage	Danish marine waters.
Data resolution	5 x 5 km
Unit	Time, see Dalskov *et al.* (2012).
Time period	2010

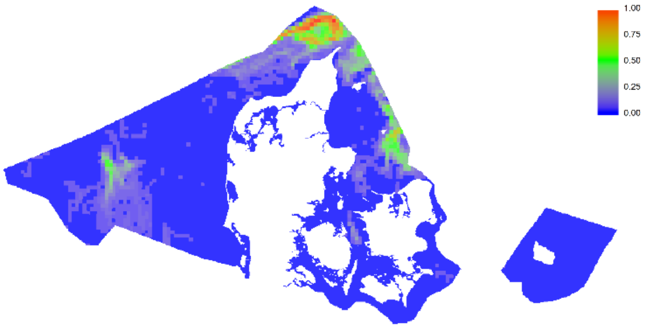
A2.1.27. Demersal fishing (mesh size 16-32 mm)

Description	VMS effort of demersal fishing (mesh size 16-32 mm) in Danish marine waters.
Map	
Data source	DTU Aqua (Dalskov *et al.* 2012)
Data processing	See Dalskov *et al.* (2012).
Spatial coverage	Danish marine waters
Data resolution	5 x 5 km
Unit	Time, see Dalskov *et al.* (2012).
Time period	2010

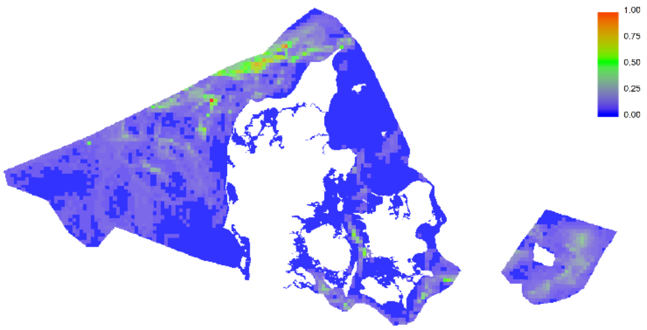
A2.1.28. Demersal fishing (mesh size 32-69 mm)

Description	VMS effort of demersal fishing (mesh size 32-69 mm) in Danish marine waters.
Map	
Data source	DTU Aqua (Dalskov *et al.* 2012)
Data processing	See Dalskov *et al.* (2012).
Spatial coverage	Danish marine waters
Data resolution	5 x 5 km
Unit	Time, see Dalskov *et al.* (2012).
Time period	2010

A2.1.29. Demersal fishing (mesh size 69-99 mm)

Description	VMS effort of demersal fishing (mesh size 69-99 mm) in Danish marine waters.
Map	
Data source	DTU Aqua (Dalskov *et al.* 2012)
Data processing	See Dalskov *et al.* (2012).
Spatial coverage	Danish marine waters
Data resolution	5 x 5 km
Unit	Time, see Dalskov *et al.* (2012).
Time period	2010

A2.1.30. Demersal fishing (mesh size ≥100 mm)

Description	VMS effort of demersal fishing (mesh size >100 mm) in Danish marine waters.
Map	
Data source	DTU Aqua (Dalskov *et al.* 2012)
Data processing	See Dalskov *et al.* (2012).
Spatial coverage	Danish marine waters
Data resolution	5 x 5 km
Unit	Time, see Dalskov *et al.* (2012).
Time period	2010

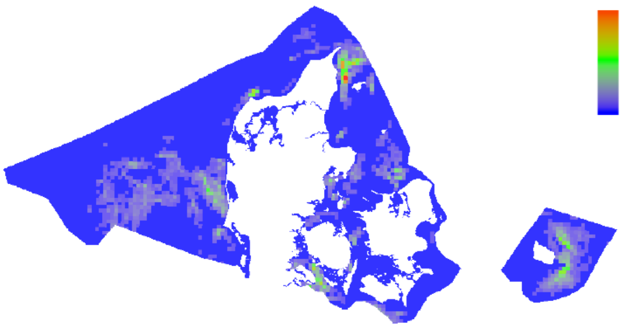
A2.1.31. Longlines

Description	VMS effort of longline fishery in Danish marine waters.
Map	
Data source	DTU Aqua (Dalskov *et al.* 2012)
Data processing	See Dalskov *et al.* (2012).
Spatial coverage	Danish marine waters
Data resolution	5 x 5 km
Unit	Time, see Dalskov *et al.* (2012).
Time period	2010

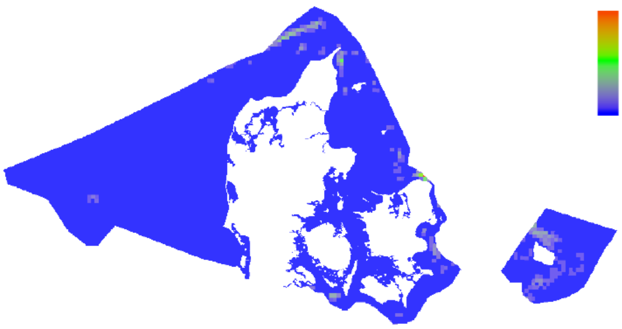
A2.1.32. Mussel dredging

Description	VMS effort of mussel dredging in Danish marine waters.
Map	
Data source	DTU Aqua (Dalskov *et al.* 2012)
Data processing	See Dalskov *et al.* (2012).
Spatial coverage	Danish marine waters
Data resolution	5 x 5 km
Unit	Time, see Dalskov *et al.* (2012).
Time period	2010

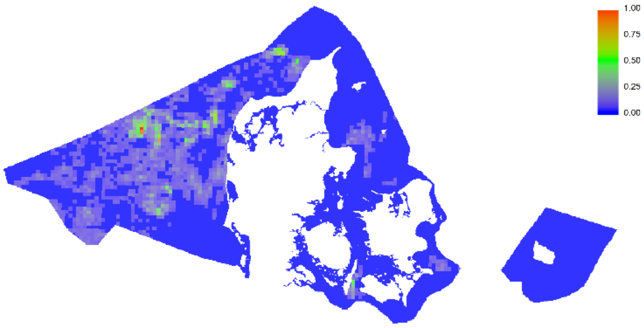
A2.1.33. Pelagic fishing (mesh size 16-32 mm)

Description	VMS effort of pelagic fishing (mesh size 16-32 mm) in Danish marine waters.
Map	
Data source	DTU Aqua (Dalskov *et al.* 2012)
Data processing	See Dalskov *et al.* (2012).
Spatial coverage	Danish marine waters
Data resolution	5 x 5 km
Unit	Time, see Dalskov *et al.* (2012).
Time period	2010

A2.1.34. Pelagic fishing (mesh size 32 – 80 mm)

Description	VMS effort of pelagic fishing (mesh size 32-80 mm) in Danish marine waters.
Map	
Data source	DTU Aqua (Dalskov *et al.* 2012)
Data processing	See Dalskov *et al.* (2012).
Spatial coverage	Danish marine waters
Data resolution	5 x 5 km
Unit	Time, see Dalskov *et al.* (2012).
Time period	2010

A2.1.35. Set net (all mesh sizes)

Description	VMS effort of fishing with set nets (all mesh sizes) in Danish marine waters.
Map	
Data source	DTU Aqua (Dalskov *et al.* 2012)
Data processing	See Dalskov *et al.* (2012).
Spatial coverage	Danish marine waters
Data resolution	5 x 5 km
Unit	Time, see Dalskov *et al.* (2012).
Time period	2010

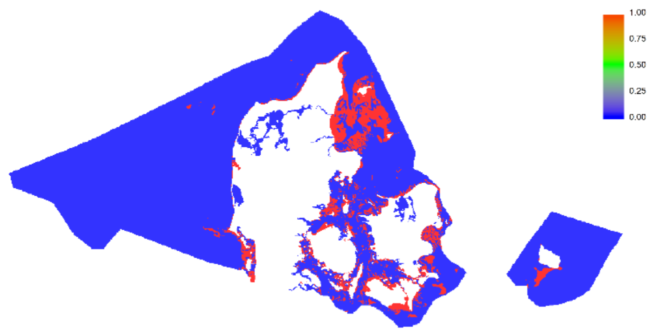
A2.2 Ecosystem components

Please note that all ecosystem component data were log(x+1)-transformed and normalized to values between 0 and 1 (see section 2.2.1). Thus, the value "1" exists at all maps, even though the highest value in the original dataset varies quite a lot. Please also note that the colour scale represents values from 0 to 1. The value "1" is shown by a red colour, the value "0" is indicated by a blue colour and the value 0.5 is shown with a green colour.

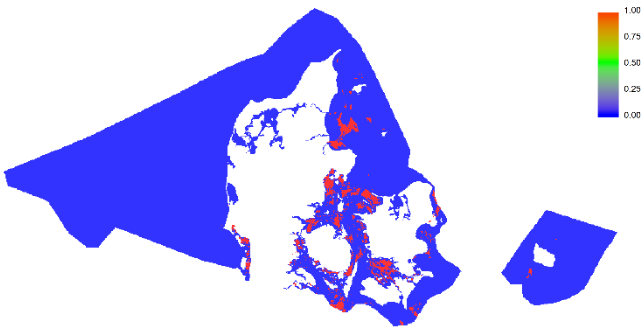
A2.2.1. Communities associated with infralittoral hard bottom

Description	Infralittoral hard bottom in the Danish marine areas
Map	
Data source	EUSeaMap2 (Al-Hamdani, 2016)
Data processing	Habitat classes A3, A3.1, A3.3, A3.4, A3.5, A3.6, and A5.13, from EUSeaMap2, were for the present study categorized as the habitat type "infralittoral hard bottom".
Spatial coverage	Danish marine waters
Data resolution	1 km x 1 km
Unit	Presence/absence
Time period	2001 - 2010

A2.2.2. Communities associated with infralittoral sand

Description	Infralittoral sand in the Danish marine areas
Map	
Data source	EUSeaMap2 (Al-Hamdani, 2016)
Data processing	EUSeaMap 2 Habitat class A5.23 was for the present study categorized as "infralittoral sand".
Spatial coverage	Danish marine waters
Data resolution	1 km x 1 km
Unit	Presence/absence
Time period	2001 - 2010

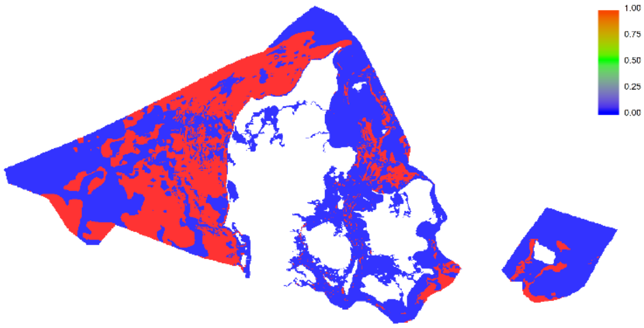
A2.2.3. Communities associated with infralittoral mud

Description	Infralittoral mud in the Danish marine areas
Map	
Data source	EUSeaMap2 (Al-Hamdani, 2016)
Data processing	EUSeaMap2 Habitat classes A5.33, and A5.34 were re-categorized as "infralittoral mud".
Spatial coverage	Danish marine waters
Data resolution	1 km x 1 km
Unit	Presence/absence
Time period	2001 - 2010

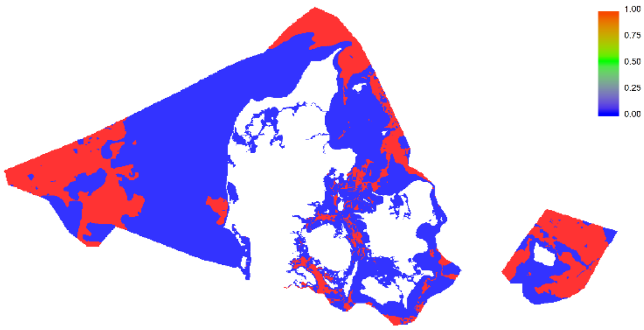
A2.2.4. Communities associated with circalittoral hard bottom

Description	Circalittoral hard bottom in the Danish marine areas
Map	
Data source	EUSeaMap2 (Al-Hamdani, 2016)
Data processing	Habitat classes A4.4, A4.5, A4.6, A5.14 and A5.15, from EUSeaMap2, were for the present study categorized as the habitat type "circalittoral hard bottom".
Spatial coverage	Danish marine waters
Data resolution	1 km x 1 km
Unit	Presence/absence
Time period	2001 - 2010

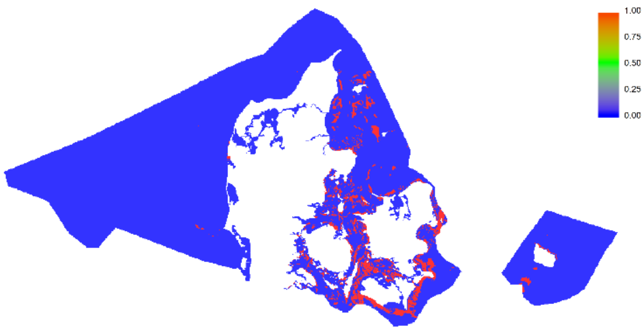
A2.2.5. Communities associated with circalittoral sand

Description	Circalittoral sand in the Danish marine areas
Map	
Data source	EUSeaMap2 (Al-Hamdani, 2016)
Data processing	Habitat classes A5.25, A5.27, A6.3, and A6.4, from EUSeaMap2, were for the present study categorized as the habitat type "circalittoral sand".
Spatial coverage	Danish marine waters
Data resolution	1 km x 1 km
Unit	Presence/absence
Time period	2001 - 2010

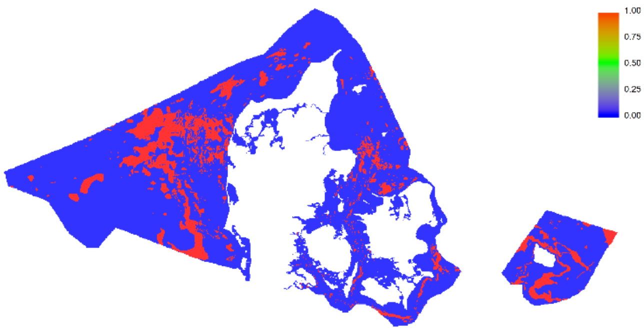
A2.2.6. Communities associated with circalittoral mud

Description	Circalittoral mud in the Danish marine areas.
Map	
Data source	EUSeaMap2 (Al-Hamdani, 2016)
Data processing	Habitat classes A5.35, A5.36, A5.37, and A6.5, from EUSeaMap2, were for the present study categorized as the habitat type "circalittoral mud".
Spatial coverage	Danish marine waters
Data resolution	1 km x 1 km
Unit	Presence/absence
Time period	2001 - 2010

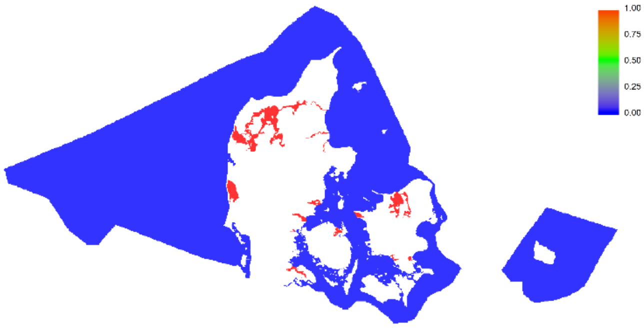
A2.2.7. Communities associated with infralittoral mixed sediments

Description	Infralittoral mixed sediments in the Danish marine areas
Map	
Data source	EUSeaMap2 (Al-Hamdani, 2016)
Data processing	Habitat class A5.43 from EUSeaMap2 was for the present study categorized as the habitat type "infralittoral mixed sediments".
Spatial coverage	Danish marine waters
Data resolution	1 km x 1 km
Unit	Presence/absence
Time period	2001 - 2010

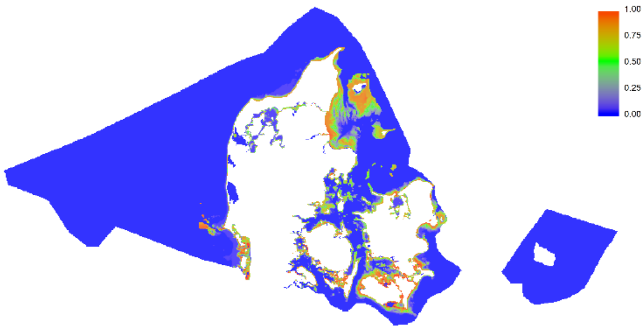
A2.2.8. Communities associated with circalittoral mixed sediments

Description	Circalittoral mixed sediments in the Danish marine areas
Map	
Data source	EUSeaMap2 (Al-Hamdani, 2016)
Data processing	Habitat classes A5.44 and A5.45, from EUSeaMap2, were for the present study categorized as the habitat type "circalittoral mixed sediments".
Spatial coverage	Danish marine waters
Data resolution	1 km x 1 km
Unit	Presence/absence
Time period	2001 - 2010

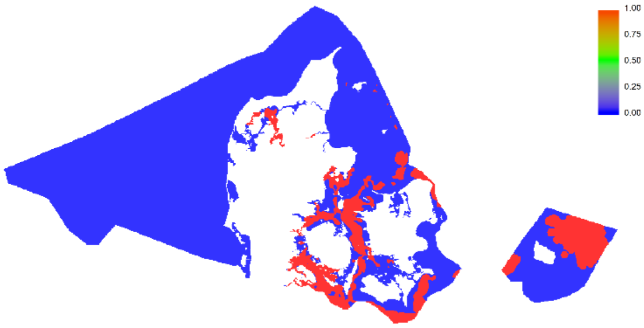
A2.2.9. Communities associated with estuaries

Description	Estuaries and fjord complexes in the Danish marine areas
Map	
Data source	RALAHA
Data processing	Selected estuaries, fjord complex and semi-enclosed bights were defined in ArcGIS.
Spatial coverage	Danish marine waters
Data resolution	1 km x 1 km
Unit	Presence/absence
Time period	2016

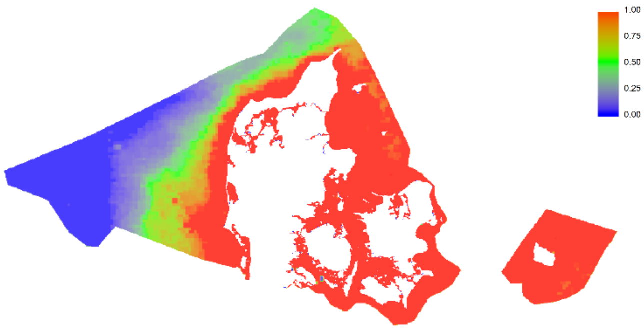
A2.2.10. Eelgrass distribution

Description	Potential distribution of eelgrass, *Zostera marina*, in Danish waters based on a GIS model
Map	
Data source	SYMBIOSE (Mohn *et al.* 2015).
Data processing	Maps was developed by image analysis of figure C3 in appendix C in the SYMBIOSE report.
Spatial coverage	Danish marine waters in the depth interval 0-10m, except Ringkøbing Fjord, Nissum Fjord and Nissum Bredning.
Data resolution	1 km x 1 km
Unit	Predicted probability
Time period	2000-2010

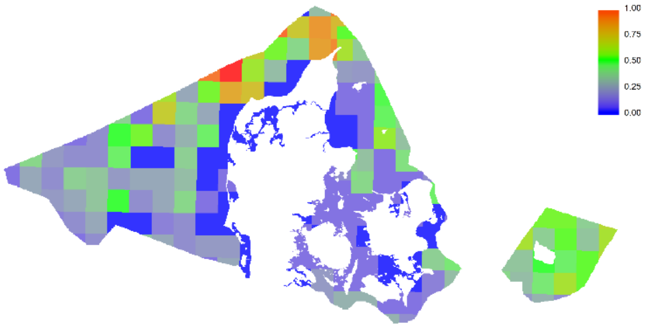
A2.2.11. Oxygen deficit

Description	Oxygen deficit
Map	
Data source	The Danish Environmental Protection Agency's monthly reports of oxygen depletion (Danish Environmental Protection Agency, 2017, http://svana.dk/vand/havet/havmiljoe/iltsvind/)
Data processing	Modelled monthly maximum area of oxygen deficit (< 4 mg/l) was combined in ArcGIS.
Spatial coverage	Danish marine waters
Data resolution	1 km x 1 km
Unit	Presence/absence
Time period	Months: July-October. Years: 2012-2016

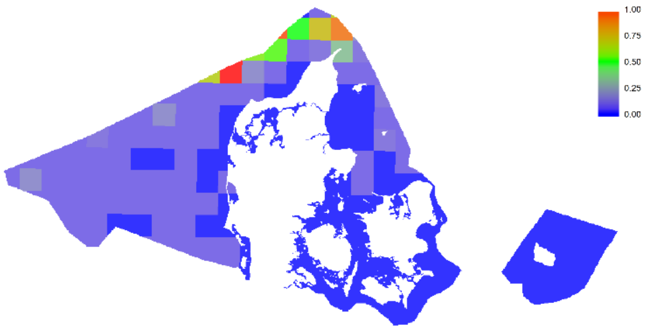
A2.2.12. Plankton communities

Description	Plankton communities in nutrient poor and rich waters
Map	
Data source	SYMBIOSE (Mohn *et al.* 2015).
Data processing	Map was developed by image analysis of figure C5 in appendix C in the SYMBIOSE report.
Spatial coverage	Danish marine waters.
Data resolution	1 km x 1 km and smoothing factor 20 km.
Unit	Chlorophyll concentration index
Time period	2003 - 2010

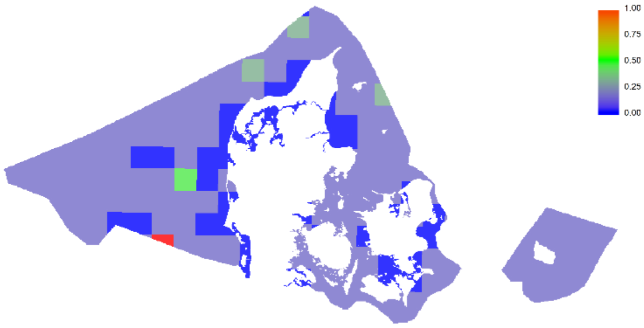
A2.2.13. Cod (*Gadus morhua*)

Description	Distribution of Cod in Danish marine waters
Map	
Data source	DTU Aqua (Warnar *et al.* 2012)
Data processing	Combined BITS and IBTS trawl survey results. See Warnar *et al.* (2012)
Spatial coverage	Most of the Danish marine waters, except few areas near coasts. See (Warnar *et al.*2012) for further information.
Data resolution	≈ 30 x 30 km
Unit	See Warnar *et al.* 2012
Time period	2001 - 2010

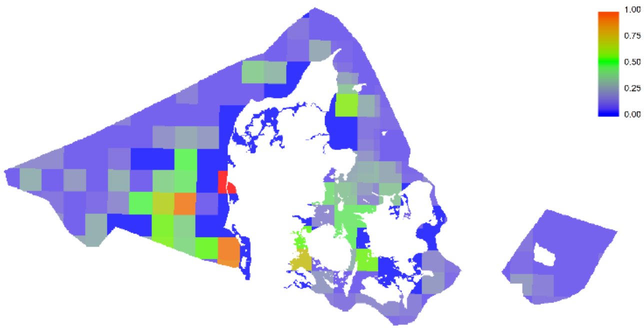
A2.2.14. Coalfish (*Pollachius virens*)

Description	Distribution of Coalfish in Danish marine waters
Map	
Data source	DTU Aqua (Warnar *et al.* 2012)
Data processing	Combined BITS and IBTS trawl survey results. See Warnar *et al.* (2012)
Spatial coverage	Most of the Danish marine waters, except few areas near coasts. See (Warnar *et al.* 2012) for further information.
Data resolution	≈ 30 x 30 km
Unit	See Warnar *et al.* 2012
Time period	2001 - 2010

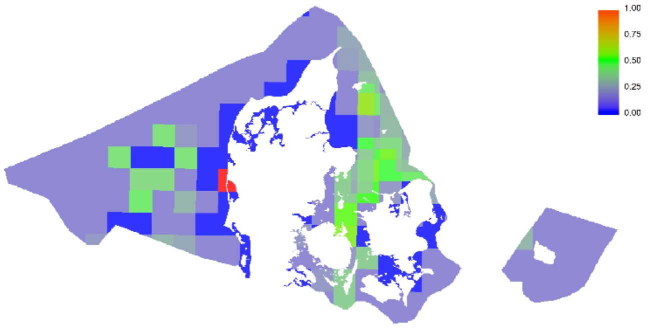
A2.2.15. Common Dogfish (*Scyliorhinus caniculus*)

Description	Distribution of Common Dogfish in Danish marine waters
Map	
Data source	DTU Aqua (Warnar *et al.* 2012)
Data processing	Combined BITS and IBTS trawl survey results. See Warnar *et al.* (2012)
Spatial coverage	Most of the Danish marine waters, except few areas near coasts. See Warnar *et al.* (2012) for further information.
Data resolution	≈ 30 x 30 km
Unit	See Warnar *et al.* (2012)
Time period	2001 - 2010

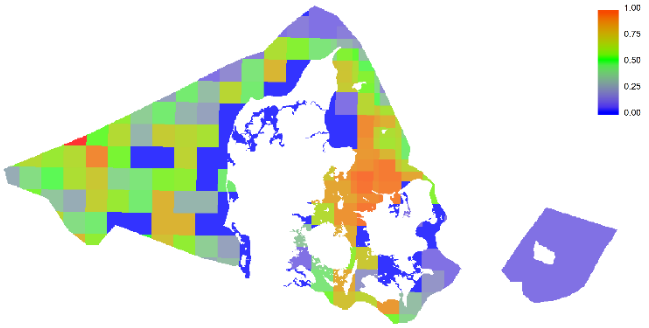
A2.2.16. Common Hooknose (*Agonus cataphractus*)

Description	Distribution of Common Hooknose in Danish marine waters
Map	
Data source	DTU Aqua (Warnar *et al.* 2012)
Data processing	Combined BITS and IBTS trawl survey results. See Warnar *et al.* (2012)
Spatial coverage	Most of the Danish marine waters, except few areas near coasts. See Warnar *et al.* (2012) for further information.
Data resolution	≈ 30 x 30 km
Unit	See Warnar *et al.* (2012)
Time period	2001-2010

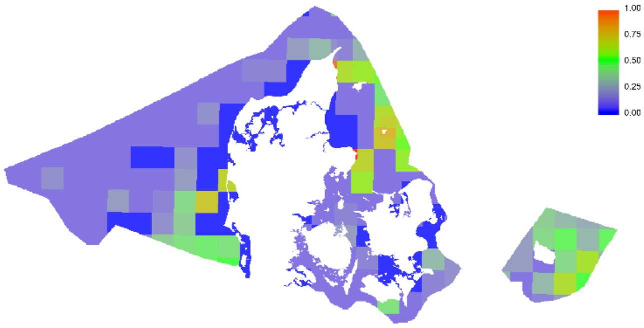
A2.2.17. Common Sole (*Solea solea*)

Description	Distribution of Common Sole in Danish marine waters
Map	
Data source	DTU Aqua (Warnar *et al.* 2012)
Data processing	Combined BITS and IBTS trawl survey results. See Warnar *et al.* (2012)
Spatial coverage	Most of the Danish marine waters, except few areas near coasts. See Warnar *et al.* (2012) for further information.
Data resolution	≈ 30 x 30 km
Unit	See Warnar *et al.* (2012)
Time period	2001-2010

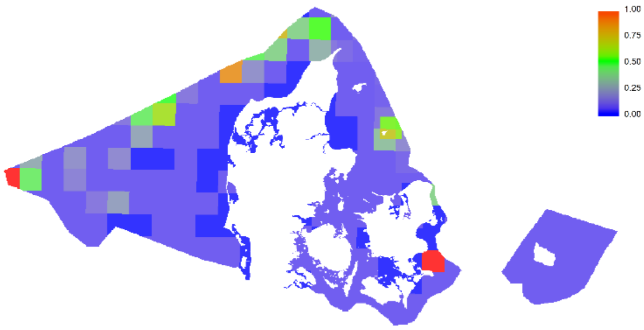
A2.2.18. Dab (*Limanda limanda*)

Description	Distribution of Dab in Danish marine waters
Map	
Data source	DTU Aqua (Warnar *et al.* 2012)
Data processing	Combined BITS and IBTS trawl survey results. See Warnar *et al.* (2012)
Spatial coverage	Most of the Danish marine waters, except few areas near coasts. See Warnar *et al.* (2012) for further information.
Data resolution	≈ 30 x 30 km
Unit	See Warnar *et al.* (2012)
Time period	2001 – 2010

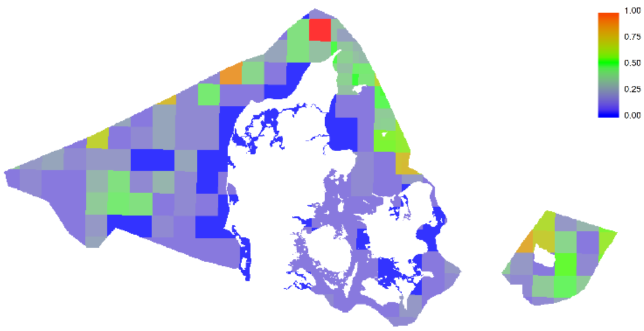
A2.2.19. Flounder (*Platichthys flesus*)

Description	Distribution of Flounder in Danish marine waters
Map	
Data source	DTU Aqua (Warnar *et al.* 2012)
Data processing	Combined BITS and IBTS trawl survey results. See Warnar *et al.* (2012)
Spatial coverage	Most of the Danish marine waters, except few areas near coasts. See Warnar *et al.* (2012) for further information.
Data resolution	≈ 30 x 30 km
Unit	See Warnar *et al.* (2012)
Time period	2001 - 2010

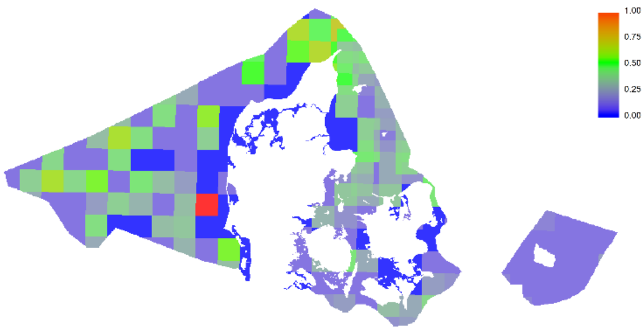
A2.2.20. Haddock (*Melanogrammus aeglefinus*)

Description	Distribution of Haddock in Danish marine waters
Map	
Data source	DTU Aqua (Warnar *et al.* 2012)
Data processing	Combined BITS and IBTS trawl survey results. See Warnar *et al.* (2012)
Spatial coverage	Most of the Danish marine waters, except few areas near coasts. See Warnar *et al.* (2012) for further information.
Data resolution	≈ 30 x 30 km
Unit	See Warnar *et al.* (2012)
Time period	2001 - 2010

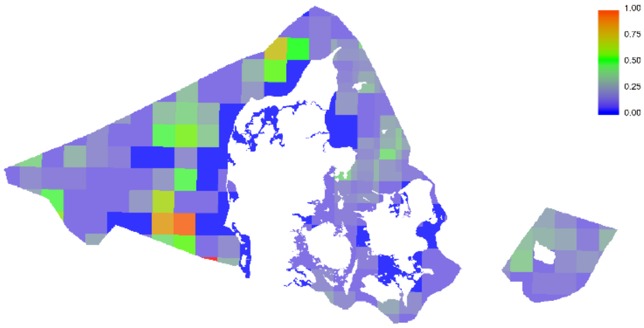
A2.2.21. Herring (*Clupea harengus*)

Description	Distribution of Herring in Danish marine waters
Map	
Data source	DTU Aqua (Warnar *et al.* 2012)
Data processing	Combined BITS and IBTS trawl survey results. See Warnar *et al.* (2012)
Spatial coverage	Most of the Danish marine waters, except few areas near coasts. See Warnar *et al.* (2012) for further information.
Data resolution	≈ 30 x 30 km
Unit	See Warnar *et al.* (2012)
Time period	2001 - 2010

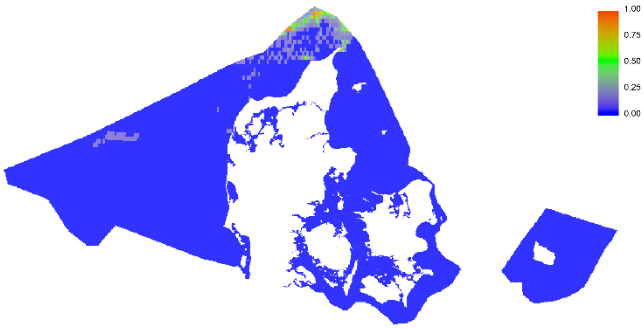
A2.2.22. Lumpfish (*Cyclopterus lumpus*)

Description	Distribution of Lumpfish in Danish marine waters
Map	
Data source	DTU Aqua (Warnar *et al.* 2012)
Data processing	Combined BITS and IBTS trawl survey results. See Warnar *et al.* (2012)
Spatial coverage	Most of the Danish marine waters, except few areas near coasts. See Warnar *et al.* (2012) for further information.
Data resolution	≈ 30 x 30 km
Unit	See Warnar *et al.* (2012)
Time period	2001 - 2010

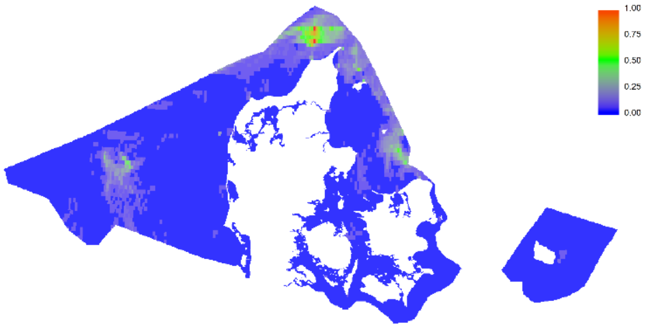
A2.2.23. Mackerel (*Scomber scombrus*)

Description	Distribution of Mackerel in Danish marine waters
Map	
Data source	DTU Aqua (Warnar *et al.* 2012)
Data processing	Combined BITS and IBTS trawl survey results. See Warnar *et al.* (2012)
Spatial coverage	Most of the Danish marine waters, except few areas near coasts. See Warnar *et al.* (2012) for further information.
Data resolution	≈ 30 x 30 km
Unit	See Warnar *et al.* (2012)
Time period	2001 - 2010

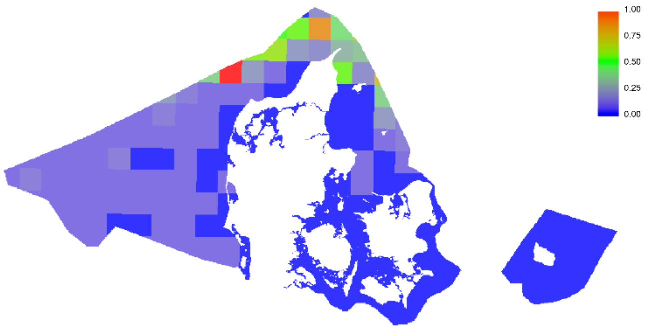
A2.2.24. Northern Prawn (*Pandalus borealis*)

Description	Distribution of Northern Prawn in Danish marine waters
Map	
Data source	DTU Aqua (Warnar *et al.* 2012)
Data processing	Combined BITS and IBTS trawl survey results. See Warnar *et al.* (2012)
Spatial coverage	Most of the Danish marine waters, except few areas near coasts. See Warnar *et al.* (2012) for further information.
Data resolution	≈ 30 x 30 km
Unit	See Warnar *et al.* (2012)
Time period	2001 - 2010

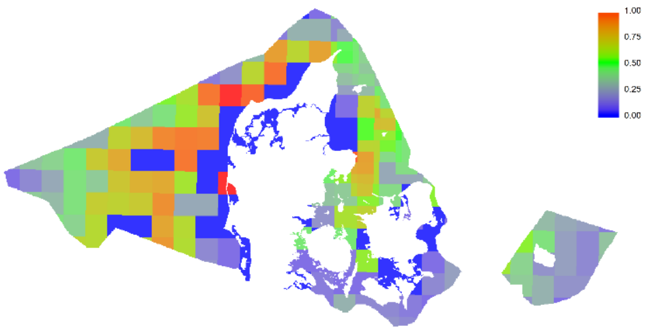
A2.2.25. Norway Lobster (*Nephros norvegicus*)

Description	Distribution of Norway Lobster in Danish marine waters
Map	
Data source	DTU Aqua (Warnar *et al.* 2012)
Data processing	Combined BITS and IBTS trawl survey results. See Warnar *et al.* (2012)
Spatial coverage	Most of the Danish marine waters, except few areas near coasts. See Warnar *et al.* (2012) for further information.
Data resolution	≈ 30 x 30 km
Unit	See Warnar *et al.* (2012)
Time period	2001 - 2010

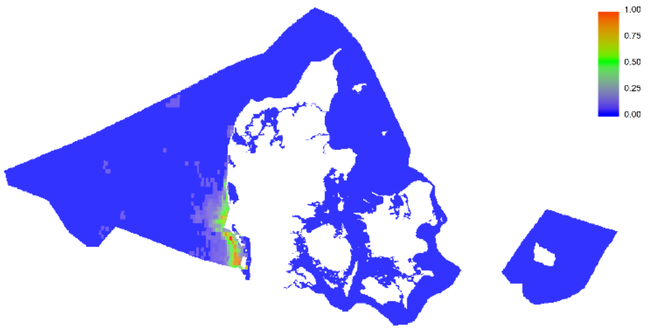
A2.2.26. Norway pout (*Trisopterus esmarkii*)

Description	Distribution of Norway Pout in Danish marine waters
Map	
Data source	DTU Aqua (Warnar *et al.* 2012)
Data processing	Combined BITS and IBTS trawl survey results. See Warnar *et al.* (2012)
Spatial coverage	Most of the Danish marine waters, except few areas near coasts. See Warnar *et al.* (2012) for further information.
Data resolution	≈ 30 x 30 km
Unit	See Warnar *et al.* (2012)
Time period	2001 - 2010

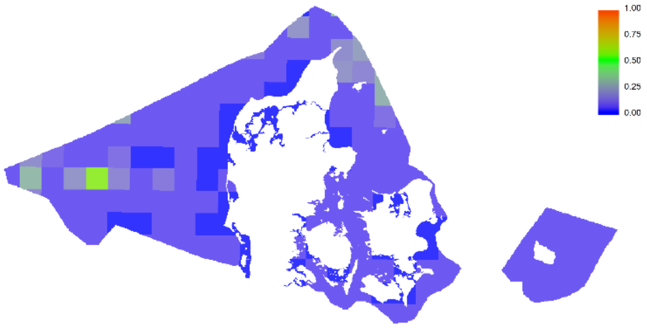
A2.2.27. Plaice (*Pleuronectes platessa*)

Description	Distribution of Plaice in Danish marine waters
Map	
Data source	DTU Aqua (Warnar *et al.* 2012)
Data processing	Combined BITS and IBTS trawl survey results. See Warnar *et al.* (2012)
Spatial coverage	Most of the Danish marine waters, except few areas near coasts. See Warnar *et al.* (2012) for further information.
Data resolution	≈ 30 x 30 km
Unit	See Warnar *et al.* (2012)
Time period	2001 - 2010

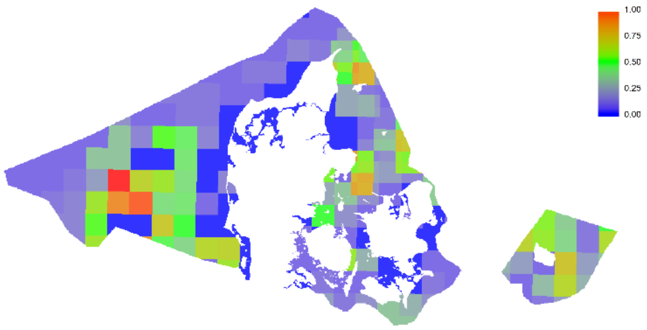
A2.2.28. Shrimp (*Crangon crangon*)

Description	Distribution of Shrimp in Danish marine waters
Map	
Data source	DTU Aqua (Warnar *et al.* 2012)
Data processing	Combined BITS and IBTS trawl survey results. See Warnar *et al.* (2012)
Spatial coverage	Most of the Danish marine waters, except few areas near coasts. See Warnar *et al.* (2012) for further information.
Data resolution	≈ 30 x 30 km
Unit	See Warnar *et al.* (2012)
Time period	2001 - 2010

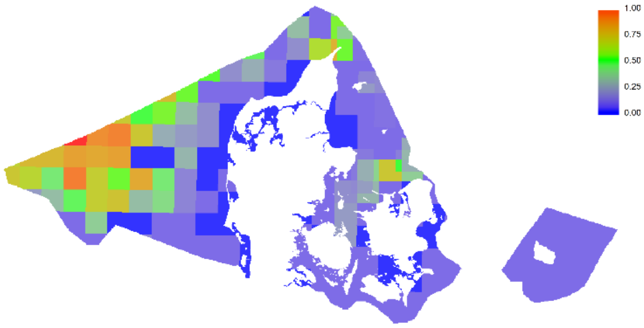
A2.2.29. Spiny Dogfish (*Squalus acanthias*)

Description	Distribution of Spiny Dogfish in Danish marine waters
Map	
Data source	DTU Aqua (Warnar *et al.* 2012)
Data processing	Combined BITS and IBTS trawl survey results. See Warnar *et al.* (2012)
Spatial coverage	Most of the Danish marine waters, except few areas near coasts. See Warnar *et al.* (2012) for further information.
Data resolution	≈ 30 x 30 km
Unit	See Warnar *et al.* (2012)
Time period	2001 - 2010

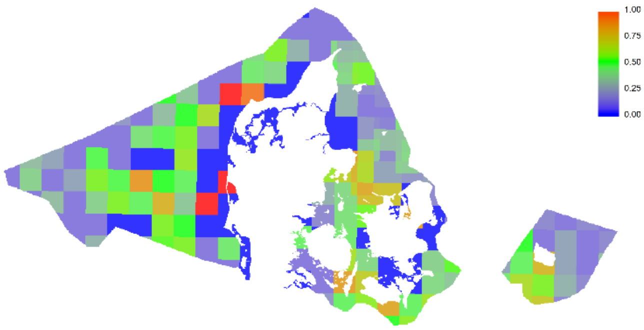
A2.2.30. Sprat (*Sprattus sprattus*)

Description	Distribution of Sprat in Danish marine waters
Map	
Data source	DTU Aqua (Warnar *et al.* 2012)
Data processing	Combined BITS and IBTS trawl survey results. See Warnar *et al.* (2012)
Spatial coverage	Most of the Danish marine waters, except few areas near coasts. See Warnar *et al.* (2012) for further information.
Data resolution	≈ 30 x 30 km
Unit	See Warnar *et al.* (2012)
Time period	2001 - 2010

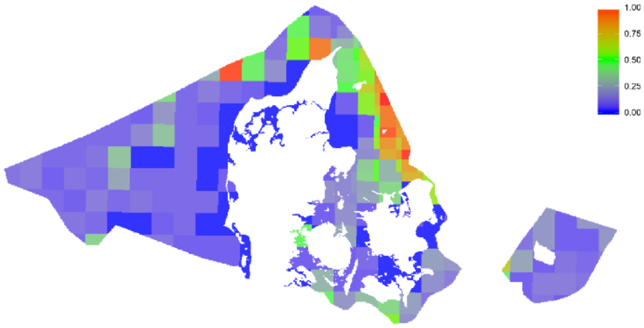
A2.2.31. Starry Ray (*Raja radiate*)

Description	Distribution of Starry Ray in Danish marine waters
Map	
Data source	DTU Aqua (Warnar *et al.* 2012)
Data processing	Combined BITS and IBTS trawl survey results. See Warnar *et al.* (2012)
Spatial coverage	Most of the Danish marine waters, except few areas near coasts. See Warnar *et al.* (2012) for further information.
Data resolution	≈ 30 x 30 km
Unit	See Warnar *et al.* (2012)
Time period	2001 - 2010

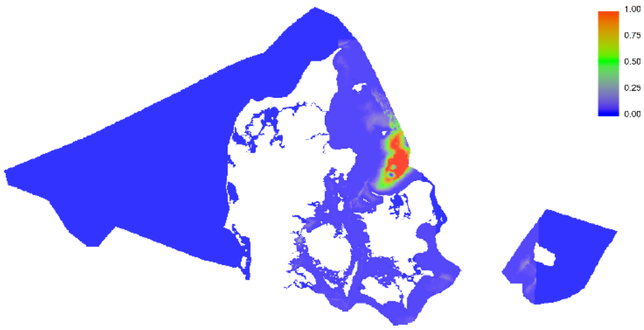
A2.2.32. Turbot (*Psetta maxima*)

Description	Distribution of Turbot in Danish marine waters
Map	
Data source	DTU Aqua (Warnar *et al.* 2012)
Data processing	Combined BITS and IBTS trawl survey results. See Warnar *et al.* (2012)
Spatial coverage	Most of the Danish marine waters, except few areas near coasts. See Warnar *et al.* (2012) for further information.
Data resolution	≈ 30 x 30 km
Unit	See Warnar *et al.* (2012)
Time period	2001 - 2010

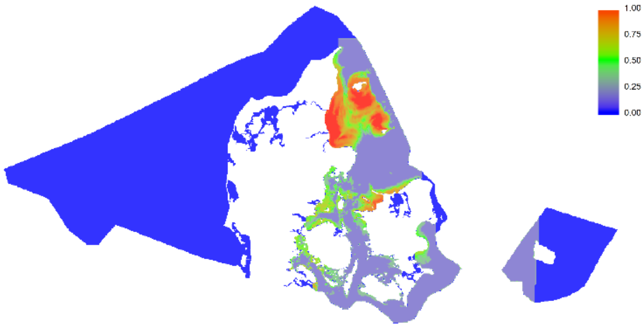
A2.2.33. Whiting (*Merlangius merlangus*)

Description	Distribution of Whiting in Danish marine waters
Map	
Data source	DTU Aqua (Warnar *et al.* 2012)
Data processing	Combined BITS and IBTS trawl survey results. See Warnar *et al.* (2012)
Spatial coverage	Most of the Danish marine waters, except few areas near coasts. See Warnar *et al.* (2012) for further information.
Data resolution	≈ 30 x 30 km
Unit	See Warnar *et al.* (2012)
Time period	2001 - 2010

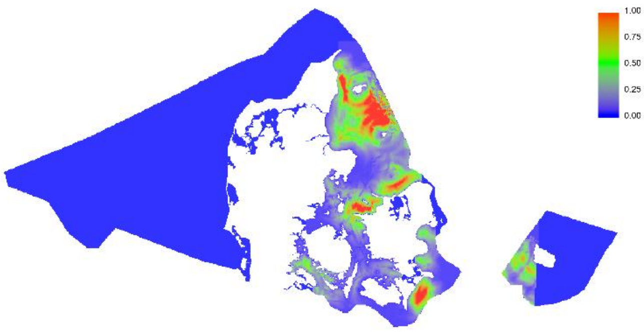
A2.2.34. Auks: Guillemot (*Uria aalge*), Razorbill (*Alca torda*)

Description	Modelled density of Auks wintering in Danish marine waters
Map	
Data source	SYMBIOSE (Mohn *et al.* 2015).
Data processing	Map developed by image analysis of figure E1 in appendix E in the SYMBIOSE report.
Spatial coverage	Most of the open ocean parts of the inner Danish waters and the western Bornholm basin. See (Mohn *et al.* 2015) for further information.
Data resolution	1 km x 1 km
Unit	Individuals per grid cell
Time period	January – March 2008

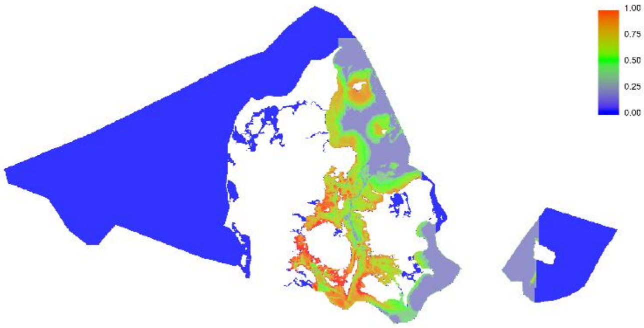
A2.2.35. Common Scoter (*Melanitta nigra*)

Description	Modelled density of Common scoter wintering in Danish marine waters
Map	
Data source	SYMBIOSE (Mohn *et al.* 2015).
Data processing	Map developed by image analysis of figure E2 in appendix E in the SYMBIOSE report.
Spatial coverage	Most of the open ocean parts of the inner Danish waters and the western Bornholm basin. See (Mohn *et al.* 2015) for further information.
Data resolution	1 km x 1 km
Unit	Individuals per grid
Time period	January – March 2008

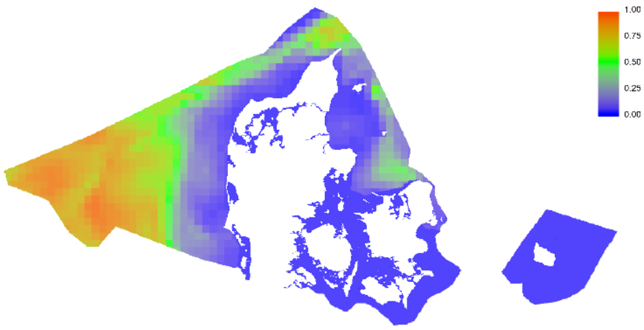
A2.2.36. Divers: Red-throated Diver (*Gavia stellate*), Black-throated Diver (*Gavia arctica*)

Description	Modelled density of Divers wintering in Danish marine waters
Map	
Data source	SYMBIOSE (Mohn *et al.* 2015).
Data processing	Map developed by image analysis of figure E3 in appendix E in the SYMBIOSE report.
Spatial coverage	Most of the open ocean parts of the inner Danish waters and the western Bornholm basin. See (Mohn *et al.* 2015) for further information.
Data resolution	1 km x 1 km
Unit	Individuals per grid
Time period	January – March 2008

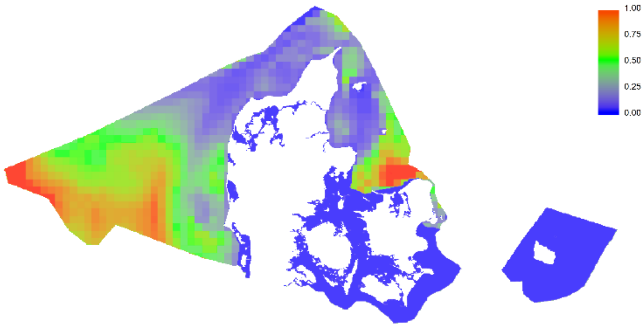
A2.2.37. Eider (*Somateria mollissima*)

Description	Modelled density of Eider wintering in Danish marine waters
Map	
Data source	SYMBIOSE (Mohn *et al.* 2015).
Data processing	Map developed by image analysis of figure E4 in appendix E in the SYMBIOSE report.
Spatial coverage	Most of the open ocean parts of the inner Danish waters and the western Bornholm basin. See (Mohn *et al.* 2015) for further information.
Data resolution	1 km x 1 km
Unit	Individuals per grid
Time period	January - March 2008

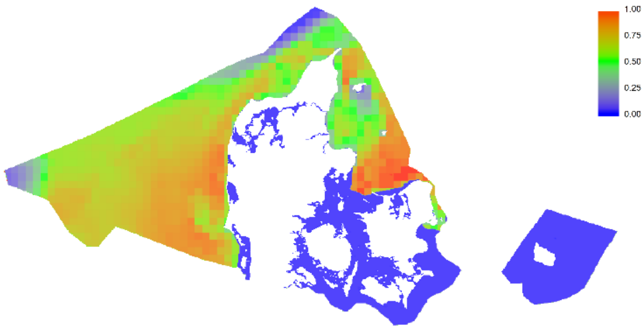
A2.2.38. Fulmar (*Fulmarus glacialis*)

Description	Modelled distribution of Northern Fulmar
Map	
Data source	HARMONY (Andersen & Stock, 2013).
Data processing	Data from HARMONY were used.
Spatial coverage	North Sea
Data resolution	10 x 10 km
Unit	Predicted probability
Time period	1995 - 2004

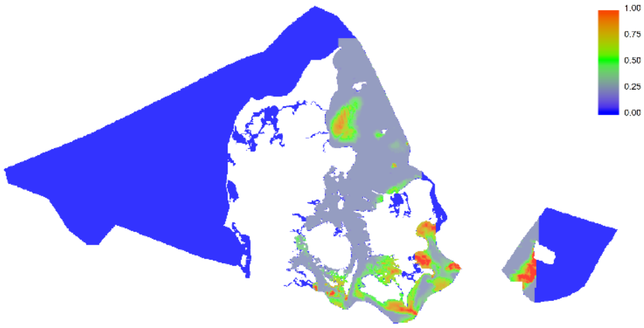
A2.2.39. Gannet (*Morus bassanus*)

Description	Modelled distribution of Northern Gannet
Map	
Data source	HARMONY (Andersen & Stock, 2013).
Data processing	Data from HARMONY were used.
Spatial coverage	North Sea
Data resolution	10 x 10 km
Unit	Predicted probability
Time period	1995 - 2004

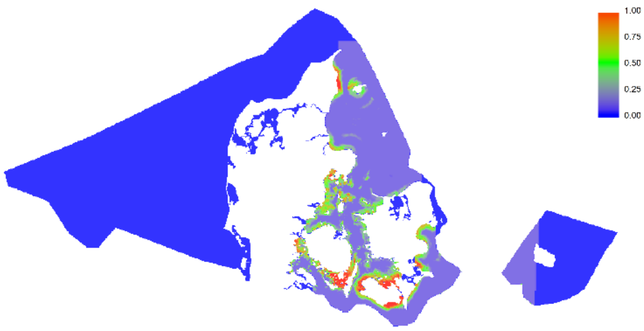
A2.2.40. Kittiwake (*Rissa tridactyla*)

Description	Modelled distribution of Kittiwake
Map	
Data source	HARMONY (Andersen & Stock, 2013)
Data processing	Data from HARMONY were used.
Spatial coverage	North Sea
Data resolution	10 x 10 km
Unit	Predicted probability
Time period	1995 - 2004

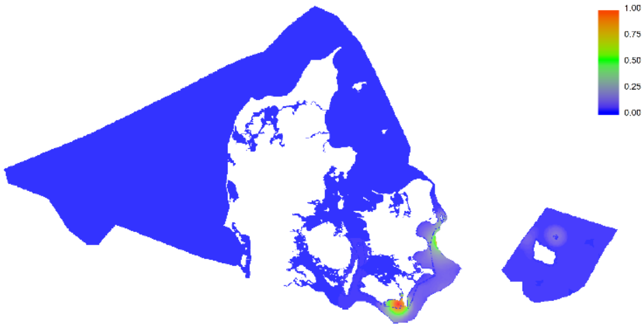
A2.2.41. Long-tailed Duck (*Clangula hyemalis*)

Description	Distribution and density of Long-tailed Ducks wintering in Danish marine waters
Map	
Data source	SYMBIOSE (Mohn *et al.* 2015).
Data processing	Map deveoped by image analysis of figure E8 in appendix E in the SYMBIOSE report.
Spatial coverage	Most of the open ocean parts of the inner Danish waters and the western Bornholm Basin. See (Mohn *et al.* 2015) for further information.
Data resolution	500 x 500 m
Unit	Individuals per grid
Time period	January – March 2008

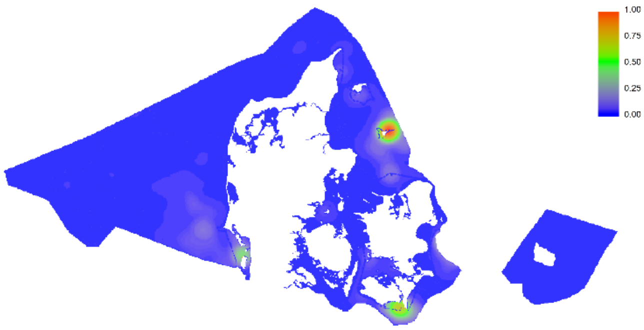
A2.2.42. Red-breasted Merganser (*Mergus serrator*)

Description	Distribution and density of Red-breasted Merganser wintering in Danish marine waters
Map	
Data source	SYMBIOSE (Mohn *et al.* 2015).
Data processing	Map developed by image analysis of figure E9 in appendix E in the SYMBIOSE report.
Spatial coverage	Most of the open ocean parts of the inner Danish waters and the western Bornholm Basin. See (Mohn *et al.* 2015) for further information.
Data resolution	500 x 500 m
Unit	Individuals per grid
Time period	January – March 2008

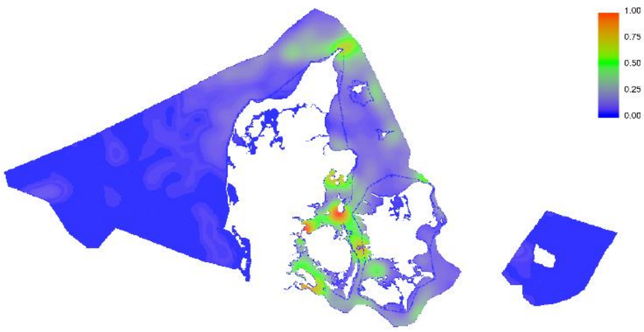
A2.2.43. Grey Seal (*Halichoerus grypus*)

Description	Density of Grey Seals in Danish marine waters
Map	
Data source	SYMBIOSE (Mohn *et al.* 2015).
Data processing	Map developed by image analysis of figure F1 in appendix F in the SYMBIOSE report.
Spatial coverage	Great Belt, the Sound, the Bornholm Basin and the Baltic Sea. See (Mohn *et al.* 2015) for further information.
Data resolution	1 km x 1 km and smoothing factor 20 km
Unit	Individuals per grid
Time period	November 2000 – May 2013

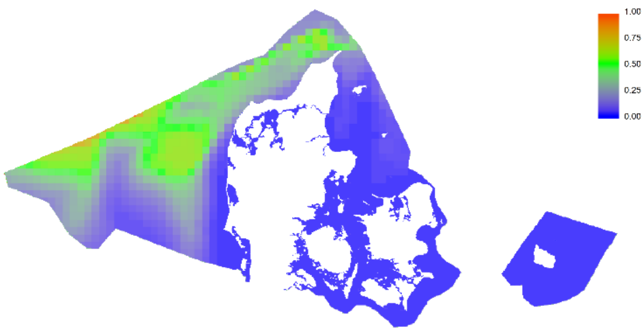
A2.2.44. Harbour Seal (*Phoca vitulina*)

Description	Density of Harbour Seals in Danish marine waters
Map	
Data source	SYMBIOSE (Mohn *et al.* 2015).
Data processing	Map developed by image analysis of figure F2 in appendix F in the SYMBIOSE report.
Spatial coverage	Most part of the Danish marine waters except some parts of the North Sea, Kattegat, Little Belt and the Bornholm Basin. See (Mohn *et al.* 2015) for further information.
Data resolution	1 km x 1 km and smoothing factor 20 km
Unit	Individuals per grid
Time period	April 2001 – May 2013

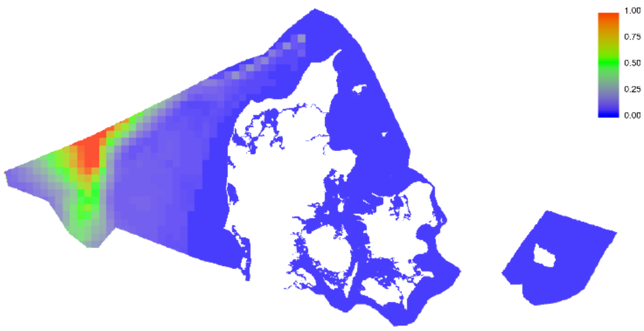
A2.2.45. Harbour Porpoise (*Phocoena phocoena*)

Description	Density of Harbour Porpoise in Danish marine waters
Map	
Data source	SYMBIOSE (Mohn *et al.* 2015).
Data processing	Map developed by image analysis of figure F3 in appendix F in the SYMBIOSE report.
Spatial coverage	Data covers most of the Danish marine waters, but is only representative of animals tagged in the Kattegat, Skagerrak and the Belt Sea.
Data resolution	1 km x 1 km and smoothing factor 20 km
Unit	Individuals per grid
Time period	April 1997 – November 2012

A2.2.46. Minke Whale (*Balanoptera acutorostrata*)

Description	Modelled distribution of Minke Whale in Danish marine waters
Map	
Data source	HARMONY (Andersen & Stock, 2013).
Data processing	Data from HARMONY were used.
Spatial coverage	North Sea
Data resolution	10 x 10 km
Unit	Predicted probability
Time period	1994 and 2005 surveys combined

A2.2.47. White-beaked Dolphin (*Lagenorhynchus albirostris*)

Description	Modelled distribution of White-beaked Dolphin in Danish marine waters
Map	
Data source	HARMONY (Andersen & Stock, 2013).
Data processing	Data from HARMONY were used.
Spatial coverage	North Sea
Data resolution	10 x 10 km
Unit	Predicted probability
Time period	1994 and 2005 surveys combined

Annex 3: Participants in the survey

The following 12 persons have kindly contributed with their expertise to the setting of effects distances and sensitivity weight by filling in a spread sheet produced for this specific activity:

1. Zyad Al-Hamdani, senior researcher (PhD), GEUS
2. Jesper H. Andersen, chief scientist (PhD), NIVA Denmark
3. Karen Edelvang, head of section (PhD), DTU Aqua
4. Anders Erichsen, senior project manager, DHI
5. Linus Hammar, analyst (PhD), Swedish Agency for Marine and Water Management (SwAM)
6. Therese Harvey, researcher (PhD), NIVA Denmark
7. Emilie Kallenbach, research assistant, NIVA Denmark
8. Samuli Korpinen, research manager (PhD), Finnish Marine Research Centre (MRC-SYKE)
9. Ciaran Murray, researcher (PhD), NIVA Denmark
10. Peter Rask Møller, associate professor (PhD), Natural History Museum of Denmark (SNM)
11. Johnny Reker, programme manager, European Environment Agency (EEA)
12. Thomas Kirk Sørensen, programme manager, WWF Denmark

The conclusions presented in this report are those of the authors and does not necessarily reflect their institutions points of views. Contributors to the study (e.g. provision of data and/or setting of effect distance and sensitivity weights) who are not explicitly listed as authors of this report have had no involvement whatsoever in other parts of the study and consequently do not hold any responsibility for the results, interpretations and conclusions.

Annex 4: Overview of case studies

The ranking is made for Denmark as a whole and for the following individual 'systems' with neighbouring coastal and off shore water indicated in parenthesises:

1. Aabenraa Fjord (southern parts of the Little Belt)
2. Augustenborg Fjord / Als Fjord (southern parts of the Little Belt)
3. Horsens Fjord (northern parts of the Great Belt)
4. Isefjorden (southern parts of the Kattegat)
5. Kalundborg Fjord (northern parts of the Great Belt)
6. Karrebæk Fjord / Karrebæksminde Bugt (Smålandsfarvandet, southern parts of the Great Belt)
7. Kolding Fjord (central parts of the Little Belt)
8. Limfjorden, western parts (eastern parts of the North Sea)
9. Limfjorden, eastern parts (Ålborg Bugt, northern parts of the Kattegat)
10. Mariager Fjord (Ålborg Bugt, central parts of the Kattegat)
11. Odense Fjord (northern parts of the Great Belt)
12. Præstø Fjord (Fakse Bugt, Arkona Basin)
13. Randers Fjord (Hevring Bugt, central parts of the Kattegat)
14. Ringkøbing Fjord (coastal parts of the eastern North Sea, open part of the North Sea)
15. Roskilde Fjord (northern part of Isefjorden, southern parts of the Kattegat)
16. Vejle Fjord (northern parts of the Little Belt)

A map of the case studies can be on the next page together with indications of the land-fjord-coast-open water 'transects' being analysed.

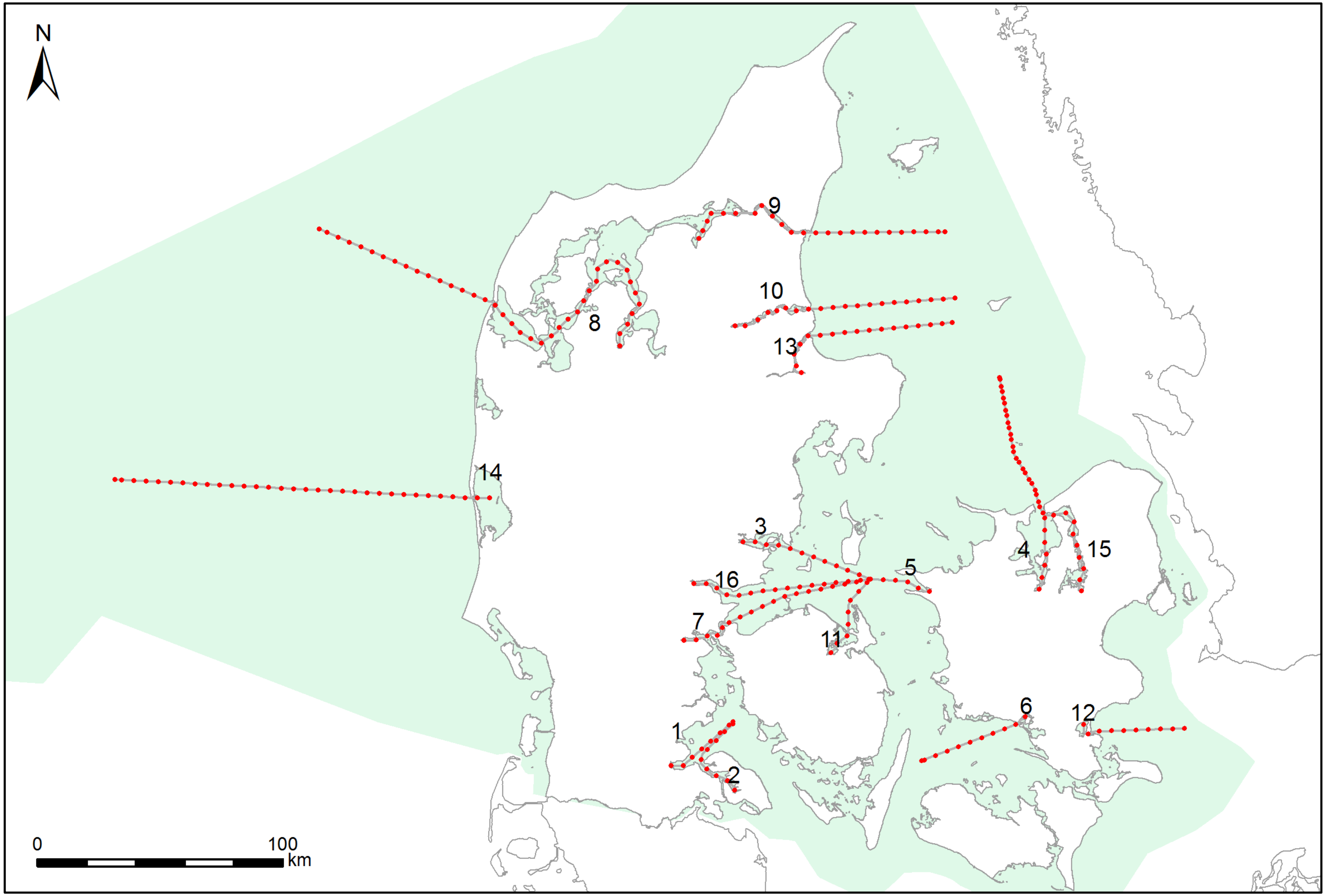


Figure A4.1 *Location of transects for the 16 gradient studies.*

Annex 5: Sensitivity weights

The table contains the sensitivity weights, derived from the median value of all respondants replies. Description of stressors and ecosystem components can be found in Annex 2 and in Tables 2.2.and 2.3.

Ecosystem Component ID

Stressor ID	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47
1	2	2	2	3	3	2	2	2	2	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	3	1	1
2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	2	2	2	3	3
3	2	2	2	2	2	2	2	2	2	3	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	3	3	2	2	2
4	1	1	2	2	1	1	2	2	2	4	3	3	1.5	1	1	2	2	1	1	2	1	1	1	1	1	1	1	2	1	1	1	2.5	1	2	2	2	2	2	2	2	2	2	2	2	2	1	1
5	1	1	1	1	1	1	2	1	1	2	1	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
6	2	2	2	2	1	1	1	1	2	3	1	2	1.5	2	1.5	1.5	1.5	1	1	1.5	1.5	2	1.5	2	1	1	1.5	1.5	1	2	1.5	1.5	2	1	1	1	1	1	1	1	1	1	2	2	2	1	1
7	1	2	2	2	2	2	2	1	3	3	4	3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	1	1
8	2.5	2.5	2.5	2.5	2.5	2.5	2	2.5	3	3	1	2	3	2.5	2	2.5	2.5	2	2	2.5	3	2	2	2	2	2	2	2.5	2	2	2	2.5	2.5	2	2	2	2	2	2	2	2	2	2.5	2.5	2.5	3	3
9	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	3	3	3	2	2
10	4	5	5	4	4	4	4	4	5	5	5	5	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2	2	3	2	2	2	2	2	2	2	2	2	2
11	1	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	3	3	3	3	3	3	3	3	3	4	4	4	4.5	4.5
12	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	3	3	3	3	3	3	3	3	3	4	4	4	4	4
13	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	3	3	3	3	3	3	3	3	3	4	4	4	4	4
14	2	1.5	2	2	1.5	1.5	1.5	1.5	3	2.5	1	2	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	3	3	3	3	3	3	3	3	3	3	3	3	2.5	2.5
15	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2
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17	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2
18	3	3	3	1.5	1.5	2	2	1.5	3	3	1	1	1	1	1	1	1	1	1	1	1	3	1	1	1	1	1	1	1	1	1	1	1	5	5	5	5	5	5	5	5	5	2	2	2	1	1
19	3.5	3.5	3.5	3	3	3	3	3	4	4	4.5	4	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1	1
20	2	2.5	2	2	1	1	1	1	3	4	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	1	1
21	1	1	1	1	1	1	1	1	1	2.5	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
22	3	3	1	3	3	1	2.5	3	2.5	4	2	2	1.5	2	1	2	1.5	1	1	1.5	1	1	1	1	1	1	1	2.5	1	1	1	1.5	1	2	2	2	3	2	1	1	2	3	2	2	2	1	1
23	2	2	2	2	1	1	1	1	2.5	2.5	1	1	2	2	1.5	2	2	2	2	2	2	2	1.5	2	1	2	1.5	2	2	2	1.5	2	2	2	2	2	2	2	2	2	2	2	3	3	3	1	1
24	1	1.5	1	1	1	1	1	1	1	2	1	1	4	4	4	4	4	4	4	4	4	4	4	4	2	5	4	4	4	4	4	4	4	2	2	2	2	2	2	2	2	2	2	2	2	1	1
25	1	1.5	1	1	1	1	1	1	1	2	1	1	4	4	4	4	4	4	4	4	4	4	4	4	2	5	4	4	4	4	4	4	4	2	2	2	2	2	2	2	2	2	2	2	2	1	1
26	1.5	2	1.5	1.5	1	2	1.5	1.5	1.5	1	1	1	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	2	2	2	2	2	2	2	2	2	2	2	2	1	1
27	1.5	2	1.5	1.5	1	2	1.5	1.5	1.5	1	1	1	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	2	2	2	2	2	2	2	2	2	2	2	2	1	1
28	1.5	2	1.5	1.5	1	2	1.5	1.5	1.5	1	1	1	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	2	2	2	2	2	2	2	2	2	2	2	2	1	1
29	1.5	2	1.5	1.5	1	2	1.5	1.5	1.5	1	1	1	4	4	4	4	4	4	4	4	4	4	4	4	3.5	4	4	4	3	4	4	4	4	2	2	2	2	2	2	2	2	2	2	2	2	1	1
30	1.5	2	1.5	1.5	1	2	1.5	1.5	1.5	1	1	1	4	4	4	4	4	4	4	4	4	4	4	4	3.5	4	4	4	3	4	4	4	4	2	2	2	2	2	2	2	2	2	2	2	2	1	1
31	1.5	1.5	1.5	1.5	1.5	1	1	1	1.5	1	1	1	4	4	4	4	4	4	4	4	4	4	4	4	1.5	2	4	4	4	4	4	4	4	2	2	2	2	2	2	2	2	2	2	2	2	1	1
32	3	3	2	2	2	2	1	2	2.5	4.5	3	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	3	2	2	2	2	3	3	3	3	1	1
33	2	2	2	2	2	2	2	2	2	1.5	1	1	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	2	2	2	2	2	2	2	2	2	2	2	2	1	1
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35	2	2	2	2	2	2	2	2	2	1.5	1	1	4	4	4	4	4	4	4	4	4	4	4	4	3	4	4	3.5	4	4	4	4	4	2	2	2	2	2	2	2	2	2	2	2	2	1	1

Annex 6: Ranking, additional figures

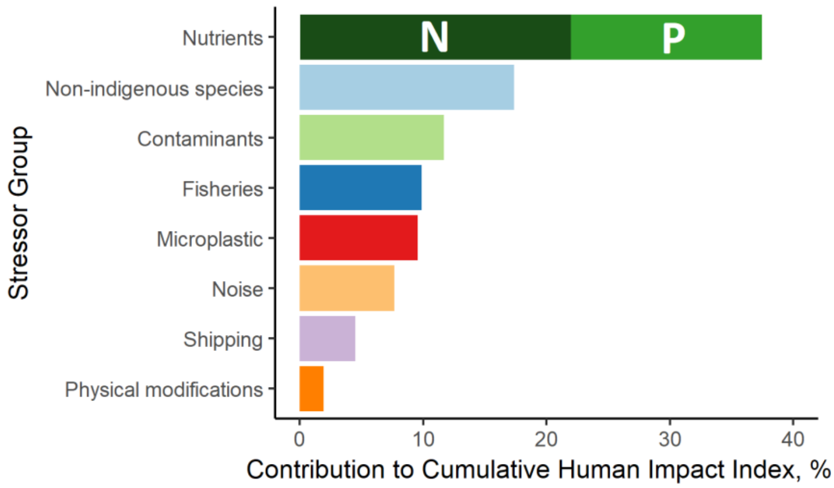

Figure A6.1 *Grouped stressor contributions in percentage of total cumulative impact for entire Danish waters.*

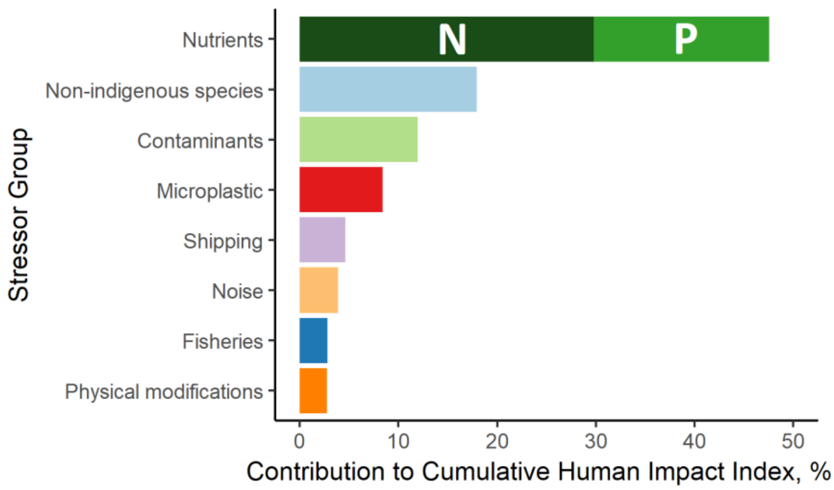

Figure A6.2 *Grouped stressor contributions in percentage of total cumulative impact, for WFD 1 nm area.*

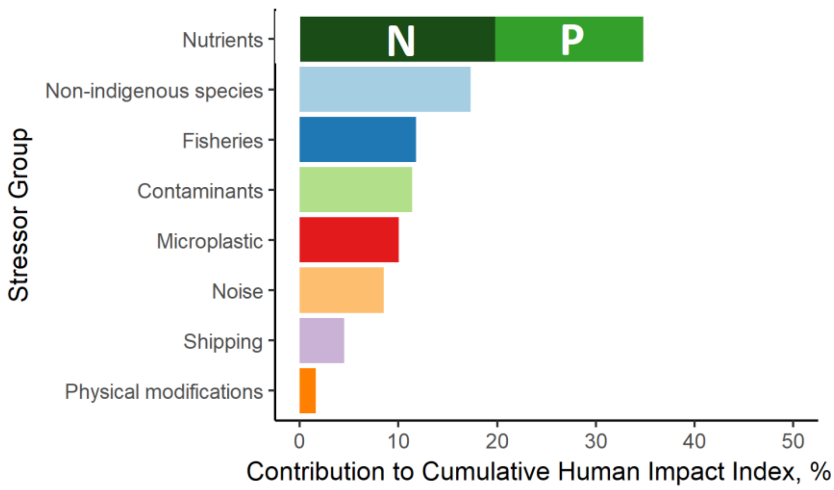

Figure A6.3 *Grouped stressor contributions in percentage of total cumulative impact, offshore areas.*

NIVA Denmark is the name, water is our game

NIVA Denmark Water Research is a regional office of the Norwegian Institute for Water Research (NIVA) and has just recently been established to resolve environmental issues concerning the freshwater and marine systems that relate to Denmark.

NIVA Denmark has primary focus on research-based implementation of a number of EU's directives inter alia the Water Framework Directive and the Marine Strategy Framework Directive together with international conventions (HELCOM, OSPAR, BDC). We occasionally provide consultancy to authorities and small and medium-sized companies.

NIVA Denmark is a place for practice, observation, testing and synthesis. Key research and test areas include eutrophication, hazardous substances, biodiversity, and ecosystem health as well as the implications of multiple human activities in marine waters and in streams, rivers and lakes. We develop indicators, monitoring methods and tools to assess the state of an ecosystem in order to carry out analyses and contribute to evidence based and sustainable solutions to the challenges we and the environment face.

NIVA Denmark, as a regional office to NIVA has thus the backing of more than 200 dedicated researchers and experts.

NIVA Denmark
Winghouse
Ørestads Boulevard 73
DK-2300 Copenhagen
Telephone: +45 8896 9670
E-mail: post@niva-denmark.dk
www.niva-denmark.dk