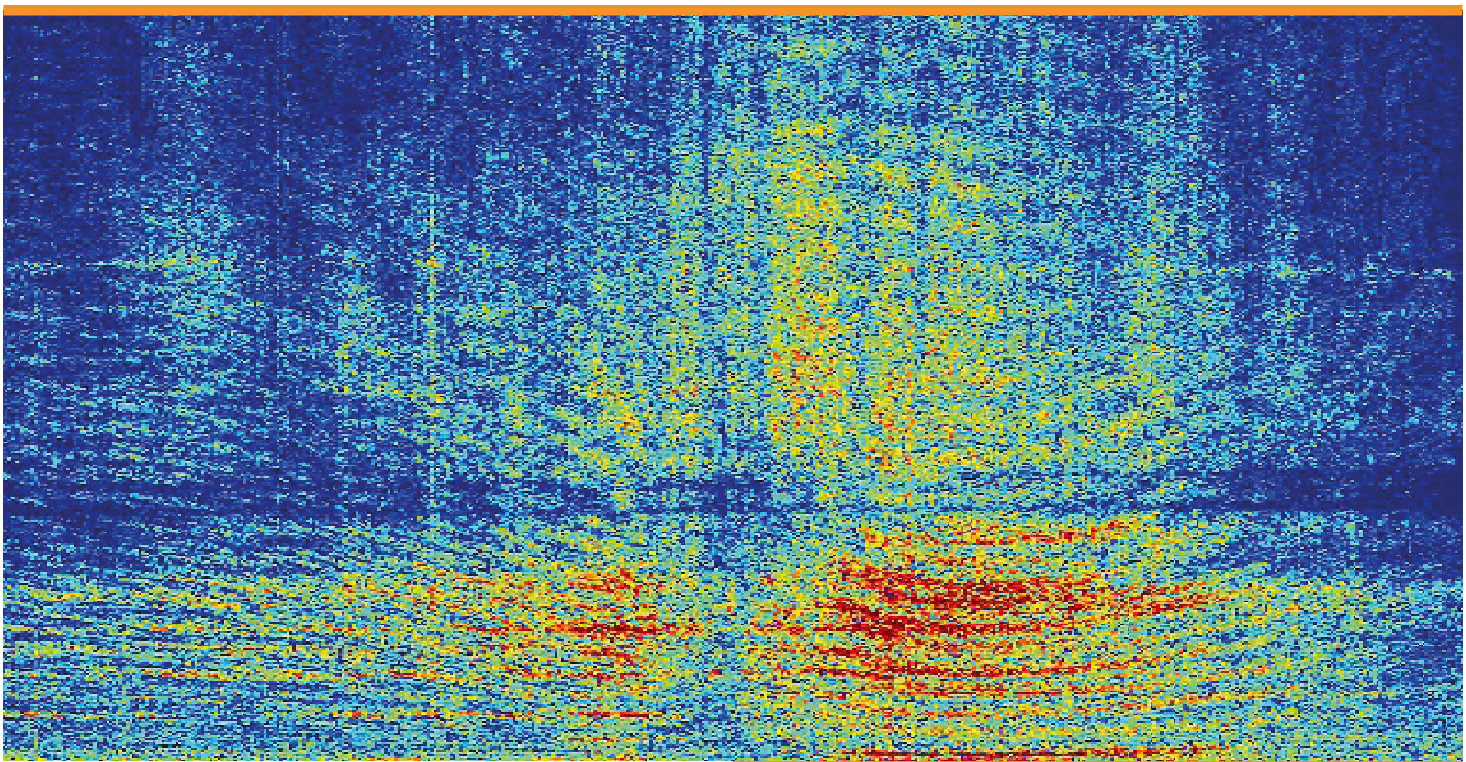
Possible effects of ship noise on fish in Danish waters



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By Bjarne Stage, Asbjørn Christensen, Dionysios Krekoukiotis, Heidi Andreasen, and Henrik Mosegaard

DTU Aqua
National Institute of Aquatic Resources

Colophon

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1. Introduction

This report has been prepared for the Department of the Ministry of Environment and Food of Denmark in support of the Department's work, on implementation of the Marine Strategy Framework Directive (MSFD) /1/.

According to the Marine Strategy Framework Directive, Descriptor 11, good environmental status requires that the introduction of energy, including underwater noise is at a level that does not adversely affect populations of marine animals. The Marine Strategy Framework Directive has been implemented in the Danish Marine Strategy Law /2/. The law includes Danish sea areas on the territorial sea and in the exclusive economic zones in the North Sea and the Baltic Sea.

A variety of sources of noise such as pile driving in construction projects, seismic surveys, and use of low frequency sonar in military exercises are conducted over shorter periods of time and is handled by special approval procedures. On the other hand, underwater noise from ship traffic is generated throughout the year and is so far not covered by approval procedures. The work in this project has therefore concentrated on underwater noise from ship traffic.

The work to establish good environmental conditions for marine animals is lacking knowledge of the consequences of noise on fish, among other species cod, herring, and sprat. These species are used as indicator species in this report in assessing the environmental status.

According to the Marine Strategy Framework Directive, Member States shall establish threshold values for anthropogenic continuous low-frequency sound to not exceed levels that adversely affect populations of marine animals. Member States shall endeavour to establish threshold values by 15 July 2018. The possibilities for meeting this objective, has been investigated in this project.

In order to avoid duplication of work, the work in this project, as far as modelling of acoustic noise from ship traffic is concerned, builds on the project Baltic Sea Information on the Acoustic Landscape (BIAS) carried out in HELCOM auspices /3/.

The work on the effects of sound on fish is a multidisciplinary field that involves a variety of professionals with very different backgrounds, such as policymakers, civil servants, marine mammal scientists, fisheries scientists, and acoustical engineers. During this project it has become apparent that different disciplines use different approaches and terminology. With this in mind, it has been attempted to present the material as an introduction to the subject for policymakers and others without prior knowledge to measurements of underwater noise.

2. MSFD D11C2 requirements

The Commission Decision on criteria and methodological standards on good environmental status of marine waters /4/ divides MSFD Descriptor 11 into D11C1 for impulsive sound and D11C2 for continuous low-frequency sound. Noise from ships is not impulsive and is thus covered by D11C2. The requirements for D11C2 are summarized below:

<table>
<tr><td colspan="3">Descriptor 11: Introduction of energy, including underwater noise, is at levels that do not adversely affect the marine environment.</td></tr>
<tr><td colspan="3">D11C2</td></tr>
<tr><td colspan="3">Criteria, including criteria elements, and methodological standards</td></tr>
<tr><td>Criteria elements</td><td>Criteria</td><td>Methodological standards</td></tr>
<tr><td>Anthropogenic continuous low-frequency sound in water.</td><td>D11C2 — Primary: The spatial distribution, temporal extent and levels of anthropogenic continuous low-frequency sound do not exceed levels that adversely affect populations of marine animals. Member States shall establish threshold values for these levels through cooperation at Union level, taking into account regional or subregional specificities.</td><td>Scale of assessment:
Region, subregion or subdivisions.

Use of criteria:
The extent to which good environmental status has been achieved shall be expressed for each area assessed as follows:

For D11C2, the annual average of the sound level, or other suitable temporal metric agreed at regional or subregional level, per unit area and its spatial distribution within the assessment area, and the extent (%, km2) of the assessment area over which the threshold values set have been achieved. The use of criteria D11C2 in the assessment of good environmental status for Descriptor 11 shall be agreed at Union level. The outcomes of these criteria shall also contribute to assessments under Descriptor 1.</td></tr>
<tr><td colspan="3">For D11C2 monitoring: Annual average, or other suitable metric agreed at regional or subregional level, of the squared sound pressure in each of two '1/3-octave bands', one centred at 63 Hz and the other at 125 Hz, expressed as a level in decibels in units of dB re 1 μPa, at a suitable spatial resolution in relation to the pressure. This may be measured directly, or inferred from a model used to interpolate between, or extrapolated from, measurements. Member States may also decide at regional or subregional level to monitor for additional frequency bands. Criteria relating to other forms of energy input (including thermal energy, electromagnetic fields and light) and criteria relating to the environmental impacts of noise are still subject to further development.</td></tr>
<tr><td colspan="3">Units of measurement for the criteria: D11C2: Annual average (or other temporal metric) of continuous sound level per unit area; proportion (percentage) or extent in square kilometres (km2) of assessment area with sound levels exceeding threshold values.</td></tr>
<tr><td colspan="3">Descriptor 1: Biological diversity is maintained. The quality and occurrence of habitats and the distribution and abundance of species are in line with prevailing physiographic, geographic and climatic conditions.</td></tr>
<tr><td colspan="3">Descriptor 3: Populations of all commercially exploited fish and shellfish are within safe biological limits, exhibiting a population age and size distribution that is indicative of a healthy stock.</td></tr>
<tr><td colspan="3">Descriptor4: All elements of the marine food webs, to the extent that they are known, occur at normal abundance and diversity and levels capable of ensuring the long-term abundance of the species and the retention of their full reproductive capacity.</td></tr>
</table>

Further MSFD Descriptors 1, 3, and 4 are listed as these descriptors may be affected by a possible adverse effect of anthropogenic sound on fish populations. It is stated that the criteria relating to the environmental impacts of noise are still subject to further development. Member States may decide at regional or subregional level to monitor sound pressure in two 1/3-octave frequency bands, one centred at 63 Hz and the other at 125 Hz, or in additional frequency bands. Further it can be agreed at regional or subregional level, to use the annual average of the sound level, or other suitable temporal metric. The flexibility thus incorporated in the interpretation of the D11C2 is an advantage, as it in this report will become evident that it is difficult to give a meaningful description of the impact of ship noise on marine populations based on average levels of squared sound pressure in the 1/3-octave frequency bands 63 Hz and 125 Hz.

3. Ecosystem services

The framework of ecosystems services provides useful guidance in situations where the societal interest is in both preserving the marine environment and in ensuring continued economic development. This requires that a trade-off among multiple ecosystem services must be made. To make informed decisions in such circumstances requires that a sufficient amount of data in a sufficient quality is available. Figure 1 illustrates a simplified situation centered on commercially exploited fish stocks.

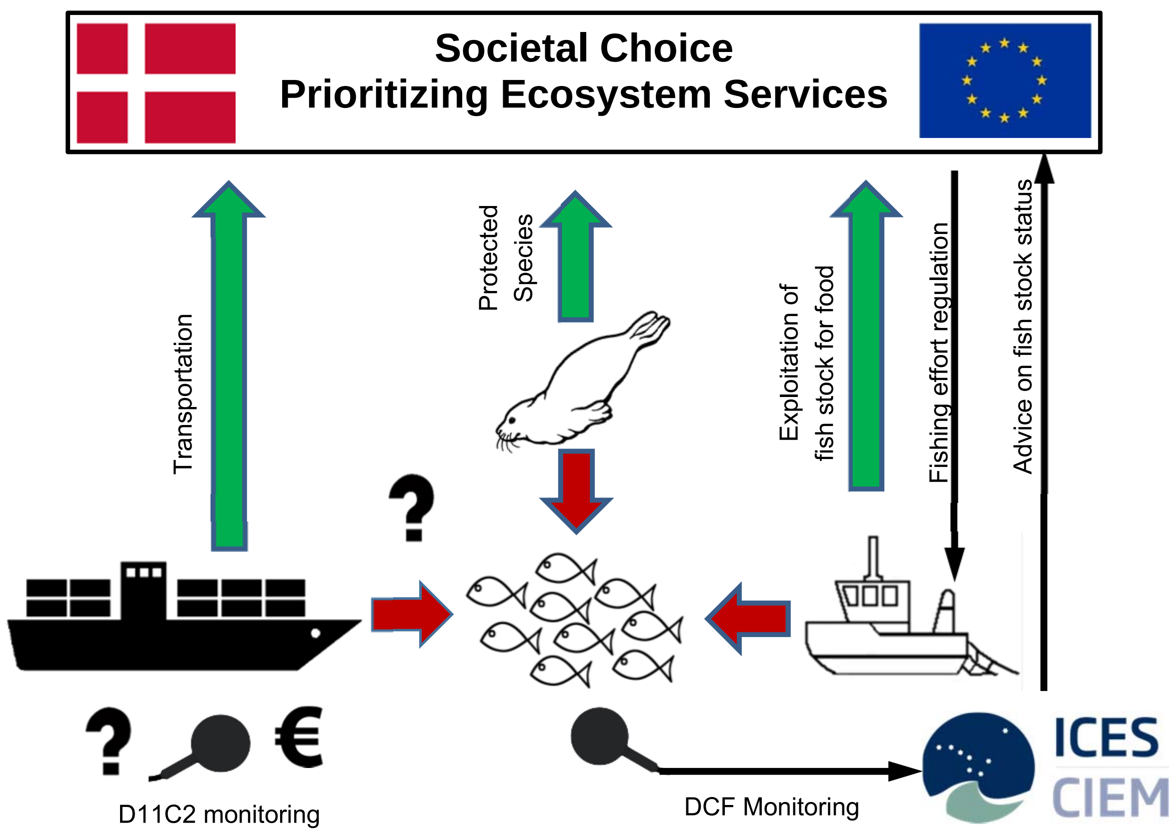

Figure 1. Ecosystem services centered on commercially exploited fish stocks.

The ecosystem service sea food is obtained by commercial exploitation of fish stocks. In order to preserve healthy stocks, fisheries are managed under the Common Fisheries Policy (CFP) /5/. To support the CFP, Member States every year contribute to a comprehensive campaign of collection of fish and fisheries data in accordance with the Data Collection Framework (DCF) /6/. This includes detailed rules regarding the expenditure incurred by Member States for the collection and management of the basic fisheries data. The International Council for the Exploration of the Sea (ICES) acts as independent advisors on fish and fish stocks.

The health of the fish stocks is governed by recruitment, growth and mortality of fish. The mortality of fish is divided into natural mortality and fisheries mortality. The natural mortality includes death by predators and a possible mortality due to effects from shipping. In any case the fishing effort is adjusted to assure that the fishing mortality is at a level that preserves healthy stocks. It can therefore be stated that ship traffic in general does not pose a threat to the health of fish stocks as long as fishing mortality provides a buffer for the stocks. This statement does not exclude that certain fish species might suffer problems on spawning grounds or along migration routes. But should a reduction in the transportation effort result in more fish due to population level effects on fitness and survival, these fish will be caught by fishermen and used for food. However, this is a societal choice.

Within the DCF, data is collected on both fish and fishing. This allows the causal relation between the two to be continually monitored. The present D11C2 monitoring prescribes collection of data on ships, but not on fish. Without data on both it will not be possible to establish a quantitative causal relationship. Further some rules regarding the expenditure incurred by Member States for the D11C2 data collection seems to be missing.

4. Sound exposure and fish behaviour

Popper et al. /7/ have collected current knowledge on sound exposure on fishes in a guideline. Little is known and much work lies ahead if this field is given priority. In the meantime interim procedures must be adopted to complete the task.

Fishes are exposed to ship noise in different ways depending on the stage of their life cycle. Eggs and larvae may be immobile or drift around in the water mass whereas adult fish are mobile. Eggs and larvae have no means of avoiding an approaching ship and can receive a fatal dose of noise, whereas adult fish will swim away to avoid being injured by sound. For eggs and larvae the effect of a passing ship may be injury due to over exposure. For adult fish the effect of a passing ship will influence fitness and survival.

The question is at what sound level, a fish will become affected and swim away from the source. The hearing of fish extends over a range of frequencies as illustrated in figure 2. Correlating the response of fish with the sound level in two narrow frequency bands centred at 63 Hz and 125 Hz while ignoring sound in the rest of the hearing range of the fish, might not lead to the best results.

Human exposure to sound in air is measured in the audible range from 20 Hz to 20,000 Hz based on a hearing threshold of 20 μPa. The frequency weighted scale corresponding to human hearing is called dB(A). A set of threshold values for this scale has been established, that is used in standards and legislation /10/.

Inspired by the success of using a frequency weighted scale for humans, Nedwell et al. /11/ proposed a similar scale dB_{ht}(*Species*) where the frequency weighting is based on the audiogram of the species. Threshold values for various fish behaviour are provided. It would be possible, with some assumptions on the shape of the spectrum of ship noise, to use this to determine behaviour thresholds at 63 Hz and 125 Hz. This has not been attempted here.

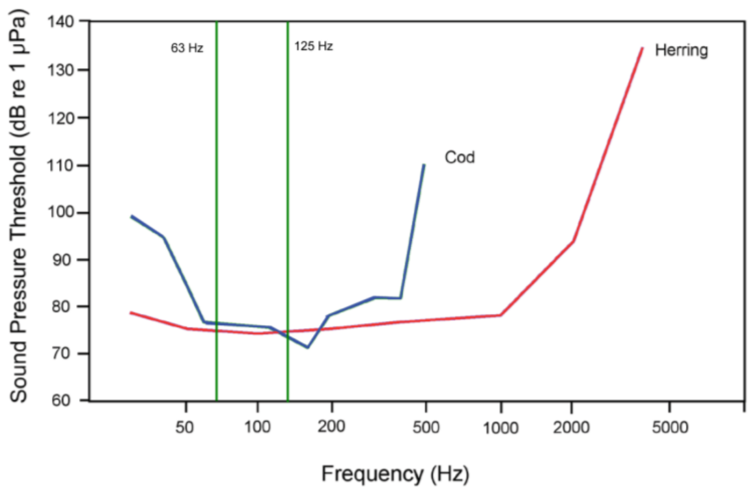

Figure 2. Audiograms for the Atlantic cod (*Gadus morhua*) /8/ and the Atlantic herring (*Clupea harengus*) /9/. No audiogram data is available for the European sprat (*Sprattus sprattus*), but as the sprat in many ways are similar to herring the audiogram for herring will apply in this context. The two monitoring frequency bands in D11C2 are shown with green lines.

5. The nature of ship noise

MSFD D11C2 is concerned with anthropogenic continuous low-frequency sound in water. Ship noise has been categorized as such.

If a hydrophone is placed in the ocean, far from shipping lanes, the hydrophone will record a signal corresponding to the sound from natural sources such as wind and waves plus the sounds from distant ships. The sound from these distant ships is low frequency as the high frequencies have been attenuated by their propagation in sea water. The signal usually has a low level. The signal has no start and no end and is a finite-power signal /12/. This type of signal is traditionally analysed using RMS values and power spectral analysis. The term continuous sound seems to refer to this situation although continuous as a term in signal processing is the opposite of discrete.

If a hydrophone is placed in a shipping lane, the hydrophone will record a signal corresponding to the sound from natural sources such as wind and waves plus the sounds from ships passing nearby. The sound from nearby ships have a high sound level due to the proximity to the source and broadband character with a frequency band of approximately 1 Hz – 100.000 Hz. The passage of a single ship will create a signal that slowly grows to a maximum and then fades out. The signal has a start and an end and is a finite-energy signal /12/. This type of signal is traditionally analysed using short time Fourier analysis and calculations of features to describe the signal such as peak level and duration. It is presumably the peak value that will scare the fish. Averaging a signal like this can thus hardly be justified. This type of signal can be termed transitory.

D11C2	**Reality**
Continuous	Transitory
Low-frequency	Broadband
Low amplitude	High amplitude
Finite-power signal	Finite-energy signal
Averaging	Short time analysis

Table 1. Comparison of terms in D11C2 and reality

The terms used in D11C2 are compared with the reality of a ship passing nearby in table 1. This is a fundamental source of incommensurability that should be resolved. Failing to do so, will waste resources.

To get a feeling for the current intensity of ship traffic, one of the most heavily trafficked straits in Danish waters, the great Belt can be considered. The Danish Maritime Authority records the movement of all AIS equipped vessels in Danish waters and provides yearly count of vessels passing passage lines /13/. In 2016 a total of 34851 vessels of all sizes passed the Great Belt Bridge. This corresponds to an average of 4 ships per hour.

6. Ship sound exposure descriptors for fishes

As it has become clear in the foregoing, descriptor D11C2 is probably not the most precise way to assess the degree to which ship noise adversely affects populations of marine animals. First the dynamics of the situation has to be taken into account as illustrated in Table 2. Different situations require different descriptors depending on whether the sound source and the marine animal are immobile or mobile.

	Marine Animal		
Source	**Immobile**	**Drifting**	**Mobile**
Immobile	Dose	Drifting dose	Permanent denial
Mobile	Dose	Drifting dose	Temporal denial

Table 2. Factors influencing ship noise impact on fishes.

Eggs and larvae may be immobile or drift around in the water mass and are thus vulnerable to mortal and recoverable injuries from high levels of sound from ships. A descriptor for this situation will record the volume of water mass is affected by levels of sound exceeding a damage threshold. If a drift model is used the accumulated effect of multiple exposures can be taken into account. The impact on immobile marine animals living on the seafloor can be assessed the same way.

Adult fish are mobile and will thus swim away to avoid an approaching noisy vessel. Thus the area temporarily occupied by the noisy vessel will be denied to the fish. The same applies to situations where masking of fish sound is involved.

To complicate matters, marine animals may perform vertical diurnal migration in the water mass which combined with the complexity of propagation of sound in the sea can prevent an intuitive understanding. These effects, although important, should therefore not be included in a descriptor. This can be included in follow up investigations initiated by the descriptor exceeding a threshold.

Source Level Descriptor

The origin of the noise is passing ships. These ships can be simply characterized by their source level at the range of frequencies they emit. Alternatively they can by characterized by an acoustic ship signature if the emitted sound is not omni directional. In the BIAS project /14/ the RANDI3 model has been used for initial estimates of ship source levels. In this model the ship source level depend on the length of the ship to a power of two and on the speed of the ship to a power of six. Creating a geographical map of source level traffic intensity is a powerful yet simple and inexpensive way to create an overview of where possible problems with ship noise might be. Further it is directly connected to the noise sources. This is a top down approach from ship to fish, rather than the bottom up approach fish to ship used in D11C2. In the current situation, where a high degree of incommensurability exists, this approach could save resources from being wasted in more detailed approaches that will turn out to be futile due to future changes to descriptor requirements.

Area of Denial Descriptor

Given a sound level threshold that fish will avoid, the temporary area denied to the fish can be determined. This does not answer the question whether the fish will return to the area once the ship has passed. This depends on how strongly the fish is attracted to the area. This question can only be answered through experiments and modelling as discussed in section 11. Based on this method a geographical map could be created showing the percentage time an area is denied to a species due to noise from shipping. In a follow on investigation the effect of a passing ship on fish fitness and survival could be determined.

Exposure Descriptor

This descriptor could be used to create a geographical map showing where a species is subject to mortal and recoverable injuries from high levels of sound from ships.

7. Determination of threshold values

According to the MSFD, Member States shall establish threshold values for anthropogenic continuous low-frequency sound to not exceed levels that adversely affect populations of marine animals in region, subregion or subdivisions, and report its spatial distribution within the assessment area, and the extent (%, km2) of the assessment area over which the threshold values set have been achieved. The assessment in the Danish sea areas can be based on the soundscape results in the BIAS project.

As it has become clear in the foregoing, setting thresholds for D11C2 in its current form is not without problems. The soundscape calculations in the BIAS project are based on the specifications for D11C2. A pragmatic approach is therefore needed to provide a meaningful interpretation of thresholds. The suggested process is illustrated in figure 3.

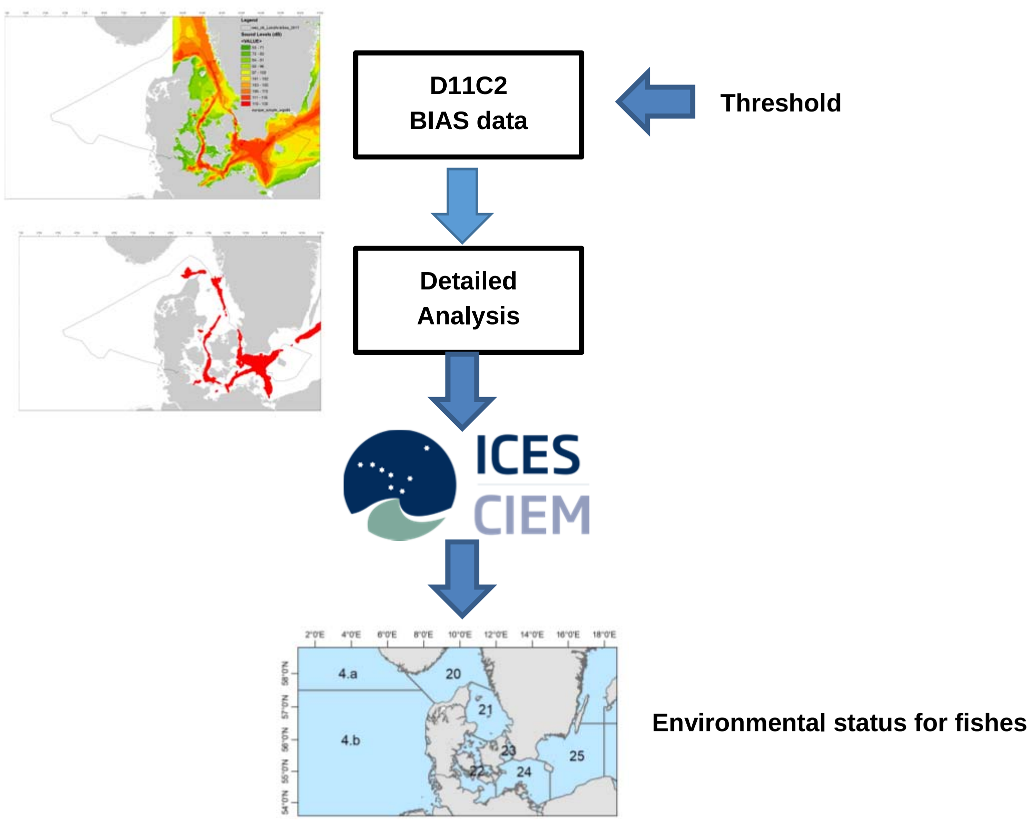

Figure 3. Illustration of a possible approach to determine environmental status for fishes.

The complexity of determining environmental status for fishes based on a sound level threshold is overwhelming and certainly not easy to understand. The approach suggested here is to break the process up into smaller and more manageable stages.

The first step is to mentally remove any detailed causality between D11C2 and the wellbeing of fishes. D11C2 is a detector that will find areas where there might be a problem. Whether there is a problem in an area can only be determined in a following stage of detailed analysis. The D11C2 detector may find areas that later turn out to be non-problematic and it may miss areas that later turn out to be problematic. These problems can be solved by using a better descriptor. For at start, the D11C2 is suitable as a detector.

The detailed analysis stage can be anything from detailed modelling to experiments *in situ*. In any case, this will be a costly part of the process. It is therefore important, for a start, not to set the threshold value so low that an unmanageable number of areas will have to be analysed in detail.

It is further suggested that the results of the detailed analysis is provided as input to ICES for the yearly work on fish stock assessment. The output from ICES will be assessment following ICES areas and subdivisions. The incommensurability between MSFD regions and ICES areas should be resolved. Following this approach further ensures that two government bodies come up with different results on the environmental status of the same fish stocks.

An example of a BIAS soundscape /14/ prepared in accordance with D11C2 is shown in figure 4.

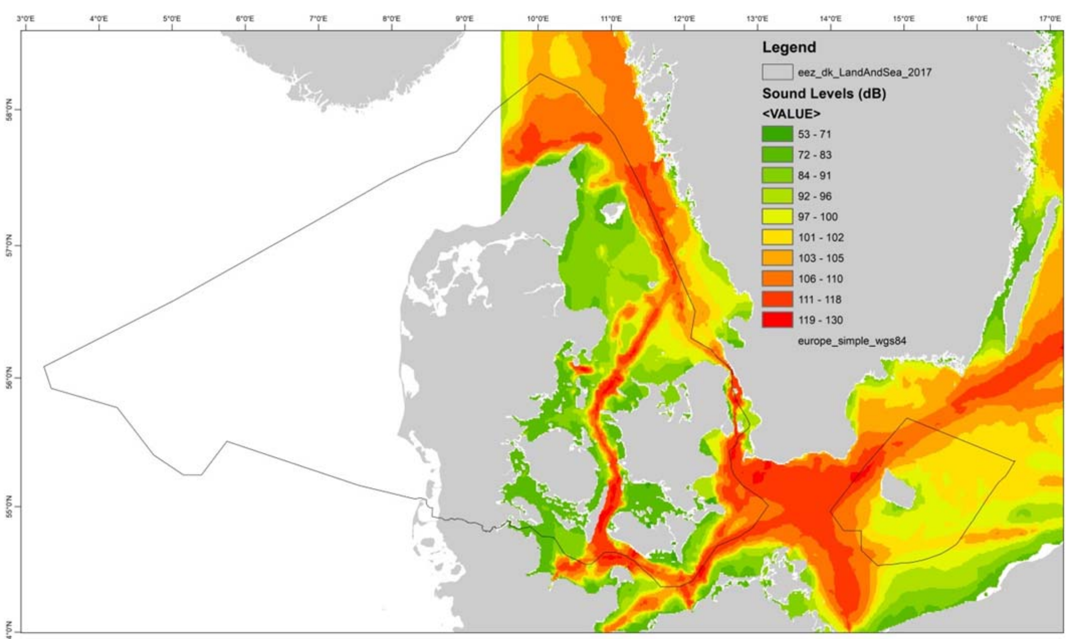

Figure 4. Example of BIAS Soundscape. Median map for the 125 Hz 1/3-octave frequency band and 10th percentile, for the full water column in January 2014. Sound levels in dB re 1μPa.

To detect areas where fish are adversely affected by ship noise, the first places to look is where the loudest sounds occur. The 10th percentile of the soundscape represents the loudest sounds. In figure 4, the shipping lanes are clearly visible, since they correspond to places where the sound is generated. A few ferry routes can be identified.

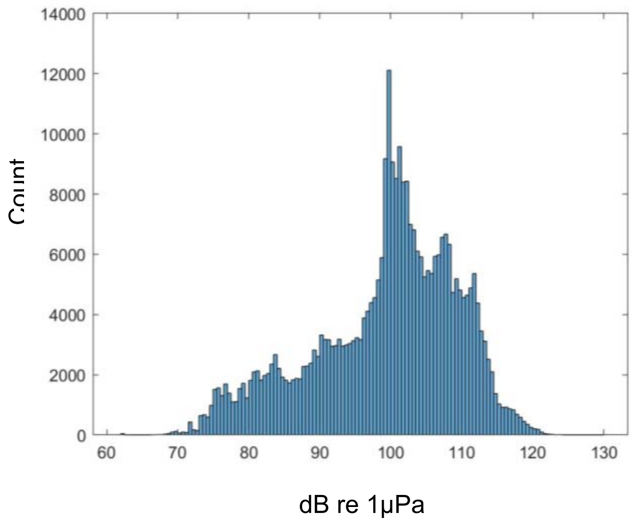

Figure 5. Histogram of data in figure 4.

Figure 5 shows a histogram of the sound level values in figure 4. This is the basis for selecting sound level thresholds. Figure 6-8 show the results for thresholds of 120, 115 and 110 dB re 1μPa.

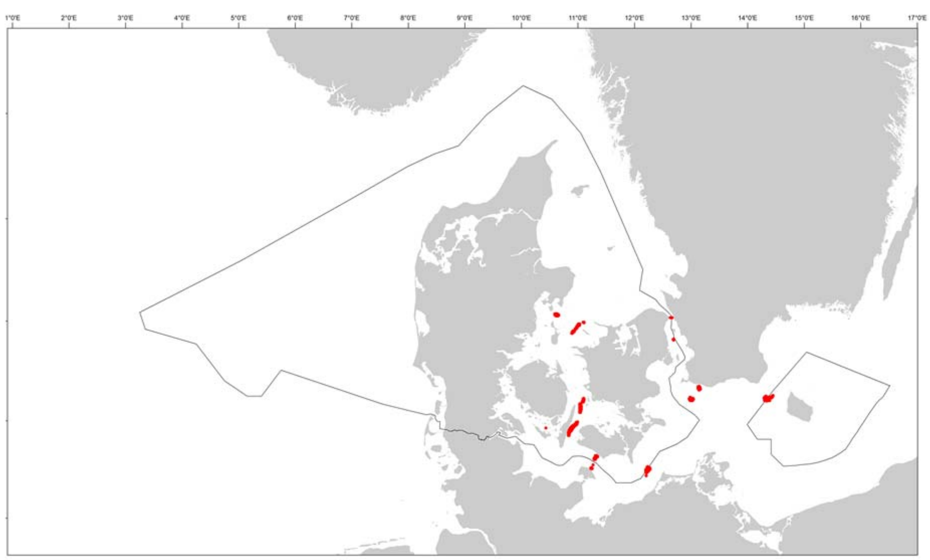

Figure 6. Data in figure 4 thresholded at 120 dB re 1μPa

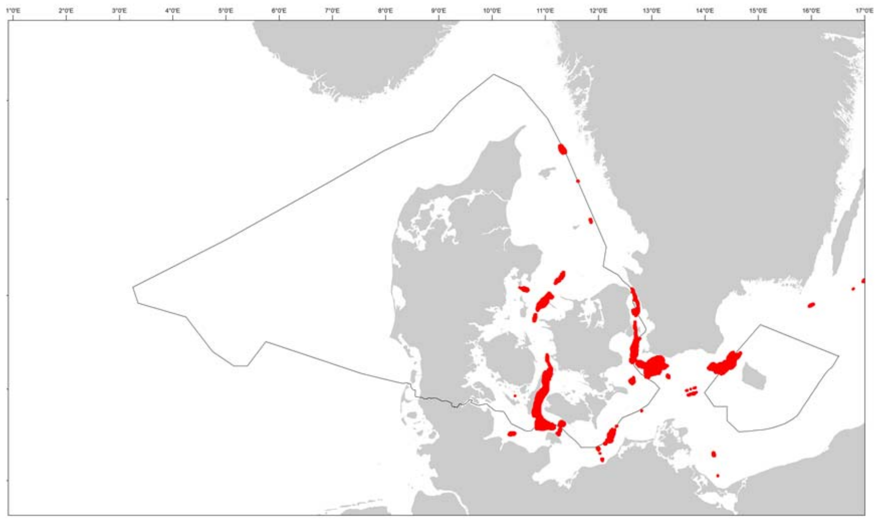

Figure 7. Data in figure 4 thresholded at 115 dB re 1μPa

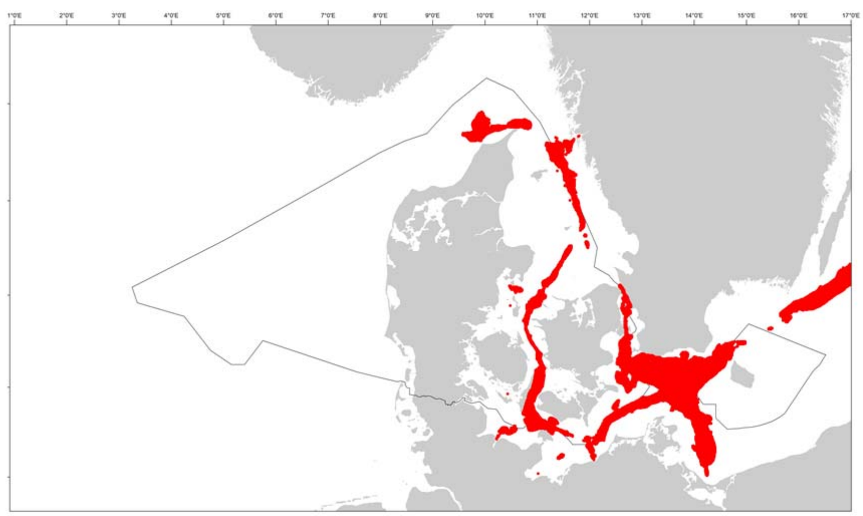

Figure 8. Data in figure 4 thresholded at 110 dB re 1μPa

The final step is to decide on a threshold. This depends on a judgement of the severity of the effects of ship noise on fishes and on the available budget for the following detailed analyses. Taking a precautionary approach a threshold of 115 dB re 1μPa would seems like a good starting point in this example. If problems are detected during detailed analysis, the threshold can always be lowered at a later time.

8. The BIAS soundscape planning tool

In parallel with the project Baltic Sea Information on the Acoustic Soundscape (BIAS), a GIS-based online soundscape planning tool for underwater noise was designed. The BIAS soundscape planning tool can handle and visualize both the measured data and the modelled soundscape maps from BIAS. The tool provides a number of interactive functionalities to evaluate the spatial and temporal sound characteristics within a user-defined geographical region. More information can be found in the BIAS soundscape planning tool user guide /16/.

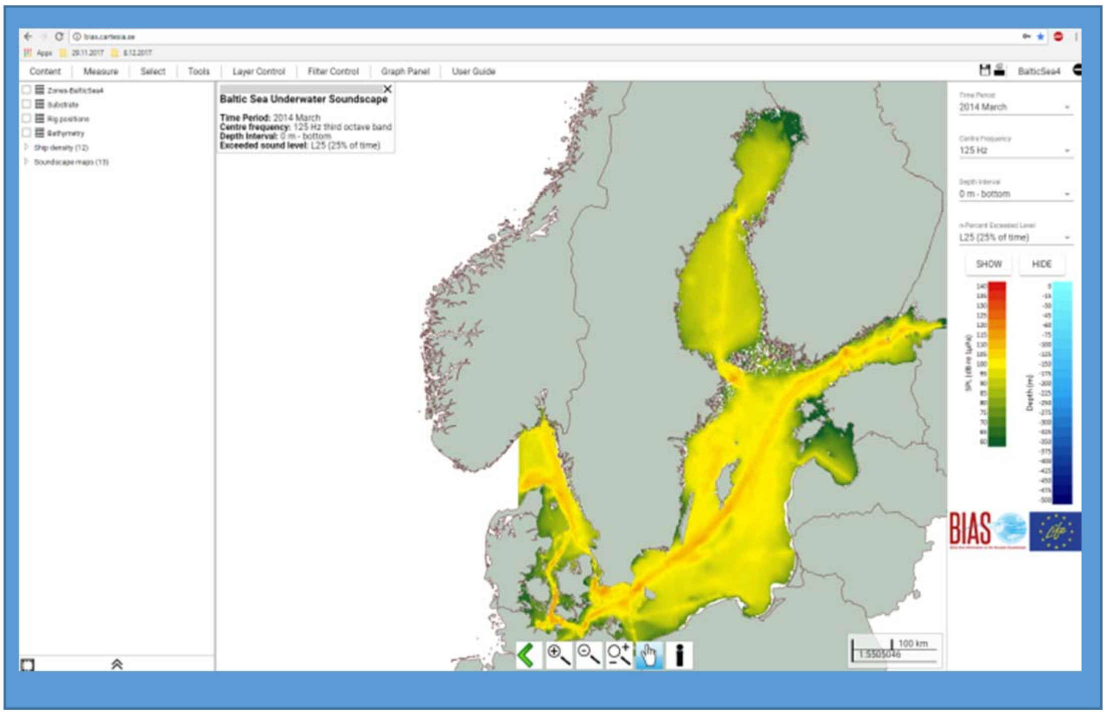

Figure 9. User interface of the BIAS soundscape planning tool.

The BIAS soundscape planning tool provides an alternative to the procedure described in section 7 to handle BIAS data. Input to the tool can be a geographical area corresponding to for example the spawning grounds for a species. Then the acoustical properties can be computed interactively to characterize this area.

9. Spawning and nursery grounds

This section presents maps of spawning and nursery grounds for the indicator species Cod (*Gadus morhua*), Herring (*Clupea harengus*), and Sprat (*Sprattus sprattus*). The maps have been provided to the Department of the Ministry of Environment and Food of Denmark in the form of georeferenced raster files for import into GIS tools for further analysis.

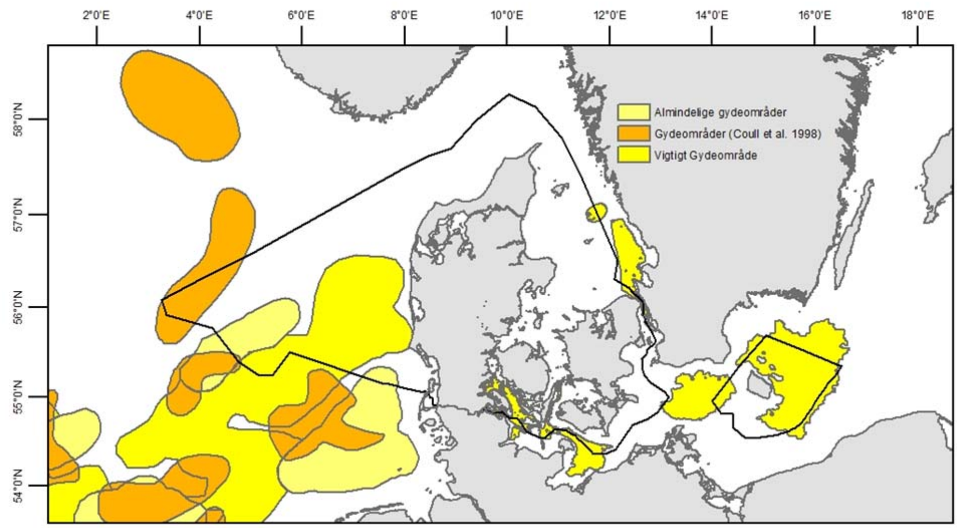

Figure 10. Cod (*Gadus morhua*) spawning grounds. Light yellow: Ordinary spawning grounds, Yellow: Important spawning grounds /17/-/25/. Orange: Spawning grounds /26/.

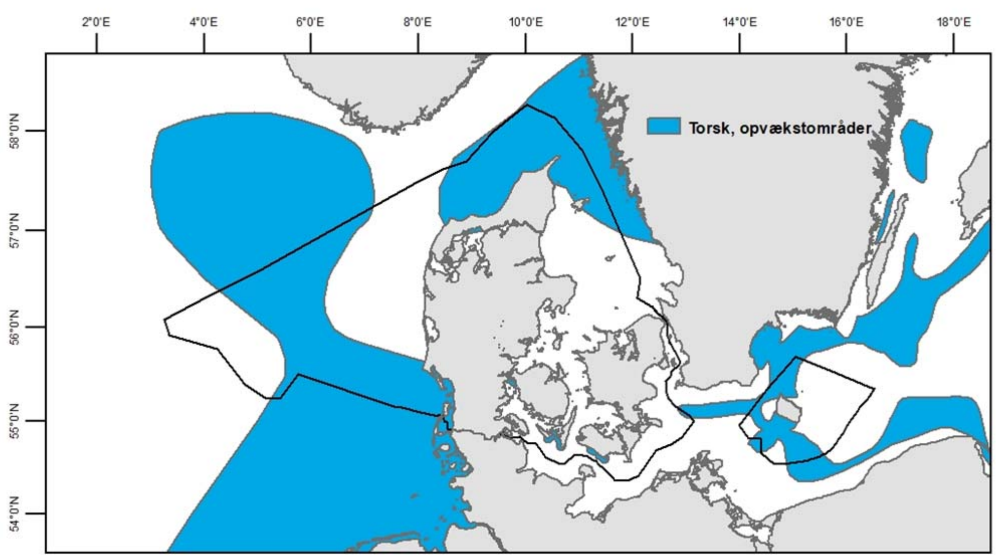

Figure 11. Cod (*Gadus morhua*) nursery grounds. Blue: Nursery grounds /19/, /26/-/32/.

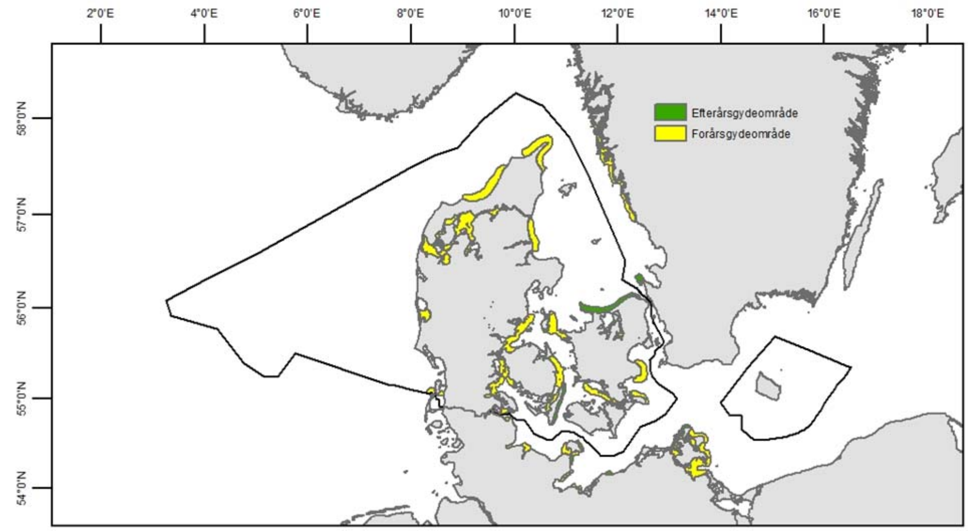

Figure 12. Herring (*Clupea harengus*) known spawning grounds. Yellow: Spring spawners, green: autumn spawners, /24/, /33/.

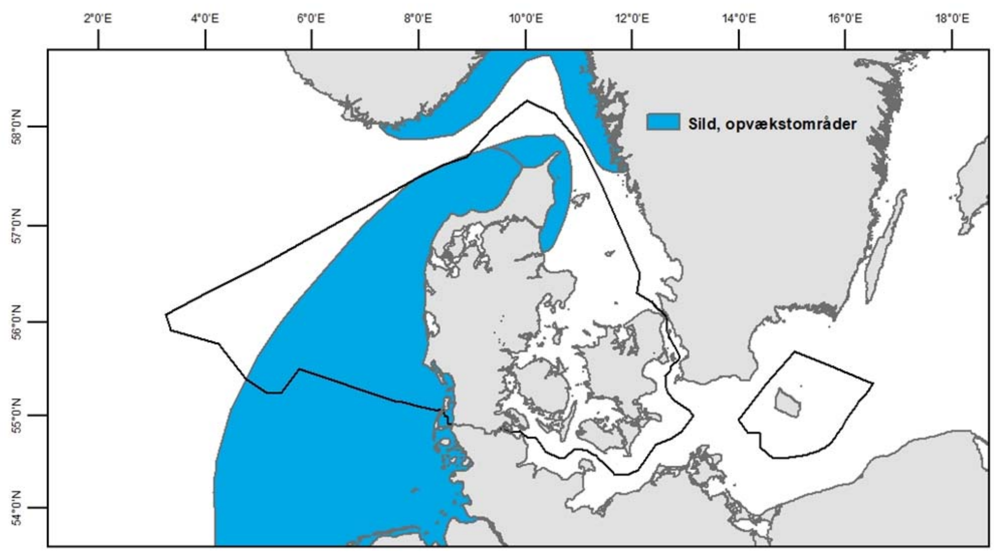

Figure 13. Herring (*Clupea harengus*) known nursery grounds. Blue: Nursery grounds, /24/, /26/, /34/.

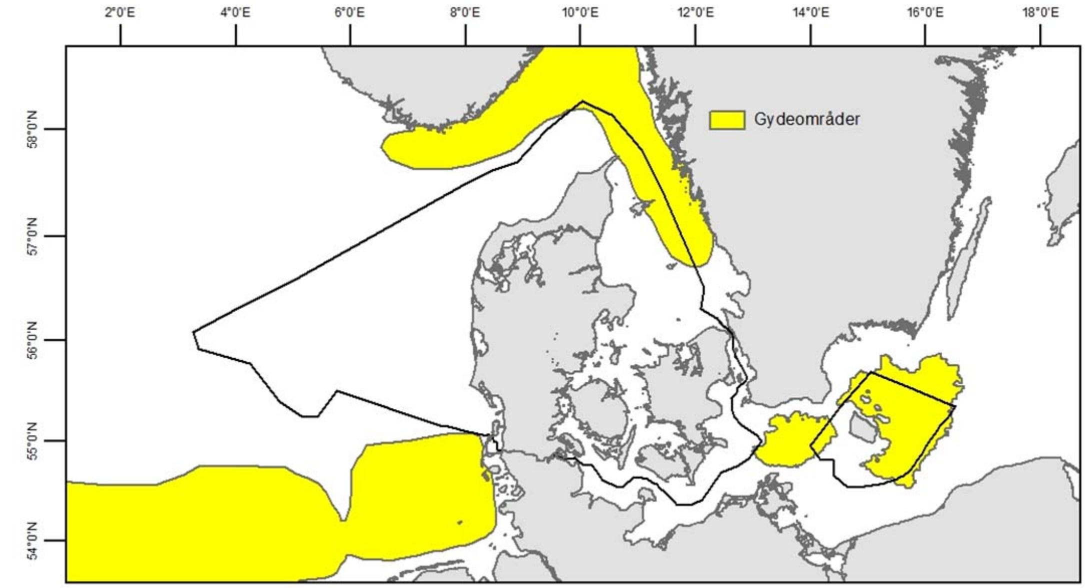

Figure14. Sprat (*Sprattus sprattus*) known spawning grounds. Yellow: Spawning grounds, /24/, /26/, /27/, /35/.

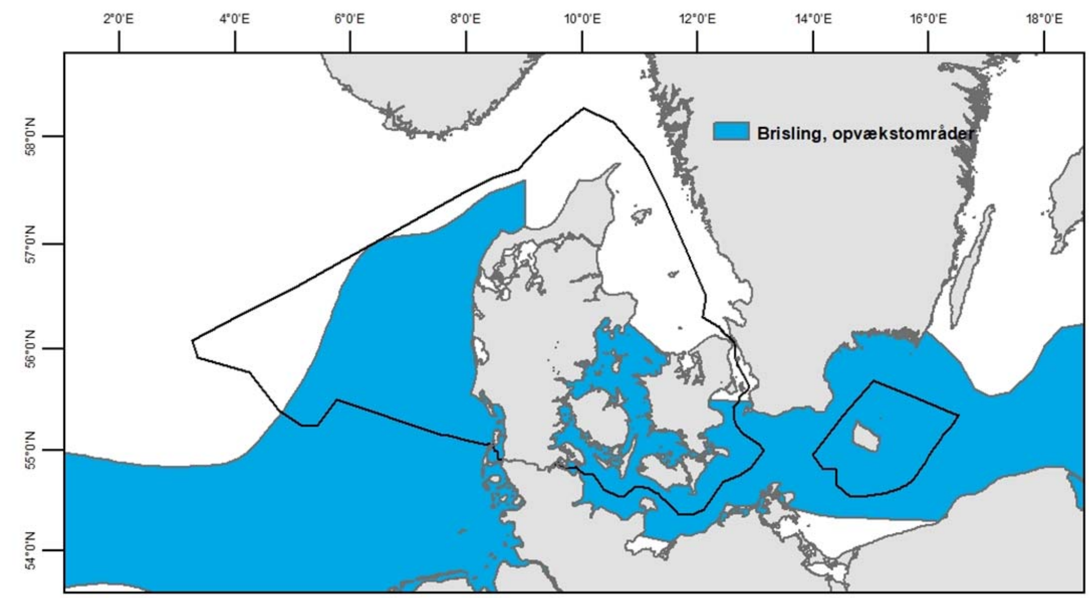

Figure15. Sprat (*Sprattus sprattus*) known nursery grounds. Blue: Nursery grounds, /24/, /26/, /34/, /36/, /37/.

10. Catch data

This section presents maps of 11 year averages of catches in csquares for the indicator species Cod (*Gadus morhua*), Herring (*Clupea harengus*), and Sprat (*Sprattus sprattus*). Catch and VMS data are extracted from the DTU Aqua database. The maps have been provided to the Department of the Ministry of Environment and Food of Denmark in the form of georeferenced raster files for import into GIS tools for further analysis.

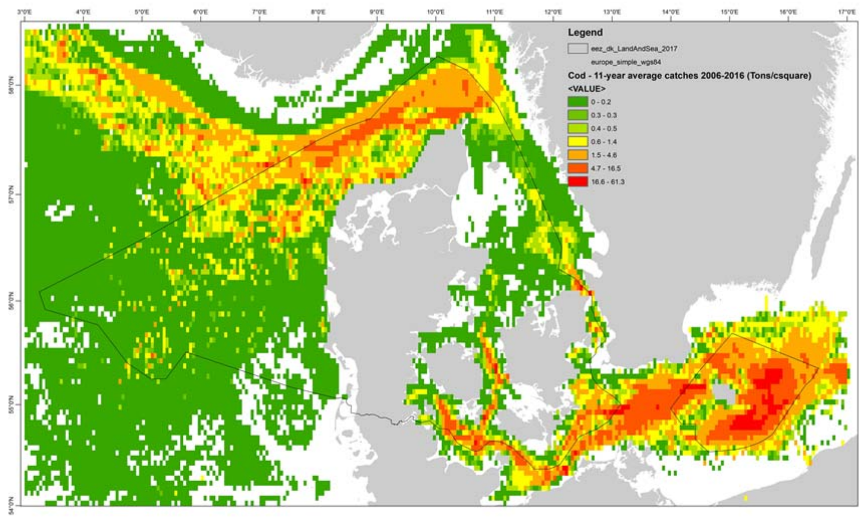

Figure16. Cod (*Gadus morhua*) 11 year average of catches (tons/csquare)

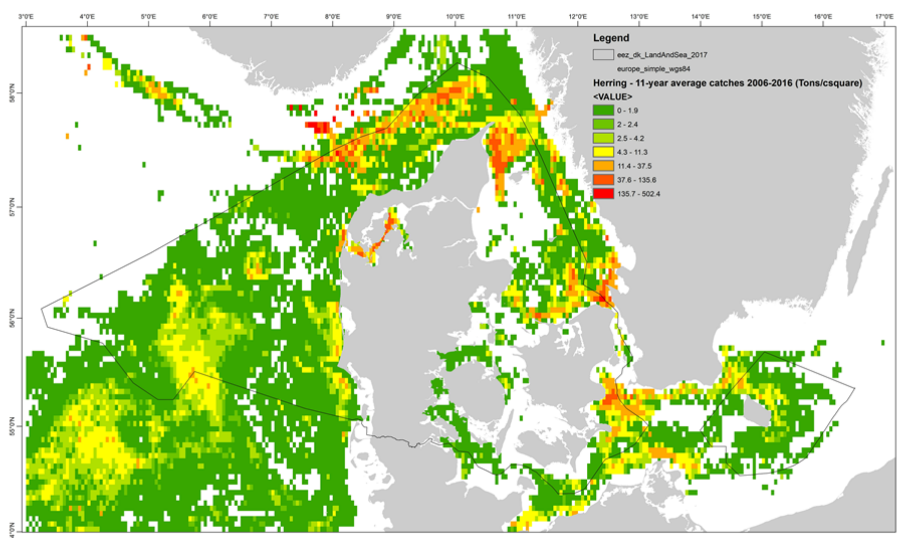

Figure17. Herring (*Clupea harengus*) 11 year average of catches (tons/csquare)

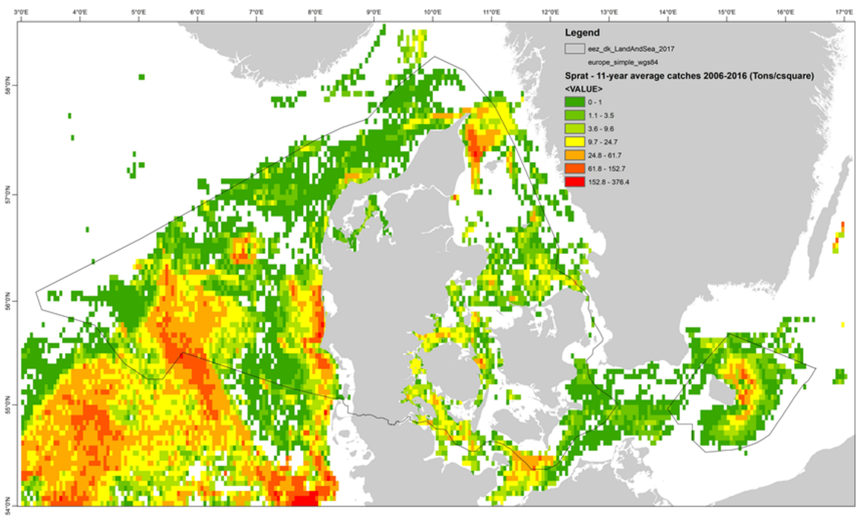

Figure 18. Sprat (*Sprattus sprattus*) 11 year average of catches (tons/csquare)

11. Modeling fish behaviour

A simplified individual-based model has been developed that can simulate the change in fish behaviour in an area where ships pass by. The model is based on behavioural observations of fish in relation to sound. The purpose of the model is to determine how the distribution of fish can be affected by ship noise including situations where ship noise levels are changed. The model uses the soundscapes produced in the BIAS project as input to the analysis. For further details see Christensen /38/.

12. Recommendations

Quantification of the effect of ship noise on fish stocks is difficult and not possible with the current state of knowledge. The fish stocks in Danish waters are well managed, in good health or recovering. The effect of ship noise on fish stocks, if a significant threat, is mitigated by adjusting the fishing effort on the stocks. There are no clear and immediate threats to fish from ships. It is recommended that work on effects of sound on fishes is coordinated with ICES in order to preserve compatibility with this well-established context.

Determining a meaningful environmental status for fish stock based on D11C2 using threshold values on BIAS data is not easy. In this report, a method has been devised that will work in the short run. It is recommended though, that initiative is taken to revise D11C2 in order to resolve the incommensurability issues.

13. Recommendations for further work

It is recommended that future work is concentrated on the following subjects:

1) Design of descriptors that describe the effects of ship noise more precisely.
2) Experiments *in situ* where sound from ships and reactions of fish are measured simultaneously. For these experiments a laboratory at sea should be established. Øresund will be a strong candidate for such a laboratory, as both ships, herring and cod are present.
3) Continued development of an individual-based model. This development can be coupled to the experimental activities under 2) in order to obtain data to verify the model.
4) Integration of work on D11C2 with work on fish stocks in ICES in order to avoid any potential incommensurability issues.

Acknowledgements

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