Essential fish habitats in the Baltic Sea

Identification of potential spawning, recruitment and nursery areas

HELCOM
Baltic Marine Environment Protection Commission

Species & habitats

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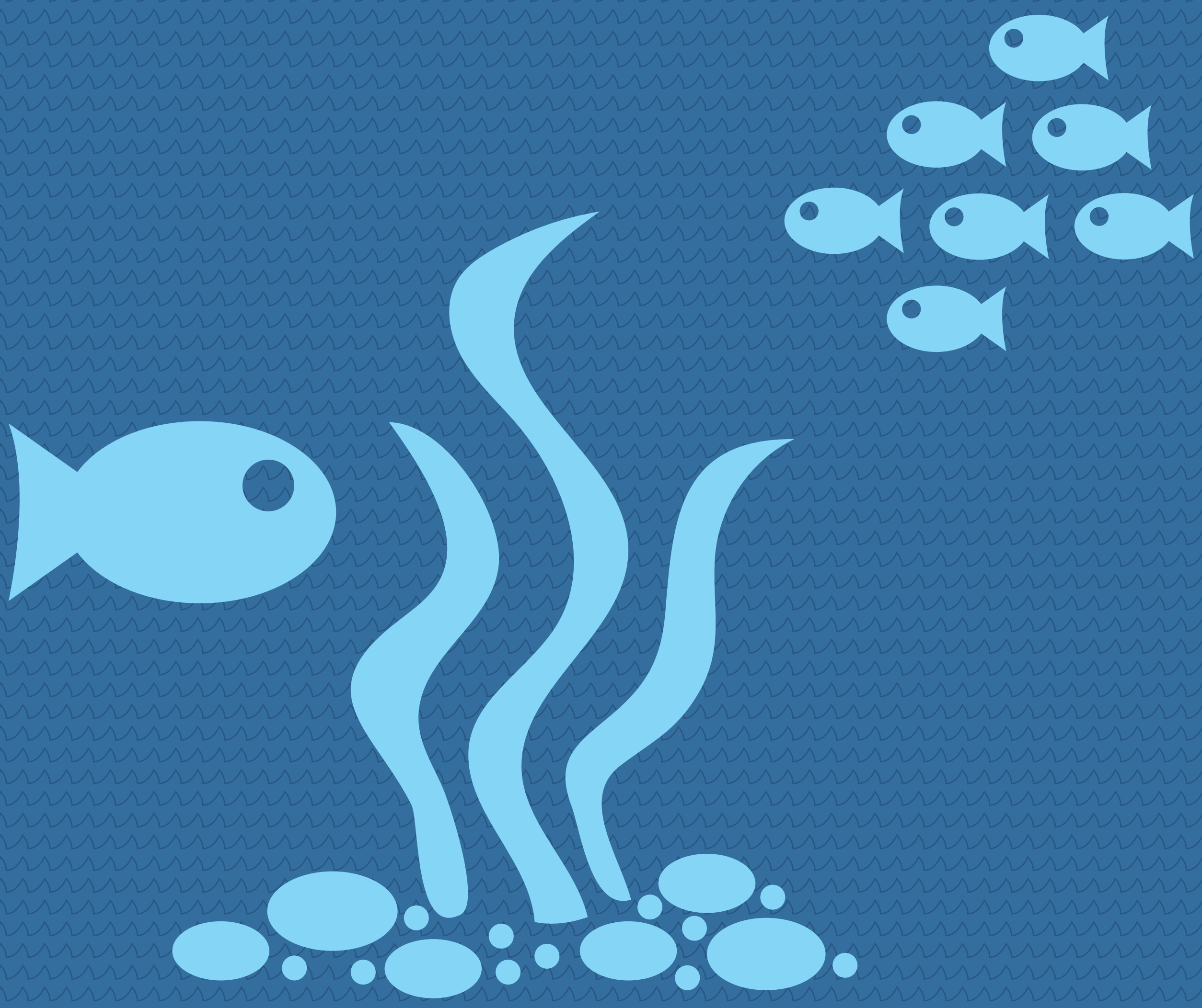

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Summary

Fish, as well as other aquatic organisms, are highly dependent on the conditions of their living environment to sustain health and viable populations. Maps that identify the location of important habitats for key species are a valuable tool for marine management. The habitat maps can, for example, support the planning of environmental management actions or contribute to an ecosystem-based maritime spatial planning.

There has so far been a lack of regionally coherent spatial information on fish habitats in the Baltic Sea. Mapping is typically restricted by data limitations, which is enhanced by the need to identify potentially coherent data at the regional scale, and by the challenge of depicting dynamic population properties in a representative way on the map.

In the following report, we explore the possibility to produce regionally coherent maps on essential fish habitats in the Baltic Sea based on currently available knowledge. Our focus is on widely distributed fish species, and on spawning, nursery and recruitment areas, which represent central ecological functions that need consideration in marine management and maritime spatial planning. Based on the results, we develop a set of regional habitat maps for selected fish species and life cycle stages. New Baltic-wide maps representing potential spawning areas of herring, sprat, European flounder and Baltic flounder, as well as potential nursery areas of flounders are presented. Additionally, previously available maps on potential cod spawning areas, as well as perch and pikeperch recruitment areas are re-evaluated and improved.

Data to support the mapping of essential fish habitats has been recently enhanced by national and joint Baltic projects, and this fact was an important enabler of the current work. The presented maps hence represent the best available information at a coherent Baltic Sea regional scale at their time of development, supported and further refined by a subsequent Helcom review process.

However, sufficient data for mapping was not yet available for some parts of the Baltic Sea and selected species. It is suggested that these gaps are filled in future work. Also, points for further improvement are identified for the presented maps. To give a fuller representation of essential fish habitats one should especially include more information for fish in coastal areas and in the western Baltic Sea. One should also consider additional life stages for some of the included species, since both spawning, nursery, feeding and migration areas are important exemplifications of essential fish habitats. Another key area for development is to develop a stronger understanding on how the current distribution of functional essential fish habitat is limited by human activities, and how to improve management in these situations. These needs are even more emphasized by climate change, which is expected to have dramatic influence on the distribution of fish and fish habitats in the future.

1. Introduction

Aquatic species are highly dependent on the conditions of their living environment to sustain healthy and viable populations. For fish, the preferred habitat is highly variable among species, and many fish species use different habitat types during different parts of their life cycle, such as for spawning, nursery, feeding or migration (Seitz *et al.* 2014).

Essential habitats are those waters or substrates necessary for a species or population to complete their life cycle, and loss or degradation of essential habitats may impact population sizes. In this work, we refer to "essential fish habitats" as "environments of particular importance for a fish species to complete its life cycle or maintain its populations". This concept of essential fish habitats may include spawning areas, nursery areas for larvae and juveniles, adult feeding areas, migratory corridors, and other possible specific areas to which a species is highly restricted.

Our definition thereby aligns with that of the Magnusson-Stevens Fisheries Conservation Act (2007), which is a commonly used definition in fisheries management, and which defines essential fish habitats as "waters and substrate necessary to fish for spawning, breeding, feeding or growth to maturity", and with the work of Kraufvelin *et al.* (2018) who in a broad sense defined essential fish habitats as any environment that is needed for the maintenance of a fish population, and more specifically defined coastal essential fish habitats as shallow and nearshore waters and substrates necessary to any life-stage of fish for spawning, breeding, feeding or growth to maturity. Here, we specifically focus on spawning and recruitment areas.

Maps that identify the location of essential fish habitats are a tool for marine management, to ensure that human activities do not affect the habitats in a way that may restrict the health of fish populations. Such maps can, for example, help identify areas where actions to reduce pressures are particularly important, support the designation of protected areas, or contribute to an ecosystem-based maritime spatial planning.

So far, there has generally been a lack of regionally coherent spatial information on essential fish habitats in the Baltic Sea (Bergström *et al.* 2007, Modin 2008, Kraufvelin *et al.* 2018, HELCOM 2018a). The Baltic Scope project (2017) recommended the joint identification of essential fish habitats, including spawning, nursery and growth areas, for the whole Baltic Sea for species of interest to fisheries as one priority to further support MSP in the Baltic Sea.

Defining essential fish habitats is challenging for several reasons. The process of mapping aquatic habitats is generally restricted by data limitations and by the need to combine information from different data sources in a coherent way. There may also be ecological constraints, related to defining the appropriate spatial scale for a certain feature, and potential changes in the location of a certain habitat over time. In the case of fish, the suitability of spawning or feeding areas depends not only on physical and topographical characteristics, which are constant over time, but also on hydrological characteristics which show seasonal and inter-annual variation, such as temperature conditions or the movements of water masses (hydrodynamics). In addition, the presence of other species may be decisive for how suitable the habitat is in reality, such as the presence of suitable vegetation in a spawning area or the presence of zooplankton in a recruitment area. To delineate habitats on a map, one also needs to consider that habitat suitability varies along environmental gradients. Whereas areas with minimum environmental conditions can be identified, for example in relation to the minimum salinity required for successful spawning for a marine species, the environmental range representing optimal conditions is usually smaller. Lastly, human induced pressures such as fishing, eutrophication, or physical disturbance impact habitat quality and how effectively species can utilize the habitat in reality.

In the following report, we explore the possibility of producing regionally coherent maps on essential fish habitats in the Baltic Sea based on currently available knowledge, and suggest a set of Baltic-wide maps on potential key habitats for selected fish species and life cycle stages. Maps were developed for selected life stages of herring, sprat, European flounder and Baltic flounder, for which no maps were previously available in HELCOM. Additionally, previously available maps for cod spawning areas, as well as perch and pikeperch recruitment areas were re-evaluated and improved (For an overview, see Table 1). The maps are available at the HELCOM Map and Data Services[1]. The purpose of the presented maps is to support the identification of areas of particular concern with respect to ecological values and the provision of ecosystem services related to widely distributed fish species in the Baltic Sea. By this, the maps can support maritime spatial planning and environmental management, including actions to reduce human impacts in areas of high nature value in the Baltic Sea.

1 maps.helcom.fi/website/mapservice

2. Methods

2.1. Outline of the work process

The results presented in this report originate from work within the Pan Baltic Scope project[1] and from a joint regional Expert Workshop on essential fish habitats, which was organized by HELCOM and the Pan Baltic Scope project (HELCOM 2018a). The development took place in steps. First, partner researchers of Pan Baltic Scope made an overview of current knowledge on essential fish habitats in the Baltic Sea and used this information to make initial proposals for those species and aspects (spawning areas, recruitment areas, nursery areas) that were considered feasible based on available information (Box 1, Table 1). The researchers then circulated the initial proposals to a wider group of nationally nominated experts, who also took part in the joint HELCOM – Pan Baltic Scope workshop (HELCOM 2018a) to evaluate the overview and validate the proposed maps. The workshop discussed the maps and the approach applied and made further recommendations on how to improve them. The participants also took part in ensuing work over correspondence to finalize the development. The work in progress was subsequently presented to the meetings of HELCOM Fish-Pro III 1-2019 (HELCOM 2019a) and HELCOM VASAB MSP WG 18-2019 (HELCOM 2019b) for comments, and to HELCOM State & Conservation WG 10-2019 and 11-2019 (HELCOM 2019c, d) for endorsement. Comments and guidance for improvement received during these steps are included in the results presented below.

1 Co-funded by the European Maritime and Fisheries Fund. www.panbalticscope.eu

2.2. Focal species and aspects

The focus of the development was on fish spawning, recruitment and nursery areas, as these represent central ecological functions that need consideration in marine management and maritime spatial planning. Spawning areas include those habitats where ripe adults concentrate, spawn and release their eggs, and where the eggs develop (e.g. Seitz *et al.* 2014). These areas are a limiting factor for fish populations if the availability of functional spawning habitats is not sufficient to support population maintenance or growth (Mumby *et al.* 2004, Sundblad *et al.* 2014). For species with pelagic or mobile eggs and larvae, such as sprat, herring, European flounder and cod, the distribution of the spawning area may be significantly smaller than that of the area were juveniles occur, so that the spawning area contributes to the population at a much larger scale. For species with a limited dispersal of the larval stage, such as perch and pikeperch, the spawning areas and the areas were juveniles reside often overlap (Sundblad *et al.* 2014, Kallasvuo *et al.* 2017), and such crucial areas for population maintenance are here referred to as recruitment areas. Finally, nursery

Table 1. Overview of the presented maps. The last column shows the principal mapping approach (See section 2.3.)

Species	Type of fish habitat	Relation to previously available regional map	Mapping approach
Cod (*Gadus morhua*)	Spawning area	New – Previous map (HELCOM 2018b) was reworked	Environmental envelope
Sprat (*Sprattus sprattus*)	Spawning area	New – No previous map	Environmental envelope
Herring (*Clupea harengus membras*)	Spawning area	New – No previous map	Habitat associations
European flounder (*Platichthys flesus*)	Spawning area	New – No previous map	Species distribution modelling combined with environmental envelope
Baltic flounder (*Platichthys solemdali*)	Spawning area	New – No previous map	Species distribution modelling combined with environmental envelope
Flounders (*Platichthys* spp.)	Nursery area	New – No previous map	Species distribution modelling
Perch (*Perca fluviatilis*)	Recruitment area	Updated – Previous map (HELCOM 2018b) was re-examined and improved	Species distribution modelling combined with direct mapping.
Pikeperch (*Sander lucioperca*)	Recruitment area	Updated – Previous map (HELCOM 2018b) was re-examined and improved	Species distribution modelling combined with direct mapping

Box 1

Main data sources

The developed maps build on previous work in the Baltic Sea, including the following projects:

HELCOM HOLAS II project (HELCOM holistic assessment on the ecosystem health of the Baltic Sea, 2014-2018). This comprehensive project to assess the state of the Baltic Sea during 2011-2016 included, among other things, an assessment of spatial cumulative impacts (HELCOM 2018b). To support the assessment, maps on key ecosystem components in the Baltic Sea were developed and agreed on by HELCOM Contracting Parties. The maps focus on the spatial distribution of species, habitats and habitat types with a wide distribution in the Baltic Sea and are publicly available at the HELCOM Maps and Data services[1]. Regarding fish habitats, maps representing recruitment areas for perch, recruitment areas for pikeperch, and spawning areas for cod were considered further in the work presented in the current report. Further, maps representing habitat-forming species (vegetation) and habitat types from HOLAS II were used in the delineation of essential fish habitat maps for herring. HOLAS II also include maps on the abundance of cod, herring and sprat that were not used as a basis for the current work, as new approaches were used instead.

The BALANCE project[2] (Baltic Sea Management – Nature Conservation and Sustainable Development of the Ecosystem through Spatial Planning, 2005-2007). This Baltic-wide project aimed to develop informed marine management tools for the Baltic Sea, based on spatial planning, cross-sectoral and transnational co-operation (e.g. Ekebom *et al.* 2008). The work included a definition of Baltic Sea marine landscapes and the development of habitat maps, which were also used as a basis in the current report (Al-Hamdani and Reker 2007). The work further included an evaluation on the state of knowledge on essential fish habitats (Bergström *et al.* 2007). The project was EU co-funded within the BSR INTERREG III B Program.

The Baltic Scope project[3] (2015-2017) was the first Baltic Sea project to bring together national authorities with a planning mandate to collaborate in transboundary maritime spatial planning. The project also collected information about essential fish habitats from national plans. It was concluded that countries used very different approaches to map essential fish habitats. For future work, the project recommended to produce common essential fish habitat maps for fish species with a Baltic-wide distribution (Baltic Scope 2017). The project was co-funded by the European Maritime and Fisheries Fund.

The BONUS INSPIRE project[4] (Integrating spatial processes into ecosystem models for sustainable utilization of fish resources, 2014-2018) included the aim to resolve the habitat requirements of different life stages of Baltic fish species, focusing on cod, herring, sprat and flounder (Ojaveer *et al.* 2018). In doing so, the project combined field surveys and traditional methods with the application of modern analysis and modelling techniques. The project was funded by the Baltic BONUS programme, the EU and national funding institutions in the Baltic Sea countries.

The Fish-Hab-II project (2017-2018) developed habitat maps for different life stages of ten commercially important species in Danish waters. The maps were produced for the Kattegat, Belt Seas, the Sound and the western Baltic Sea area (from 9.59° to 13.72°E and from 54.21° to 57.78° N), and included, for example, EFH maps based on predictive models for cod, European flounder, plaice and sole (Støttrup *et al.* 2019). The project was funded by the European Maritime and Fisheries Fund.

The NCM Workshop on Essential Fish Habitats was funded by the Nordic Council of Ministers and organized by the Swedish University of Agricultural Sciences was held in 2015 with the objectives to review existing knowledge on the role, mapping and monitoring of essential habitats of coastal fish in the Baltic Sea (Kraufvelin *et al.* 2016). The workshop did not produce spatial information but collated and developed a structured knowledge-base for different areas around the Baltic Sea, regarding the characteristics of essential fish habitats in coastal areas. The outcome included, for example, information on how essential fish habitats can be defined in relation to other abiotic and biotic variables, biotopes or biotope complexes, as well current threats to these (Kraufvelin *et al.* 2018).

In addition, **several nationally coordinated activities and initiatives** to develop maps on nature values were considered. As one such example, the Finnish MSP is developing synthesis maps describing "ecologically significant underwater nature areas", covering the entire Finnish coastal area and representing all different ecosystem aspects: essential fish habitats, plants, macroalgae, bottom animals, seals, water birds etc. Good spatial data is available from existing monitoring and the extensive VELMU inventory program[5].

The Copernicus Marine Environment Monitoring Service[6] has provided environmental variables covering whole Baltic Sea, which were used in several of the maps.

1 maps.helcom.fi/website/mapservice
2 www.balance-eu.org
3 www.balticscope.eu
4 www.bonus- inspire.org
5 www.ymparisto.fi/en-US/VELMU
6 marine.copernicus.eu

areas are here defined as areas where juvenile life stages concentrate and which also support the adult population at a significantly larger spatial scale (Beck *et al.* 2001, Dahlgren *et al.* 2006).

Data availability to support the mapping of spawning areas was explored for seven species with commercial and ecological importance and a wide distribution in the Baltic Sea, and such maps were developed for cod, sprat, herring, European flounder, and Baltic flounder. Additionally, existing maps on recruitment areas for perch and pikeperch were evaluated and updated. Finally, a map on nursery areas was completed for flounders. This map shows potential nursery areas for European and Baltic flounder together, as these are not possible to distinguish based on field data and to large extent overlap with each other. It is suggested that additional maps on nursery areas are added to the set when data and models are sufficiently developed to support this, particularly for cod, plaice, sole and flounder in the Western Baltic.

2.3. Mapping approaches

Maps on essential fish habitats can be produced in several ways. The maps presented in this report were sometimes produced in different ways, depending on available information for each species. This section gives a summary of the different types of approaches that were considered in the work. The approaches applied for each of the species is presented in section 2.5, and an overview is provided in Table 1.

Direct data. The most reliable verification of a fish habitat is typically by direct mapping, based on inventory or monitoring data. However, since collecting field data is costly, comprehensive inventory data on fish is often scarce. It is also challenging to ascertain that the mapping results have reliable coverage. This is especially true for parameters representing fish spawning, recruitment and nursery areas, such as the presence and abundance of fish eggs, larvae, and young of the year, which are only present during part of the year. Hence, available direct data to support mapping have limited spatial extent, and comprehensive data at the whole Baltic Sea scale do not exist for any of the focal species. However, available data can still be used for the areas they represent, if they have adequate resolution and coverage, and ensuring that the variable descriptions (units) are comparable among different areas. Available direct data can also support other approaches, mentioned below, or be used to validate maps produced by other approaches.

Species distribution models. Spatial predictive modelling produces maps with fuller spatial coverage, which describe the probable distribution of fish habitats. Direct data from inventories, or monitoring, are used as a basis for developing statistical models depicting the relationship between the key variable and environmental parameters. Typical important environmental parameters in the case of fish habitats are for example depth, salinity, and wave exposure, among others. The statistical models are then combined with spatial data on the environmental parameters identified as having predictive importance, to identify areas with similar environmental properties as the fish habitats identified in the inventory. Resulting maps show the probability of occurrence of the essential fish habitat in focus, according to the applied model, to be further validated against other information.

Environmental envelope approach. The envelope approach builds on similar principle as species distribution models, but is not dependent on spatially referenced input data. The environmental envelope for a certain species and life stage is defined based on ecological knowledge on its limiting required environmental conditions. The key environmental variables and their threshold values are identified for example based on experimental studies or other relevant literature. In the absence of published information, expert judgement can be considered. The important aspects to decide on are which environmental variables should be included in defining the envelope, and what threshold levels to apply for these variables.

Habitat associations. If information to support the environmental envelope approach is insufficient, the fish habitat may be depicted on an overarching level based on the distribution of benthic habitats that the focal species and life stage is mainly associated with. Data that could be useful include spatial information on habitat types or habitat- building species. Maps on Natura 2000 habitat types might also be relevant to consider, even though obtained estimates should be associated with high uncertainty as differences among countries can be expected in how the Natura 2000 habitat types are defined and delineated.

2.4. Validation and evaluation of data quality

The initial maps should as far as possible be validated against other sources of knowledge before finalization. The purpose of the validation is to identify and correct for errors, which may occur due to uncertainties in several factors, such as the precision of the applied input data, ecological assumptions, the generality of the models, and others. If the validation suggests consistent errors in comparison with external information, the selection of approach, key environmental variables or threshold values should be re-examined. The maps should, further, be associated with information on data quality aspects when presented.

In the current case, the validation and evaluation of data quality were carried out by the HELCOM Pan Baltic Scope EFH WS (HELCOM 2018a) and in later steps by correspondence with national experts (for example HELCOM 2019 c, d). When clearly justified, the initial maps were adjusted manually. For example, the applied approach might have picked up highly modified or disturbed areas where spawning is in fact not possible (examples include channels, lagoons, city harbors), or additional areas were added referring to locally available mapping data. Data quality aspects in relation to the presented maps are shown in Chapter 3 and discussed in Chapter 4.

2.5. Approaches applied for the different species

Available data and knowledge were examined for each of the seven species and the focal aspects to decide on a mapping approach. Among mapping approaches, direct mapping and species distribution modelling were preferred whenever feasible. However, sufficiently developed research to support this was not available for pelagic habitats. Hence, the environmental envelope approach was applied for the maps on spawning areas of cod and sprat. For flounders, a combination of species distribution modelling and environmental envelope was used. For herring spawning habitats, available data were only sufficient to support a broad mapping based on habitat associations (For an overview, see Table 1).

Further, for the process of mapping of essential fish habitats, Planque *et al.* (2007) classified maps into either potential, realized or effective essential fish habitats, depending on what underlying data and assumptions the maps were based on. By their definitions, “potential habitats” are those where water masses or substrates can support a particular life stage during a certain period of time, based on for example known environmental constraints. “Realized habitats”, again, are those which have been observed to uphold that life stage, based on for example sampling to show that fish eggs are present. Last, “effective habitats” are those which support the highest densities or have the highest relative contribution to the population. In relation to this classification, the Baltic-wide maps presented here represent potential habitats, or areas where the focal habitat is likely to be found based on known environmental constraints and validated by available sampling. Mapping either realized habitats or effective habitats as defined by Planque *et al.* (2007) was not realistic at the Baltic wide scale in our work, due to the many uncertainties involved as outlined above. For more information on the mapping approaches applied here, see section 2.5. Some more details on the key information considered for each of the species and focal aspects are presented below.

Box 2.

Potential future scenarios under climate change

The importance of climate-related variables, such as salinity, temperature and oxygen, for cod spawning in the Baltic Sea stresses the need to develop forecasts and spatial scenarios on how spawning areas may be affected by climate change. In the Swedish maritime spatial planning process, small steps were taken in this direction by identifying potential climate refugia.

Climate refugia are areas where the effects of climate change on the ecosystem are estimated to be relatively milder (Dahlgren and Havenhand 2017). Through modelling based on projected climate-related changes in the future, the Swedish MSP process searched to identify potential climate refugia for (inter alia) Eastern Baltic cod using climate scenarios from IPCC. Models based on projected changes in salinity and oxygen under IPCC scenarios RCP 4.5 and RCP 8.5 indicated that even Eastern Baltic cod will most probably not have successful spawning in the Baltic Sea in year 2100. At RCP 4.5, a marginal area of potentially suitable habitat was considered but would likely be too small to sustain the population, also given foreseen interannual variability in environmental conditions (Törnqvist *et al.* 2019).

2.6. Cod

Cod (*Gadus morhua*) occurs from the Kattegat to the Baltic Proper and is hence the most widely distributed predatory fish species in the Baltic Sea. Cod is important commercially, but it is also a key species in the ecosystem. It is the predominating predatory fish species in the open sea, and a central link in the food web that connects benthic and pelagic systems. By the delineation applied in fisheries management, cod is represented by three stocks in the region: Eastern Baltic cod, Western Baltic cod, and Kattegat cod (ICES 2019a, b). The map focused on spawning areas for cod.

The hydrographical environment is of high importance for cod spawning in the central Baltic Sea. Spawning success is mainly dependent on suitable salinity and oxygen conditions, as well as on temperature. For these reasons, the spawning success of cod is substantially different in different parts of the region, and it also varies among years. Conversely, a lack of suitable oxygen and salinity conditions has negative effects on spawning success, via effects on fertilization efficiency and egg survival. Eggs occurring close to the seabed also face increased risk of mortal sedimentation. These hydrographical conditions depend strongly on climate change, as well as on eutrophication levels in the case of oxygen. In addition, the fact that the cod population is strongly reduced may affect to what extent some potential spawning areas are utilized in reality. Available evidence show that the extent of suitable cod spawning areas has decreased over time in the Baltic Sea. For example, the progress of decline of cod spawning areas in the Arkona deep, Gdansk deep and Gotland deep during 1971-2010, was shown through a combination of hydrodynamic modelling and Lagrangian particle tracking by Hinrichsen *et al.* (2016; Figure 1). These findings raise questions about the current function of the Gotland deep for cod spawning, as known previously (Bagge *et al.* 1994). They also emphasize the critical need for sustainable management of the Bornholm deep and the Arkona deep, as further emphasized by climate change (Box 2).

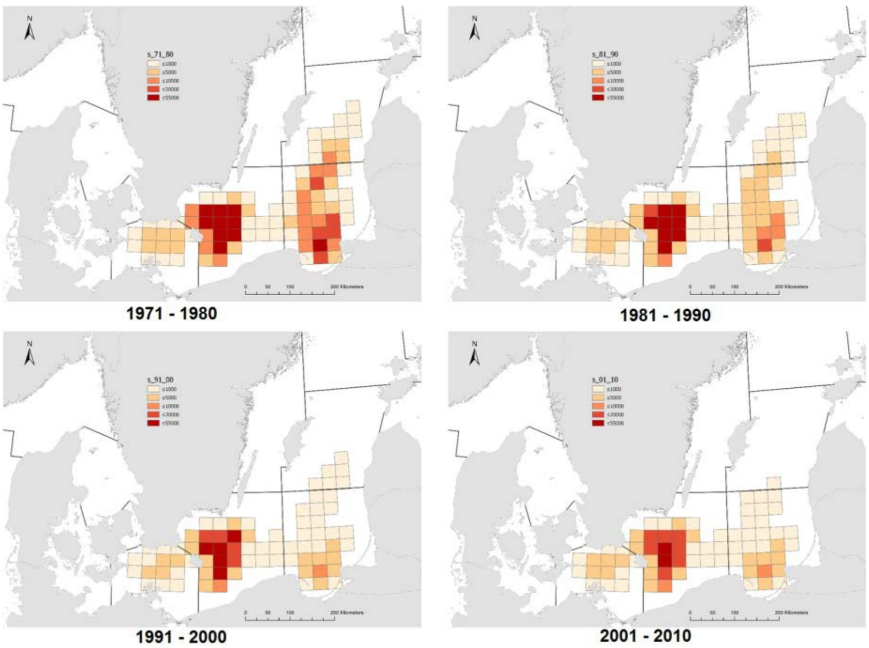

Figure 1. Progression of suitable habitat status for spawning grounds for cod in southeast Baltic Sea 1971–2010. (Aggregated on basis of Hinrichsen *et al.* 2016).

In the western Baltic, the hydrographical conditions are less critical, and instead cod population abundance and age structure are relatively more important factors for recruitment. The western and eastern Baltic cod stocks partly overlap, and the Arkona deep is estimated to be functional for spawning of both stocks (Hüssy 2011).

The previously existing regionally agreed map on cod spawning areas was developed within the HELCOM HOLAS II project (HELCOM 2018b) based on information from literature. The map was approved by all HELCOM Contracting Parties in a review process. However, the HELCOM Pan Baltic Scope EFH WS recommended that the new map on spawning areas of cod should rather be developed, using an environmental window approach that considers the different ecological characteristics of Eastern Baltic cod and Western Baltic cod, and includes available information on Kattegat cod. Background information for each of these stocks is presented below.

Eastern Baltic cod. Studies of the horizontal distribution of cod eggs and larvae have identified the Bornholm Basin, the Gdansk Deep and the Gotland Basin as the major potential spawning grounds for Eastern Baltic cod. In the eastern Baltic the spawning period is extended, from March to August. During the 1970s and late 1980s, peak spawning took place between the end of April and mid-June. A gradual shift in the timing of spawning to the end of July was observed in the 1990s and later years (Bagge *et al.* 1994; Wieland *et al.* 2000). Suitable environmental conditions for egg and larvae production for Eastern Baltic cod occur regularly throughout all years recorded in the Bornholm basin. The abundance of cod eggs during the main spawning time is in general the highest in the Bornholm deep. Additionally, cod spawning takes place regularly in the Slupsk Furrow (ICES 2018). Since the mid-1980s, cod spawning is very rare in the Gdansk and Southern Gotland basins. Reproduction conditions improves during baroclinic inflows of marine water from the North Sea. For example, a Major Baltic Inflow in 2014-2015 led to a certain, but relatively short-time, improvement of cod reproductive volume and larval production in these areas (Morholts *et al.* 2015, Naush *et al.* 2014). However, the Gdansk and Gotland basins have overall small contributions to cod recruitment since the mid-1980s, which are observed in some years only. The reduction is related to weaker and less frequent baroclinic inflows, stagnation processes in the basins, as well as low stock size (MacKenzie *et al.* 2000, Köster *et al.* 2009, Plikshs *et al.* 2015, Köster *et al.* 2017).

The use of spawning area and rate of successful spawning depends on the spawning stock size and suitable environmental conditions. Environmental threshold values for spawning were suggested at salinity >11 (ensuring egg buoyancy and fertilization), oxygen > 2mL/L (egg survival) and temperature > 1.5°C (Westin and Nissling 1991, Wieland *et al.* 1994).

Western Baltic cod. Western Baltic cod spawns from January to May, with the main spawning period from March to April (Bleil *et al.* 2005, 2009). Spawning areas are regions of deeper than 20 m in the Kiel Bight, the Fehmarn Belt and the Mecklenburg Bight. Environmental threshold values for spawning of Western Baltic cod have been suggested at salinity 18-33 (ensuring egg development and survival), and temperature > 2°C (Nissling and Westin 1997, Rohlf 1999, Hussy *et al.* 2012).

Kattegat cod. Spawning in Kattegat cod takes place from beginning of January to end of April. The spawning peaks in January to February (Vitale *et al.* 2005), and shows is a spatial gradient with later spawning in the southern areas. Spawning aggregations have been observed north of Læsø in the central Kattegat (Bartolino *et al.* 2012), southern Kattegat including Skälderviken and Laholm Bay (Hagstrom and Wickström 1990, Svedäng and Bardon 2003), and in the Sound and Great Belt (Bagge *et al.* 1994). However, with the declining stock, spawning is no longer observed in many of the earlier spawning sites. Active spawning sites are reported off the coast of Falkenberg in Sweden or, more predominantly, in the southeastern Kattegat very close to the entrance to the Sound (Vitale *et al.* 2008, Börjesson *et al.* 2013). Støttrup *et al.* (2019) showed salinity and depth to be significant predictors for cod spawning areas in the Kattegat. They used generalized additive models based on survey data for predicting spawning areas. Results showed important spawning grounds in the areas off Falkenberg, and to the south along the Swedish coast in the southeastern part of the Kattegat around the entrance to the Sound and the Sound (See also Box 1). The HELCOM Pan Baltic Scope EFH WS suggested to apply a salinity threshold of 18 for spawning also for Kattegat cod (Nissling and Westin 1997, Hussy *et al.* 2012).

2.6.1 Sprat

Sprat (*Sprattus sprattus*) is a small-bodied clupeid. It occurs in the entire Baltic Sea, mainly in open sea areas. Sprat is pelagic schooling species, which preys on zooplankton and fish eggs and functions as prey for top predators, such as cod. It represents one of the most important commercially exploited fish species in the Baltic Sea. In fisheries management, sprat is assessed as a single stock within the ICES subdivisions 22-32 in the Baltic Sea (ICES 2019a). The map focused on spawning areas for sprat.

The highly stratified, deep basins in the central Baltic are known to be the major spawning grounds of Baltic sprat. The spawning time is different in different parts of the Baltic Sea, and overall recruitment success varies tightly with temperature (Baumann *et al.* 2006). Spawning typically occurs from February to August in the deeper parts of Bornholm and Gdansk Basins. Further north, it starts later, giving an overall shorter time window for spawning. Sprat eggs are pelagic and are assumed to have a minimum limit for survival and buoyancy at a salinity of 6 (Petereit *et al.* 2009). Recent fisheries surveys indicate that sprat spawning does no longer occur in the Gulf of Finland.

There was no previously existing map on sprat spawning grounds covering all of the Baltic Sea, why a new proposal for such a map was developed.

2.6.2 Herring

Atlantic herring (*Clupea harengus*) is alongside sprat the most abundant pelagic clupeid in the Baltic Sea. It is widely distributed and common in all sub-basins. The Baltic Sea herring is smaller than herring in the Atlantic and is well adapted to the low salinity. Herring feeds in the pelagic, where it mainly eats zooplankton but also other species. It is an important prey for cod and marine mammals, and has significant commercial importance in all of the Baltic Sea. Genetic studies and observations on spawning behavior suggest that herring shows strong local population structure in the Baltic Sea (e.g. Jørgensen *et al.* 2005). In fisheries management, Baltic herring is assessed based on four stock units, representing western Baltic spring spawning herring (ICES subdivisions 22-24), Central Baltic Sea (subdivisions 25-27, 28.2, 29 and 32), Gulf of Riga (subdivision 28.1, and Gulf of Bothnia (subdivisions 30-31; ICES 2019a). The map focused on spawning areas of herring.

Herring spawns in shallow coastal areas, and in offshore shallows. It has demersal eggs, which are attached to the seabed substrate. There are populations of both spring spawning and autumn spawning herring in the Baltic Sea, out of which spring spawning herring strongly dominates today. Available information on the distribution of herring spawning grounds are mainly based on direct local observations (see references in next section). In addition, spatial predictive modelling based on physical parameters on a smaller-than regional scale has been initially explored (Modin 2008).

Studies on herring spawning grounds have been made mainly in four areas: in the Greifswalder Bodden, the Gulf of Riga and Pärnu Bay, the Askö-Landsort area in Sweden and on the Finnish coast extending from the Gulf of Finland to the Bothnian Sea. All studies were made by SCUBA diving, which allows direct observations of herring spawn on the bottom. The first surveys of herring spawn were carried out in the 1940s and 1950s in the Gulf of Riga (Rannak 1959). The same spawning areas were also revisited in the 1980s by Raid (1990). In the Greifswalder Bodden, Scabell & Jönsson (1984) and Jönsson *et al.* (1984) studied the spawning substrates and egg densities of the Rügen herring, and Klinkhardt *et al.* (1985) described the successive use of spawning beds during the spawning season in the same area. Scabell and Jönsson (1989) presented the monitoring program used in the spawning areas of the Rügen herring in the 1980s. In the Gulf of Riga, Ojaveer (1981) and Raid (1990) studied the density and mortality of herring eggs on the spawning grounds, and Kornilovs (1994) made similar studies on the Latvian coast. In the east coast of Sweden (Askö archipelago), Aneer and Nellbring (1982) made an extensive survey of spawning beds and described the characteristics of herring spawning at the end of the 1970s. Aneer *et al.* (1983) also made observations on the herring's spawning act in situ in the Askö area. In the Archipelago Sea, characteristics of herring spawning have been studied by Rajasilta *et al.* (1986, 1989, 1993), Oulasvirta *et al.* (1985) and Kääriä *et al.* (1988, 1997). To gather information on spawning grounds along the Swedish east coast, covering the coasts of the Bothnian Bay, the Bothnian Sea, and the Baltic proper, an interview study directed towards persons with extensive local experience of fishes and fishing was carried out in 2003 (Gunnartz *et al.* 2011). More recent studies in the Baltic Sea cover Lithuanian coast (Šaškov *et al.* 2014, Näslund *et al.* 2011). The Vistula Lagoon and Pomeranian Bay are important spawning grounds of herring (Popiel 1955, 1984, Strzyżewska 1969, Fey 2001, Fey *et al.* 2014a, 2014b, Krasovskaya 2002).

According to the study results, herring spawn in quite similar conditions around the Baltic Sea. In the innermost archipelagos, spawning in spring takes place mainly on shallow bottoms (0-8 m), but in the autumn at some greater depths (Oulasvirta 1987). Herring prefers aquatic vegetation as a spawning substrate but does not show selection for any substrate type (Aneer 1989). The herring schools visit the same spawning grounds one generation after another (Raid 1990), and in some spawning areas the spawning beds are used successively during the spawning season (Klinkhardt *et al.* 1985, Rajasilta *et al.* 1993). The common conclusion from the studies is that herring spawns in relatively shallow areas, mostly in areas characterized by hard bottom or on soft bottoms with erect vegetation. The specific site for spawning within these areas may, however, be variable both among years and within the same season, as it also depends strongly on hydrological characteristics, such as temperature and currents.

There was no previously existing map on herring early life stages covering all of the Baltic Sea, why a map on potential herring spawning areas was developed.

2.6.3 Flounder

The taxonomic status of flounders in the Baltic Sea (*Platichthys* spp.) was revisited shortly before the time of this study. It has long been known that flounders in the Baltic Sea have two different reproductive strategies, representing offshore spawning populations with pelagic eggs, and coastal spawning populations with demersal eggs (Solemdal 1967, Nissling *et al.* 2002). These two strategies were shown by Momigliano *et al.* (2017) to belong to two closely related but distinct species. Flounder with demersal eggs was described as a new species, the Baltic flounder, *Platichthys solemdali* (Momigliano *et al.* 2018). The two species have overlapping feeding and wintering areas in the central Baltic Sea, but are spatially separated during spawning time. The maps focused on spawning areas of European flounder and Baltic flounder, respectively, and on recruitment areas for both flounder species taken together.

Since the formal delineation between European and Baltic flounder was made very recently, there were no studies formally addressing physiological features of the two verified species, but relevant information was obtained from earlier studies that distinguished the two now formally described distinct species as two different spawning ecotypes.

European flounder (*Platichthys flesus*) is a key species in many areas of the Baltic Sea, with a focus in the central and south-western sub-basins. European flounder spawns exclusively in deep offshore basins of the south-western and central Baltic Sea, where salinity is high enough for successful fertilization and water density is sufficiently high for the eggs to float in the water column to avoid the anoxic bottom waters (Nissling *et al.* 2002, Ustups *et al.* 2013). The species migrates between coastal and open sea areas during its life cycle. Adults feed in shallow, coastal areas during summer and move out to deeper areas in winter, where the spawning takes place in spring. Early juvenile life stages, again, reside in shallow coastal areas until recruiting to the adult population (e.g. Carl *et al.* 2008). Available literature suggests that the environmental limits for spawning of European flounder are rather similar to those of cod with respect to salinity, and may suggest that its requirements for oxygen are lower than for some other fish species (Steffensen *et al.* 1982, Fonds *et al.* 1992). Results from the hydrodynamic modelling suggest that the level of connectivity may be high (Hinrichsen *et al.* 2017b).

Baltic flounder (*Platichthys solemdali*) spawns in shallow coastal areas and on offshore banks. In these spawning areas the eggs do not float, as is the case for European flounder, but sink to the bottom. Demersally spawning flounders have been observed to lay their eggs on sandy and rocky bottom, or on rocky substrates covered with algae (Bonsdorff and Norkko 1994). Early juvenile life stages reside in shallow coastal areas until recruiting to the adult population (Nissling *et al.* 2015). Similar as for European flounder, adult Baltic flounder has a migrating behavior so that it feeds in coastal areas during summer and moves to deeper areas in winter. In contrast to European flounder, it however spawns demersally in coastal areas,

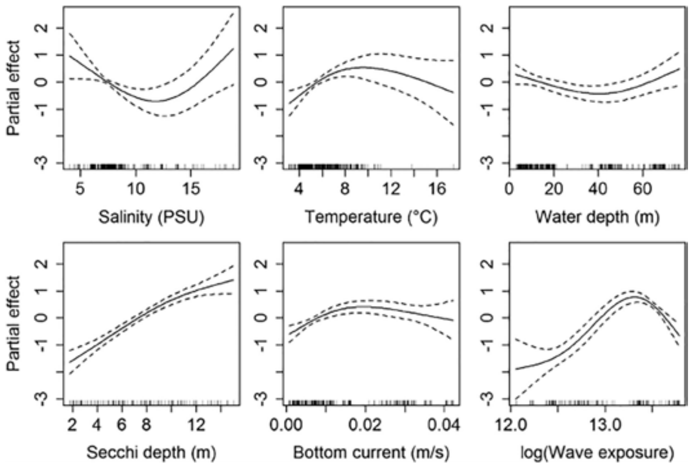

Figure 2. General model for flounder spawning areas in the Baltic Sea. Response curves of environmental variables in a statistical predictive model. This general model was based on data representing both Baltic and European flounder data (referred to as "ecotypes" at that time). Dashed lines show the 95% confidence interval. Source: Orio *et al.* (2017)

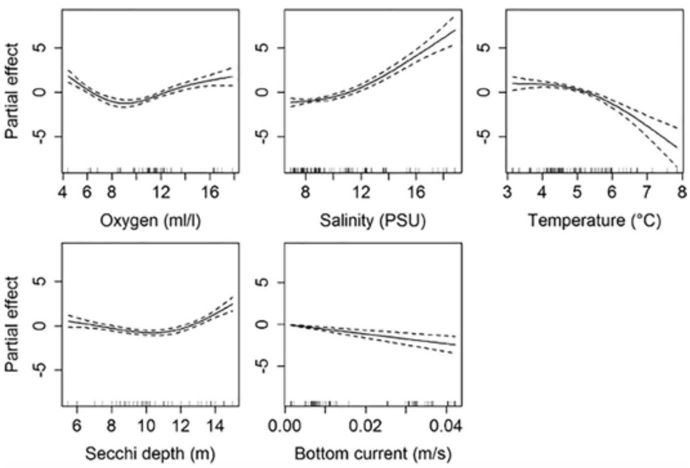

Figure 3. Model for pelagic spawning flounder (representing European flounder). Response curves of environmental variables in a statistical predictive model. This model was made separately for data on mature flounder in deep areas. Dashed lines show the 95% confidence interval. Source: Orio *et al.* (2017)

and the salinity requirements for spawning of Baltic flounder are lower. Successful spawning for demersally spawning Baltic flounder may be expected at salinities down to around 5-7 (Nissling *et al.* 2002). Low oxygen concentration poses a less important restriction to spawning as the coastal near-shore spawning waters are in most cases well oxygenated.

2.6.4 Spawning areas of European flounder

Potential spawning habitats for flounders in the Baltic Sea were characterized and spatially predicted by Orio *et al.* (2017), based on catches of flounder in gillnet surveys during the spawning season. The basis for the study was to map mature flounder during or very close to the spawning season, when they were expected to occur in their preferred spawning habitat, and subsequently use the catch observations together with observed environmental data as a basic for predictive modelling over a larger geographical area (Figure 2). The focus of the study was on the southern and central Baltic Sea, using depth transects at 11 locations (427 stations). The approach provides a wide-ranging description of potential spawning areas in the Baltic Sea, with statistical documentation of the expected relationships to environmental variables. A separate model for pelagic spawning flounder (here interpreted as European flounder) showed a negative relation with temperature and bottom current, and a positive relation with salinity (Figure 3).

The main uncertainties in the results by Orio *et al.* (2017) are expected due to temporal differences in sampling and spawning time between different areas, so that there is some variability in how close to spawning the flounders were at the time of capture. In some areas, there also occurred spent flounder in the samples, which means that the flounder could spawned in another place than where they were captured. This is not expected to affect results at the coarse geographical scale used here, but may affect the small-scale patterns (primarily depth distributions). Generally, the spawning occurs earlier in the western parts of the Baltic Sea. In addition, low captures of flounder at some of the stations might not only reflect poor habitat preference but may also reflect other factors, for example a reduced spatial expansion due to low population size. If that is the case, the predicted habitat range may be underestimated. This may potentially affect results for pelagic spawners[2] in ICES subdivisions 26-28, whereas pelagic spawners in subdivisions 24-25 have fairly strong populations (Orio *et al.* 2017b).

To prevent extrapolation outside the realistic range of sampled environmental conditions, Orio *et al.* (2017) restricted their predictions to areas within the physiological limits for fertilization of flounder egg and survival, based on salinity and oxygen conditions. The spatial predictions were also limited in relation to depth, to account for the existence of two different spawning types (which were later described as separate species by Momigliano *et al.* 2017, 2018). The depth limit for pelagic spawners was set to areas deeper than 30 m and the bottom salinity to at least 10, referring to Hinrichsen *et al.* (2017b). In relation to oxygen concentrations, the prediction was set to 0 in all areas with bottom oxygen concentrations below 1 ml/l. In reality, the geographical range of suitable spawning areas for European flounder is expected to vary along with spatial variation in these hydrological variables, which are forced by climate change as well as human impact related to eutrophication. An increase of suitable spawning areas can be expected for example in connection to Major Baltic Inflows.

2 Representing European flounder

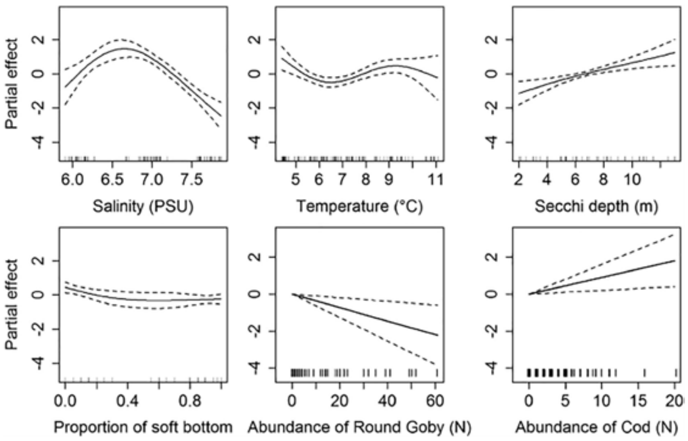

Figure 4. Model for demersal spawning flounder (representing Baltic flounder). Response curves of environmental variables in a statistical predictive model. This model was made separately for data on mature flounder in shallow areas. Dashed lines indicate the 95% confidence interval. Source: Orio *et al.* (2017)

2.6.5 Spawning areas of Baltic flounder

The predictions of potential spawning habitats for flounders in the Baltic Sea carried out by Orio *et al.* (2017) and presented above for European flounder are also relevant for Baltic flounder. Among their principal results were observations on a dual water depth distribution and salinity preference of flounders at spawning time, which they interpreted as distinct responses to these environmental variables by the two ecotypes, later redefined to two species (Figure 2). The separate model for the demersal ecotype (*P. solemdali*) showed a salinity optimum at around salinity 7 (Figure 4). The model indicated no strong relationship to vegetation or substrate, although rocky habitats seemed to be preferred over pure soft substrate (Orio *et al.* 2017)

The main uncertainties in demersal flounder model are the same as those presented for European flounder (above). Additionally, in some areas, a negative interaction with the presence of round goby may lead to underestimations in prediction (this is encompassed in Figure 4).

To prevent unrealistic extrapolation outside the range of sampled environmental conditions, Orio *et al.* (2017) restricted the predictions to areas within the physiological limits for eggs fertilization and survival. The predictions were also adjusted in relation to depth, to account for the existence of two different spawning types (which were later described as separate species by Momigliano *et al.* 2017, 2018). For demersal spawners, the predictions were restricted to areas shallower than 30 m and with salinity of at least 6, referring to Nissling *et al.* (2002) and Hinrichsen *et al.* (2017b). In relation to oxygen concentrations, the prediction was set to 0 in all areas with bottom oxygen concentrations < 1 ml/L.

2.6.6 Nursery areas for flounder

As shown in the sections above, the two flounder species in the Baltic Sea, European flounder (*Platichthys flesus*) and Baltic flounder (*Platichthys solemdali*) have different reproductive strategies and their principal spawning areas are spatially and temporally separated. The Baltic flounder spawns in shallow waters while European flounder spawns in deeper areas. Despite these differences, larvae of both species settle in shallow areas, so that the two species share the same nursery habitat. Both European and Baltic flounder spawn in spring, the former in late winter to spring and the latter in spring and early summer. Young of the year fish can be observed from June to September on shallow sea beds, primarily sandy substrates.

Juvenile flounder (young of the year) have been sampled by three different principal methods In the Baltic Sea: beach seine, push net and mini trawl. The three methods differ in how large area they cover, but since all methods sample a known surface area, their results can be converted to "catch per unit area" to be comparable. A dedicated data request was carried out within the Pan Baltic Scope project and showed that comparable survey data are available for many parts of the Baltic Sea, albeit with data gaps in the southern Baltic Sea (Figure 5). The natural distribution range of the two flounder species does not extend into the Gulf of Bothnia or inner Gulf of Finland, at least not with respect to spawning areas.

A spatial predictive model was applied to make use of currently available data and create a map of potential nursery areas of flounder. Data from all identified available surveys of juvenile flounder were collected and compiled for the modelling (Figure 5). While in a few of the datasets occasional older juveniles may have been included, the absolute majority of the observed fish were young of the year individuals, why the model will represent the distribution of the youngest year-class. Only results from surveys performed in June-September from 2004-2018 were used, to represent the nursery season and the current situation. This resulted in a total of 2,114 samples. To harmonize the datasets, all abundance estimates were converted to "juvenile flounder per square meter".

Values for the environmental predictor variables were extracted in GIS for each sampling point. The following variables were used: salinity, wave exposure, water depth, slope of the bottom, surface temperature (mean for June-September), bottom currents, and distance to high probability spawning area for European flounder.

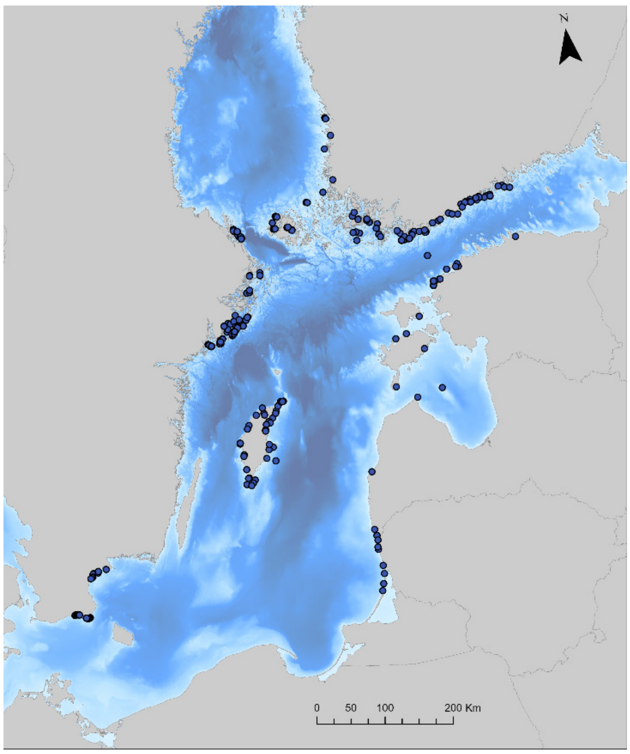

Figure 5. Data sampling points used in the juvenile flounder model.

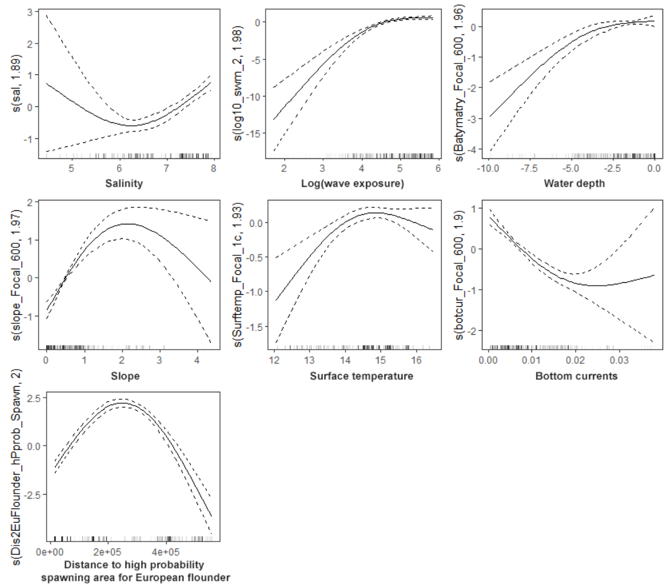

Figure 6. Response curves from the juvenile flounder model. The generalized additive model explained 41.3 % of the deviance in the data and the R^2-value was 0.32.

For making spatial predictions of flounder nursery areas, a generalized additive model with flounder abundance as response variable and the seven environmental predictor variables was constructed (Figure 6). The northern and eastern boundaries of the spatial model were defined based on the predicted areal extent of the spawning areas of Baltic flounder (see above) combined with information on where juvenile flounder was caught in the surveys.

Based on the models, high probability nursery areas were defined as areas with a predicted abundance over 0.03 juvenile flounder per square meter. Potential nursery areas were defined by predicted abundance levels between 0.0001 and 0.03 juvenile flounder per square meter. Areas with a predicted abundance below 0.0001 were not defined as flounder nursery areas.

2.6.7 Perch

Perch (*Perca fluviatilis*) is a predominating species in many coastal areas of the Baltic Sea, and a key species in coastal fish communities of the Northern and central Baltic Sea. While young perch feed on zooplankton before they shift to feeding on benthic animals, adult perch are predominantly piscivores. It is a widely appreciated for recreational fishing but also has commercial importance for small-scale coastal fisheries. The map focused on recruitment areas of perch.

Perch is a species of freshwater origin, and hence it spawns predominantly in freshwater tributaries and coastal areas close to freshwater outlets. Along the coasts of Finland and Sweden, perch can also spawn further away from freshwater outlets if there are enclosed bays which warm up early in the season (Snickars *et al.* 2010, Bergström *et al.* 2013, Sundblad *et al.* 2014). In the southern Baltic Sea, such as the Curonian lagoon, perch spawns closer to the coast, in areas where vegetation or other structures create suitable spawning conditions (Jankevičius *et al.* 1959, Gaigalas 2001, 2011). Genetic studies and tagging studies suggest that perch has a local population structure with limited dispersal away from its recruitment area (e.g. Olsson *et al.* 2011).

A regional map on recruitment areas of perch was made available at the HELCOM Maps and data services during the HOLAS II project (HELCOM 2018b) when it was approved by all HELCOM Contracting Parties in a dedicated review process. The existing map was considered by HELCOM Pan Baltic Scope EFH WS 1-2018, who proposed adjustments to the areas covered in Russia, and amendments to the text on data quality.

2.6.8 Pikeperch

Pikeperch (*Sander lucioperca*) is found in coastal areas across the Baltic Sea, predominantly in high-turbidity archipelago areas and close to freshwater tributaries. It is an appreciated species for the fisheries. Adult pikeperch are piscivores. The map focused on recruitment areas for pikeperch.

Pikeperch is of freshwater origin. It spawns predominantly close to freshwater tributaries to the Baltic Sea but also tolerates relatively higher salinities (Ložys 2004, Lehtonen *et al.* 1996). As pikeperch generally prefers turbid waters it is often associated with relatively more eutrophic areas (Bergström *et al.* 2013, 2019). Pikeperch shows local population structure and is assumed to show limited dispersal away from its recruitment area (Säisä *et al.* 2010). Populations are highly affected by fishing in many coastal areas (Lehtonen *et al.* 1996, Mustamäki *et al.* 2014)

Similar as for perch, a regional map on pikeperch recruitment areas was made available at the HELCOM Maps and data services during the HOLAS II project. The existing map was considered by HELCOM Pan Baltic Scope EFH WS 1-2018, who proposed adjustments to the areas covered in Estonia and Lithuania, and amendments to the text on data quality.

2.7. Aggregation of data layers

An additional consideration for the purposes of maritime spatial planning (MSP) is that there can be a need to synthesize and combine the data for different species further, to depict core areas for essential fish habitats at a general level. The HELCOM Pan Baltic Scope EFH WS (HELCOM 2018a) considered the production of aggregated essential fish habitat maps for use in MSP processes and identified some key points for how such maps should preferably be developed at the Baltic Sea regional scale:

Before producing aggregated maps, it should be ensured that all maps to be combined are presented on a comparable scale. They are preferably transformed either to representing only values between 0 and 1, or to the binominal scale (representing only values 0 or 1).

It should also be ensured that the maps represent similar aspects, to provide a meaningful aggregated map. For example, essential fish habitat maps may describe either spawning, nursery habitats, or some other aspect.

When the maps are combined in GIS, as described above, the theoretical maximum value in the aggregated map is the total number of maps that are included. However, it should be noted that in reality this theoretical maximum only occurs in the rare case that all included data layers overlap spatially at least somewhere in the studied area. If the aggregated map is to be used further in comparisons with other data layers, the values should also be transformed to vary between 0 and 1.

The aggregated map should be supplemented with information on its seasonal relevance, to recognize the fact that fish species use different habitats during different seasons. In some cases, seasonally comparable information is required to be able to use the aggregated map in a relevant way. For other purposes, information on the average situation over the year (annually representative information) is sufficient. When applicable, an overall aggregated map representing all essential fish habitats could be supplemented with separate aggregated maps for each quarter of the year, to show differences in seasonality.

When presenting the results at a Baltic scale, it should be made clear that the expected number of essential fish habitats is different between different parts of the Baltic Sea due to natural factors, such as salinity.

When using the resulting map, it should be noted that an unweighted aggregation gives equal influence to very common and less frequent species, and that several potentially important species of concern may risk being unconsidered, if they are not represented in the underlying maps.

Data limitations should be communicated, stating for example if the aggregated map lacks information for some key aspects of essential fish habitats, or other data limitations.

These aspects are intended as initial considerations, to be developed further. An illustrative example on to show these principles applied to the work presented in this document is presented in Section 3.9.

3. Results

The following chapter presents the resulting maps (Figures 7-14), together with background information on each of the data layers (Sections 3.1-3.8, Tables 2-9). The maps are also available at the HELCOM Maps and Data Service[1].

3.1. Potential spawning areas for cod

Cod (*Gadus morhua*) is represented by three stocks in the Baltic Sea; Eastern Baltic, Western Baltic and Kattegat cod, which is reflected in the map. "Potential spawning areas" were initially delimitated based on Hüssy (2011). In addition, the Gdansk deep as delineated by Bagge *et al.* (1994) was included as it sometimes contributes to reproduction of Eastern Baltic cod (Hinrichsen *et al.* 2016). The Gotland basin has ceased to contribute to the reproduction of cod (Hinrichsen *et al.* 2016). These definitions were applied in the HOLAS II project (HELCOM 2018b) based on approval by all HELCOM Contracting Parties in a review process (there referred to as 'occasional successful spawning' and 'successful spawning'). Following HELCOM (2018a) additional potential spawning areas were identified by environmental thresholds for egg development and survival based on salinity and oxygen conditions (Hinrichsen *et al.* 2016) during 2011-2016. Separate thresholds were used for Eastern Baltic, Western Baltic and Kattegat cod. Areas denoted "high probability spawning areas" correspond to where the initial delineations (Hüssy 2011, Bagge *et al.* 1994) achieve the environmental threshold values (Table 2, Figure 7).

1 maps.helcom.fi/website/mapservice

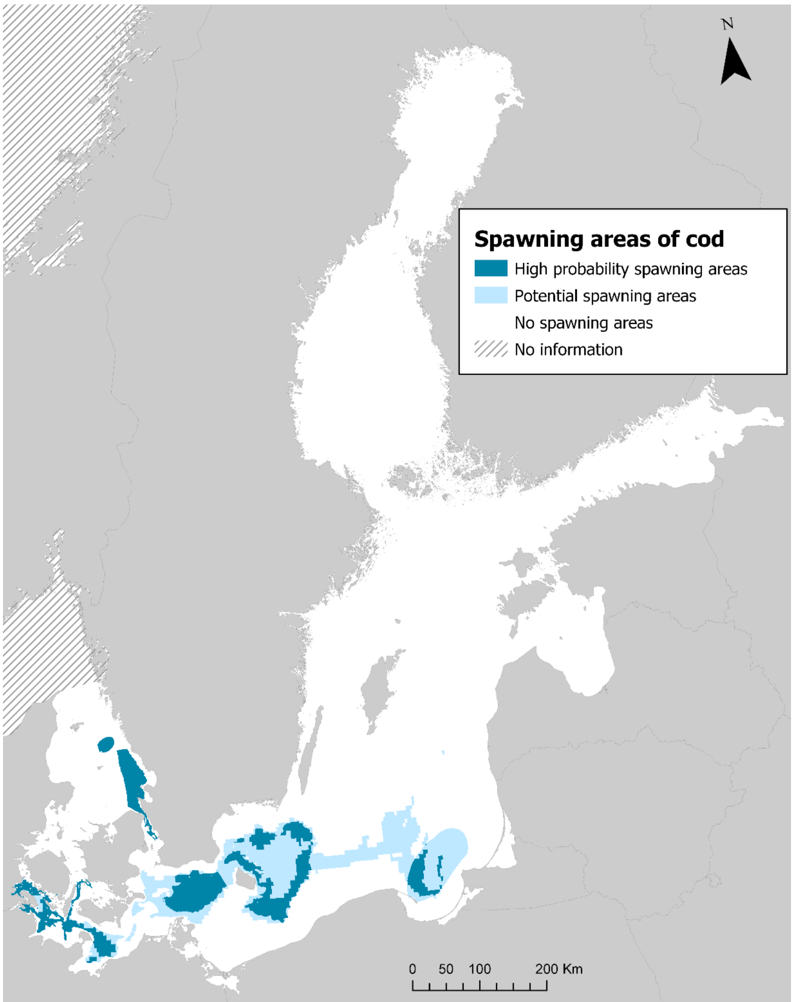

Figure 7. Potential spawning areas for cod.

Table 2. Data table for potential cod spawning areas

Species	**Cod *(Gadus morhua)***
Stocks	Kattegat cod: ICES subdivision 21, Western Baltic cod: ICES subdivisions 22-24 Eastern Baltic cod: ICES subdivisions 24 + 25-32
EFH type	Potential spawning areas
Approach	Literature review combined with identification of environmental window for spawning based on: salinity and oxygen for Eastern Baltic cod, and on: salinity and depth for Western Baltic Cod and Kattegat cod
Time period	2011-2016
Data source	Initial polygon data received from Karin Hüssy, DTU Aqua, Denmark. The method for delineating the spawning area is described in Hüssy (2011) Salinity and Oxygen: Copernicus Marine Environment Monitoring Service, SMHI The data represents monthly data for years 2011-2016 downloaded from Copernicus Marine Environment Monitoring Service (http://marine.copernicus.eu). Reanalysis products of SMHI for years 1989-2004, 5.5km grid cells. The layers represent conditions at the sea floor. For salinity, extrapolation to some coastal areas that were outside the original data due to low resolution of the grid was carried out. Depth: Swedish Agency of Marine and Water Management. For Metadata, see SwAM (2019), p 232-236.
Variables and thresholds	Eastern Baltic cod: Salinity > 11, Oxygen > 1.5 ml/L (annual average) Western Baltic cod and Kattegat cod: Salinity > 18, Depth >20 m
References	Bagge *et al.* (1994), Hüssy (2011), Hüssy *et al.* (2012), Hinrichsen *et al.* (2016)
Data quality	The Arkona deep is functional for spawning of both the Eastern and the Western Baltic cod and in effect, the definition of the Arkona Basin as a high probability areas in the Arkona Basin reflect the result for Eastern Baltic cod. The effective distribution of cod spawning areas is highly dependent on the prevailing hydrological regime, and the presence of spawning also depends on seasonally variable hydrographical conditions, such as temperature, salinity and oxygen. Seasonal differences lead to a progressive spawning season towards the east, typically starting in Kattegat and the Sound in January/February and ending in July/August in the Bornholm area. Fluctuations in temperature can delay the spawning season up to two months. It is difficult to collect egg samples to verify cod spawning, as cod eggs may drift in deep areas, and instead the level of ichthyoplankton is a main source for estimation of good environmental conditions for cod spawning. Modelling based on ichthyoplankton should be validated by comparison with distribution of running adults, to resolve the potential influence of prevailing current speed. The proposed delineations are also influenced by research on the maturity of adults and histology of gonads. The adult and juvenile cod are distributed far outside of the spawning areas depicted in the map. Attribute information: Raster value representing no spawning (0), potential spawning area (0.5) and high probability spawning area (1).

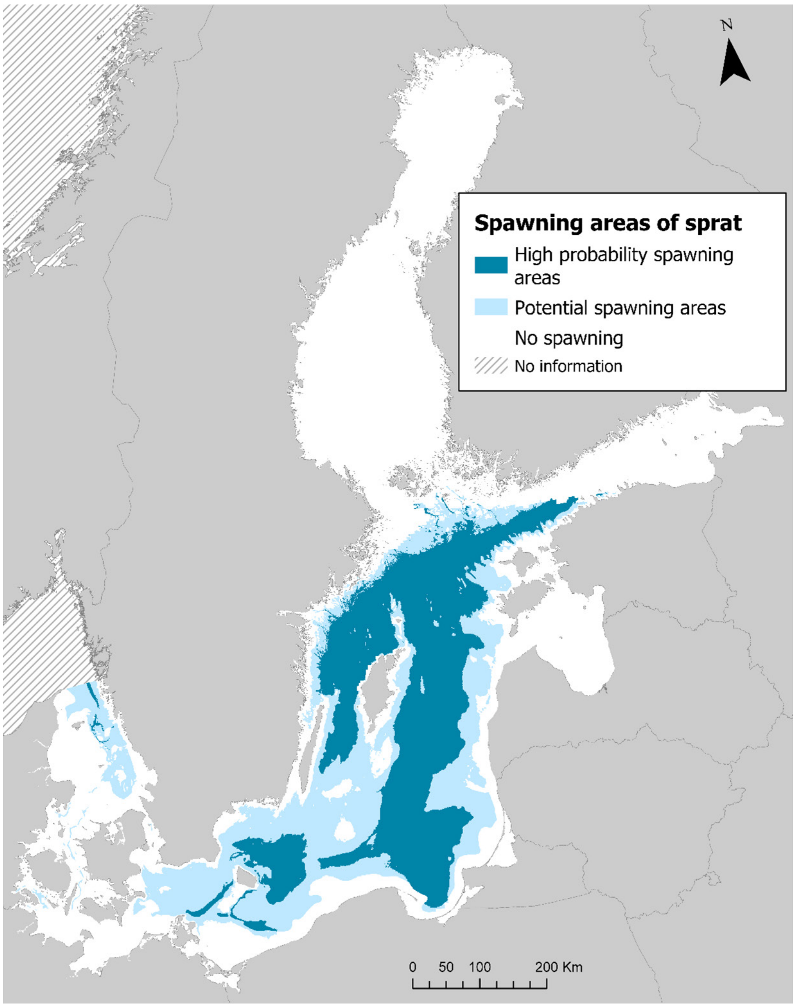

Figure 8. Potential spawning areas for sprat.

3.2. Potential spawning areas for sprat

Sprat (*Sprattus sprattus*) occurs in the entire Baltic Sea, and mainly in open sea areas. It is assessed as a single stock in the Baltic Sea within fisheries management. Sprat eggs are pelagic, and sprat spawning is well known from the deep basins in the central Baltic, where it typically occurs from February to August. Further north, spawning starts later in the year, and is less certain. Recent fisheries surveys indicate that sprat spawning does no longer occur in the Gulf of Finland. Sprat spawning areas were delineated using environmental variables due to lack of coherent field data across the Baltic Sea countries. "Potential sprat spawning areas" were delineated as areas with salinity > 6 and water depth > 30 m, but for the Arkona Basin depth > 20 m was used (Grauman, 1980, Bauman *et al.* 2006, Voss *et al.* 2012). "High probability spawning areas" were delineated for areas deeper than 70 m (Table 3, Figure 8).

Table 3. Data table for potential sprat spawning areas

Species	**Sprat *(Sprattus sprattus)***
Stocks	Sprat in subdivisions 22-32 (ICES)
EFH type	Potential spawning areas
Approach	Environmental envelope, corrected for areas 20-40 m south of Bornholm.
Time period	2011-2016
Data source	Depth: Baltic Sea Bathymetry database (http://data.bshc.pro/#2/51.8/20.1), complemented in some coastal areas with Seifert *et al.* (2001) Salinity: Copernicus Marine Environment Monitoring Service, SMHI. The data represents monthly data for years 2011-2016 downloaded from Copernicus Marine Environment Monitoring Service (http://marine.copernicus.eu). Reanalysis products of SMHI for years 1989-2004, 5.5km grid cells. The layers represent conditions at the sea floor. Extrapolation to some coastal areas that were outside the original data due to low resolution of the grid was carried out
Variables and thresholds	Potential spawning area: Depth > 30 m, Salinity > 6 (annual average) High probability spawning area: Depth >70 m, Salinity > 6 (annual average)
References	Grauman (1980), Bauman *et al.* (2006), Voss *et al.* (2012), HELCOM (2018a), National information from Poland
Data quality	The map is based on literature and environmental variables, not actual data on sprat spawning. The map might overestimate the spawning area west and north of Gotland. The data layers on environmental variables are based on modelling. Attribute information: Raster value representing no spawning (0), potential spawning area (0.5) and high probability spawning area (1).

3.3. Potential spawning areas for herring

Herring (*Clupea harengus*) is widely distributed in the Baltic Sea and is common in all sub-basins. Herring feeds in the pelagic, mainly on zooplankton, and is an important prey for cod, other fish, and marine mammals. In fisheries management, herring in the Baltic Sea is sub-divided into several stocks. Herring spawns in coastal areas or offshore shallows. It has demersal eggs, which are attached to the substrate. Spawning may occur both in spring and autumn, depending on population, but spring spawning dominates today. Spawning areas of herring were identified by main habitat associations, based on existing observations of herring spawning grounds in the Baltic Sea. 'Potential spawning areas' were delineated based on the distribution of any of the following: modelled photic zone, photic hard bottom, charophytes, Fucus spp, *Furcellaria lumbricalis*, and *Zostera marina*, several data layers were combined due to uncertainty in the coverage of some of them, 'High probability' spawning areas were identified as areas where the modelled photic zone overlaps with any of the other layers. The habitat variables were identified by other existing HELCOM data layers (Table 4, Figure 9).

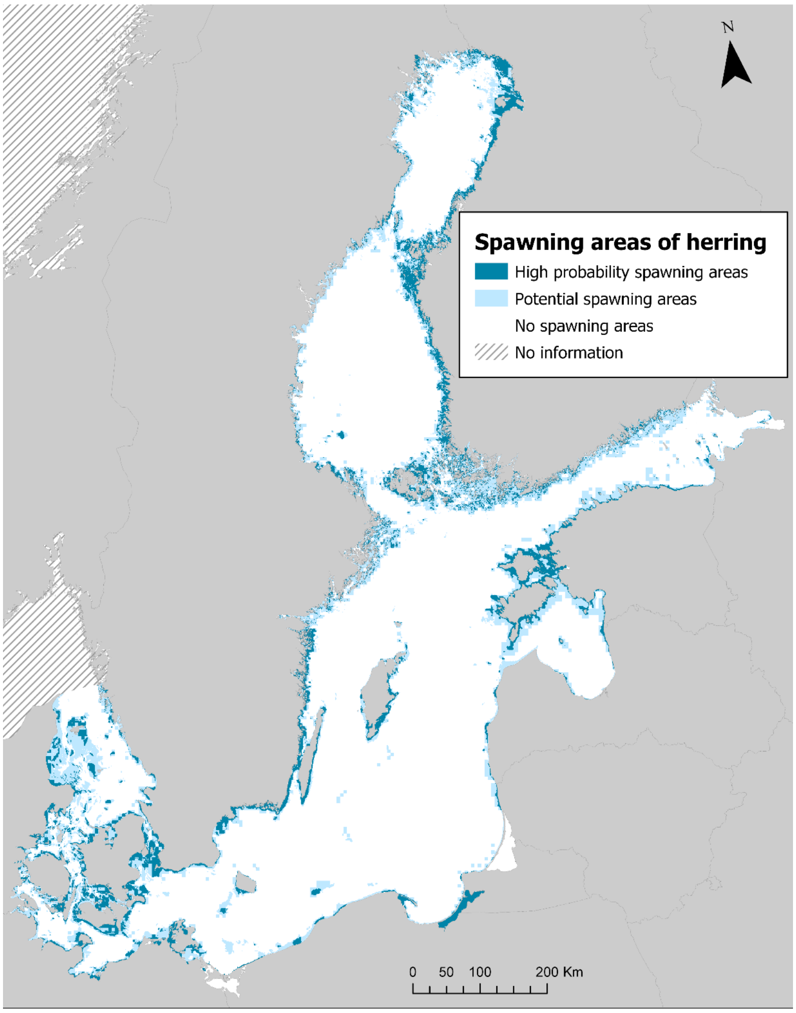

Figure 9. Potential spawning areas for herring.

Table 4. Data table for potential herring spawning areas

Species	**Herrring *(Clupea harengus)***
Stocks	Herring in ICES subdivisions 22-24 (spring spawning), subdivisions 25-27, 28.2, 29 and 32, subdivision 28.1 (Gulf of Riga), subdivisions 30-31.
EFH type	Spawning areas
Approach	Habitat associations combined with manual corrections to eastern Gulf of Finland (Neva inlet), Curonian lagoon, Szczechin lagoon, Vistula lagoon and German waters.
Time period	2011-2016
Data source	Photic zone: As produced within the EU Interreg IIIB project BALANCE (HELCOM 2018c). Seabed sediments – Photic hard bottom: Benthic biotope complexes in the Baltic Sea based on a combination of geological sediment data from the EU Interreg IIIB project BALANCE and light availability data from EUSeaMap (HELCOM 2018). Charophyte distribution: HOLAS II Dataset “Charophyte distribution” (HELCOM 2018d), representing the distribution of charophytes (Chara spp, Nitella spp, Nitellopsis spp, Tolypella spp) mainly based on data submission by HELCOM contracting parties. Submitted point data were originally gathered in national mapping and monitoring campaigns, or for scientific research. Scientific publications were used to complement the data for the Curonian, Vistula and Szczechin lagoons. Polygon data from Poland was digitized based on the Polish Marine Atlas. From Estonian waters, a predictive model was used (200m resolution), which was converted to presence/absence using minimized difference threshold criteria. All data (point, polygon and the raster presenting predicted presence of charophytes) were generalized to 5km x 5km grid cells. Fucus species’ distribution: HOLAS II Dataset “Fucus distribution” (HELCOM 2018d), based on data submission by HELCOM contracting parties. Mainly pointwise occurrences of Fucus were submitted, as originally gathered in national mapping and monitoring campaigns, or for scientific research. From Estonian waters, a predictive model was used (200m resolution), that was converted to presence/absence using minimized difference threshold criteria. All data (point, and the raster presenting predicted presence of Fucus) were generalized to 5km x 5km grid cells. *Furcellaria lumbricalis* distribution: HOLAS II Dataset “*Furcellaria lumbricalis* distribution” (HELCOM 2018d), based on data submission by HELCOM contracting parties. Mainly pointwise occurrences of Furcellaria were submitted, originally gathered in national mapping and monitoring campaigns, or for scientific research. From Estonian waters, a predictive model was used (200m resolution), that was converted to presence/absence using minimized difference threshold criteria. For Poland, only confirmed occurrence of Furcellaria was included (Slupsk bank, Rowy reef and reef at Orlowo cliff). All data (point, and the raster presenting predicted presence of Furcellaria) were generalized to 5km x 5km grid cells. *Zostera marina* distribution: HELCOM HOLAS II Dataset “*Zostera marina* distribution” (2018d). The data was based on data submission by HELCOM contracting parties. Mainly pointwise occurrences of eelgrass were submitted, originally gathered in national mapping and monitoring campaigns, or for scientific research. Polygon data from Puck Bay (Poland) was digitized based on Polish Marine Atlas and Orlowo cliff area was added based on expert knowledge. From Estonian waters, a predictive model was used (200m resolution), that was converted to presence/absence using minimized difference threshold criteria. All data (point, polygon and the raster presenting predicted presence of eelgrass in the Estonian waters) were generalized to 5km x 5km grid cells.
Variables and thresholds	Distribution of Photic zone, Photic hard bottom, Charophytes, Fucus spp., *Furcellaria lumbricalis*, *Zostera marina* The resulting data layer was corrected by removing recruitment areas in eastern Gulf of Finland (Neva inlet), Curonian lagoon, Szczechin lagoon and enhancing that of the Vistula lagoon.
References	HELCOM (2018c, 2018d), Kanstinger *et al.* (2018), Popiel (1984), Strzyżewska (1969), Fey (2001), Fey *et al.* (2014a, 2014b), Krasovskaya (2002).
Data quality	The data layer is mainly developed based on main habitat associations as identified from scientific literature, not actual data on herring spawning. The delineations are based on other data layers (benthic and habitat-related ecosystem components) for which mapping is not exhaustive and sampling density may vary between countries. Underlying data layers on vegetation (Fucus, Furcellaria, charophytes, Zostera) are based on inventory data and species distribution models. Information on the distribution of Furcellaria is lacking from Russia. Herring preferably spawns in shallow areas. However, the layer does not include depth as a variable, as some known spawning areas offshore would not be included if the depth restriction is used. Due to constraints in the resolution of the underlying data layer, the map also identifies areas shallower than one meter as potential spawning areas of Baltic herring. However, spawning of Baltic herring does not usually occur in such shallow depth. The map represents potential spawning areas. In addition, behavioral components and hydrographic factors influence on the actual chose of spawning site at a certain occasion. Due to these constraints, the data layer on Baltic herring spawning habitats should be considered as a rough estimation. Attribute information: Raster value representing no spawning (0), potential spawning area (0.5) and high probability spawning area (1).

3.4. Potential spawning areas for European flounder

European flounder (*Platichthys flesus*) is a key species in many coastal areas of the Baltic Sea, mainly in the central and southern sub-basins. Adults feed in shallow, coastal areas during summer and move out to deeper areas in winter, where the spawning takes place in spring. European flounder spawns above the sea floor in deep water, in areas with sufficiently high salinity for fertilization and pelagic egg development. 'Potential spawning areas' were initially delineated by a species distribution model (Orio *et al.* 2017) developed based on years 1993-1997 to consider a period with relatively better oxygen conditions, but applied with more recent data (2011-2014). The area was further delineated to encompass only areas deeper than 30 m in order to represent pelagic spawning habitat. 'High probability spawning areas' were identified as the sub-section encompassing salinity > 10. It should be noted that flounders in the Baltic Sea were recently separated into two species, and that spawning areas of the Baltic flounder (*Platichthys solemdali*) are described separately. The two data layers do not overlap and can be combined to obtain a map on spawning areas for both flounder species taken together (Table 5, Figure 10).

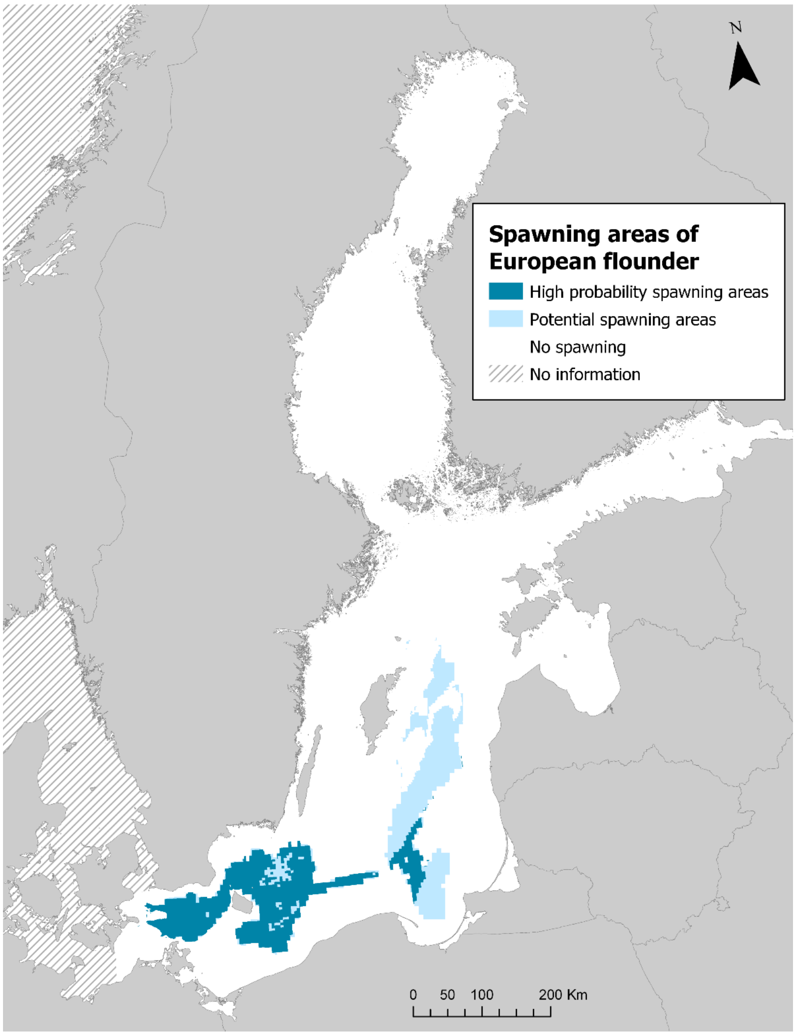

Figure 10. Potential spawning areas for European flounder.

Table 5. Data table for potential European flounder spawning areas

Species	European flounder *(Platichthys flesus)*
Stocks	ICES identifies two stocks of European flounder in the Baltic Sea: ICES subdivisions 22-23 (Belt Sea and the Sound), and 24-25 (West of Bornholm and Southern Central Baltic Sea).
EFH type	Spawning areas
Approach	Species distribution modelling combined with identification of environmental salinity window and depth conditions for spawning.
Time period	2011-2014
Data source	Model results from Orio *et al.* 2017a. Depth: Baltic Sea Bathymetry database (http://data.bshc.pro/#2/51.8/20.1) complemented in some coastal areas with IOW bathymetry data (Seifert *et al.* 2001). Salinity: Copernicus Marine Environment Monitoring Service, SMHI The data represents monthly data for years 2011-2014 downloaded from Copernicus Marine Environment Monitoring Service (http://marine.copernicus.eu). Reanalysis products of SMHI for years 1989-2004, 5.5km grid cells. The layers represent conditions at the sea floor. Extrapolation to some coastal areas that were outside the original data due to low resolution of the grid.
Variables and thresholds	Depth > 30 m Salinity > 10
References	Orio *et al.* (2017a), Momigliano *et al.* (2018), Nissling *et al.* (2002)
Data quality	The data layer is based on species distribution modelling focusing on mature flounder at the spawning stage and should be considered a rough estimation. The data layers on environmental variables are based on modelling. Other variables than those tested in the model may also be influential. The studies from which the thresholds values for environmental variables have been obtained are based on publications conducted before the separation of Baltic flounder from European flounder but have taken the specific characteristics of the separate spawning ecotypes into account. Note: the map on European flounder spawning areas is currently missing information for the western Baltic Sea including the Kattegat. Attribute information: Raster value representing no spawning (0), potential spawning area (0.5) and high probability spawning area (1).

3.5. Potential spawning areas for Baltic flounder

Baltic flounder (*Platichthys solemdali*) is a key species in many coastal areas of the Baltic Sea. It is the only endemic fish species of the Baltic Sea. Baltic flounder spawns in shallow coastal areas and on offshore banks, with eggs developing on the sea floor Successful spawning may be expected at salinities down to around 5-7 (Nissling *et al.* 2002). 'Potential spawning areas' were initially delineated by a species distribution model (Orio *et al.* 2017) developed based on years 1993-1997 to consider a period with relatively better oxygen conditions, but applied with more recent data (2011-2014). The area was further delineated to encompass only areas shallower than 30 m in order to represent the demersal spawning habitat. 'High probability spawning areas' were identified as the sub-section encompassing salinity > 6. It should be noted that flounders in the Baltic Sea were recently separated into two species, and that spawning areas of the European flounder (*Platichthys flesus*) are described separately. The two data layers do not overlap and can be combined to obtain a map on spawning areas for both flounder species taken together (Table 6, Figure 11).

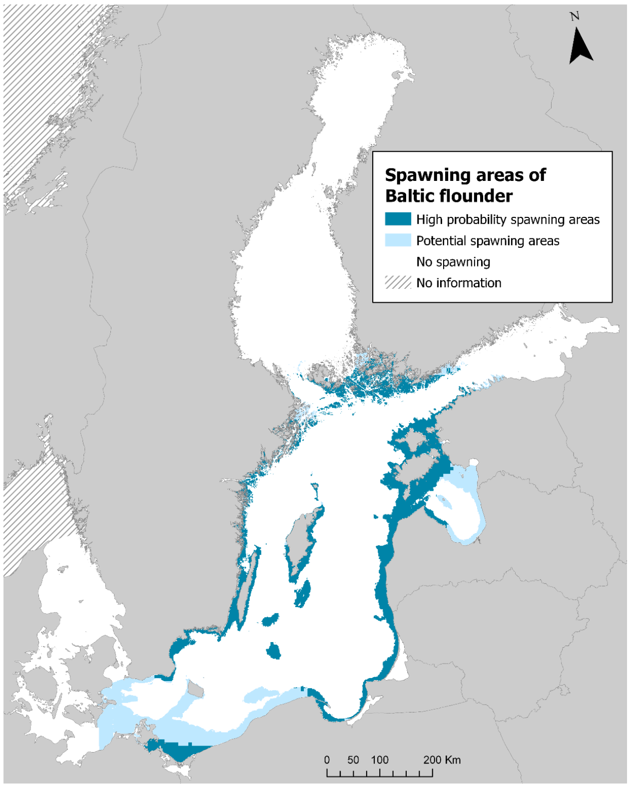

Figure 11. Potential spawning areas for Baltic flounder

Table 6. Data table for potential Baltic flounder spawning areas

Species	**Baltic flounder *(Platichthys solemdali)***
Stocks	ICES identifies two stocks of Baltic flounder: ICES subdivisions 26, 28 (East of Gotland and Gulf of Gdansk), and 27, 29-32 (Northern Central Baltic Sea and Northern Baltic Sea).
EFH type	Spawning areas
Approach	Species distribution modelling combined with identification of environmental salinity window and depth conditions for spawning, supplemented with additional information from monitoring in Estonian waters.
Time period	2011-2014
Data source	Model results from Orio *et al.* (2017a) Depth: Baltic Sea Bathymetry database (http://data.bshc.pro/#2/51.8/20.1) complemented in some coastal areas with IOW bathymetry data (Seifert *et al.* 2001). Salinity: Copernicus Marine Environment Monitoring Service, SMHI. The data represents monthly means of May for years 2011-2014 (http://marine.copernicus.eu). Reanalysis products of SMHI for years 1989-2004, 5.5km grid cells. The layers represent conditions at the sea floor. Extrapolation to some coastal areas that were outside the original data due to low resolution of the grid.
Variables and thresholds	Depth < 30 m Salinity > 6
References	Orio *et al.* (2017), Momigliano *et al.* (2018), Nissling *et al.* (2002)
Data quality	The data layer is based on species distribution modelling focusing on mature flounder at the spawning stage and should be considered a rough estimation. The data layers on environmental variables are based on modelling. Other variables than those tested in the model may also be influential. The studies from which the thresholds values for environmental variables have been obtained are based on publications conducted before the separation of Baltic flounder from European flounder but have taken the specific characteristics of the separate spawning ecotypes into account. Attribute information: Raster value representing no spawning (0), potential spawning area (0.5) and high probability spawning area (1).

3.6. Potential nursery areas for flounders

The two flounder species in the Baltic Sea (*Platichthys flesus* and *P. solemdali*) have different reproductive strategies, spawning in the pelagic and in shallow waters, respectively. However, they utilize the same type nursery habitat. For both species, young of the year are found on shallow bottoms from June to September, primarily on sandy substrates. Flounder nursery areas were predicted by a generalized additive model with flounder abundance as response variable and seven map-based predictor variables. The model was based on data from available surveys of juvenile flounder in the Baltic Sea, compiled within the Pan Baltic Scope project. To represent the nursery season and the current situation, only results from surveys performed in June-September during 2004-2018 were used, resulting in totally 2,114 samples. All abundance estimates were harmonized to numbers of juvenile flounder per square meter. Values for the predictor variables were extracted for each sampling point in GIS. The following environmental variables were used: salinity, wave exposure, water depth, slope of the bottom, surface temperature, bottom currents, and distance to high probability spawning area for European flounder (Table 7, Figure 12).

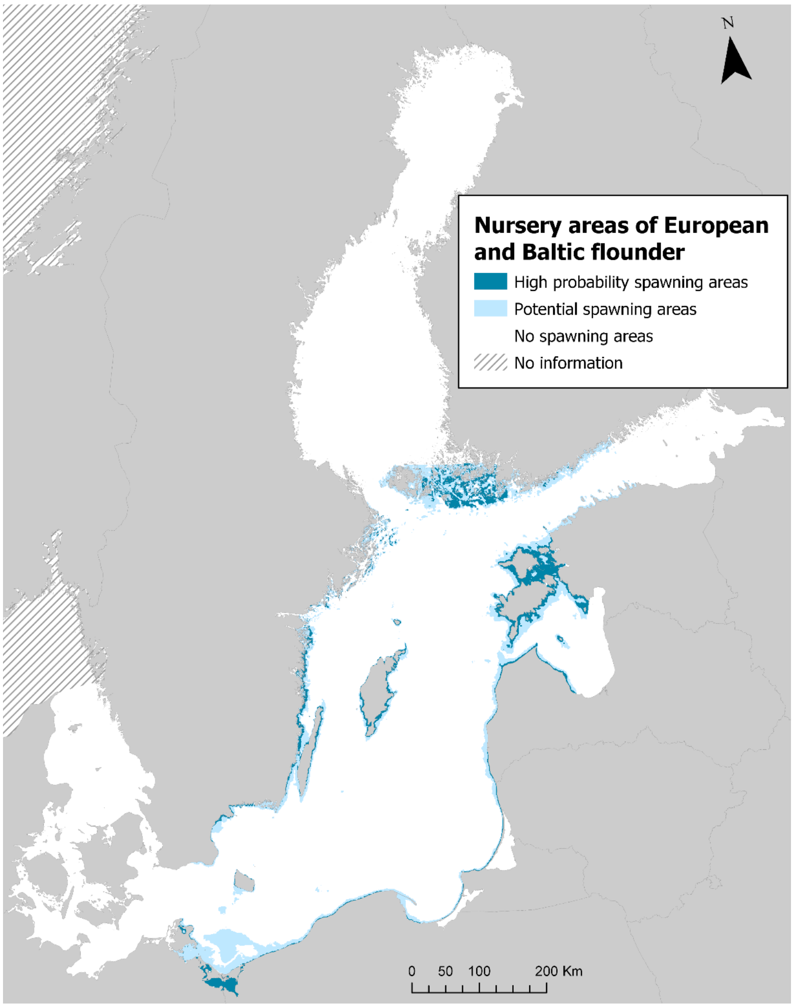

Figure 12. Potential nursery areas for European and Baltic flounder.

Table 7. Data table for potential flounder nursery areas

Species	**Baltic flounder *(Platichthys solemdali)* and European flounder *(Platichthys flesus)***
Stock	Baltic flounder: ICES subdivisions 26, 28 (East of Gotland and Gulf of Gdansk), and 27, 29-32 (Northern Central Baltic Sea and Northern Baltic Sea). European flounder: ICES subdivisions 22-23 (Belt Sea and the Sound), and 24-25 (West of Bornholm and Southern Central Baltic Sea).
EFH type	Nursery areas
Approach	Species distribution modelling
Time period	2004-2018
Data source	Model results as described in Chapter 2 of this report Salinity: Monthly means in March-May from 2014-2016 for salinity at the seafloor. within a 600 m radius from the sampling point. Extracted from the hydrodynamic Baltic Sea Ice-Ocean Model (BSIOM, Lehmann *et al.* 2002). Wave exposure: Log transformed wave impact index calculated for the whole Baltic Sea (Isæus 2004). Depth: Mean water depth within a 600 m radius from sampling point according to the Baltic Sea Bathymetry database (http://data.bshc.pro/#2/51.8/20.1). Slope: Mean slope within a 600 m radius from sampling point, based on data produced within the EU Interreg IIIB project BALANCE (HELCOM 2018). Surface temperature: Monthly means of June-September for years 2016-2018 downloaded from Copernicus Marine Environment Monitoring Service (http://marine.copernicus.eu). The data is from the HBM model produced by the Danish Meteorological Institute (DMI, http://ocean.dmi.dk/models/hbm.uk.php). Bottom currents: Mean bottom current velocity within a 600 m radius from sampling point, based on data produced within the EU Interreg IIIB project BALANCE (HELCOM 2018). Distance to high probability spawning area for European flounder: as shown in section 3.4 of this report.
Variables and thresholds	High probability nursery areas represent areas with a predicted abundance > 0.03 juvenile flounder/m² based on the applied data sets and model. Potential nursery areas represent predicted abundance levels between 0,0001 and 0,03 juvenile flounder/m². Areas with a predicted abundance < 0.0001 juvenile flounders/m² are defined as not being flounder nursery areas.
Reference	This report, chapter 2
Data quality	Data on juvenile flounder abundances to support the spatial model is missing from Denmark, Germany, Poland and Russia. Predictions are uncertain in these areas, and especially along the south coast of the Baltic Sea. The mix of data from different years, months and gear types may have contributed to increasing the variability in the dataset, even though a relatively high deviance explained by the model (41%) shows that it has predictive power. The spatial resolution of the predictor variables varies between 200 m and 2 km, which gives coarse predictions locally even though values are representative at an overall regional scale. The prediction is limited by a lack of accurate spatial information on surface sediments. Sandy substrates are well known as important flounder nursery habitats. Unfortunately, the only available sediment map on a Baltic Sea wide scale was too inaccurate for shallow waters where juvenile flounder occurs and was therefore excluded from the model. The map on flounder nursery areas does not make assumptions on species identity in any area. Attribute information: Raster value representing no nursery area (0), potential nursery area (0.5) and high probability nursery area (1).

3.7. Potential recruitment areas for perch

Perch (*Perca fluviatilis*) is a key species in many Baltic coastal areas. It is of freshwater origin and spawns predominantly in freshwater tributaries, close to the coastline, or in enclosed bays. Species distribution modelling have shown the importance of suitable environmental conditions for perch reproduction. Young perch has limited dispersal from its spawning area, and tagging studies have shown that most (50-95 % of the recaptures of perch are made up to 20 km from tagging site in the Baltic Sea (Johnsson 1978, Böhling and Lehtonen 1985, Veneranta *et al.* 2020, Saks *et al.* 2020). Due to lack of coherent data on perch spawning and nursery areas across the Baltic Sea countries, environmental variables were used in delineating potential recruitment areas for perch. The map was originally developed within the HOLAS II project (HELCOM 2018b) when it was approved by all HELCOM Contracting Parties in a dedicated review process. Potential perch recruitment areas were delineated as areas with suitable condition of depth, wave exposure and salinity. Thresholds were obtained from literature, and selected to rather overestimate than underestimate the recruitment area. For the Finnish coastline, a national model was used. The map was subsequently considered by the Pan Baltic Scope project, who proposed adjustments to thresholds for some areas in Russian waters, and corrections to Estonian and German waters (Table 8, Figure 13).

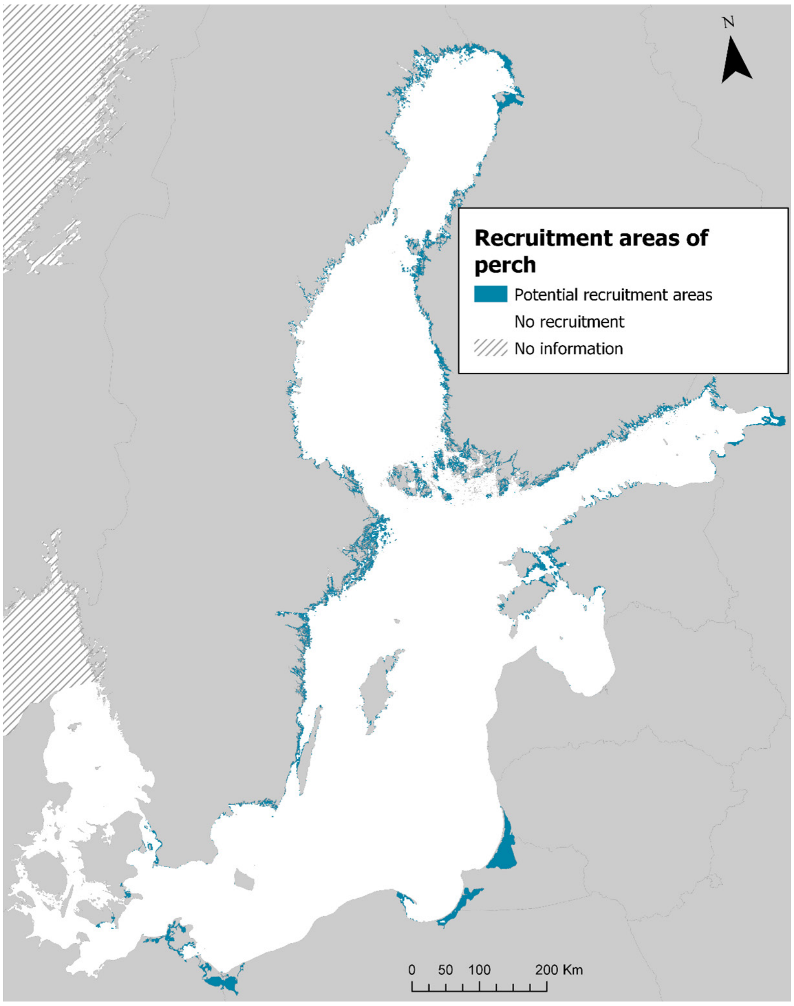

Figure 13. Potential recruitment areas for perch

Table 8. Data table for potential perch recruitment areas

Species	**Perch *(Perca fluviatilis)***
Stock	Several, undefined
EFH type	Recruitment areas
Approach	Environmental window, national modelling approach in Finnish waters, supplemented with corrections to Estonian, German and Russian waters based on national validation with monitoring data.
Time period	2011-2014
Data sources	Depth: Baltic Sea Bathymetry database (http://data.bshc.pro/#2/51.8/20.1), complemented in some coastal areas with IOW bathymetry data (Seifert *et al.* 2001). Wave exposure: Wave Impact Index calculated for the whole Baltic Sea (Isæus 2004). Salinity: Monthly means of May for years 2011-2014 downloaded from Copernicus Marine Environment Monitoring Service (http://marine.copernicus.eu). Reanalysis products of SMHI for years 1989-2004, 5.5km grid cells. A May mean for 2011-2014 was calculated. Extrapolation to some coastal areas that were outside the original data due to low resolution of the grid. National model for Finnish waters generalized to 1x1 km grid (Kallasvuo *et al.* 2017).
Variables and thresholds	Depth < 4 m (for Danish waters < 3 m), Logged exposure < 5 (For Koporo Bay and Narva Bay in Russian waters < 5.23) Salinity < 10. Based on the model for the Finnish coastline, perch recruitment areas were defined as: Unsuitable for reproduction: P(catch larvae) < 0.5, Suitable for reproduction: P(catch larvae) > 0.5, Important for reproduction: the smallest area where the expected cumulative larval abundance is 80% of the total expected abundance over study area.
References	Snickars *et al.* (2010), Bergström *et al.* (2013), Skovrind *et al.* (2013), Sundblad *et al.* (2014), Kallasvuo *et al.* (2017), HELCOM (2018a), this report
Comments and data quality	Recruitment area here refers to essential habitats for young of the year perch (based on inventory data from spawning until the end of the first summer). The map is based on literature and environmental variables, derived from inventory data. The species distribution modelling studies, where the thresholds values for environmental variables have been obtained, are from the northern Baltic Sea. Here, the same thresholds have been applied in the southern Baltic. Also, the data layers on environmental variables are based on modelling. Due to these constraints, the data layer should be considered as a rough estimation. Attribute information: Raster value representing the potential occurrence of perch recruitment area (either 0 or 1).

3.8. Potential recruitment areas for pikeperch

Pikeperch (*Sander lucioperca*) is a species of freshwater origin, which spawns predominantly in freshwater tributaries and has a relatively limited dispersal away from its recruitment area. Species distribution modelling studies have shown the importance of suitable environmental conditions for pikeperch recruitment. Due to lack of coherent data on pikeperch spawning and nursery areas across the Baltic Sea countries, the distribution of pikeperch recruitment areas was delineated based on areas with suitable conditions of depth, wave exposure, salinity, water transparency (Secchi depth) and distance to deeper (10 m) waters. The threshold values were obtained from literature. Temperature, although important for pikeperch, was left out due to high variation in timing of suitable spawning temperatures across the Baltic Sea. The map on pikeperch recruitment areas was originally developed within the HOLAS II project (HELCOM 2018b) when it was approved by all HELCOM Contracting Parties in a dedicated review process after correction to Swedish waters. The map was subsequently considered by the Pan Baltic Scope project, who proposed adjustments to Estonian, German, Lithuanian and Polish waters (Table 9, Figure 14).

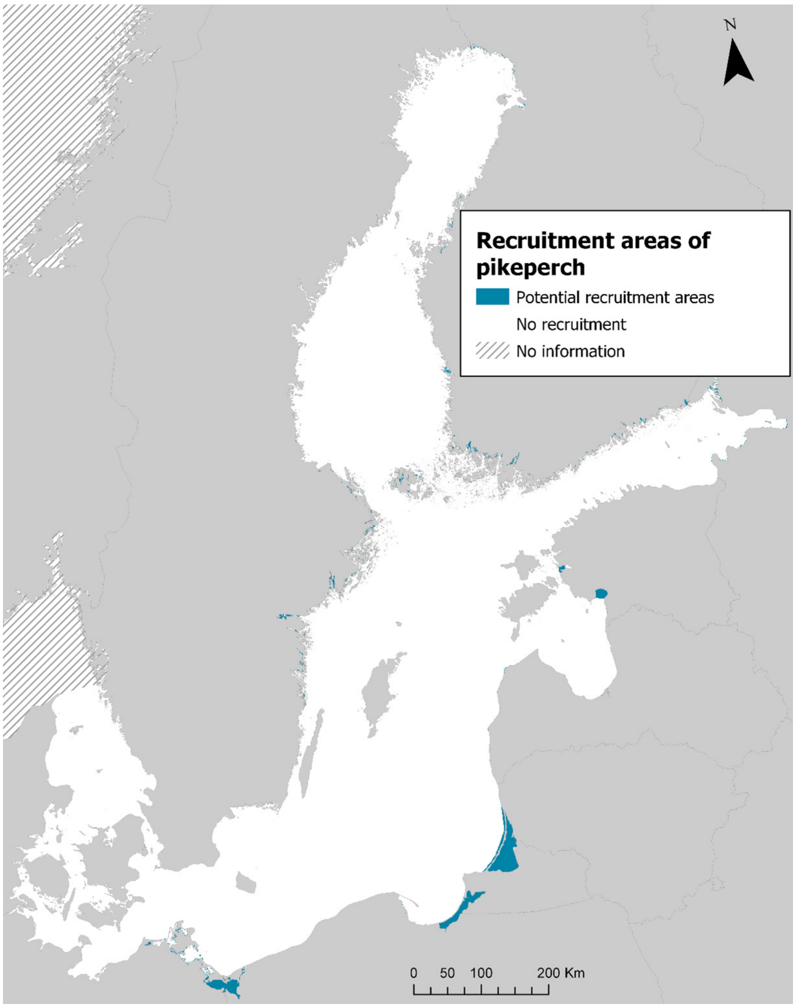

Figure 14. Potential recruitment areas of pikeperch.

Table 9. Data table for potential pikeperch recruitment areas

Species	**Pikeperch *(Sander lucioperca)***
Stock	Several, undefined
EFH type	Recruitment areas
Approach	Environmental window with national approach for Finnish waters, selected data points corrected for Estonian, German, Lithuanian, Polish, and Swedish waters.
Time period	2011-2014
Data source	Depth: Baltic Sea Bathymetry database (http://data.bshc.pro/#2/51.8/20.1), complemented in some coastal areas with IOW bathymetry data (Seifert *et al.* 2001). Wave exposure: Wave Impact Index calculated for the whole Baltic Sea (Isæus 2004). Salinity: Monthly means of May for years 2011-2014 downloaded from Copernicus Marine Environment Monitoring Service (http://marine.copernicus.eu). Reanalysis products of SMHI for years 1989-2004, 5.5km grid cells. A May mean for 2011-2014 was calculated. Extrapolation to some coastal areas that were outside the original data due to low resolution of the grid. Secchi depth: Satellite based (MERIS) composite layer of May 2011, kindly provided by Krista Alikas at Tartu Observatory, Estonia (Alikas and Kratzer 2017). National model for Finnish waters generalized to 1x1 km grid (Kallasvuo *et al.* 2017).
Variables and thresholds	Depth < 5 m, Logged exposure < 5 Salinity < 7 Secchi depth < 2 Distance to deep (10m) water < 4km. Based on the model for the Finnish coastline, pikeperch recruitment areas were defined as: Unsuitable for reproduction: P(catch larvae) < 0.5, Suitable for reproduction: P(catch larvae) > 0.5, Important for reproduction: the smallest area where the expected cumulative larval abundance is 80% of the total expected abundance over study area.
References	Veneranta *et al.* (2011), Bergström *et al.* (2013), Sundblad *et al.* (2014), Kallasvuo *et al.* (2017), Gunnartz *et al.* (2011), (HELCOM 2018b), this report
Comments and data quality	Recruitment area here refers to essential habitats for young of the year pikeperch (based on inventory data from spawning until the end of the first summer). The map is based on literature and environmental variables, derived from inventory data. The species distribution modelling studies, where the thresholds values for environmental variables have been obtained, are from the northern Baltic Sea. Also, the data layers on environmental variables are based on modelling. Here, same thresholds have been applied in the southern Baltic. Due to these constraints, the data layer should be considered as a rough estimation. In addition, temperature is important for pikeperch recruitment but was not included as a delineating variable due to high variation in timing. The data layer may underestimate pikeperch in Finnish waters with respect to habitats for young of the year pikeperch, as it focused on newly-hatched larvae when the dispersal is more limited compared to later in the season. Attribute information: Raster value representing the potential occurrence of pikeperch reproduction area (either 0 or 1).

3.9. Aggregated map

Figure 15 shows an aggregated map in which all data layers presented in figures 7-14 are added to each other with equal weight to each layer. The data layer on flounder nursery areas (Figure 12) is only included where it does not overlap with spawning areas for European flounder or Baltic flounder (Figures 10-11), in order to not double-count habitats for the same species.

The aggregated map has a maximum value of four, which occurs in some coastal areas where spawning/recruitment areas for herring, Baltic flounder, perch, and pikeperch overlap. In addition, the importance of deep areas of the southern Baltic Sea for spawning of cod, sprat, and European flounder is clearly seen.

As the aggregate map (Figure 15) is limited to the available data layers, it is not completely representative of the region. The most evident gaps occur West of the Arkona Basin, for example information on spawning areas of European flounder is missing from these areas. Importantly, several other species are also relevant West of the Arkona Basin, but are not included in this report, for example sole (*Solea solea*), but also turbot (*Scophthalmus maximus*) and plaice (*Pleuronectes platessa*). This information should be added in order for the aggregated map to be relevant also for this area (See also Chapter 4 for a discussion on this).

In the coastal zone generally, a delineation of nursery areas for cod is missing but would be important for a more complete picture. The possibility to develop such as map was considered by HELCOM (2018a) but was not considered feasible at the Baltic Sea scale based on available data at the time.

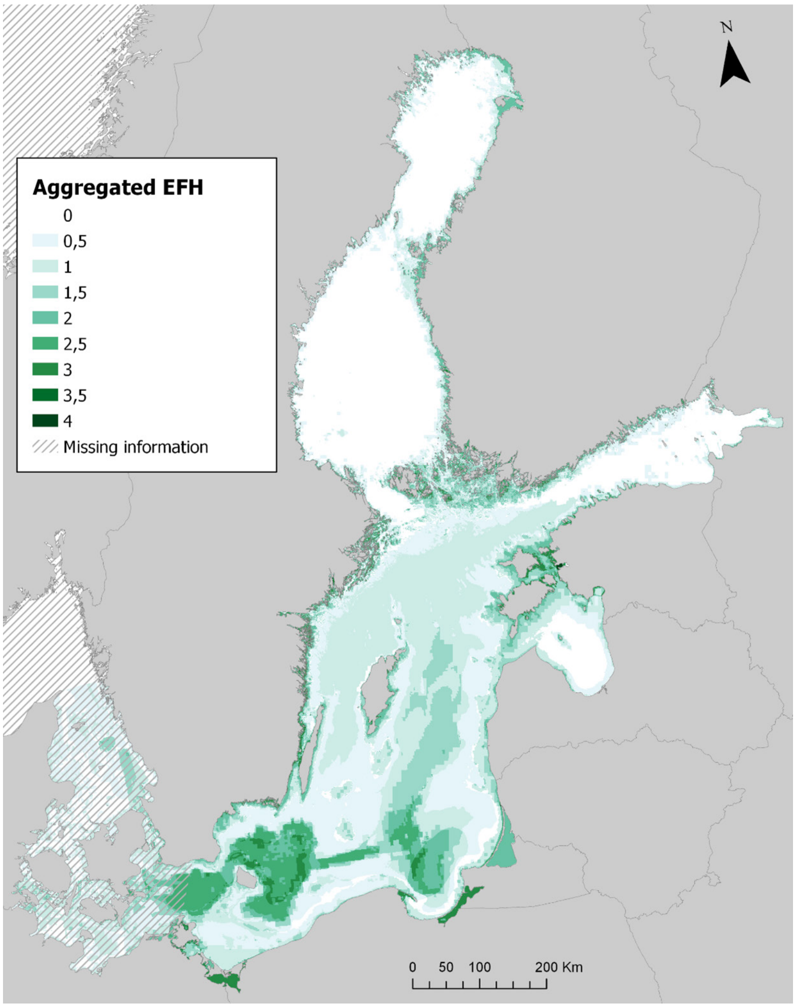

Figure 15. Aggregate essential fish habitat map with data layers for the seven different species (Figures 7-14) stacked on top of each other. The data layer on flounder nursery areas is only included where it does not overlap with any of the layers on flounder spawning areas, in order to not double-count results for the same species. However, it should be noted that the aggregated map is not representative for essential fish habitats in the whole Baltic Sea area, as information on some additionally important species and life stages are still missing. Most importantly, information on spawning areas of European flounder is lacking West of the Arkona Basin. Also, information on sole which would be relevant for this areas is missing. Kattegat holds essential fish habitats for several species that are not included here. Uncertainties in relation to each of the included data layers are presented in tables 2-9.

4. Discussion

4.1. Potential uses of the maps – MSP, environmental management and green infrastructure

Spatial information on distribution of species and habitats is important to support various aspects of marine management. It is needed for example in maritime spatial planning (MSP), where national plans have to ensure that ecosystem considerations the potential vulnerability of species and habitats to pressures from human activities are taken into account (e.g. EC 2014, Kraufvelin *et al.* 2018). Maps on the distribution of species and habitats are also used in spatial assessment of cumulative impacts (HELCOM 2018d, Bergström *et al.* 2019). These maps are important for identifying areas that are subject to high levels of pressures and may need priority in conservation or environmental management actions. This report contributes to these needs by identifying areas of potential key importance for fish.

The maps which are presented here have also been initially included in a suggested approach for mapping green infrastructure in the Baltic Sea, developed within the Pan Baltic Scope project (Ruskule *et al.* 2019). Green infrastructure is still an emerging concept, especially in marine environments, but is seen as a promising tool to support ecosystem-based management and spatial planning (See for example Liquete *et al.* 2015). The purpose is to help identify areas which are essential for ensuring the resilience of the marine ecosystem and the delivery of a wide range of ecosystem services, hence contributing to human well-being. In MSP, green infrastructure can identify structures of ecological importance from a landscape perspective which might not be included in networks of legally protected areas, hence highlighting additional aspects of importance.

Ruskule *et al.* (2019) suggested a matrix approach for identifying ecosystem components of key importance for ecosystem services and ecological value. The approach also encompassed the maps on essential fish habitats presented here (see also Bergström *et al.* 2019, Miloš and Bergström 2019). However, further efforts are needed to complete the work, especially in the area of developing spatial data of adequate quality (Ruskule *et al.* 2019). Also, the work developed so far is focused on essential habitats, but does not consider feeding areas, migration corridors or aspects of connectivity among populations, which are other important component of green infrastructure, both on land and at sea (Liquete *et al.* 2015).

Some further development needs, specifically with respect to essential fish habitats, are presented below.

4.2. Suggestions for the further development of the essential fish habitats concept

This report presents maps on selected potential spawning, recruitment and nursery areas for seven fish species in the Baltic Sea. Hence, the maps show information for a subset of all species that are actually present and are focused on selected life stages. Our general inventory of data availability (Chapter 2) showed that data to support the mapping of spawning, recruitment and nursery areas for fish in the Baltic Sea has been greatly improved by recent national and joint Baltic projects, but that sufficient data is still lacking for many parts of the Baltic Sea and selected species. In particular, coastal areas lack data. The maps presented here represent the best available information at a coherent Baltic Sea regional scale at their time of development. A recommended long-term aim would be to obtain regional maps on relevant essential fish habitats for all widely distributed fish species in the Baltic Sea, considering at least spawning and nursery areas.

To give a fuller representation of essential fish habitats one should especially include more information for species in coastal areas and in the western Baltic Sea. One should also consider additional life stages for some of the included species, since both spawning, nursery, feeding and migration areas are potential essential fish habitats. The availability and quality of juvenile feeding areas may be particularly important, as they directly influence juvenile growth and survival, and thereby the level of recruitment to adult populations.

Some information on juvenile (and adult) habitats is already available for the Baltic Sea regions, but was not considered developed enough to form the basis of maps at the regional scale. However, the possibilities to model important areas for juvenile cod should be considered as a next step. In addition, accounting for the spatio-temporal dynamics of essential fish habitats would be of relevance, as many fish are highly dependent on prevailing temperature, oxygen and salinity regimes (see for example Hinrichsen *et al.* 2017a). With respect to species additions, it would be particularly important to include maps on sole and on other flatfishes with respect to the distribution of spawning areas of these west of the Arkona Basin. Furthermore, once habitats of different life-history stages for any given species have been adequately mapped, the degree of connectivity between them is also of key importance (Brown *et al.* 2019). Knowledge on migration between essential fish habitats will help to identify potential population sinks and sources, increasing the relevant information available to planners and decision makers.

A novelty in this report was possible due to the fact that flounder of the Baltic Sea was recently separated into two distinct species, with Baltic flounder being identified as endemic to the region. Even though the presence of two distinct flounder species was only recently documented (Momigliano *et al.* 2017), the presence of types of flounder in the Baltic Sea has been long known to research (e.g. Solemdal 1967, Nissling *et al.* 2002). Based on information from previous studies on ecotypic differences between the different types of flounder, and based on recommendations from experts on flounder ecology in the region, separate maps for potential spawning areas of European and Baltic flounders were developed (Figures 10-11). The main difference between the species is the genetics and the reproductive characteristics, such as spawning behavior and morphological and functional differences in the eggs and sperm. As the two species are morphologically similar, their nursery areas could not be separated, and the map of flounder nursery areas is representative of both flounder species taken together. There is currently no evidence that the nursery area characteristics would differ between the two species, nor reason to expect this. The main environmental variable contributing to the potential of an area for being a nursery for either Baltic or European flounder is the larval supply, which is related to the level of connectivity between a potential nursery and the spawning area. The effective connectivity again is affected by distance and transport mediating currents. A suggestion how to combine information for the different flounder maps, if this is wanted, was presented in Section 3.9.

4.3. Data quality aspects

The maps were developed based on indirect or modelling approaches, since direct inventory data was not available in a comparable way across the region for any of the species. Over time, it would be important to enhance the base of knowledge and data that the maps are based on, hence to improve their quality, reliability and utility. It should be appreciated that the maps are in most cases a rough representation that enables comparisons at the relatively coarse, regional scale. If the maps are applied at the national or local scale they would benefit from being complemented with more detailed information, when available. The quality aspects for each of the separate maps is presented in Chapter 3.

We foresee that modelling approaches will continue to be important for producing large scale spatial information, but emphasize that inventory data from mapping efforts are still key, both for building such models and for validating them. To support the development, better mechanistic understanding on the required environmental conditions for certain life stages is also of high importance, as well the availability and quality of spatial data on important environmental variables, such as salinity and depth. While important across the range of the Baltic, many very coastal areas suffer from a lack of fish monitoring effort, which is required to inform these distribution models and reduce their uncertainty. Another common aspect is that for all maps that use hydrological model output, these estimates are quite inaccurate close to the coast. This becomes very important when considering a very coastal habitat such as for example juvenile flatfish and herring spawning.

For particular species, the lack of direct inventory data on herring spawning was a restriction to providing more detailed maps on herring spawning areas. It would also be important to resolve present uncertainties in the distribution of spawning areas of sprat towards the northern Baltic Sea. With respect to environmental variables, the mapping is additionally challenged by the fact that spawning of many species is strongly influenced by temperature, which varies between years and is tightly coupled to climate change.

4.4. Implications for application

The presented maps are referred to as “potential habitats” as they are generally based on indirect information, rather than on actual observations to verify that the habitat is actually functional and to what level. As a general way to account for data restrictions in their spatial delineation, Planque *et al.* (2007) classified fish habitats into potential habitats, realized habitats and effective habitats. By their definitions, “potential habitats” include areas were water masses or substrates can uphold a particular function during a particular life stage or period of time (for example based on known environmental constraints), as opposed to “realized habitats” which have proven to actually inhabit the fish during that life stage (for example based on sampling showing that fish eggs are present). Last, “effective habitats” are those areas which are seen to support the highest densities or have the highest relative contribution to the population.

Comparing the different maps presented in this report, the maps which are based on spatial distribution models are likely more accurate, in the sense that they are closer to the concept of realized habitats, compared to those which are developed based on environmental envelopes. One way to further evaluate the maps of “potential” essential fish habitats, would be to compare them systematically with corresponding information on “realized habitats”, where available. Such an evaluation could help identify to what extent they represent functional habitats and to what extent they represent habitats that are suitable according to natural environmental conditions, but may not be functional due to other factors, such as impacts of human activity or poor connectivity. It would also be important to generally move from maps based on environmental envelopes to maps based on statistical models.

In some further applications of the maps, for example if they are used to resolve spatial uses, the concept of “effective habitats” may be more useful as it can more precisely identify areas of currently highest value for fish and/or fisheries. On the other hand, the concept of “potential uses” may be more adequate to identify areas where measures to reduce pressure may be needed. Focusing on only “effective habitats” could bring the risk that in a degraded environment, only those few habitats left are addressed or protected, while improving an already poor situation would require the reestablishment also of other potential habitats to eventually become effective ones.

4.5. How to consider future changes

Fish populations are often highly dynamic. Most evidently, their spawning success and individual growth are often tightly coupled to variability in climate-related factors, such as temperature and salinity, and these factors may also influence on the suitability of potential essential fish habitats over different seasons and years (see for example Hinrichsen *et al.* 2017a). In addition, human pressures such as overfishing, physical modification of habitats, and elevated oxygen consumption related to eutrophication lead to changes over time in both the quality of fish habitats and the size of populations that can make use of these. A key area for future development is to develop a stronger understanding on how the current distribution of functional essential fish habitat is affected by human activities and how to improve management in these situations. These needs are even more emphasized by climate change, which is expected to have dramatic influence on the distribution of fish and fish habitats in the future.

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