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Review

Which factors can affect the productivity and dynamics of cod stocks in the Baltic Sea, Kattegat and Skagerrak?

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ABSTRACT

Stocks of Atlantic cod (*Gadus morhua*) in the Baltic Sea, Kattegat and Skagerrak (N. Europe) have been strongly exploited for decades bringing them into an enduringly depleted status. Scientific cod stock related advice for targeted and mixed fisheries is provided on an annual basis by the International Council for Exploration of the Sea. This advice forms a basis for ministerial decisions on, e.g., the total allowable catch and management plans. Despite measures to reduce fishing-induced mortality of cod, such as catch and effort restrictions, increased gear selectivity, closed areas and seasons, clear signs of recovery are yet to be seen. Thus, traditional advice for the management of these stocks may have to be complemented by advice on supporting measures focusing on other pressures hampering the recovery of cod. The present study elaborates on potential supportive measures for cod stock recovery in the Baltic Sea, Kattegat, and Skagerrak (including local populations where applicable), based on current knowledge. The list of measures presented here is the outcome of in-depth discussions on the state-of-the-art knowledge, among cod experts and further with stakeholders with the aim to follow principles of ecosystem-based fisheries management. Following the identification of different pressures on and prerequisites for the separate stocks, the listed measures differ between stocks and include cod bycatch mortality reduction, alterations in fisheries affecting food sources for cod, restocking, protection of juvenile habitats, and reduced predation. The literature review and the list of measures are intended to provide decision-support for managers and policymakers aiming to provide conditions for the cod stocks to recover.

1. Introduction

Many stocks of Atlantic cod (*Gadus morhua*) are in poor condition after collapses in several parts of the northern Atlantic and nearby regional seas (Rose, 2019; Sguotti et al., 2019). The Baltic and North Seas (N. Europe; Fig. 1) are no exceptions. Apart from the northernmost parts of the non-tidal estuarine Baltic Sea, cod exert, or used to exert, a central structuring function in these systems (BACC, 2015; Silberberger et al., 2018). Having been fished for human consumption since the earliest colonisation of the region (Sörgard, 2019), the cod grew in societal importance during and following the industrial revolution (Ask and Svedäng, 2019). Abundance and consequently landings were particularly large in the 1970s and 1980s, followed by a sharp decline with respect to all stocks (Ask and Svedäng, 2019).

The International Council for the Exploration of the Sea (ICES) provides advice on cod stocks and divides the study area into subdivisions (SDs). There are genetically differentiated cod stocks in the North Sea and the adjacent Baltic Sea (Barth et al., 2017, 2019, Fig. 1). These are 1) the North Sea stock, also covering the Skagerrak (Subarea 4; SD20 in Fig. 1; ICES, 2021a), 2) local coastal stocks in the Skagerrak (SD20; Barth et al., 2017), 3) the Kattegat stock (SD21; ICES, 2021b), 4) the Western Baltic stock (in SD22-24 of the Baltic Sea west of Bornholm,

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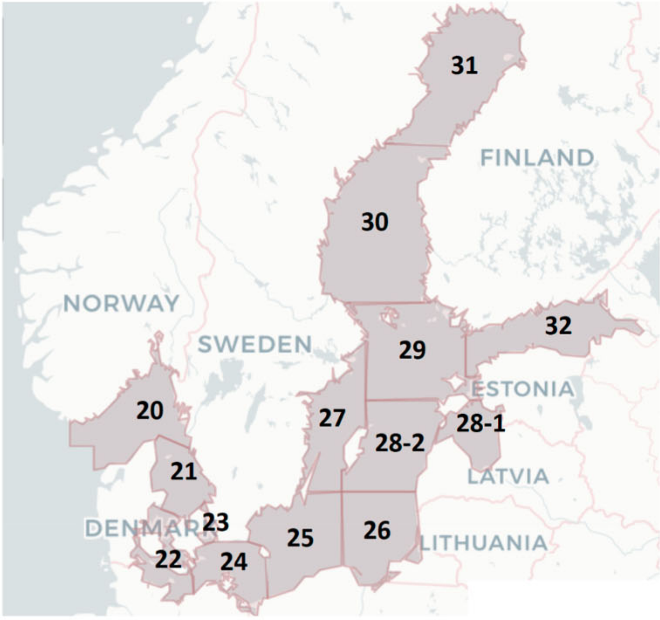

Fig. 1. The study area: the eastern North Sea and the Baltic Sea, divided into ICES subdivisions (SDs). SD20: The Skagerrak. SD21: The Kattegat. SD 22–32: The Baltic Sea. Base map: www.openstreetmaps.org (Open Data Commons Open Database License).

including the Danish straits and the Sound; i.e., Öresund; ICES, 2021c), and 5) the Eastern Baltic stock (in the Baltic Sea, mainly east of Bornholm but also west of it; SD25-32 in Fig. 1; ICES, 2021d).

All these stocks have during previous decades been quite heavily exploited or even overfished, and subsequently, targeted cod fishing either has become prohibited, or has been sharply restrained based on advice from ICES (2021a, b, c, d). Restrictions have mainly concerned limitations of fishing opportunities and various technical measures, and the science and management response has often been "too little, too late" (see e.g., Cardinale et al., 2017). Following these measures, only temporary signs of recovery of some stocks have been seen (see ICES, 2021a, c). Spawning stock biomasses (SSBs) have remained lower, or much lower, than management targets allowing a maximum sustainable yield and often below limits indicating increased risk of recruitment failure (B_{lim}). .

Fisheries recovery plans may fail due to environmental drivers underpinning stock dynamics. Variability in ecosystem processes is rarely included in fisheries management (Skern-Mauritzen et al., 2016). Bentley et al. (2020) showed that failure to account for ecosystem information may lead to suboptimal fisheries management and that there is a need to include ecosystem information to support fisheries advice. Excluding environmentally driven changes in fisheries production could reduce future fisheries yields (Halpern et al., 2015; Gaines et al., 2018). There is growing focus in science, management and policy on implementation of ecosystem-based fisheries management (EBFM; Pikitch et al., 2004; Weijerman et al., 2021; Karnauskas et al., 2021), recognising the need for a holistic approach. One of the main principles of EBFM is adaptive management (Long et al., 2015) and current cod management needs to become more adaptive. Only controlling targeted fishing for the cod stocks in the Baltic and North Seas is not enough since several other factors in addition to fisheries also affect cod stocks and may in some cases be even more important for shaping stock dynamics than targeted fishing (Mérillet et al., 2020).

The Swedish government recently assigned its responsible authority (the Swedish Agency for Marine and Water Management, SwAM) to propose measures for cod stock conservation and recovery, in addition to those intended to limit directed cod fishing. The current study was performed as a commission from SwAM based on this governmental assignment.

This study aims to give an overview of the most important environmental pressures on, and anthropogenic threats to, cod stocks in the Baltic Sea, Kattegat and Skagerrak. Based on this overview and following holistic principles of EBFM (Long et al., 2015), we elaborate advice including other measures than those that regulate the targeted cod fisheries, potentially promoting recruitment and lowering mortality rates of cod.

2. Historical and current stock status

Local stocks, or spawning components, were historically present and productive along the coast and in the Skagerrak fjords (SD20) but many have been severely depleted since the 1980s–1990s (Svedäng, 2003; Svedäng and Bardon, 2003). Despite gradually increasing regulations to reduce fishing mortality since 2003 (Sköld et al., 2011), these stocks still occur in very low abundances, and mature cod is rarely caught in scientific surveys along the Swedish Skagerrak coast (Svedäng et al., 2019). Spawners are still present, as evidenced by local production of eggs, however, in comparatively low abundances (Svensson et al., 2019). This might indicate slow recovery but also that the stock has an impaired reproductive capacity (Svedäng et al., 2019).

The historically important and large North Sea cod stock, which also extends into the Skagerrak (SD20) and northern Kattegat (SD21), has declined since World War II (Bartolino et al., 2012), but with indicated signs of recovery following reduced fishing mortality up until 2015. However, since then, fishing mortality has increased again, and this stock is now assessed as being harvested unsustainably and is at risk of having reduced reproductive capacity (ICES 2021a).

Like the North Sea stock, the formerly productive Kattegat stock has declined since World War II (Bartolino et al., 2012). The SSB of cod in the Kattegat (SD21) is currently very low in a historical sense, with the lowest values of SSB estimated for 2020, prompting ICES to again recommend zero catch in 2021 (ICES, 2021b). There is no targeted cod fishing in the Kattegat since several years back; all catches consist of bycatches (ICES, 2021b).

The Western Baltic cod stock (SD22-24) is also in a long-term decline. Although fishing mortality has decreased since year 2000, it has been above reference points (F_{MSY}) since 1985. The SSB has decreased and has been below reference points ($MSY_{Btrigger}$) since about 2007 (ICES, 2021c). The targeted fishery is currently closed.

Finally, the Eastern Baltic cod SSB (SD25-32) peaked strongly around 1980, after which it collapsed and is now below reference values (B_{lim}; ICES, 2021d). Fishing mortality has also decreased sharply (ICES, 2021d) and the EU fishing quota has not been fully used since 2007, coinciding with widespread reduction in body condition and growth (Casini et al., 2016a). The SSBs of the four latter stocks are provided in Fig. 2.

3. Environmental factors affecting cod populations

3.1. Eutrophication and hypoxia

Eutrophication stimulates phytoplankton production, and when dead phytoplankton (particulate organic matter) decompose, oxygen is consumed, whereby hypoxia or anoxia can occur due to incomplete or absent mixing of the water column and to the scarce inflow of oxygen-rich, highly saline waters from the Kattegat (Major Baltic Inflows). Eutrophication may initially have benefited cod and other fish species in the Baltic Sea in the 20th century by increasing productivity and thereby increasing food supply for fish (Thurow, 1997). However, currently, hypoxia and several other (see below) adverse eutrophication effects on cod stocks dominate over positive effects. Hypoxia or anoxia is occasionally or permanently found in many parts of the Baltic and North Seas but it is currently particularly harmful for cod in the Baltic Proper, where such strongly stratified water layers overlap with Eastern Baltic

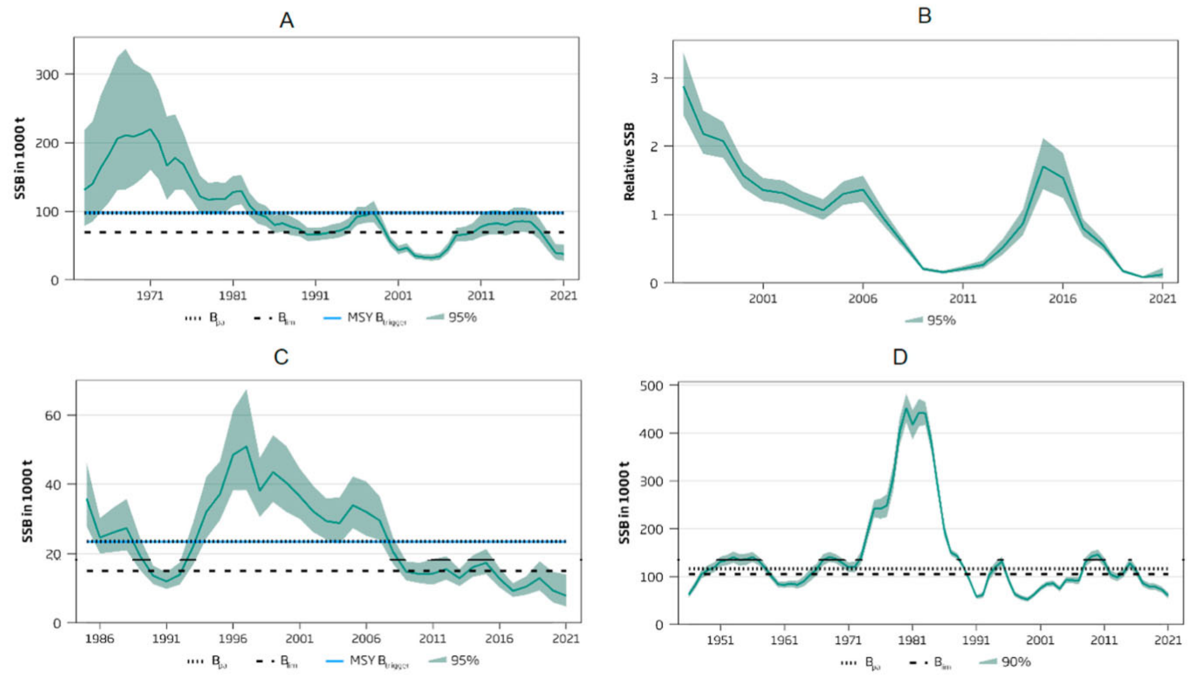

Fig. 2. Spawning stock biomasses (SSB) in the study area. ICES estimates for periods available from the most recent model simulations. Please note that these periods differ between stocks. A. SSB in the North Sea, eastern English Channel and Skagerrak. B. Relative SSB in Kattegat. C. SSB in subdivisions 22–24 (mainly Western Baltic cod). D. SSB of Eastern Baltic cod. B_{lim}, B_{PA} and MSY $B_{trigger}$ are biomass limit values used in fish stock assessment. Images from ICES (2022), Creative Commons (CC BY 4.0) license.

cod habitats. Eutrophication is the primary cause of hypoxia in this area, although climate change may have exacerbated hypoxia (Meier et al., 2019). The Kattegat used to have widespread problems with hypoxia in the 1980s but the eutrophication situation there has improved since then (HELCOM, 2018). Hypoxia decreases the reproduction success of cod (von Dewitz, 2018; Limburg and Casini, 2019; Murray et al., 2019; Köppen and Reckermann, 2020), and impairs its growth and condition either directly affecting its physiology or indirectly affecting its benthic prey availability (Casini et al., 2016a, 2021; Limburg and Casini, 2019; Rose, 2019; Brander, 2020; Neuenfeldt et al., 2020). In addition, hypoxia constrains the extent of suitable habitat, forcing cod to dwell in more restricted areas leading to increased densities and increased overlap with competing species such as flounder (Casini et al., 2016a; Orio et al., 2019). Moreover, eutrophication and increased growth of planktonic and epiphytic algae have caused declines in canopy-forming species, such as eelgrass (*Zostera marina*) and brown algae (Baden et al., 2003; Moy and Christie, 2012; Boström et al., 2014; Filbee-Dexter and Wernberg, 2018). These habitat-forming species are important for cod in its growing juvenile stages, especially on the coast in the Sound, Kattegat and Skagerrak (Ljungberg, 2013) which receives anthropogenic nutrients through enriched water from the Baltic as well as from local sources (Håkanson and Bryhn, 2011). Nutrient emissions to the Baltic peaked in the 1980s and have now been brought back to 1950s levels in a regionally coordinated effort to combat eutrophication and associated hypoxia (HELCOM, 2018). The regional Baltic Sea Action Plan is to decrease emissions even further, but due to large previous emissions, the long water residence time, strong stratification and intensive sediment-water interactions, eutrophication related problems in the Baltic Sea are likely to persist for decades to centuries even with very ambitious abatement schemes (Murray et al., 2019).

3.2. Algal toxins

Algae, bacteria, sponges, etc., are known to produce chemical compounds with toxic properties. As the species distribution differs between regions, various toxins may be of importance regarding effects on fish health. In the Baltic Sea, cyanotoxin nodularin and polybrominated phenols such as tribromophenols (TBPs), hydroxyl- and methoxylated polybrominated diphenyl ethers (OH/MeO-PBDEs) and polybrominated dibenzodioxins (PBDDs) are omnipresent in the Baltic food web with concentrations of TBPs and OH/MeO-PBDEs measured in herring increasing significantly since the 1980s (Faxneld et al., 2014). Nodularin, TBPs and OH/MeO-PBDEs and PBDDs have toxic properties that include neurotoxic, cytotoxic and genotoxic effects in fish (see Lindqvist, 2016 and references therein, Ohta et al., 1994; Persson et al., 2009; Pearson et al., 2010). In addition, these toxins have potential to reduce the function of the energy metabolism via their potential to cause oxidative stress (Chen et al., 2020) and disturb the oxidative phosphorylation (Legradi et al., 2014). Elevated levels of hydroxylated polybrominated diphenyl ether (e.g., 6-OH-BDE 47) have been reported from commercially harvested cod from the Baltic Sea (Roszko et al., 2015) and nodularin has been detected in liver from cod sampled in the southern Baltic Sea (ICES subdivision 24, site 5) *(*Sipiä et al., 2001*)*. Both historical events as well as experimental studies show how cod, and particularly cod larvae, can be sensitive to algal toxins produced in the Skagerrak/Kattegat region (Granéli et al., 1989; Aanesen et al., 1998). Yet, studies on measured levels of algal toxins in cod are scarce and further studies are needed to assess the impact of algal toxins on cod health.

Fast growing filamentous algae and cyanobacteria, known producers of algal toxins, are favoured by eutrophication in the Baltic Sea (Håkanson and Bryhn, 2011). In addition, nodularin as well as brominated phenols are induced by environmental stress such as alterations in salinity and light exposure (Dahlgren et al., 2015). Thus, actions to reduce effects of eutrophication in the Baltic Sea is likely a crucial task in efforts to reduce harmful effects of exposure to algal toxins on cod.

3.3. Climate change

The most important climate effects for cod are temperature increases and possible salinity decreases (Saraiva et al., 2019). Temperature increases due to climate change tend to affect all Atlantic cod stocks negatively, since cod is a marine coldwater species (Rose, 2019). Other probable effects of increasing temperatures are faster growth at younger stages (Neuheimer and Grønkjær, 2012) and potentially a decreased asymptotic body size of older individuals (Lindmark, 2020) which may impact the reproductive potential of stocks.

The biomass of cod stocks generally has a negative correlation with temperature, partly because the preferred zooplankton for cod larvae is generally negatively affected by temperature increases (Rose, 2019). In the Baltic Sea, however, changes in salinity affecting zooplankton species composition may have been a more important climate related factor than temperature in explaining impaired cod larval feeding in the past (Köster et al., 2005; Möllmann et al., 2008). Higher water temperatures in the Baltic Sea instead appear to have benefited zooplankton consumed by European sprat (*Sprattus sprattus*) larvae and adults (Nissling, 2004; MacKenzie and Köster, 2004), thereby inducing higher sprat predation on cod eggs (Köster and Möllmann, 2000; Möllmann, 2019; Soudijn et al., 2021).

Furthermore, increases in water temperature may reduce habitat accessibility, as these become less beneficial for juvenile cod (Ljungberg, 2013; Dinesen et al., 2019). In the Baltic Sea, climate change may also increase freshwater runoff and thereby decrease salinity, although future projections regarding salinity are quite uncertain (Saraiva et al., 2019). Likewise, an ensemble modelling study by Gröger et al. (2019) projected a freshening of southern Skagerrak. A possible salinity decrease could limit food availability for cod in planktivorous stages and impair salinity and oxygen conditions for cod reproduction and recruitment (BACC, 2015; Orio, 2019). Moreover, climate-induced ocean acidification may overall be harmful for cod recruitment (Stiasny et al., 2019). The available long-term model scenarios of cod stock states include the risk that cod may disappear completely from the Baltic Sea during the current century, as an effect of climate driven recruitment failure (Lindegren et al., 2010; Rose, 2019). Measures to reduce greenhouse gas emissions driving climate change are being taken in many countries, but global targets only include reductions in global warming (IPCC, 2018), which would thus not improve conditions for the studied cod stocks but rather only decrease their degradation rates.

3.4. Lack of suitable recruitment habitat

Cod uses different habitats in different life stages. During its juvenile stages, important habitats for cod are complex three-dimensional structures consisting of eelgrass and macroalgal beds, biogenic reefs, rocks and boulders (Borg et al., 1997; Lindholm et al., 1999; Lilley and Unsworth, 2014; Funk et al., 2020). These habitats, in particular eelgrass meadows, are in turn negatively affected by coastal construction of jetties, harbours and marinas, in addition to eutrophication and other human activities (Boström et al., 2014; Eriander et al., 2017; Bryhn et al., 2020). In the Baltic Sea, where spawning takes place in deep areas and where juveniles are also found deeper than in the Kattegat and Skagerrak (Nielsen et al., 2013), these habitats are negatively affected by hypoxia (Casini et al., 2016a; Neuenfeldt et al., 2020) and bottom trawling (van Denderen et al., 2020).

3.5. Bottom trawling - seafloor impact

Physical disturbance of the seafloor by bottom trawling reduces benthic biomass (Hiddink et al., 2017) and resuspends particulate sediment matter (e.g., Bradshaw et al., 2012). This may indirectly affect cod by reduced abundance of food (in terms of benthic organism biomass) and suspended particulate matter that can scare away adults and juveniles (Humborstad et al., 2006), and harm or kill eggs and larvae (Westerberg et al., 1996). Decreased abundance of benthic food is accentuated in the Baltic Sea where cod and benthic fauna are also negatively affected by hypoxia (van Denderen et al., 2020). Noise, which is produced by the fishing activity may also disturb communication in connection to spawning activity and thereby influence mating decisions and reproduction success (Rowe and Hutchings, 2006). Sediment resuspension due to bottom trawling could be critical in semi-enclosed and stratified, intensively trawled areas where coastal cod spawns, e. g., the Koster and Gullmar Fjords (Linders et al., 2018). In the Baltic Sea. cod eggs have neutral buoyancy within a narrow range of salinities and a lower limit at 11 PSU (Nissling and Westin, 1997; MacKenzie et al., 2000; Hinrichsen et al., 2016). Egg abundance is often highest around the halocline, and successful development is limited to waters with oxygen concentrations >2 ml O_2/l (Nissling et al., 1994). The volume of water mass with potential for reproduction of cod is found between approximately 50 and 70 m depth (Wieland et al., 1994). As the depth of trawl fisheries in the Baltic coincides with the reproductive volume of cod, a reduction of the impact on the seafloor from bottom trawling has the potential to mitigate increased exposure of suspended particulate matter to eggs and larvae, and negative effects on food availability.

3.6. Food deficiency and starvation

The condition of Eastern Baltic cod has deteriorated significantly, and individual growth has been reduced during the past 20 years (Casini et al., 2016a, 2021; Bergenius et al., 2018; Mion et al., 2020), including signs of starvation to death (Casini et al., 2016b; Neuenfeldt et al., 2020). Although fatal starvation occurs naturally in all cod stocks (Regular et al., 2022), it seems to be particularly common within this stock. The decline in growth is a major reason why large individuals are nowadays rare in the stock (Mion et al., 2021). Poor condition and a stock size distribution dominated by small fish also negatively affects reproduction (Mion et al., 2018) contributing to explaining the low recruitment. However, poor condition and reduced growth has not been reported for the other cod stocks considered in this study.

One crucial food source for eastern Baltic cod that has decreased in the diet is the benthic isopod *Saduria entomon* (Neuenfeldt et al., 2020), which is also consumed by increasing numbers of European flounder (*Platichthys flesus*; Casini and Orio, 2019; Haase et al., 2020; Orio et al., 2020). One possible option to strengthen this cod stock could therefore be to increase the fishing effort for flounder in the area, if this can be done with minimal bycatches of cod. Some new selective gear options have already been developed and tested for this purpose (Nilsson et al., 2018; ICES 2019c).

Another important food source, which has also decreased in the diet of larger cod from the Eastern Baltic stock, is sprat (Neuenfeldt et al., 2020). This decrease probably depends on changes in the geographical distribution of sprat towards the northern Baltic Sea where there is currently virtually no cod, and that sprat abundance has decreased in the present main distribution area of Eastern Baltic cod in the southern Baltic (Eero et al., 2012; Casini et al., 2016a; Neuenfeldt et al., 2020).

Small-scale artificial feeding of captive cod using herring as fodder is currently being tested in the Baltic Proper as a way of reconditioning cod to increase its individual condition and growth. Preliminary results have indicated ceased starvation and rapid growth; i.e., weight of cod in captivity has increased in extreme cases by up to 150% in approximately 2 months (M. Boström, pers. obs.). More large-scale feeding has been tried successfully in Icelandic waters (Björnsson, 2011; Björnsson et al., 2018). Although artificial feeding addresses symptoms of starvation and not its causes, artificial feeding may nevertheless provide valuable insights into natural feeding deficiency problems and is potentially a means of raising the survival rate of the fed fish.

3.7. Parasites

Cod can have many different types of parasites, and during recent decades, roundworms (*Nematoda*) have increased in prevalence, particularly in the Baltic Proper. The liver worm *Contracaecum osculatum* has increased in both prevalence and degree of infection and cod with more infection generally have a deteriorated condition (Horbowy et al., 2016; Mehrdana et al., 2014; Ryberg et al., 2020). A recent study also identified reduced standard metabolic rate, reduction in digestive organ masses, changes in the blood plasma, body and liver, composition and fish energy source, with liver worm infection. Based on findings of reduced albumin and globulin, the study concluded that highly infected cod suffers from a chronic liver disease (Ryberg et al., 2020). A cod in good condition may host many parasites in their liver, but if the liver is in a bad condition and the cod has many liver worms per liver gram (approx. 6–8 liver worms/gram liver) cod will not grow even under favourable feeding conditions (Lunneryd et al., 2022). With food limitation, a high infection level most probably accelerates the deleterious effect. Parasite transmission and infection intensity also depends on temperature (Bowen, 1990; Palm, 1999). The increase in parasite prevalence has coincided with an increase in marine mammal abundance, particularly grey seal (*Halichoerus grypus*; Mehrdana et al., 2014). However, altering the number of mammals does not necessarily change parasite infestation in a straightforward way, possibly depending on the variety of other parasite hosts than mammals and cod (Aspholm et al., 1995; Lunneryd et al., 2015).

3.8. Thiamine deficiency

Thiamine (vitamin B_1) deficiency is a state in which this essential vitamin is not abundant enough to sustain life-maintaining functions in an organism. In marine systems, primarily bacteria and phytoplankton produce thiamine and larger organisms such as cod obtain thiamine through feeding (Sañudo-Wilhelmy et al., 2014). Thiamine deficiency can lead to a range of detrimental physical conditions, including diseases, lethargy, and death (see Balk et al., 2016 and references therein). Thiamine deficiency has been detected in several organisms from, e.g., the Laurentian Great Lakes and the southern parts of the Baltic Sea (Harder et al., 2018). A recent study showed severe thiamine deficiency in individuals from the Eastern Baltic cod stock (Engelhardt et al., 2020). Climate change and other anthropogenic stressors have been put forward as important factors affecting thiamine fluxes in the Baltic Sea (Ejsmond et al., 2019; Majaneva et al., 2020). From the perspective of the Baltic Sea, understanding of mechanisms behind the development of thiamine deficiency is essential in future research (Hylander et al., 2020). Before driving mechanisms have been identified, the problem with thiamine deficiency cannot be resolved by other means than artificially adding thiamine to cod.

3.9. Chemical pollutants including pharmaceuticals

As a top predator in a heavily polluted sea, Baltic cod have a predominance for accumulating chemical pollutants, and biomarker response suggests that contaminant levels are causing biological effects (Schnell et al., 2008). Levels of chemical pollutants of anthropogenic origin such as dioxin-like polychlorinated biphenyls (dl-PCB, PCB-118) in cod liver exceeds threshold levels in several areas of the Baltic Sea (HELCOM, 2010). In the area southeast of Gotland, concentrations of a brominated flame retardant (HBCDD), mercury and arsenic (Danielsson et al., 2020) as well as several perfluoroalkyl acids (PFAS; Schultes et al., 2020) are increasing in cod. In the Kattegat, concentrations of metals in cod are generally higher than in the Baltic. Moreover, levels of specific polycyclic aromatic hydrocarbons (PAHs) in biota appear to be exceptionally high during the last years compared to the Baltic (Danielsson et al., 2020) with a possible (only measured in blue mussels) negative effect on cod health. Coastal areas seem to be more exposed to pollutants compared to offshore areas (Björlenius et al., 2018). The spatial variations in the biomarker response as well as in contamination loads suggest differences in physiologically active concentrations and mixtures of organic contaminants.

Muscle tissue and brain from cod have been found to contain a wide range of pharmaceuticals such as psychotrophic drugs, anti-epileptics, contraceptives, antibiotics, and antihistamines (Joakim Hjelm, pers. obs.) Many of these have previously been shown to induce behavioral changes in fish (Brodin et al., 2013; Hellström et al., 2016; Sundin et al., 2019; Saaristo et al., 2019).

Chemical body burden and biological effects in cod need further investigation in order to provide any recommendations on means to reduce any possible deteriorating effects of chemical exposure on cod. Hence, a more comprehensive monitoring and analysis of chemical pollutants and pharmaceuticals could provide a better picture of how widespread this exposure is, primarily of offshore stocks but also through monitoring of coastal populations (where for example drug exposure is likely to be higher), and the role these chemicals play in poor cod reproduction.

Actions to reduce emissions of chemical pollutants in the marine environment include several conventions, regulations, directives and legislations concerning chemicals and pollutants, such as the Helsinki Convention (HELCOM), the Oslo Paris Convention (OSPAR), the Water Framework Directive (EC, 2008a) and the Marine Strategy Framework Directive (EC, 2008b).

3.10. Predation by mammals, birds and fish

Populations of grey seal (*Halichoerus grypus*), harbour seal (*Phoca vitulina*), harbour porpoise (*Phocoena phocoena*) and great cormorant (*Phalacrocorax carbo*) are top predators that have the potential to consume large quantities of fish, including cod (Hansson et al., 2017; Andreasen et al., 2017). Cormorants were virtually extirpated in the beginning of the 20th century (Engström, 2001). The populations of seals were reduced substantially due to intensive hunting in the first half of the 20th century and further reduced to very low numbers due to physiological effects caused by environmental pollutants, in the 1970s (Heide-Jørgensen and Härkönen, 1988; Hårding and Härkönen, 1999). Following conservation measures, the distribution and population sizes of seals and cormorants have increased substantially during recent decades, both in the Kattegat-Skagerrak and the Baltic Sea regions (Bregnballe et al., 2014; ICES, 2019b). Harbour porpoise is rare in the Baltic Sea, but in the Kattegat-Skagerrak area, the population has increased in numbers during the last decades following a population decline during the 20th century (Reijnders, 1992; Hammond et al., 2017).

Predation is part of complex food-web interactions in which predator preferences of both prey specis and length, as well as behaviour and spatio-temporal overlaps of predators and prey may produce direct and indirect effects such as trophic cascades (Frank et al., 2005). In general, indirect interactions are more numerous, and food webs are characterised by both top-down and bottom-up forcing (Estes et al., 2013). There is a lack of knowledge on the current contribution of cod to the mentioned top predators in different parts of the study area. Thus, impacts of top predators on different cod stocks and the relative impact of predation to other sources of natural cod mortality is not fully known.

The growing seal populations in the Baltic Sea, Kattegat and Skagerrak are likely to consume large quantities of cod (Hansson et al., 2017; ICES, 2017). In the Baltic Sea, cod stocks increased in size following the drastic decline in seal populations and environmental changes in the 20th century (Thurow, 1997; Hansson et al., 2007; Österblom et al., 2007). Similar correlations have not been documented in the Kattegat-Skagerrak area, where the populations of harbour seals decreased dramatically in size due to phocine distemper virus outbreaks in 1988 and 2002 (Härkönen et al., 2006; Bartolino et al., 2012). Nevertheless, there are a few studies showing that cod is an important prey species for seals, cormorants and porpoises, and that predator populations have potential for substantial removal of cod in the Baltic and Kattegat-Skagerrak regions (Ovegård et al., 2016; ICES, 2017; Hansson et al., 2017; Eero et al., 2019). Previous results from assessments of the impact of grey seals on cod in the Baltic Sea concluded that the predation effects were small in comparison to impact from fisheries and environmental changes, and that the grey seal population on its own was uncapable of preventing a recovery of the cod stock (Hansson et al., 2007; MacKenzie et al., 2011). However, during the past 10 years since these studies were carried out, the seal populations have increased dramatically, while the productivity of the Eastern Baltic stock has declined due to the substantially impaired growth rates. In the Skagerrak, the harbour seal population has shown early signals of density dependence of restrained somatic growth as a consequence of nutritional stress. This indicates that this top predator has an impact on the ecosystem and vice versa (Hårding et al., 2018). Some studies from the northern Atlantic indicate that seals have a crucial role in preventing recovery of depleted cod stocks (Benoit m.fl., 2011; Hammill et al., 2014; Cook et al., 2015; Trijoulet et al., 2018; Aarts et al., 2019; Neuenhoff et al., 2019), whereas other studies suggest limited impact of seals on cod stocks (Trzcinski et al., 2006; Alexander et al., 2015; Houle et al., 2016; Baudron et al., 2019).

The grey seal preference regarding prey size can have a profound impact on natural mortality. O'Boyle and Sinclair (2012) made an extensive literature review on the feeding habits of grey seal, including the prey size composition. Even though the review indicated that grey seal prefers small cod (average 35 cm length), the size composition varied greatly between locations and years. O'Boyle and Sinclair (2012) concluded that seals eat what is available and small cod are more abundant. Furthermore, when seals consume large cod, they do not consume the head and therefore, otoliths from larger individuals may be underrepresented in seal scat analysis (O'Boyle and Sinclair (2012); Neuenhoff et al., 2019. However, recent studies from the Southern Baltic have showed that grey seals prefer cod of 55–65 cm length (Eero et al., 2019).

In addition to predation from marine mammals and seabirds, clupeids are major predators on cod eggs and larvae in the Baltic Sea (Köster and Möllmann, 2000; Soudijn et al., 2021). The abundance of clupeids, sprat in particular, has increased substantially in the Baltic Sea since the 1980s (ICES, 2021e). Thus, while sprat serves as an important food source for cod there (Neuenfeldt et al., 2020), it may concurrently constrain its reproductive success.

3.11. Bycatch

Targeted fisheries for cod still exist in the North Sea/Skagerrak. For the other cod stocks in this study, bycatch of cod in fisheries targeting other species nowadays has a greater impact than the fishing mortality in directed cod fisheries (Bergenius et al., 2018). In the Skagerrak and Kattegat, most of the cod bycatch occurs in mixed trawl fisheries targeting the crustaceans Norway lobster (*Nephrops norvegicus*) and Northern prawn (*Pandalus borealis*), and demersal fish species. Since 2013, sorting grids are mandatory for all countries' vessels fishing for *Pandalus*, although there is an option to use a fish retention device in combination with the grid to keep bycatches of larger fish. The sorting grid reduces bycatches of juvenile cod significantly, but large cod contributing to the spawning stock are still caught as the retention device can be used (Bergenius et al., 2018). Inside 4 nautical miles (the trawling limit) from the Swedish coast, sorting grids without retention devices are mandatory in the *Pandalus* and *Nephrops* fisheries, which effectively reduces bycatch of all sizes for cod and other roundfish species (Valentinsson and Ulmestrand, 2008, Madsen and Valentinsson, 2010). In the central Baltic (SD24, 25, 26, 27, 28-2 and 29 in Fig. 1) and the Sound (SD23), most of the cod bycatches occur in trawls targeting flatfish and in passive gears targeting European eel (*Anguilla anguilla*) or coastal fish species (Bergenius et al., 2018). However, it should be noted that cod bycatches in the pelagic fisheries targeting herring and sprat are not subject to fisheries-independent observer monitoring in any of the studied sea areas so the knowledge on the significance of cod bycatches in pelagic fisheries is limited (Bergenius et al., 2018).

Survival of discarded cod from the major gear categories (trawls, seines and gillnets) is generally assessed as very low (Benoît et al., 2013; Morfin et al., 2017). However, cod released from live catching passive gear such as fyke nets, pots and traps have been demonstrated to have higher survival probability than from trawls and gillnets (Humborstad et al., 2016; Ljungberg and Lunneryd, 2018). Fishers using those gears are therefore exempted from the landing obligation in both the Baltic and the North Sea regions (Commission Delegated Regulation (EU) 2018/306; Commission Delegated Regulation (EU) 2019/2238). The exemption is conditioned on the immediate release of discarded cod under the sea surface in order to minimise seabird predation. Similar to trawls, pots and fykenets can also be modified with escape windows to release non-target species (Ovegård et al., 2011). The exemption could be more strictly enforced, and information campaigns could improve adherence to the releasing conditions, as there are indications of non-compliance. In the Kattegat and Skagerrak, the use of a sorting grid could be made mandatory for all vessels targeting *Nephrops* and *Pandalus*, and not only inside the Swedish trawling limit, which is currently the case. In the Baltic, more selective gear development would be necessary for targeted flatfish fisheries, based on the bottom trawls described by Nilsson et al. (2018) and ICES (2019c). Increased monitoring and knowledge on bycatch, particularly for pelagic fisheries, would give further insights into the risk for bycatches.

3.12. Combined stressors

The overview above demonstrates that there is a wide range of interacting stressors on cod stocks in the Baltic Sea, the Kattegat and the Skagerrak, which in combination with targeted cod fishing may serve as enduring obstacles for stock recovery. In several cases, knowledge on the quantitative, synergistic and cumulative effects of these and other environmental stressors on cod stocks is weak or absent, and there is a strong need for further research on such effects.

4. Management implications

4.1. General

The great importance of fishing activities for the development and status of cod stocks are well known from studies of all cod stocks worldwide (see e.g., Sguotti et al., 2019). However, the majority of cod stocks are impacted by other factors that go beyond the direct fishing impacts. The importance of those factors needs to be identified on a stock-specific basis given the diversity of environmental factors affecting the distinct stocks. The present study partly aims to identify relevant measures. In the event that future environmental measures would be taken or considered with the aim to strengthen cod stocks in the Baltic Sea, Kattegat and Skagerrak, this section lists potential measures area-wise based on their assessed potential for conserving and rebuilding the different stocks (Table 1). This list does not imply that other measures are ineffective, but they were assessed as being less efficient in the short term, or less urgent. The list is an outcome from discussions among the authors, after an expert workshop and a stakeholder meeting, and was based on potential effectiveness and feasibility. Advantages and disadvantages are also listed (Table 1) and discussed. Economic costs of measures were not explicitly considered. As previously mentioned, targeted cod fishing has already been stopped (in the Baltic Sea and Kattegat) or been considerably restricted in (in Skagerrak) without apparent signs of stock recovery. Predicting stock recovery has also been very difficult with respect to other cod stocks (Hutchings and Rangeley, 2011; Sguotti et al., 2019). It is therefore not possible to give any time frame regarding when the ranked measures could have an effect. The exact design of each possible measure should, if applied, be elaborated by future studies, or by managers in close collaboration with experts on the particular scientific field. Moreover, since the impact of large predators, impaired recruitment habitats, bycatches, etc., on cod stocks in Swedish waters is not known well enough, measures should preferably be designed as scientific experiments in which the effects of the measures can and should be adequately evaluated.

One of the main principles of EBFM is adaptive management (Long

Table 1
Advantages and limitations of selected measures for cod stock recovery in the Baltic Sea, Kattegat and Skagerrak in 2021.

Target	Stock	Measure	Advantages	Limitations
Sustainable fishing mortality	Skagerrak offshore, Western Baltic	Adaptive restrictions on targeted fishing	Reduced fishing mortality	
Sustainable fishing mortality	All	Reducing bycatches	Reduced fishing mortality	Difficult to enforce
Increasing number of individuals in stocks	Eastern Baltic, Kattegat, Skagerrak coastal	Restocking	Increased number of juveniles. Improved stock structure	Novel method with unknown effects
Reducing predation	All	Substantial culling of predators to reduce predator populations	Reduced natural mortality	Subject to disagreement. Disputed stock level effects.
Reducing predation	All	Culling of predators to prevent population increases	Prevented natural mortality increase	Disputed stock-level effects
Strengthening recruitment	All	Preserving recruitment habitats	Improved recruitment habitats	Conflicts of interest with stakeholders in the areas in question. Novel method.
Strengthening recruitment	Skagerrak coastal	A seasonal ban against bottom trawling for *Pandalus* during the period of spawning and the early larval stage in the enclosed Gullmar fjord.	Improved recruitment in a limited area	Potential conflict with *Pandalus* fishers. Unpredictable stock level effects.

et al., 2015), which includes process-based learning and taking changing conditions and new knowledge into account (Westgate et al., 2013). In adaptive management, measures should at least partly be treated as a scientific experimental design (Walters, 2007). It should thus be stressed that all measures taken must be monitored closely and followed up in an adaptive EBFM.

4.2. Reducing fishing mortality

Targeted cod fishing and mixed fishing can still be reduced in offshore Skagerrak. Current stock status is assessed as being unsustainable in relation to the Maximum Sustainable Yield (ICES, 2021d). Targeted fishing on the remaining stocks has been discontinued. However, there is substantial potential to reduce cod bycatch in most of the study area. In particular, fisheries in the western Baltic Sea with cod bycatch target, e.g., flatfish, including bycatch of cod, using trawls, gill- and trammelnets. In the Kattegat, bottom trawling could be constrained to only allow the use of sorting grids without retention devices that catch cod, or by using other gears with equivalent species selective properties. In the Skagerrak outside the trawling limit, there is a considerable bycatch of cod in the bottom trawl fisheries, for *Pandalus* and *Nephrops*, in practice maintaining mixed fisheries. In the Skagerrak inside the trawling limit, bycatch in all fishing gears could be further reduced, especially in bottom trawls. Reducing bycatch may be quite labour intensive, since it may involve gear development, research and monitoring (Santos et al., 2022). It may also be difficult to enforce.

4.3. Restocking

Cod stocks in the Skagerrak, including fjord-type cod, and in Kattegat display weak genetic separation, while the Baltic stocks differ strongly from the others (Berg et al., 2015; Barth et al., 2019). Thus, supportive restocking of cultivated cod from neighbouring stocks would have the highest potential in coastal Skagerrak and Kattegat, especially in the archipelago and in the fjords. The expert workshop and the authors overall expressed support for the idea. It was concluded that breeding cod could be taken for cultivation from the Gullmar fjord, the Kattegat, Norwegian fjords or the Sound. ICES (2008) previously investigated cod restocking in the Western Baltic stock and found considerable risks; e.g., that the offspring would be less well-suited to the environment. Recent cod genetics discussions have, however, maintained a more positive view of experimental cod restocking (Carl André, pers. comm.). A genetic risk analysis should be performed with the aim to further investigate the possibility of cod restocking in the Kattegat and in Skagerrak fjords. Restocking could have a better potential for success in combination with reducing predation.

4.4. Reducing predation

To obtain potential stock scale effects from reduced natural mortality would probably require large-scale seal culling, which would be controversial. Another, probably less controversial approach would be to cull seals to the extent that their aggregated predation on cod does not increase; i.e., by limiting size increases of seal populations. While cormorants also consume cod, their potential impact is smaller than the impact of seals (Hansson et al., 2017; Aarts et al., 2019).

Culling harbour seals or grey seals with the purpose to increase the cod stocks has not been carried out during the past 30 years while the seal populations have increased in size. There has been limited protective hunting in the vicinity of fishing gears. In 2019, licensed hunting for grey seals was introduced. However, the hunting still does not limit the population increase and the effect of the introduced licensed hunting has not been evaluated.

Nevertheless, conclusions can be drawn from experimental studies on other taxa. Bowen and Lidgard (2013) reviewed marine predator effects on prey populations and evaluated the efficiency of marine mammal predator control. The review concluded that predator removal can increase target prey populations but does not always do so. However, the reviewed studies mainly involved reducing a large proportion of the predator populations. It was also concluded in the review that the effects of culling are typically dependent on continuous limitation of the predator populations.

4.5. Strengthening recruitment habitats

Strengthening and protecting recruitment habitats could improve conditions for the cod stocks. This implies that different types of habitats need different protection in the Sound, Kattegat and Skagerrak (shallow; measures for protection of vegetation and other three-dimensional habitat; see maps in Fredriksson et al., 2021) and the Baltic (deeper; measures against trawling; see maps in Fredriksson and Bergström, 2019). Exactly how this protection could be optimally designed may depend on the specific area and should be the focus of future investigations. In the enclosed Gullmar Fjord, a seasonal ban against bottom trawling for *Pandalus* during the period of spawning and the early larval stage may be introduced due to the risks for eggs and larvae from harmful resuspension of particulate sediment matter. Habitat protection measures may be unpopular among fishers or other stakeholders.

4.6. Improving food availability

Food availability appears to constrain growth in the Eastern Baltic stock in particular (Casini et al., 2016a; Neuenfeldt et al., 2020; Haase et al., 2020; Orio et al., 2020). Adult cod from this stock has been observed to have a decreasing amount of sprat in its diet. Sprat has probably changed much of its habitat northwards where cod is virtually absent, and sprat abundance has decreased in the current main distribution area of Eastern Baltic cod in the southern Baltic (Eero et al., 2012; Casini et al., 2016a; Neuenfeldt et al., 2020). A possible measure against this mismatch is to decrease sprat catches where Eastern Baltic cod congregates by moving the fishing effort for sprat northwards. ICES has also suggested this in its advice from recent years (e.g., ICES, 2018, 2019a).

4.7. Knowledge provision

For the Eastern Baltic cod stock, knowledge provision is of particular importance regarding a “problem complex” connected to ecosystem effects. Symptoms such as skinny individuals, impaired immune systems and disturbed reproduction have been observed in other fish species in the area (most notably Atlantic salmon, *Salmo salar*, see, e.g., Keinänen et al., 2018; Vuorinen et al., 2020). Those changes are probably the result of a combination of different factors, such as climate change, overfishing, eutrophication and chemical pollutants. These pressures may potentially have great impacts on cod, and should be managed in a longer time perspective than that assumed for the listed measures (Table 1).

5. Conclusions

The present study represents an overview of environmental factors negatively affecting cod stocks in the Baltic Sea, Kattegat and Skagerrak. Based on an expert workshop, a stakeholder meeting and several discussions among the co-authors, a list of potential measures were produced with the intention of aiding recovery of the cod stocks there. In general, the knowledge regarding the effects of non-fisheries measures on the studied stocks is limited, making it essential to carefully monitor them and quantify their possible effects. All these measures ought to be taken into consideration for a holistic and adaptive approach to managing these cod stocks and in particular their magnitude, combined effect and timing should be further evaluated. The literature overview and the list of potential measures are meant to represent a supportive tool for policy and management decisions with respect to Atlantic cod stocks in these waters and also elsewhere.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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