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Cod and climate: a systems approach for sustainable fisheries management of Atlantic cod (*Gadus morhua*) in coastal Danish waters

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Abstract

This study applied the Systems Approach Framework (SAF) to address the issue of declining Atlantic cod fishery in coastal areas. Interviews of 58 fishers from 26 harbours and meetings with national fisheries organisations and managers revealed the perception of an offshore movement of coastal cod. Numerical modelling based on fishing survey data did not substantiate these perceptions in the data-poor coastal waters. However, Data Storage Tag (DST) information combined with bottom sea water temperature data from the spatio-temporal hydrodynamic Baltic Sea Ice-Ocean Model showed changes in potential cod habitat distribution in the Skagerrak-Kattegat and western Baltic from 1979 to 2016. Subsequently, cod habitats were defined in three categories: (i) potentially suitable ($T \leq 12$ °C); (ii) episodic ($12 < T \leq 16$ °C); and (iii) unsuitable ($T > 16$ °C). The environmental changes were linked to the socio-economic component of cod fishery. Cod catches (weight and monetary value) were retrieved using logbook information and data from the Vessel Monitoring System (VMS, 2005–2016) and the Automatic Identification System (AIS, 2006-2016). General additive modelling significantly showed the largest proportion of catches took place in the potentially suitable habitat whereas catches were lower in the episodic habitat and rare in the unsuitable habitat. The results of this first large-scale SAF application are highly valuable for adapting existing fisheries management by: (i) providing information on habitat shrinkage for Maximum Sustainable Yield (MSY) based stock assessments; (ii) adding a spatio-temporal dimension for coastal productivity relative to the vessel-based Individual Transferable Quota (ITQ) system; and (iii) providing a predictive scenario simulation tool for sustainable management under changing environmental conditions.

Keywords Climate change · Potential fish habitats · Skagerrak-Kattegat · Western Baltic · Systems approach framework (SAF) · Stakeholder engagement

Introduction

Climate change, intensive fishery and predation have been linked to the stock decline of commercially exploited demersal fish over the past 30 years and, more recently, to large scale ecosystem changes in the Northeast Atlantic and adjacent waters (Hutchings 1996; Hutchings and Ferguson 2000; Collie et al. 2008; Tomczak et al. 2012; Olsson et al. 2015; Støttrup et al. 2017a, 2017b; Frelat et al. 2018). In order to compensate for declining stock sizes fishing closures have been introduced to protect spawning areas and juvenile by-catch of demersal species (e.g. Vinther and Eero 2013; Hjelm et al. 2013; Beare et al. 2013).

Decline of fish stock size has been accompanied by changes in distribution. Climate change and hydrographic changes have been a major concern in fish species whose distributional ranges are limited by thermal boundaries (Drinkwater 2005; Righton et al. 2010). Increasing sea water temperatures were implicated in the decline of Atlantic cod (*Gadus morhua* Linnaeus, 1758) (O'Brien et al. 2000), as well as in a northward shift in distribution in the North Sea (Perry et al. 2005).

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Changes in habitat availability were implicated, exacerbated by a declining stock (Blanchard et al. 2005; ICES 2017a). Also, predation by inflating avian and marine mammal populations has increased fish mortality in coastal areas (Carrs 2000; Königson et al. 2009).

Repeated outcries from commercial fishers in the past 20 years indicated demersal target species had declined or disappeared entirely from once productive fishing grounds in coastal Danish waters, among them most notably Atlantic cod (Fig. S1). Coastal fishery became unprofitable for a number of small-scale fishing companies operating from smaller, often family-owned, vessels, which as a consequence opted out of the industry, selling to larger, off shore vessel owners. As a consequence, thriving fishing communities have disappeared along the North Sea and western Baltic coasts, and only a few remain in service in today's much reduced industrial fleet comprising mostly larger vessels fishing offshore (Branch 2009; Asche et al. 2014; Høst 2015; Dinesen et al. 2018).

Fisheries assessments of the western Baltic and Kattegat-Skagerrak cod stocks is conducted by the International Council for Exploration of the Sea at regional (ecoregion and/or basin) scale (Svedäng and Bardon 2003; Jonsson et al. 2016; ICES 2016; ICES 2017a, 2017b, 2017c, 2018). These assessments do not distinguish between coastal and offshore distributions of stocks. Economic and environmental processes affecting the various fishing sectors are neither included. The decline in the coastal commercial fishing sector reflects the need for more focus on coastal issues to sustainably manage coastal resources and resolve conflicts among stakeholders.

The change in fleet structure from many smaller coastal (using static gears such as gillnets, fyke nets and longlines) to fewer larger off-shore dermersal trawling vessels, may partially be explained by the declines in coastal fish stocks. This being promoted by the vessel-based Individual Transferable Quotas (ITQs) introduced in 2007 by EU governments to regulate demersal fisheries (The Danish Agrifish Agency 2015). ITQs were set under the European Common Fisheries Policy (CFP) as a measure to improve cost-effectiveness (i.e. cost per unit effort) of demersal fisheries alongside technological advances and enhanced gear efficiency (further information on the CPF available at https://ec.europa.eu/fisheries/cfp_en.) The ITQs represent a proportion of the Total Allowable Catches (TACs) allocated annually to each country for each species and fish stock and ICES subdivision.

The Systems Approach Framework (SAF) is developed specifically to address and facilitate management challenges within such complex and transboundary systems (Hopkins et al. 2011; Hopkins et al. 2012; Støttrup et al. 2019). The SAF provides a formal structure for an Integrated Coastal Management (ICM) process embedded in strong public participation (Gillgren et al. 2018) and encompassing a scientific and public-knowledge based environmental-socio-economic (ESE) assessment(s) of key policy issue(s).

The overall aim of this study was through a SAF application to assimilate more scientific knowledge into policy decision making developing more appropriate scenario solutions for sustainable management of coastal cod stocks. This was carried out by: (i) identification of the characteristics and magnitude of the issue based on fishers interviews; (ii) empirically verifying the spatio-temporal changes of coastal cod fishery as perceived by Danish fishers; (iii) quantifying potential drivers for changes of cod distribution in the Skagerrak-Kattegat and western Baltic; (iv) conducting an ESE assessment and simulating scenarios of potential management options; and (v) discussing management scenarios with stakeholders to improve system sustainability within existing management.

Material and methods

This case study application of the SAF followed the structure developed by the EU project SPICOSA (Hopkins et al. 2011, 2012) and further advanced by BONUS BaltCoast (Støttrup et al. 2019) (for further details see www.safhandbook.net). It included the SAF steps: (i) Issue Identification; (ii) System Design; (iii) System Formulation; and (iv) System Assessment; and with recommendations for tasks to be addressed in the steps (v) Implementation; and (vi) Monitoring and Evaluation.

Issue Identification tasks in this study included stakeholder and institutional mapping, as well as stakeholder engagement and identification of the key issue(s). Fisheries and environmental managers and fisheries organisations were engaged via meetings held in response to commercial fishers outcries of declining catches/fish in coastal areas and their preferences were discussed. Formal interviews of 58 coastal fishers from 26 Danish harbours were conducted to retrieve qualitative spatial information of the areas of concern of declining cod catches over the past 5–10 years (Støttrup et al. 2014a, 2014b). Based on this, the Policy Issue was defined in collaboration with stakeholders. This step also addressed theoretic cause-effect chains of the system related to declining cod stocks using the descriptive society-environment interaction and problem definition tools, DPSIR (Driver, Pressure, State, Impact, Response)(EEA 1999) and CATWOE (Customers, Actors, Transformation process, World view, Ownership of the system, Environmental constraints (Basden and Wood-Harper 2006) (CATWOE tool available at: https://www.toolshero.com/problem-solving/catwoe-analysis/)(for further guidelines see: www.safhandbook.net).

System Design included identification of the virtual system and external hazards, data mining, and preliminary modelling with the aim to empirically identify cause-effects chains between spatio-temporal changes in coastal fish stocks and linkages to potential environmental and anthropogenic drivers. ICES stock assessments from 2017 were included as background information of the status of the North Sea-Skagerrak-Kattegat and the western Baltic cod stocks and related management advice and measure targets (ICES 2017a, 2017b, 2017c).

System Formulation comprised formulation and development of an Ecological-Socio-Economic (ESE), including the individual ESE components and auxiliary models. ICES International Bottom Trawl Survey (IBTS) and Baltic International Trawl Survey (BITS) station (Fig. S2) adult cod data for the period from 1995 to 2015 (1st and 3rd quarter, GOV trawl; data available at http:datras.ices.dk) were used preliminarily to identify changes in adult cod distribution and potential declines in coastal areas. Time series data (1988–2013) of survey catches were plotted for individual ICES areas (i.e. c-squares) to detect changes in adult cod abundance in respectively shallow (<35 m depth) and deeper (≥35 m depth) in Danish waters (Støttrup et al. 2014b). Spatio-temporal changes in distribution of adult cod were also analysed using a Log Gaussian Cox Process (LGCP) based statistical model implemented in an open source R package (available at http://www.rforge.net/lgc) developed by Kristensen et al. (2014) and Nielsen et al. (2014).

ICES fishery surveys are, however, data-poor in shallow waters at depth ≤ 15 m, and inadequate to resolve cause-effects chains between response variables and potential drivers in coastal systems. Alternative data for cod distribution were therefore explored.

Information of cod distributional behaviour in response to water temperature was retrieved from electronic Data Storage Tags (DSTs) data. Atlantic cod with a body length > 45 cm were caught and tagged in costal Danish Waters (Neuenfeldt et al. 2007; Neuenfeldt et al. 2009). Each data point is an individual cod measurement of experienced temperature every 12 min. Only datasets >90 days length ($n = 43$ individuals, corresponding to >470,000 temperature observations) were chosen for the analysis (as in Righton et al. 2010, also herein see the thermal niche mean and range observed in the Baltic and Kattegat-Skagerrak cod stocks).

The DST information was used to identify three thermal habitats for adult cod based on bottom sea water temperature (T °C). A simple exclusion criterion was applied, assuming that the highest 1.5% of temperature observations can be considered cod individuals sampling temperature regions that are avoided. The cod population habitat was then divided into three temperature categories: (i) potentially suitable (≥95% of all temperature observations); (ii) episodic (≤3.5% of all temperature observations); and (iii) unsuitable (≤1.5% of all temperature observations). Categories (ii) and (iii) reflect the behavioural nature of reactions to temperature thresholds, which are sensed by the fishes as scalars, resulting in a low (assumed 5% in total) fraction of residence time outside the potentially suitable habitat generated by sampling the environment.

The boundaries of these three thermally defined habitats were applied to a high-resolution hydrodynamic model of the Baltic Sea Region for the period from 1979 to 2016) developed in the BONUS Inspire project (Lehmann 2000) (model data available at http://www.bsh.de/webcode/1652854). The hydrodynamic model domain of the Baltic Sea Ice-Ocean Model (BSIOM) comprises the entire Baltic Sea including the Gulf of Bothnia, Gulf of Finland, Gulf of Riga as well as the Belt Sea, Kattegat and Skagerrak (Lehmann and Hinrichsen 2000). The model is based on 60 vertical levels and a horizontal resolution of ~2 km (latitudinal distance of 0.0225° and longitudinal distance of 0. 045°, and with a total grid size of 538 grid points for latitude and 478 for longitude) using a Arakawa b-grid (http://www.oc.nps.edu/nom/modeling/grids.html) (Lehmann and Hinrichsen 2000). Values of bottom sea water temperature sbt_ra were extracted as monthly means to represent the temporal variation in the thermal condition of the benthic habitat.

Spatial distribution of cod landings were retrieved using logbook information (statutory for vessel length ≥ 10 m in the Kattegat and ≥ 8 m in the Baltic Sea) and data from the Vessel Monitoring System (VMS 2005–2011, vessel length ≥ 15 m; VMS 2012–2016, vessel length ≥ 12 m) and the Automatic Identification System (AIS 2006–2016) at the same spatial scale and geo-positions used for the hydrodynamic model. When fishing instances were covered by both VMS and AIS, the logbook information was only associated with the VMS data to avoid double counting. Thus, while the VMS data comprise the larger vessels (and larger part) of the fishing fleet, the AIS data covers the smaller sized fishing vessels (vessel length < 12 m).

Cod landings values were calculated in weight (tonnes) and monetary value (€100 = DKK745) per vessel per metier per day distributed across VMS and AIS recorded fishing hours, and subsequently summed to a monthly scale. While VMS and AIS data comprise positive values of cod landings, identification of zero-values is difficult to estimate because information of target species for individual trips are ambiguous due to multiple use of metiers within the area. CPUE estimations would, thus, be somewhat arbitrary.

Cod catches by the Danish demersal fleet from 2005 to 2016 (logbook, VMS data of demersal trawl and AIS data for the demersal and static fleet) information were analysed as a function of bottom sea water temperature (monthly means derived from BSIOM) and position (longitude, latitude) fitting a Generalized Additive Model (GAM) of the form

$$\ln(Catch_i) \sim N(\mu_i, \sigma^2)$$

$$\mu_i = \beta_0 + f_1(Temperature) + f_2(Year) + f_3(Longitude, Latitude),$$

where f_i denote smooth functions of the co-variates and σ the standard deviation.

The monthly distribution of unsuitable habitats was calculated for the episodic and unsuitable levels. To investigate potential temporal trends, linear regression models were fitted using the maximum annual distributions for the two levels.

The System Assessment included a workshop were ESE modelling results and potential management scenarios were discussed with a wider group of scientists and the Danish national fisheries managers responsible for implementation of the annual cod TACs and ITQs for the Danish fishing fleet.

The analysis was done in R (R Core Team 2018), GAM fitting was done using the `mgcv` package (Wood et al. 2016) and plotting of maps used R packages: `ggplot2` (Wickham 2016) and `ggrepel` (Slowikowski 2017).

See the Supplementary Material for Tables S1 and S2 and Figs. S1 to S6.

Results

Issue identification

The management issue was generated bottom-up from a group of stakeholders who claimed their livelihood was negatively impacted due to declines in coastal fish catches/populations. This became a high priority issue for both the fishing industry as well as for fisheries managers at the national level resulting in their commissioning a study to map the characteristics and magnitude of the issue. The key stakeholders were identified as commercial and recreational coastal fishersmen with vessel-registration in a Danish harbour, local and national fisheries organisations (The Danish Fisheries Organisation, DFPO; The Danish Coastal Fisheries Organisation; The Danish Recreational Fishers Organisation, DFF) fisheries managers responsible for the national implementation of fisheries regulations and quota distribution (The Danish Ministry of Foreign Affairs), and nature managers (The Danish Ministry of Food and Environment, The Danish Nature Agency) responsible for the national implementation of EU directives under the Natura 2000 network, the Birds Directive (BD 2009/147/EC) and Habitat Directive (HD 92/43/) accessible at http://ec.europa.eu/environment/nature/legislation/habitatsdirective/index_en.htm) and the Marine Strategy Framework Directive (MSFD 2008/56/EC) (accessible at http://ec.europa.eu/environment/marine/eu-coast-and-marine-policy/marine-strategy-framework-directive/index_en.htm).

The stakeholder interviews showed that cod, and to some extent plaice, were the primary commercial species impacted by declining catches (Fig. 1) (Støttrup et al. 2014a; Støttrup et al. 2014b). Fishers claimed that these species had moved off shore. The fishers experienced decreasing CPUE and thus they were required to sail farther to fish. Some fishers had changed target species while others were about to give up fishing altogether. The Policy Issue was thus identified as: "declining cod productivity in Danish coastal areas".

Identification of interactions between society and the environment relevant to the issue revealed two DPSIRs. The first DPSIR encompassed fisheries at the EU level without a SAF application, while the second DPSIR focusing on the Danish cod fishery and included SAF (Fig. 2). Both DPSIR were economically driven with the aim to adapt management to a state of declining fish/cod stocks. In the first phase, the economic impact of the system was specifically addressed whereas cause-effect chains of ecological impact(s) remained unresolved, and thus resulted in an economic management response. The application of SAF in the second DPSIR provided the opportunity to integrate stakeholder knowledge in the ESE assessment process thereby pushing development and use of alternative scientific modelling methods. This supported identification of one possible ecological cause-effect chain linking decline of cod catches in coastal waters to climate change.

The CATWOE mnemonic supplemented the DPSIR identification of a conflict between coastal, small scale fisheries (victims) and off shore, large scale demersal fisheries (beneficiaries) potentially resulting from the system transformation of spatio-temporal changes in cod stocks distributions, as well as the introduction of the ITQ system in 2007 for several demersal target species, among other for cod (Table S1).

EU and national quota regulation

The ITQs represent a catch share of the national quotas of commercial fish stocks. National quotas are traditional shares fixed between EU countries of Total Allowable Catches (TACs). The TACs are species and stock specific (i.e. ICES Statistical Areas) and their value (i.e. in weight or number) are fixed annually by the EU Council of Fisheries Ministers who considers proposals put forward by the European Commission (EC). The EC proposals build on scientific advice from the Scientific, Technical and Economic Committee for Fisheries (STECF). The EU Council of Fisheries Ministers may also consider recommendations directly from ICES and from Non-EU countries (further information on EU TACs and ITQs are available at https://ec.europa.eu/fisheries/cfp/fishing_rules/tacs_en).

System design - conceptual model

The stakeholder and governance structures were integrated into the Conceptual Model for the Policy Issue (Fig. 3a, b). It revealed a highly complex governance structure of fishing quota management at both the international and national scale combined with historically and economically driven quota distribution among stakeholders. The Conceptual Model also highlighted the complexity of the ecological component of the

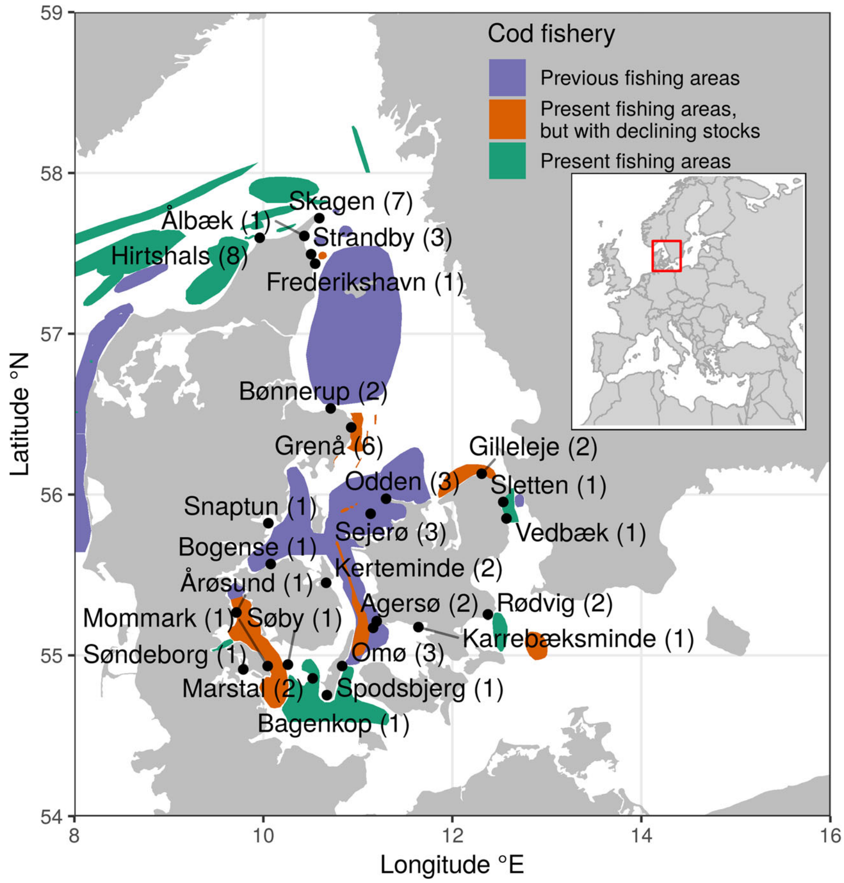


Fig. 1 Map of changes in productivity of cod fishing grounds within the Danish Exclusive Economic Zone (EEZ) and the Skagerrak-Kattegat and Western Baltic Sea as perceived by 58 coastal commercial fishers from 26 Danish harbours

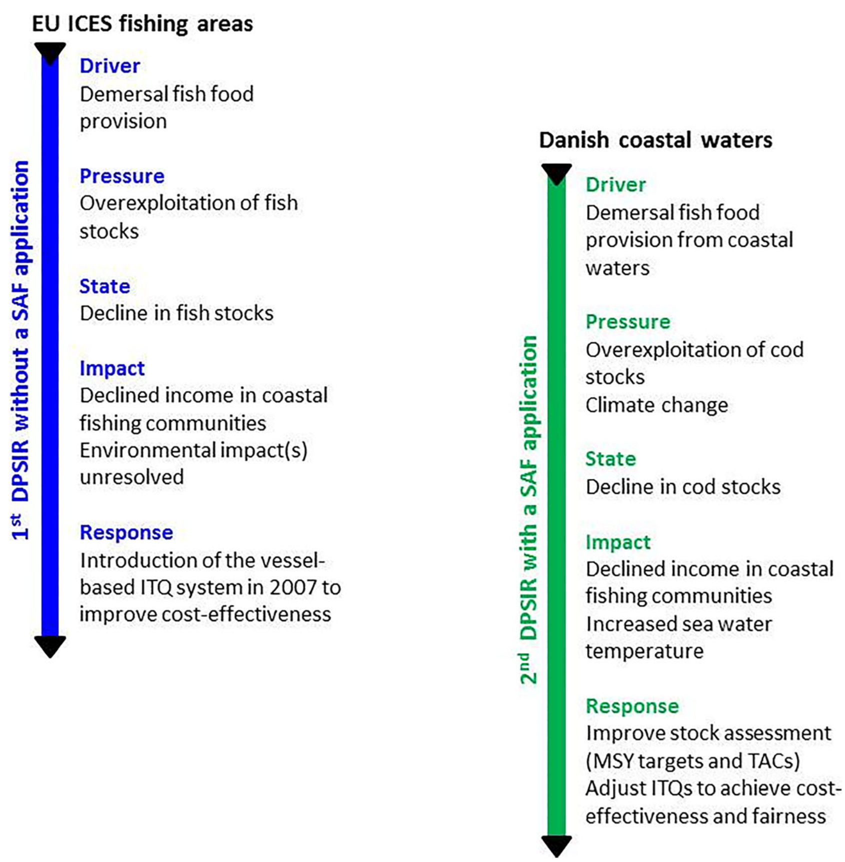


Fig. 2 DPSIRs for the issue of 'declining fish stocks in northern European waters' without a SAF process, and 'declining cod in Danish coastal waters in the Skagerrak-Kattegat and western Baltic with a SAF application

system and lack of identified cause-effect chain(s) other than fishing pressure. While fishing mortality (F) and targets are based on assessments of stock development over time using the F_{MSY} (maximum sustainable yield) approach, considerations of other ecological impacts of fish distribution, such as climate change, are not yet fully integrated in fisheries management.

System formulation

To confirm fishers' perceptions of spatial changes, ICES monitoring data was analysed using different statistical and numerical modelling approaches. However, the scarcity of data in coastal areas, although indicating local declines of cod abundance, was insufficient to explore cause-effect chains for these changes through spatial population modelling. Preliminary statistical test and modelling: Response variables included ICES survey data from the database DATRAS which also forms the basis of the annual regional fish stock assessments (ICES 2016; ICES 2017a, 2017b, 2017c). Preliminarily statistical tests did not show significant differences of cod catches between shallow, coastal waters (<35 m depth) and deeper, open waters (≥35 m depth) in most areas except in the eastern Kattegat in the Swedish EEZ (Støttrup et al. 2014b). Explorative modelling of spatio-temporal changes of distribution of target sized cod performed using the Log Gaussian Cox Process (LGCP) based statistical model between 9 and 13°E and 54–58°N did not show significant trends of off shore movement of adult cod. This could be due to data-poor coverage in coastal waters of data from the ICES survey monitoring programmes, where no stations occur in shallow waters of less than 15 m depth (Fig. S2A).

The final virtual system was required to including the ICES subdivisions (SD) used for stock assessment and quota settings of the Skagerrak-Kattegat (SD IIIa/20–21) and western Baltic (SD 22–25) cod relevant to the Danish fishery in inner coastal waters (Fig. S2B). Thus, the geographic boundaries were set to of 9–16°E, 54–59°N.

Within the virtual system, annual cod landings in the Danish fishery from 2005 to 2016 by gear targeting cod (demersal trawls, gillnets) showed a relative stable, slightly increasing trend <10,000 t $year^{-1}$ with a higher peak in 2012 and 2015 (Fig. 4). There appear to be a dramatic decline in cod landing price from €2001 to €1250 in 2008 coinciding with the global economic crisis (Fig. 4).

The BSIOM trend analysis of monthly means of bottom sea water temperature for the period 1979–2016 showed a decadal increase up to 0.6 °C 10 $years^{-1}$ in most near-coastal areas in the Skagerrak-Kattegat and western Baltic, and cooling in some of the deeper, north-eastern basins (Fig. 5).

The thermal response of Atlantic cod in the Baltic Sea is visualised in Fig. 6 based on the thermally assigned Cod habitat categories: (i) potentially suitable ($T \leq 12$ °C); (ii) episodic ($12 < T \leq 16$ °C); and (iii) unsuitable ($T > 16$ °C).

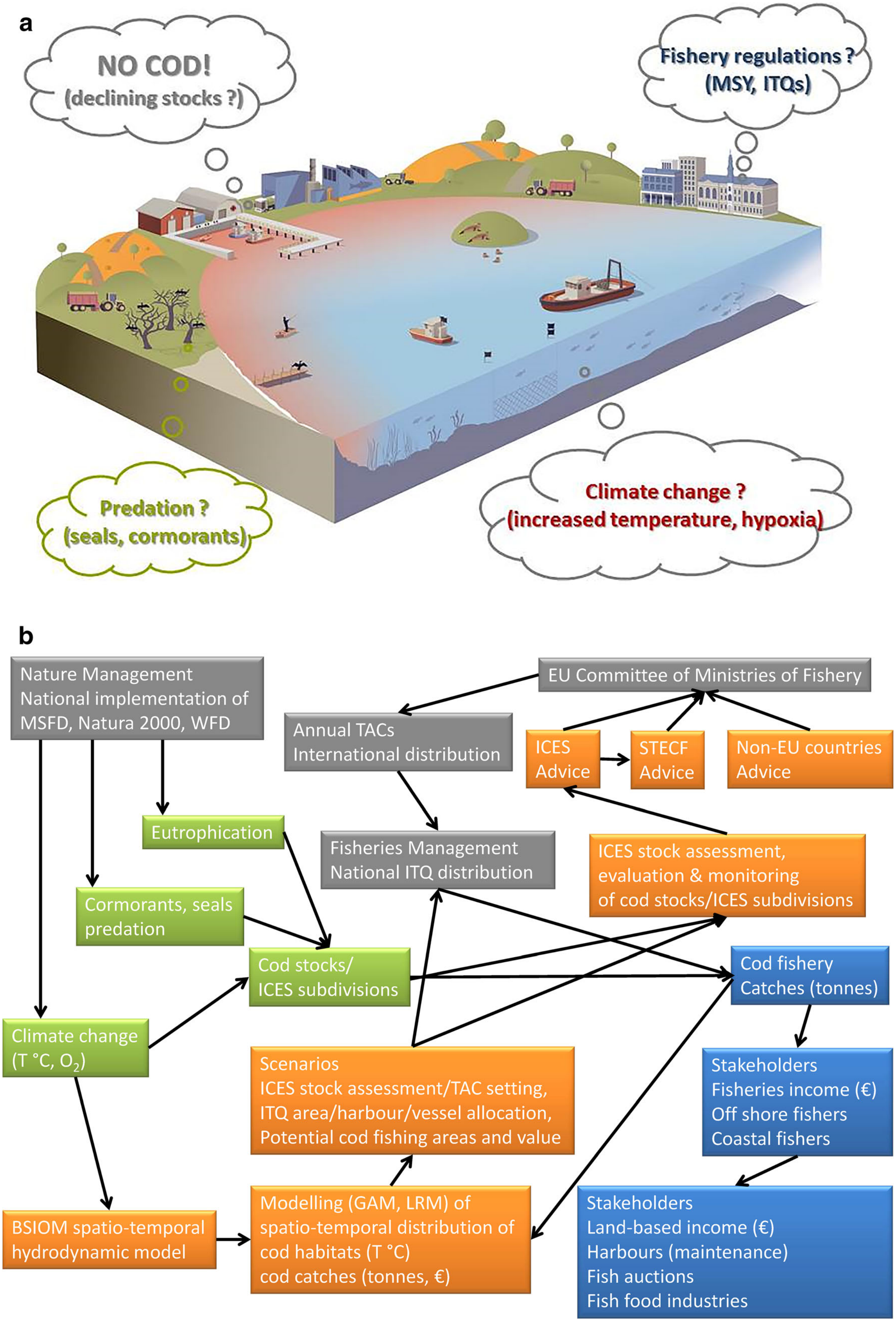
Mapping of the annual maximum distribution of the three thermally defined potential cod habitats categories showed that unsuitable habitat appear to increase in certain areas, such as in the eastern Kattegat, the southern belt seas and northern and southern coasts of the Arkona Basin (Fig. 7). In 2005–2006 maximum distribution was reach in October, whereas since 2007 the maximum distribution occurred a month's earlier, in September. Mapping of the progression over the year of the maximum distribution per months (exemplified by the 2014 condition) showed warming of coastal areas begin in May–June and peaks in August–September, and dissolves by November (Fig. S3).

The generalized Additive Models (GAMs) showed cod landings are affected by bottom water temperature (Fig. 8), with declining catches for temperatures above 10 °C, for both the larger vessels (VMS based landings) and the smaller vessels (AIS based landings). For diagnostic plots, see Fig. S4.

During the period 1979–2016 there was no overall significant temporal trend in the maximum distribution of thermally episodic cod habitats ($T > 12$ °C, Fig. 9, F-test, $F = 0.08$, $p = 0.77$). In contrast, there was a significant spatial increase of thermally unsuitable cod habitats ($T > 16$ °C, Fig. 9, F-test, $F = 8.652$, $p < 0.001$, adj. $R^2 = 0.17$). Similarly, in the individual ICES areas number 20–25, there were no significant temporal trends in the maximum distribution of episodic cod (Fig. S5, Table S2). However, the significant spatial increase of thermally unsuitable cod habitats detected in the overall virtual system were due to changes in particularly in area 23 but also area 22. The temporal trends of spatial increase of thermally unsuitable cod habitats were not significant for the remaining ICES areas although *P*-values were just above 0.05 for area 24 and 25.

During the more recent period 2005–2016 cod landings (in both weight and value) were negligible in bottom seawater exceeding 12 °C. Cod landings, however, varied substantially between the ICES subdivisions (Fig. S6). Subdivision 24 and 25 supported a large part of the landings, while landings were smaller in 20 and 22 and negligible in 21 and 23.

Fig. 3 Conceptual Model. **a**) Illustration of the issue and potential drivers; **b**) Schematic view of cause-effect chains and processes of declining cod stocks in coastal waters in the Skagerrak-Kattegat and western Baltic. Cause-effect chain unknown between decline of cod stocks in coastal waters and potential drivers: (i) unsustainable fisheries management (international/national quota allocation/MSY based TACs – overfishing og stocks, ITQs/fleet structure changes, unknown/unregulated discards);(ii) regional environmental drivers affecting locally (increased sea water temperature, spatio-temporal increase of hypoxia events, changed circulation/salinities), and (iii) regional food-chain drivers affecting locally (increased predation from seals, cormorants) ▶


a
NO COD!
(declining stocks ?)
Fishery regulations ?
(MSY, ITQs)
Predation ?
(seals, cormorants)
Climate change ?
(increased temperature, hypoxia)
b
Nature Management
National implementation of
MSFD, Natura 2000, WFD
EU Committee of Ministries of Fishery
Annual TACs
International distribution
ICES
Advice
STECF
Advice
Non-EU countries
Advice
Eutrophication
Fisheries Management
National ITQ distribution
ICES stock assessment,
evaluation & monitoring
of cod stocks/ICES subdivisions
Cormorants, seals
predation
Cod stocks/
ICES subdivisions
Cod fishery
Catches (tonnes)
Climate change
(T °C, O_2)
Scenarios
ICES stock assessment/TAC setting,
ITQ area/harbour/vessel allocation,
Potential cod fishing areas and value
Stakeholders
Fisheries income (€)
Off shore fishers
Coastal fishers
BSIOM spatio-temporal
hydrodynamic model
Modelling (GAM, LRM) of
spatio-temporal distribution of
cod habitats (T °C)
cod catches (tonnes, €)
Stakeholders
Land-based income (€)
Harbours (maintenance)
Fish auctions
Fish food industries

System assessment

During the SAF application period from 2014 to 2018 several changes of the governance structure took place which delayed and hindered stakeholder meetings with the fisheries and nature managers during the System Formulation step. However, due to the high priority of the Policy Issue, especially for the fisheries managers, stakeholders were willing to continue to engage in the System Assessment step. The new findings of the ESE assessment resulted in a common perception of the most immediate challenges to fisheries management. While monitoring could relatively easily be extend to include coastal areas, the challenges for management are more substantial. International assessment of TACs should encompass spatial changes in habitat suitability and distribution of fish production at a higher spatial resolution than hitherto. Similarly, national fisheries management measures, such as ITQ allocation, could be adapted to changes in catchability of fishable stocks.

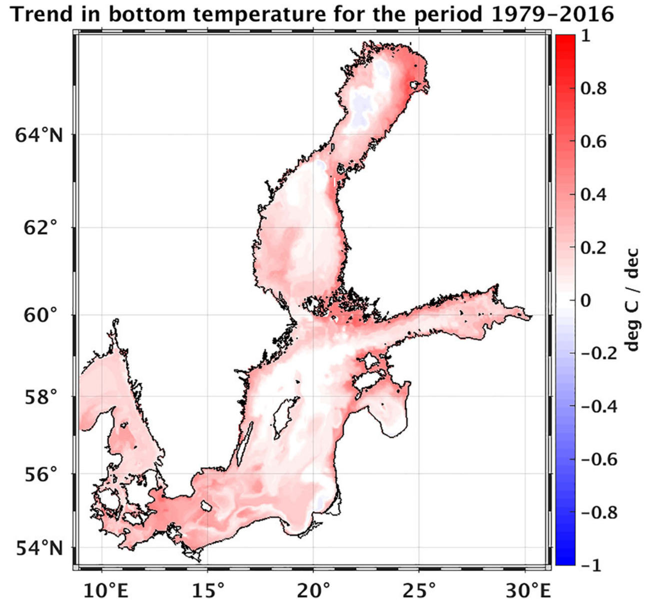


Fig. 5 Trend in bottom temperature for the period 1979–2016. The virtual system of the ESE model was delineated by the geographic coordinates 9–16°E and 54–60°N

Discussion

This study clearly demonstrated the need for a systems approach in fisheries management to include both coastal and offshore processes and ensure all fishing sectors are equally represented in management. The results of the SAF application highlighted the importance of engaging stakeholders in a clear identification of the Policy Issue. The SAF helped to structure the handling of highly complex environmental elements and ensured coupling with socio-economic elements at scales from local to international. The Design and

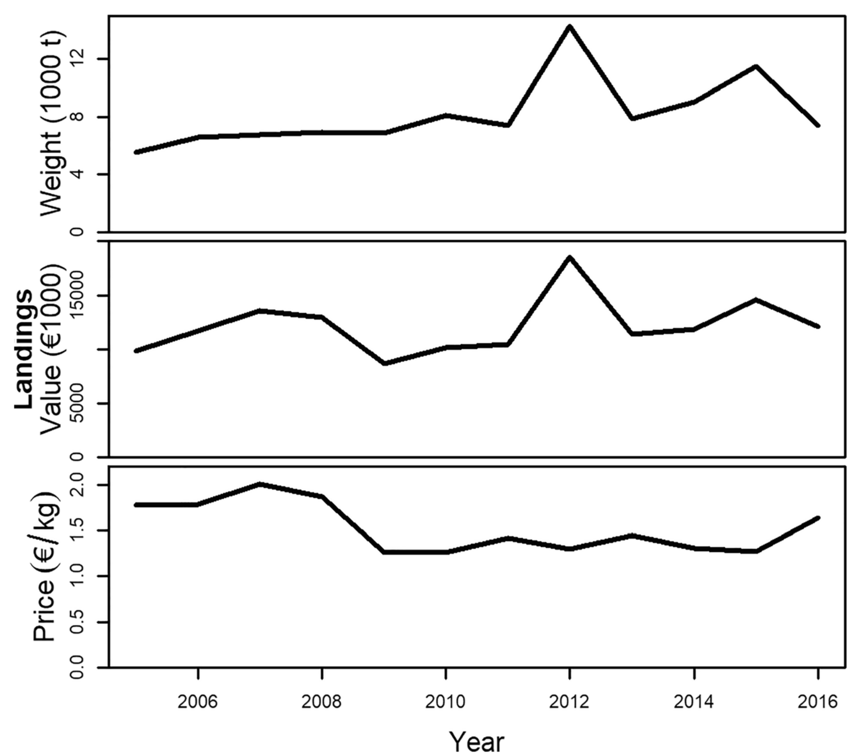


Fig. 4 Cod landings in the Danish fishery from 2005 to 2016 in the virtual system (specify gear: demersal trawl and gillnets targeting cod), expressed in weight (1000 t), value (€1000) and price (€/kg)

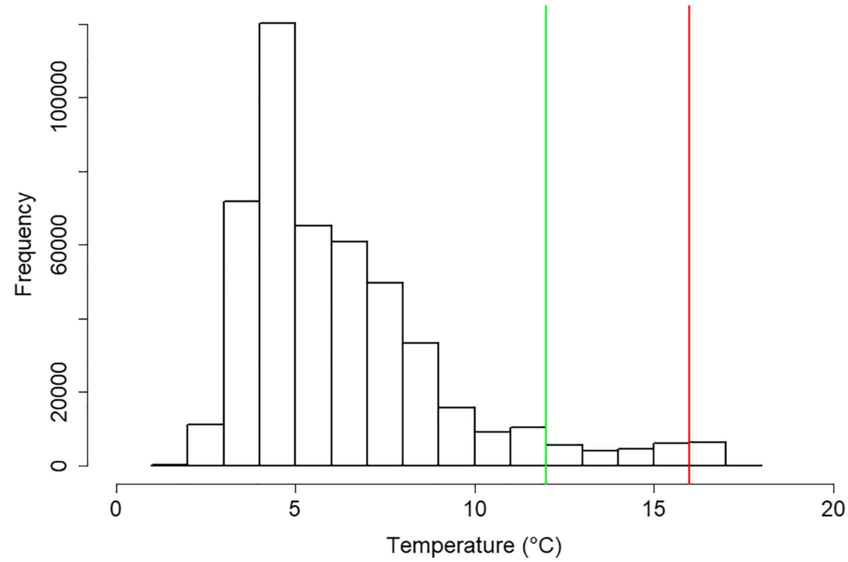


Fig. 6 Cod temperature experience in the Baltic Sea. Frequency indicates the number of 10 min intervals spent at a given temperature. The green line marks the 12 °C suitable habitat limit and the red line marks the 16 °C upper temperature limit used in this study as habitat threshold. 6334 counts between 16 °C and 17 °C represent less than 1.5% of the total number of counts represented in the graph ($n = 473{,}965$)

Formulation steps highlighted the gap in fisheries survey data on coastal areas, exemplified by this cod case study.

SAF application and stakeholder engagement

The stakeholder group consisted of only 'highly involved' (Gillgren et al. 2018) fishers, fisheries organisations and fisheries managers. Their engagement provided knowledge that was incorporated in the initial SAF steps to identify the issue and in the ESE assessment. In the System Assessment, stakeholders suggested potential scenarios that could supplement the existing management framework and render it more adaptive to changing climatic conditions.

The Issue Identification step revealed that the fisheries sector comprising coastal commercial fishers was not recognized as a separate stakeholder group (Newton and Elliott 2016), thus, problems and conflicts arising in this sector were largely overlooked. Based on the first large-scale fishers interview survey conducted in this study, the spatio-temporal elements of the issue became visible. Their perceptions were substantiated by the ICES statistics of Atlantic cod landings showing ~80% decline from 1996 to 2016 in the entire western Baltic from 38.000 to 8.000 t year^{-1} of an estimated value between €48–76 million and €10–16 million (€1.26–2.01 kg^{-1}) respectively.

The SAF application revealed that local problems for small-scale fisheries and rural harbours were managed at a regional scale treating all fishery sectors as one stakeholder group. This explained the conflicts among stakeholders and dramatic changes of the fleet structure, and suggested unsustainable use of resources in coastal areas. Furthermore, the decline in the cod stock at a regional scale combined with the shrinkage of cod habitat due to climate change may have exacerbated the decline of conditions for coastal commercial fishers.

In the SAF, the DPSIR is used to achieve a common understanding of the cause-effect chain for the issue (Støttrup et al. 2019). This cod case study showed that the response in 2007 of introducing ITQs to improve demersal fishery cost-effectiveness did not include an ESE assessment. With the SAF applied here, we introduced the ESE assessment between the identified DPSIR Impact and Response. The ESE assessment focused the work and resolved a cause-effect chain with unexpected results in the environmental component and linked with the socio-economic components to arrive to new scenarios for integrated management decisions. The SAF application thus furthered the understanding of a highly complex system and sparked discussions of alternative scenarios and measures in a manner similar to other SAF applications in coastal fisheries management (Dinesen et al. 2011; Moksness et al. 2011; Timmermann et al. 2014).

At the same time, we had problems identifying the DPSIR driver(s). The fishers claimed predation to be one of the main factors affecting coastal cod stocks. The inflating numbers of cormorants (*Phalacrocorax carbo*) and seals (*Phoca vitulina*, *Halichoereus grypus*) may have reduced cod abundance in coastal waters at a local (fjords and bays) scale (Carrs 2000; Königson et al. 2009; Andersen et al. 2019). These predators were 'visible' in the local coastal fisheries, where they caused damage to both the fish and the gear. These predator species are protected under the European Union Natura 2000 network (http://ec.europa.eu/environment/nature/natura2000/index_en.htm), which is implemented at the national level. Single sector conservation plans and delayed management response or action to these concerns escalated stakeholder conflicts at the local and national level.

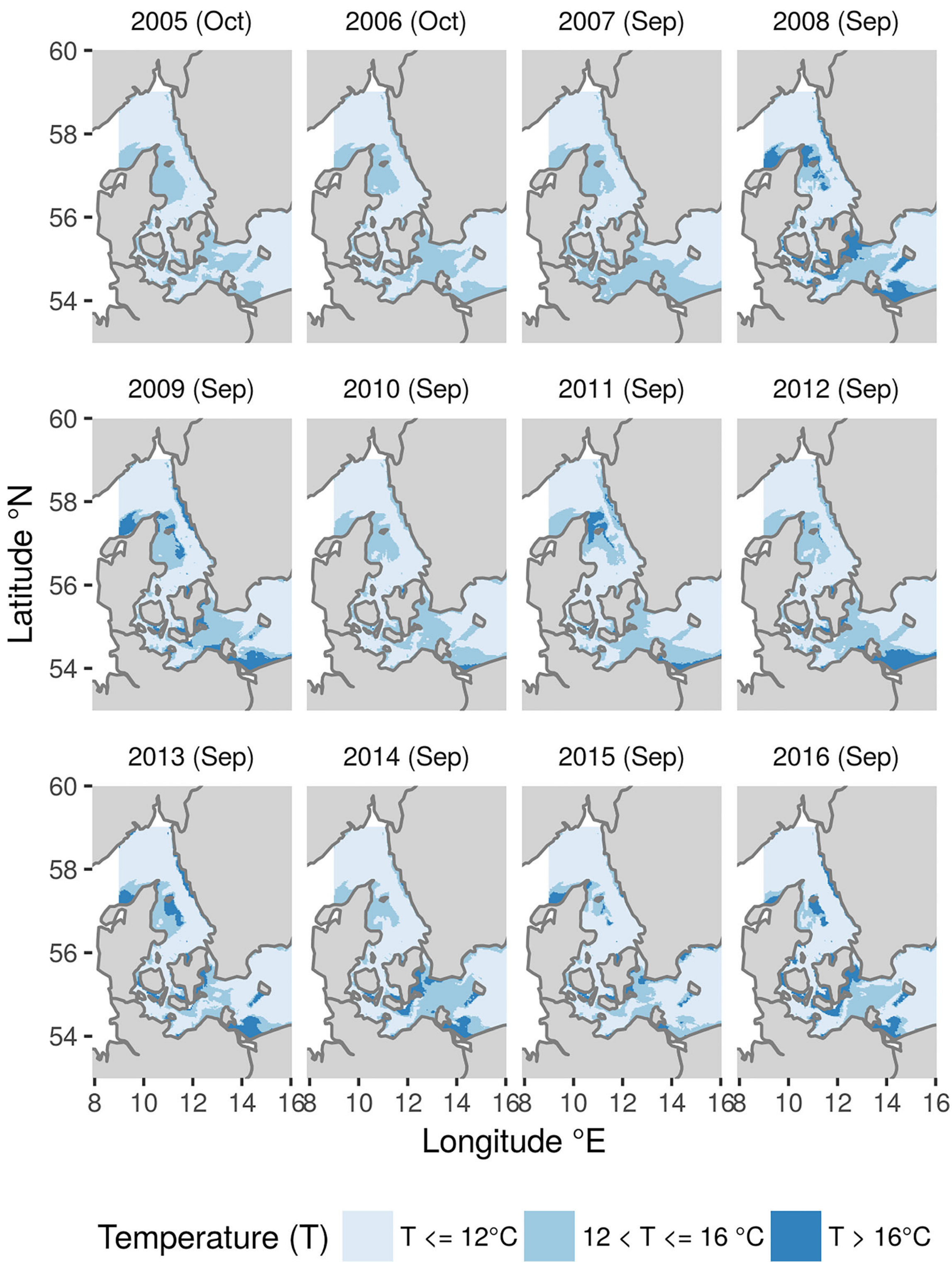


Fig. 7 Annual maximum distribution each year (month of occurrence) of suitable and unsuitable cod habitats for the period 2005–2016 defined by sea water bottom temperature as: (i) potential habitat (T < 12 °C); (ii) episodic habitat (12 °C ≤ T ≤ 16 °C); and (iii) unsuitable habitat (T > 16 °C)

Local changes in cod abundance could, however, also result from population changes at the regional scale, where they may be driven by climatic changes, possibly in combination with declining stocks (Blanchard et al. 2005), which may be attributed to overexploitation (Cook et al. 1997).

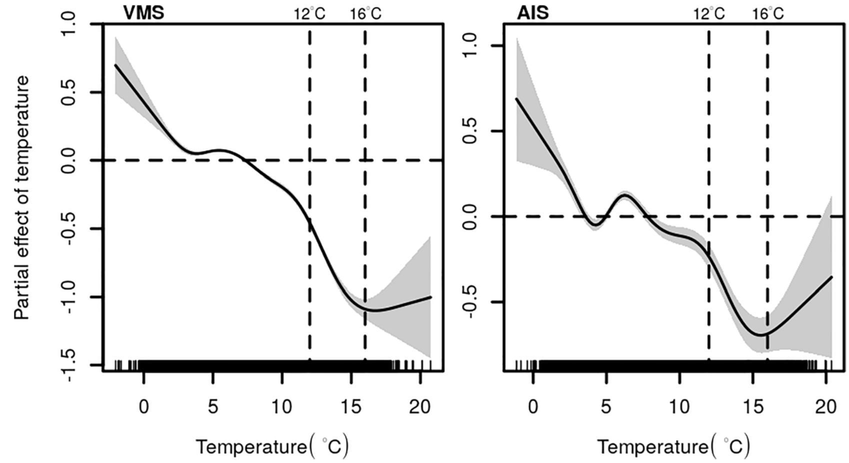


Fig. 8 Partial effect of temperature on cod catches for the period 2005–2016 from the fitted Generalized Additive Models (GAMs) based on VMS and AIS landing data, respectively. The thresholds of potential, episodic and unsuitable thermal habitats are denoted with vertical dashed lines

Data poor areas and stocks

In the SAF application, we had to reiterate between System Design and System Formulation due to the challenge of uncovering the cause-effect chain for the ecological component of the issue. As illustrated in the conceptual model, there are several potential causes which may also interact synergistically and/or cumulatively. It was apparent from the decline of the cod stocks that some causes, such as overfishing and climate change, were acting at a regional scale whereas for example predation from cormorants and seals were acting at a national or more local scale. Together with the transboundary assessment of the cod stocks at a regional scale, the virtual boundaries of the ESE model required a large-scale setting. It thus constituted the first large-scale marine application of the SAF.

In trying to verify fishers' perception of the problem, a further management gap was revealed. Survey biomass indices estimated by ICES for the western Baltic and Skagerrak-Kattegat cod stocks all showed declining trends over the past

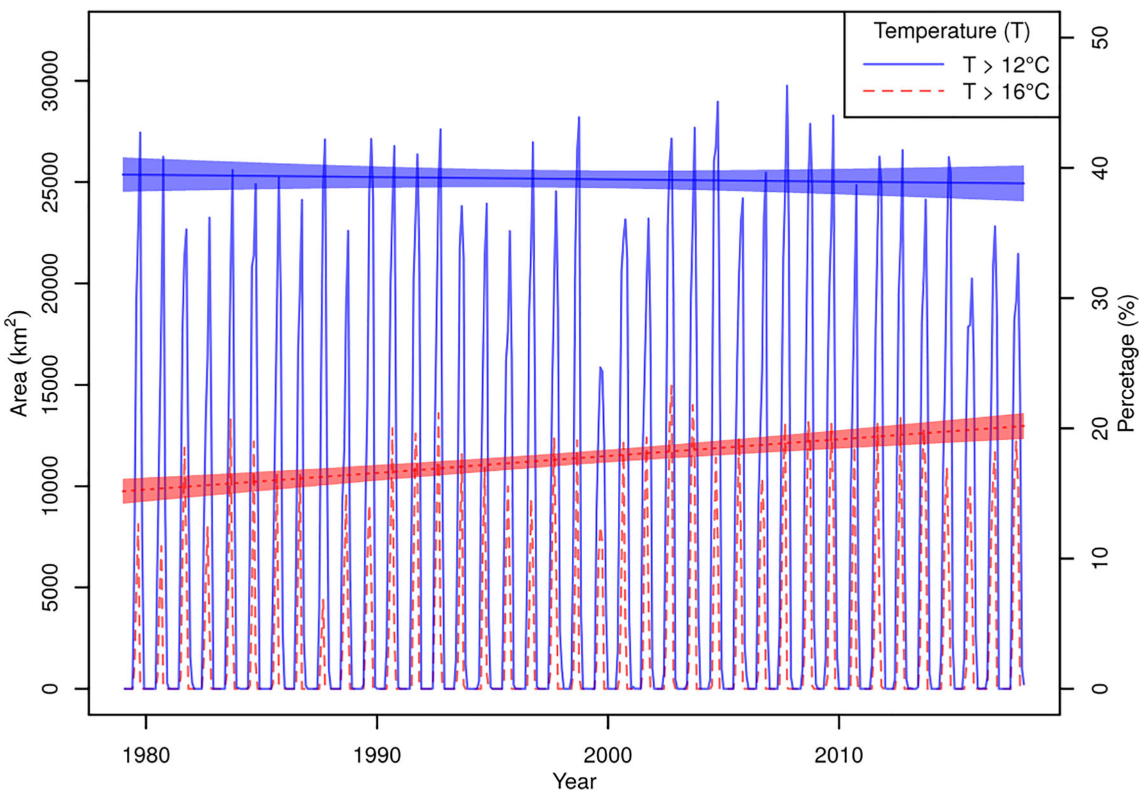


Fig. 9 Monthly distribution of episodic (solid blue line) and unsuitable habitats (dashed red line) for cod for the period 1979–2016 in terms of area (km^2) and percentage of the total study area. The solid straight lines show linear regression fits of the maximum annual distribution. Shaded areas correspond to 95% confidence intervals around the linear regression fits

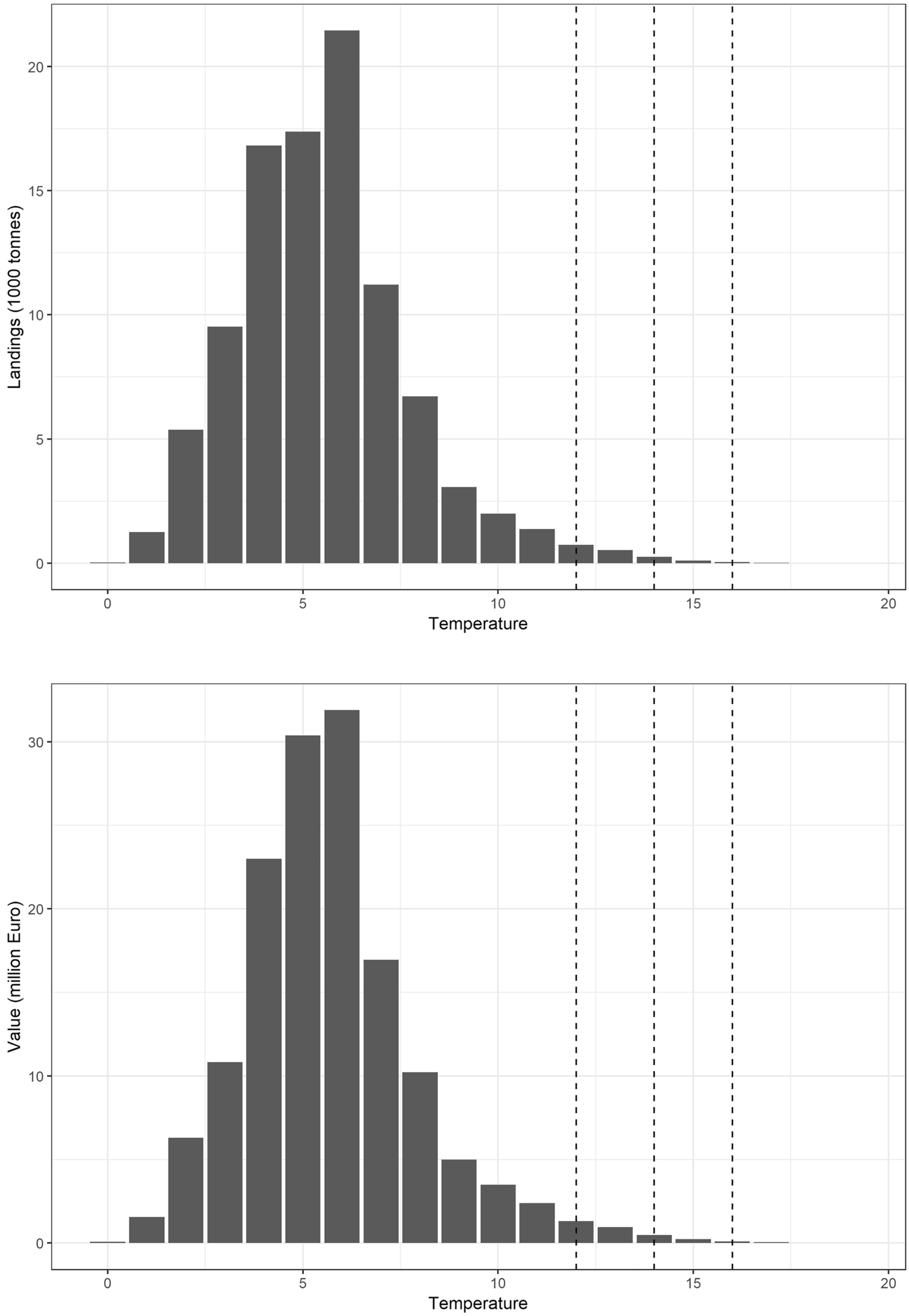


Fig. 10 Cod landings in weight (**a**) and value (**b**) for the period 2005–2016 as a function of bottom seawater temperature. The thresholds of potential, episodic and unsuitable thermal habitats are denoted with vertical dashed lines

25 years (ICES 2016; ICES 2017a; ICES 2017b; ICES 2017c). ICES surveys were, however, data-poor in coastal waters (depth ≤15 m), making it difficult to discern, if there was a steeper decline of cod in coastal areas as perceived by fishers. During the System Formulation it became apparent that the standard ICES survey data was insufficient to envisage the problem and explore cause-effect chains between fish stock changes and potential environmental, ecological and economic drivers. Here the strength of the Systems Approach allows the issue to be address from a broader perspective and gave us the opportunity to encompass different ecological data sets to explore linkages between climate change and fish distribution. In the North Sea, recent studies could not conclusively identify temperature effects on cod distribution (Neat and Righton 2007). The transitional waters of Skagerrak-Kattegat and western Baltic are topographically and hydrographically heterogeneous, suggesting that climate impact may be more pronounced.

Climate change and habitats

In considering alternative approaches for numerical modelling of cod distribution, we looked for data that could be used to define potential cod habitats. The combination of the Data Storage Tags (DSTs), a high-resolution hydrodynamic model for the Baltic Sea Region 1979–2016 and the logbook-VMS and -AIS catch data provided a unique opportunity to test, whether the spatio-temporal distribution of potential adult cod habitats matched the catch distribution of the landings. The significant correlation between the spatio-temporal distribution of the thermal habitats and cod catches in coastal areas supported the changes observed by the fishers. This promoted the stakeholder discussions to adapt management accordingly. The results also provided an explanation for the different developments within the coastal and offshore cod fisheries whereby severe declines were observed in the coastal fishery in contrast to off shore.

The stock assessment is at risk of not representing realistic abundance when a substantial proportion of the population is outside the surveyed habitat. This can happen in years when the stock size is low and either aggregated in hard bottom areas or in shrinking suitable habitats. Hard bottom habitats like reefs and wrecks aggregate cod outside the surveyed habitats (i.e. level bottom sand and mud), resulting in a potential underestimation of the population (Wieland et al. 2009). Blanchard et al. (2005) observed juvenile cod to aggregate in suitable thermal habitats and the magnitude of the habitats were important for the population size. This may be even more pronounced in adult individuals. The upper temperature tolerance in cod declines as they grow in size, reflected in the decrease in temperature for maximum growth with increased fish size (Bjornsson and Steinarsson 2002). Also, shrinkage of suitable habitats (e.g. in deeper waters) aggregate adult cod within survey areas resulting in higher population estimates in stock assessments (Rindorf and Lewy 2012). The aggregation also renders the fish more vulnerable to fishery (Rindorf and Lewy 2012). To truly capture the effect of climate change on coastal fisheries, where temperature effects are most likely to be manifested, changes in distribution of potential habitat of adult cod need to be taken into account in MSY based stock assessments.

The negligible commercial cod landings supported by the ICES subdivisions 21 (Kattegat) and 23 (Øresund) may partly be explained by the implementation of spatio-temporal fishing closures since 2009 (primarily in the winter months) to protect spawning cod (Ministry of Foreign Affairs 2010; Vinther and Eero 2013) and the use of static gears only in Øresund since 1932 (for details of the trawling ban, see Ministry of Foreign Affairs 1933a, 1933b). These management measure could mask potential causal relations between low landing values and increased area of unsuitable habitat for cod (significant for subdivision 23 but not for 21). Landings were, however, negligible at sea bottom temperatures >12 °C in all subdivisions. While landings in subdivision 22, which showed a smaller but significant spatial increase of unsuitable cod habitat, landings were high in subdivision 24 and 25 (*P*-values ~0.065 for trend lines of spatial increase of unsuitable habitat). Further spatio-temporal increase of thermally unsuitable habitat could thus impair cod fishery in these areas.

In coastal areas, cod are also highly vulnerable to predation from birds and seals (Carss 2000; Königson et al. 2009; Andersen et al. 2019). The effects are often highly localised related to nesting or breeding sites and also highly variable due to their migration patterns and large-scale recruitment capacity. Spatio-temporal data on avian and mammal predation is not available at a national or regional scale. This combined with management at a national level precluded their inclusion in the ESE model. However, we recognise their effects might be cumulative to climate change effects. This highlights the need to coordinate Natura 2000 conservation plans (e.g. cormorants and seals) at a regional scale. This management should acknowledge the transboundary population structure and dynamics. Furthermore, it should consider ecological and derived socio-economic effects of the system.

Systems based management

The ESE assessment revealed gaps in the fisheries management. Coastal areas are neither surveyed nor addressed in the assessment methods applied today. The decline in coastal fisheries went unnoticed for several decades and in response to outcries management was unable to resolve this issue due to lack of data and an understanding of cause-effect chains. The cod stock assessments need to be re-evaluated regarding the issue of climate induced shrinkage of suitable habitat, but should also include predation impacts from the inflated populations of cormorants and seals. In line with the systems approach, Link (2018) further suggests the introduction of a portfolio approach to management whereby optimal yield is not single-stock based, but takes into account multiple species when setting an aggregated upper limit for fisheries for a particular region. Link (2018) argues this would both prevent individual stocks from being overfished and at the same time minimise economic impacts exemplified by an analysis of the Alaskan regional fishery management.

In this study climate change was shown to be one driver in the decline of coastal fisheries. Since climate is beyond management, fisheries must instead be adapted to the changing conditions. This would mean a change in the existing vessel-based ITQ system and MSY and TAC based management to incorporate predicted spatio-temporal changes in suitable and fishable habitat. The ITQ system under national jurisdiction may be easier to influence and exert adaptive management compared to changing the internationally and politically agreed TACs. The international monitoring needs to be adapted to the changing environmental conditions and include coastal distribution of fish. National management implementation should considered cost-effectiveness in relation to not only gear types and vessel size but also to distance from harbour to fishable habitats. Moreover, socio-economic assessments of efficiency and equality should consider the geographic distribution of fishing harbours as well as quota allocation relative to coastal and off shore fisheries to improve sustainability and social equity (Gillgren et al. 2018; Støttrup et al. 2019).

The SAF applied in this study was the first to address large-scale fisheries related issues normally addressed through single-stock assessment of MSY to set TACs and ITQs without wider environmental and social-economic considerations. This study highlighted changes taking place in coastal areas which had been largely ignored. We provided potential solutions for improved sustainability and socio-economic equity of fisheries as well as a tool for adaptive management to deal with this issue within changing climate scenarios.

Conclusions

This study was the first large-scale, marine application of the SAF. It addressed a highly complex environmental and ecological issue with widespread socio-economic repercussions. The issue also implicated management at national and international levels. The SAF application highlighted a management gap in that monitoring and cod stock assessments did not sufficiently include coastal areas. Thus, the consequences of coastal cod decline for the small-scale coastal fisheries were not addressed by management. Changes in governance structure can delay or disrupt a SAF application but the high priority of the issue retained their participation. In this study we showed a link between climate change and cod distribution away from the coast due to shrinkage of suitable adult cod habitat. This explained the decline in cod resources for coastal fishers and their perception of an off shore movement. Adaptive management needs to be refined to include spatio-temporal effects of climate change to ensure fairness and sustainability.

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