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The more the merrier? Testing spatial resolution to simulate area closure effects on the pelagic North Sea autumn spawning herring stock and fishery

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ABSTRACT

Spatially explicit bio-economic models that are age-structured and dynamic become increasingly important, being used for different purposes including spatial management measure evaluation. One of the reasons why those complex models are still rare is the extensive data need. FishRent incorporates highly resolved economic information of multiple fleets at the same time linking this to a detailed age-structured biology of multiple species simultaneously. Additionally, it follows the European Data Collection Framework (DCF) data structure, hence the data is relatively easy to implement We adapted the temporal (annual) version of the pelagic FishRent model to be spatially explicit and incorporated seasonal migration patterns of North Sea herring. During this process, we showed the effects of increasing the spatial resolutions on simulated stock biomass and simulated fleet behaviour. When interested in the general, annual population development over the years, a relatively low resolution might suffice. Spatial effects of the fleet behaviour are, however, better captured with a higher resolution. Further, we closed the major spawning grounds at different resolutions. By doing so, we illustrated the need to incorporate a dynamic behaviour of fishing fleets and to increase fleets' flexibility by increasing the amount of accessible areas for each fleet.

1. Introduction

During the last decades, the need for tools that can estimate and evaluate trade-offs and feedback effects between the sustainable, long-term supply of resources, their management and socio-economic impacts is increasing. For this reason, Integrated Ecological-Economic Fisheries Models (IEEFMs) are becoming increasingly popular (Nielsen et al., 2017). They mathematically combine anthropogenic and natural processes addressing several disciplines from socio-economics to oceanography (Bastardie et al., 2013; Tahvonen et al., 2013; Maynou et al., 2014; Bartelings et al., 2015; Simons et al., 2015; Pascoe et al., 2016; Nielsen et al., 2017; Da-Rocha et al., 2017). Different types exist, ranging from conceptual/descriptive over strategic to tactical models with various details and resolutions. The application often depends on the research question and data availability (Fulton et al., 2015; Nielsen et al., 2017). Equilibrium or "end-to-end" models usually have an increased focus on the complexity of the whole ecosystem, including food webs, detailed functional groups and different human uses. Fulton et al. (2015) define these to have a rather strategic, long-term purpose. In this study, we however apply a tactical model, which is more focused on certain aspects of a system. FishRent is an optimization and simulation model integrating a dynamic age-structured population model with highly resolved catch-effort data and the detailed cost structure of different fleets (Salz et al., 2011; Bartelings et al., 2015; Simons et al., 2014, 2015; Rybicki et al., 2020). It provides short to mid-term economic and biological outputs for a pre-defined set of scenarios (Guillen et al., 2004). FishRent identifies the effort allocation that maximizes a certain target variable, i.e. net profit, under a set of constraints such as management measures. There exist different versions of FishRent and so far, the model has mainly been used to study the impact of management measures on demersal European fleets (Salz et al., 2011; Bartelings et al., 2015; Simons et al., 2014, 2015; STECF, 2015) but has recently been adapted as a temporal model to pelagic fleets targeting Northeast Atlantic mackerel and North Sea autumn spawning (NSAS) herring (Rybicki et al., 2020).

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A relatively recent step towards more complex IEEFMs that increase fishery dynamics is spatial explicitness. This aspect is necessary for spatial management measure evaluation, such as spatial effort management (Russo et al., 2017), spatial fishing grounds (Heath et al., 2014) or the requirements and effectiveness of marine reserves or marine protected areas (MPAs) (Pelletier and Mahévas, 2005). Marine reserves are often related to no-take zones, permanently prohibiting any anthropogenic activities, whereas MPAs are usually referred to when implementing areas where certain activities or types of fisheries are restricted (Pelletier and Mahévas, 2005; Lester et al., 2009). Employing either of the two can be important to buffer any impact on reproduction and recruitment (Lester et al., 2009). Low recruitment despite high biomass levels is currently a significant problem concerning the NSAS herring stock (Nash and Dickey-Collas, 2005; Gröger et al., 2009; Payne et al., 2009; Nash et al., 2009; Corten, 2013a,b; ICES, 2018a).

Although overfishing is not thought to be the main problem for the currently observed low NSAS herring recruitment, implementing a marine reserve or MPA for the core spawning grounds could reduce the general pressure on the spawning component of the stock. Effects of such a closure can be tested by applying a spatio-temporal version of the pelagic FishRent model. The data needed to test for temporal scenarios only is already demanding, but for spatio-temporal closure scenarios it is extensive and the error as well as uncertainty of results increases. This is also why assessment models are often neither spatially explicit nor consider seasonality (Holland and Herrera, 2012; Cadrin et al., 2020; Cadrin, 2020; Maunder et al., 2020; ICES, 2020a). Especially regarding pelagic, straddling stocks, the stock behaviour is, however, an important characteristic to consider and occurs over both, space and time (Corten, 2001; Bjørndal and Munro, 2020). The accuracy of the patterns used in models is highly significant. If the model is only spatially and not seasonally resolved, a constant biomass distribution throughout the year and therefore also annual catch rates would be assumed. This can lead to a higher simulated fishing intensity than observed in reality, in which fleets are actually limited by time and may also change fishing areas within a season. Thus, spatio-temporal models should be used for management strategy evaluation (Maunder et al., 2020).

However, the greater the model complexity, the more assumptions and decisions between desired analysis and actual data availability have to be made as the need for data to parameterize the model appropriately increases immensely. In respect to modelling effort, time and accuracy, a balance between a high spatio-temporal resolution and data necessity should occur. It is therefore important to know the limits of the underlying data in terms of time and space, which is one of the motivations behind this study. Nielsen et al. (2017) provide a good overview of different IEEFMs worldwide and compare capabilities amongst those, but they still compare models that use different spatial resolutions, study areas, species and fleets. Not many studies have yet been published that investigate trade-offs between increasing complexity and prediction accuracy of bio-economic models, mostly occurring due to the quality and availability of underlying data (Holland and Herrera, 2010, 2012; Jardim et al., 2018). Moreover, the issue of how much spatial complexity is actually necessary to evaluate the impacts of spatial management measure on fleet profitability as well as stock viability has not been addressed often (Campbell and Hand, 1998; Nielsen et al., 2019; Núñez-Riboni et al., 2021).

Additionally, the NSAS herring stock is thought to be spatially characterized by four spawning components (Shetland/Orkney, Buchan, Banks and Downs), which are also thought to differ by migration routes, recruitment patterns and growth rates (Dickey-Collas et al., 2010). These could be considered as separated sub-populations within one NSAS metapopulation, although they do overlap spatially during the feeding season (Den Held, 2009). During the year, NSAS herring is further thought to mix with other Atlantic herring stocks but due to the large population size, it is thought to be dominant in the North Sea region and is therefore managed as one unit (Quinn and Deriso, 1999; Dickey-Collas et al., 2010). This is thought to have operated well (Reiss et al., 2009; Simmonds, 2009). For management purposes, the assumption of a single stock may be more convenient but the spatial, biological definition may differ (Hintzen et al., 2015). Concerns have been raised that the observation of local population units, instead of only the whole population, is highly important in order to maintain the genetic diversity and resilience (Kell et al., 2009; Kerr et al., 2010; Payne, 2010). Kell et al. (2009), for example, investigated influences of different levels of sub-populations of Atlantic herring along the western British Isles or considering only one unit. They conclude that the benefit of incorporating sub-populations into management highly depends on the ability to assess them separately as well as on the possibility to distinctly record the different components in catch data. However, they state that the aggregation into one unit may lead to underestimating the risk of overfishing as well as overestimating the possibility to recover (Kell et al., 2009). Especially in the light of ecosystem-based approaches to management and the introduction of MPAs, they argue that a greater focus on the population structure is going to be indispensable in future.

In order to address the issue of the necessary degree of spatial complexity when incorporating seasonal migration patterns, we use the temporal pelagic FishRent version and adapt it to include seasons (instead of years only) as well as space (more than one area). In this process, we consider the different migration routes as well as seasonal biomass distributions of the different NSAS herring components, especially the more distinct southern (or Downs) component. Further, we evaluate what the effect of different spatial resolutions would be on the simulated effort distribution and net profit of key European pelagic fleets targeting NSAS herring when increasing fleets' flexibility. FishRent, is a well-suited tool when it comes to dealing with multiple fleets at the same time. It takes fleet specific cost-structure, catch rates, catch composition, quota allocations and past fishing patterns (spatial and seasonal) into account. This can be especially important when trying to estimate impacts of management objectives involving straddling stocks, which are mostly pelagic species. Finally, we determine the impacts on the stock biomass and net profit of those fleets when implementing a marine reserve for the core spawning grounds.

2. Materials and methods

2.1. Model description

The optimization and simulation model FishRent includes the economics of multiple fleets and the temporal and spatial interplay between fleets and fish stocks (Salz et al., 2011; Bartelings et al., 2015; Simons et al., 2015). It is written in the General Algebraic Modeling System (GAMS) and uses the CONOPT solver (for a detailed description see Drud, 1994) to determine effort, maximizing the total annual net profit of a fishery given the current ecological, regulatory and economic conditions. The model tries to find the optimal solution within a set of constraints. Those include a bounded vessel utilization (i.e. minimum and maximum number of days at sea per vessel, season and year), management constraints such as TAC, quotas, catch limited by biomass availability (for more details see management section for how those are implemented). For a complete model overview see Supplementary Figures S.4.1/2.

2.1.1. Economy

The calculation of net profit includes: (1) revenue of fishing activities, (2) capital and other fixed costs (e.g. administration, insurance, accountancy, maintenance costs, interest payments, and annual depreciation costs) and (3) operating costs including fuel, crew and other variable costs (e.g. expendables, income tax, landings, and sales costs) (Salz et al., 2011; Simons et al., 2015; Bartelings et al., 2015; Rybicki et al., 2020). Fish, fuel prices and catch determine effort allocation and revenue, revenue in turn influences operating costs (see Eq. S.1 to S.13 in Supplementary material), and fixed costs are proportional to the number of active vessels. On–off subsidies are not explicitly modelled in FishRent but depending on the available data they could be included as a fixed percentage that is added to the income. Discarding was not considered since reported discards by the NSAS herring fishery are usually extremely low or not present. More information concerning parameter estimations in general can be found in Supplementary material S.1/2.

2.1.2. (Dis-)investment

After the first modelled year, fleet size can decrease or increase (in terms of vessel numbers), depending on fleet profitability: (1) If fleets are profitable, reach their effort capacity, and are below their maximum investment limit, they are allowed to invest into new vessels by 4% at most. (2) If fleets are unprofitable (i.e. make losses), they can disinvest by a maximum of 10% per year. The investment limits in this model version were determined by the average maximal change of investment and disinvestment of the modelled fleets observed within the last 10 years (STECF, 2016). This approach was also used by Simons et al. (2015) and Bartelings et al. (2015).

2.1.3. Spatial and seasonal dynamics

2.1.3.1. Fleet. First, the fishing effort allocation, which is based on area, season and year, is calculated (Eqs. (1) and (2)).

$$\mathrm{TEff_j} = \mathrm{sum_{k,t}}[(\mathrm{Eff_{j,k,t}} * \beta \mathrm{s_{j,k,t}}) * \mathrm{Eff_{j,k,t}}]/(1 - \mathrm{DASOTH_j}) \quad (1)$$

$TEff_j$ is total effort for jth fleet, $Eff_{j,k,t}$ is the fishing effort for jth fleet, kth area at time t, $\beta s_{j,k,t}$ is a fishing effort multiplier (see Eq. (2)) and $DASOTH_j$ is the proportion of total days at sea observed of other species.

$$\beta \mathrm{s_{j,k,t}} = (\mathrm{TEff_{j,k,t0}} - \mathrm{Eff_{j,k,t0}})/\mathrm{Eff_{j,k,t0}} \quad (2)$$

To avoid an unrealistic interannual variation of effort, future simulated effort of individual fleets may vary between a lower and upper limit set at 60% of historically observed total effort and historically observed maximal total effort per vessel. Bartelings et al. (2015), who considered demersal fleets, set the initial value for this parameter to 80% fitting well to the corresponding multiannual plans of their fleets. However, due to the volatility of pelagic TACs we chose a lower value, which was estimated in an unpublished sensitivity analysis during the FishRent model adaptation from demersal to pelagic (Rybicki et al., 2020; for more detail concerning the effort calculation see Supplementary S.1).

Seasonal and spatial catch rates are then calculated by using the Cobb–Douglas catch production function (Eq. (3)). Fishing effort as well as total stock biomass are considered, assuming a non-linear relationship between catch and effort as well as between catch and stock size (Frost et al., 2009; Supplementary material S.1/2).

$$\mathrm{C_{t,i,j,k}} = \mathrm{c_{t,i,j,k}} * \mathrm{E_{t,j,k}}^{\alpha_{1j}} * \mathrm{CB_{t,i,k}}^{\beta_{1j}} \quad (3)$$

where $C_{t,i,j,k}$ is the catch at time t, for ith age class, jth fleet and kth area; $c_{t,i,j,k}$ is the catchability coefficient; $E_{t,j,k}$ is the fishing effort; $CB_{t,i,k}$, is the stock biomass and α_{1j} and β_{1j} determine the degree of non-linearity in the relation of catch and effort for a given stock size.

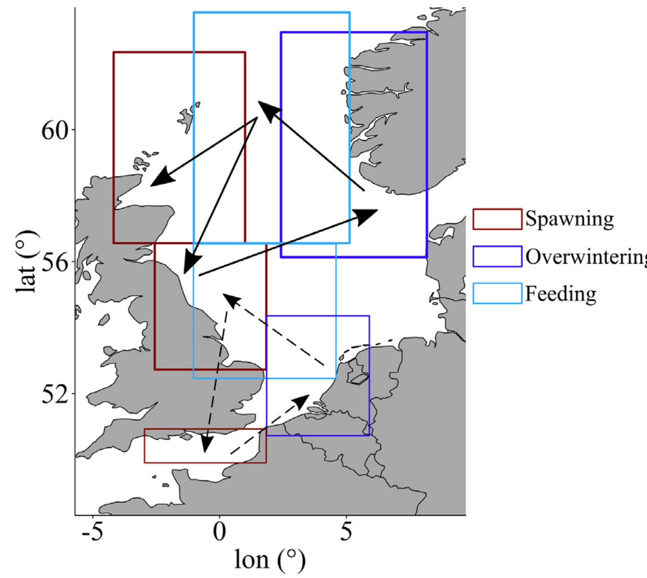

Fig. 1. Schematic of the migration routes for the different NSAS herring components (solid lined arrow: main component, striped arrow: Downs component). Red marks the area where spawning takes place between August and December, dark blue where NSAS herring is thought to overwinter between January and March and light blue where feeding occurs between April and July (after Corten, 2001, 2013a,b; Dickey-Collas et al., 2010). (For interpretation of the references to colour in the figure legends, the reader is referred to the web version of this article.)

In this study, the application of the Cobb–Douglas function is of particular importance since pelagic fish usually form large schools and a non-linear relationship between effort and amount of catch is common (Frost et al., 2009; Cruz-Rivera et al., 2018). A sensitivity analysis concerning the two parameters representing the degree of non-linearity in the relation of catch and effort for a given stock size, was already performed in Rybicki et al. (2020). They showed that changes in effort had a larger impact on the catchability and therefore also on the amount of catch per fleet than changes in biomass. This is thought to be a common observation when considering pelagic fisheries (Harley et al., 2001; Frost et al., 2009).

2.1.3.2. Stock. In general, NSAS herring migrations start in August–September with the northern and central population migrating from their feeding grounds (April–July) in the central and northern North Sea to their spawning grounds along the UK east coast and Shetland (Corten, 2001). This is the most important time for targeting NSAS herring. Afterwards, they continue to migrate to their overwintering areas in the eastern part of the North Sea along the Norwegian Trench. The southern population, however, spawns in the fourth season of the year, mostly December (Corten, 2001). This takes place in the English Channel. Overwintering occurs in the southern North Sea and feeding is, similar to the central population, typically in the central North Sea (Corten, 2001).

The following procedures are used in order to calculate and redistribute the abundance of NSAS herring according to the migration routes (Corten, 2001, 2013a,b; Dickey-Collas et al., 2010) as described before:

First, the number of individuals $N_{t,i,k}$ is estimated for each time step t, which is season (i.e. quarter of a year) and year, ith age class and kth area. This is done by applying the determined catch from the Cobb–Douglas function (Eq. (3)) in Pope's approximation (Eq. (4); Fig. 2; Pope, 1972; Supplementary material S.3) as well as the initial abundance from the latest stock assessment when starting this study (ICES, 2018a; for a fully detailed model schematic see Supplementary Figure S.4.1).

$$\mathrm{N_{t,i,k} = N_{t-1,i-1,k} * exp^{-M_i} - sum_j[(C_{t-1,i-1,j,k})/(w_i * sum_j(s_j))] * exp^{-(M_i/2)}} \quad (4)$$

where $N_{t,i,k}$ is the number of individuals at time t, ith age class and kth area, $C_{t-1,i-1,j,k}$ is the catch at time $t-1$, ith age class, kth area and jth fleet, w_i is weight at age and s_j is the catch share. Catch share is a multiplier that determines total catch, hence accounting for the remaining fishing mortality by fleets not included in the model. It is the proportion of each fleet's catch from the TAC, i.e. representing their quota shares. The instantaneous natural mortality rate is represented by M_i. Both catch share and natural mortality are constant over time.

The initial abundance was available annually and per age-group (Fig. 2, step 1). Therefore, the abundance of the sub-populations had to be spatially distributed in each season before entering into the model. This is done depending on the catch distribution. This is usually biased towards the areas of greatest interest to the fishing industry, which in case of NSAS herring are, however, also where most biomass can be found (i.e. along the north-eastern UK coast). The approach assumes the best knowledge of the fishermen, which in reality is actually very good regarding pelagic species due to extremely well-developed sonar techniques and long-term experiences of targeting the main component of NSAS herring during its spawning season in the third quarter of a year.

Next, the stock migrates based on the migration matrices for the rest of the year and the time series, accounting for the migration routes of the different spawning components (from north to south: Shetland/Orkney, Buchan, Banks (those three represent the main NSAS component) and Downs; Fig. 1; Fig. 2, step (3)). The detail of migration, however, depends on the resolution (i.e. the higher the resolution the better the simulation of migration routes; Supplementary Figs. 6–8). Hence, the abundance has to be spatially redistributed according to well-known NSAS herring migration routes following Corten (2001, 2013a,b) and Dickey-Collas et al. (2010). These distributions are also in accordance with outcomes from surveys used in the stock assessment (ICES, 2018a,b). The redistribution is done using a migration matrix fmc, in which the user pre-defines the corresponding stock proportions moving from one area to another, and varying between 0 (no fish move from area k to area kt) and 1 (all fish from area k migrate to area kt).

The corresponding equation (Eq. (5)) is defined as follows:

$$\mathrm{Nmig_{t,i,k} = N_{t,i,k} - [(N_{t,i,k} * fmc_{t,k,kt}) - (N_{t,i,kf} * fmc_{t,kf,k})]} \quad (5)$$

where $Nmig_{t,i,k}$ is the new number of individuals at time t, ith age class and kth area, and $fmc_{t,kf,kt}$ is the migration matrix where kf (from which area) and kt (to which area) define the direction of movement between areas (Fig. 2, step 3).

Finally, recruitment is simulated using a restricted (B_{lim}) hockey-stick stock-recruitment function (Payne et al., 2009; ICES, 2018b; Supplementary Eq. (15)/Figure S.3), with 1000 random stochastic iterations to include a standard error for recruitment and SSB. Median recruitment and spawning stock biomass (SSB) values are then used to calculate survival, fishing mortality and next year's TAC (see management section). At the end of each year, all individuals within one age class are transferred to the next and those older than the modelled maximum age are aggregated in the last age class, which in this case is an age-8+ group. For further detail, also for a robustness analysis of the biological module, see Rybicki et al. (2020), Bartelings et al. (2015) or Simons et al. (2014).

2.1.4. Management

Management wise, NSAS herring is modelled in the same way as in the ICES stock assessment, as one population. Within the European Union, the TAC is now supposed to be set according to the MSY approach. The fishing mortality of NSAS herring has been 44% below the advised F_{msy} on average since 2007, due to relatively low TAC settings (ICES, 2018a). Rybicki et al. (2020) used a fixed level of the averaged fishing mortality (2007–2017) by adding a multiplier to the advised F_{msy} in order to simulate a more realistic fishing mortality (for a more detailed management procedure schematic see Supplementary Figure S.4.2). This approach was also applied in this study. The Baranov catch equation was finally used in order to calculate a catch according to the target fishing mortality (0.14) (Baranov, 1918; for further detail see Simons et al., 2014, Bartelings et al., 2015, or Rybicki et al., 2020). This catch is finally used as the new TAC for the following year. No harvest control rule is currently active. Moreover, all fleets are limited by their quota, which is a fixed proportion of the TAC, as well as total catch, which has to be below 95% of the total stock biomass. This limit was introduced to guarantee that some biomass remains the water. In some scenarios, area restrictions or closures are active. This was implemented according to Bartelings et al. (2015, Eq. (6)).

$$\mathrm{\lambda * CB_{i,k,t} >= sum_j[C_{j,i,k,t}/(1 - clos_{j,k,t})]} \quad (6)$$

where λ is set to 0.95, $CB_{j,k,t}$ is the total biomass for ith age class, kth area at time t and C is catch for jth fleet. The parameter $clos_{j,k,t}$ has to be previously defined by the model user and lies between 0.001 (no closure) and 0.99 (full closure).

2.2. Data and settings

FishRent was run for a period of 16 years (2014–2030) using five fleets (Table 1) targeting NSAS herring. Only fleets where herring constituted more than 25% of the total landings value were considered in the modelling approach. Fleets are classified by vessel length categories (>40 m) and their predominant gear types (pelagic trawlers (TM) or purse seiners (PS)), following the classification of the European data collection framework as implemented by the Scientific, Technical and Economic Committee for Fisheries (STECF, 2018). Detailed economic data (e.g. costs, effort, profit etc.) was received directly from national labs and averaged over the years 2012 to 2014 into a unique start value that was used as a starting point for 2014. Here it should be highlighted, that data was not freely available in such detail when this study began, especially the economic data. Unfortunately, data from Norway could not be obtained.

For the calibration process, detailed biological data at age (i.e. abundance, natural mortality, weight, SSB and recruitment) was used from the most recent stock assessment at the beginning of this study (ICES, 2018a). Due to significant biological changes after 2014, especially in fishing mortality and weight at age, an average of five years (2012–2016) was chosen for the biological input instead of only three (2012–2014; ICES, 2018a). Again, the average was used as a starting point for 2014.

2.2.1. Scenario 1a: Incorporating seasonal biomass patterns in different spatial resolutions

We employed four spatial resolution scenarios and distributed the seasonal biomass accordingly as described in the Biology section (Figs. 3 and 4; Supplementary Figures S.6-8).

The first resolution covers only one area, i.e. the Greater North Sea (including eastern Channel), and does not include any seasonal migration patterns (Fig. 3.A). This, therefore, represents a non-spatial scenario. Hence, the dynamics of this scenario are limited to re-distributing the effort over time only. The second

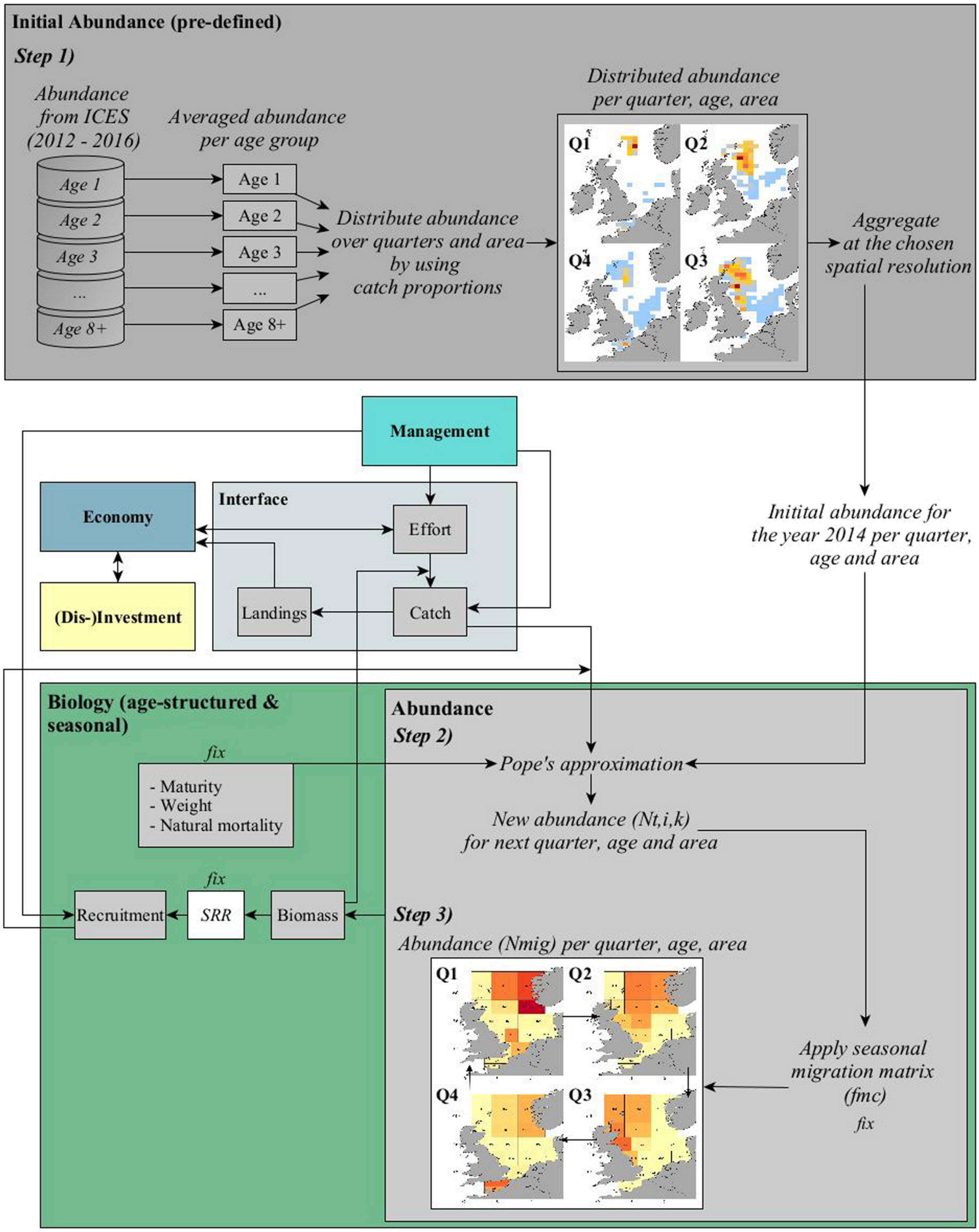

Fig. 2. Detailed schematic of the biology module in FishRent. The abundance preparation/calculations (steps 1 to 3) are shown in greater detail. (1) Initial abundance (pre-defined): The initial abundance per age group is averaged for years 2012 to 2016. Then the catch proportions are used to distribute the average abundance per age group over the seasons (i.e. quarters of a year) and areas. Next, the areas are aggregated at the relevant spatial resolution. This represents the start abundance for the initial year 2014. (2) Within the model, the new abundance $N_{t,i,k}$ is calculated for the next quarter and year t, ith age group and kth area by applying Pope's approximation. (3) This is then applied together with the seasonal migration matrix $fmc_{t,kf,kt}$ in order to calculate the abundance $Nmig_{t,i,k}$ per quarter, age and areas corresponding to known migration routes of NSAS herring and is finally used for further biomass as well as recruitment calculations. Note: SRR signifies stock-recruitment relationship function. Parameters marked as "fix" do not change over time or space. (See Supplementary Figure S.4.1. for the whole model overview).

resolution covers eight-areas (8 A), already introducing more dynamics in space (Fig. 3.B; Table 2), whereas the third incorporates eighteen-areas (18 A). In this case, the western part of the North Sea is further subdivided to capture the spatial migration patterns and the core spawning grounds more accurately than in the other two resolutions (Fig. 3.C). In all resolutions, we assume that seasonal migration patterns stay constant among modelling years and that the biomass is homogeneously distributed within

Table 1
Overview of the five fleets included into the model, their vessel sizes (in metres), primary fishing and cooling technique and the name used within this study. Note: RSW means refrigerated seawater.

Fleet	Size	Technique	Cooling technique	Name
Denmark	>40 m	Pelagic Trawler	RSW	DK (TM >40 m)
Denmark	>40 m	Purse Seine	RSW	DK (PS >40 m)
Netherlands	>40 m	Pelagic Freezer Trawler	Freezing	NL (TM >40 m)
Germany	>40 m	Pelagic Freezer Trawler	Freezing	D (TM >40 m)
United Kingdom	>40 m	Pelagic Trawler	RSW	UK (TM >40 m)

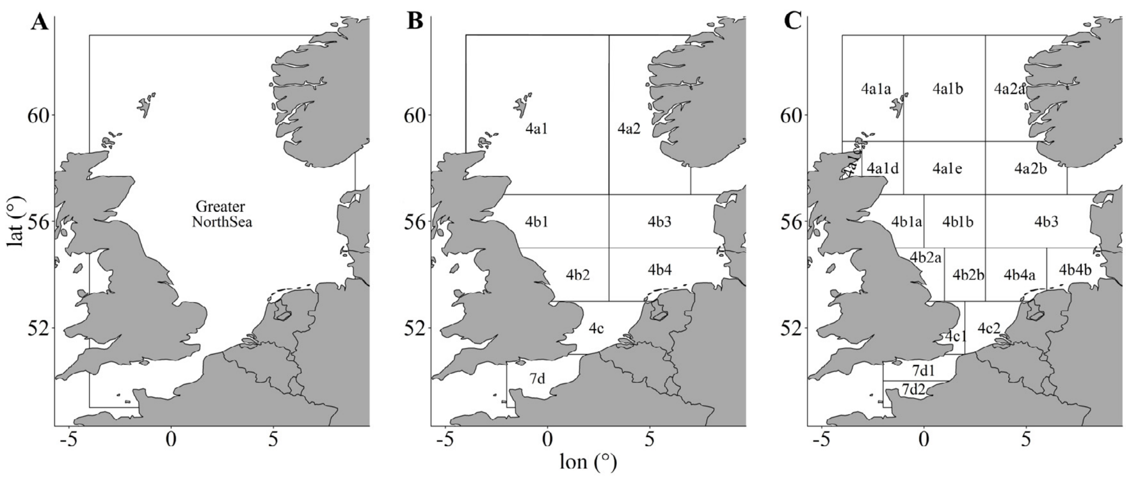

Fig. 3. Three different spatial resolutions. A: one area (1 A), B: eight areas (8 A) and C: eighteen areas (18 A).

an area (e.g. Fig. 4 for the 18 A resolution and Supplementary S.6–8 for the other resolutions). Another resolution (four areas) was tested but did not show any large differences compared to the 8 A resolution (for more information see Supplementary Figures S.5/6/9/10).

2.2.2. Scenario 1b: Increasing fleets' flexibility

During the process of scenario implementation, the inflexibility of the fleets (i.e. limitations of spatial choices to the ones already observed for the fleet) appeared to be a major problem as the fleet behaviour appeared to be very static and they are not able to vary much of their traditional patterns in terms of space and season. Thus, the area closure scenarios were difficult to implement. FishRent was originally developed for demersal fisheries, with relatively fixed fishing grounds and low seasonal patterns. During the spawning season in autumn, the NSAS herring fishery targets herring with a specific quality for specific products. Therefore, the main fishing grounds and fishing seasons are fixed to the spawning grounds and seasons, making them very static and inflexible. An attempt to increase fleet flexibility, other than introducing spatial stock dynamics, was to increase the amount of areas accessible for the fleets, because many fleets only fished in two or three areas in the initial data (Table 2; Supplementary Tables S.5/6). For this, the average catchability of an area where at least one fleet fished for herring was assigned to those fleets that did not fish in this area according to the input data. Catchability is defined as the relationship between resource abundance and the efficiency to capture the resource with a certain fishing gear (Arreguín-Sánchez, 1996). This assignment was done depending on the fishing technique because catchability is likely to be much higher for large (>100 m) freezer trawler than for smaller (24–80 m) refrigerated seawater (RSW) operated vessels, which need to return to the harbour more often. In the end the two freezer trawler fleets, the Dutch and the German, were allowed to fish within the same areas primarily increasing the areas available for the German fleet. The same approach was applied to the RSW trawler (two Danish and the UK fleet).

This scenario was performed in order to disentangle the changes in the fleet's spatial distribution due to closure or the increased flexibility added in the model (in reality, fleets have access to those additional areas).

2.2.3. Scenario 2: Closing the main spawning grounds

To show how the spatial version of the pelagic FishRent model can be used to address questions regarding spatial closures, we applied a closure scenario: the protection of the spawning stock by implementing a marine reserve for the core spawning grounds. Moreover, to show how different spatial resolutions affect outcomes, we applied this closure to the 8 A and 18 A resolution scenario (Table 2). For this, the areas covering the central spawning grounds along the UK coast were closed to any fishing activities during the third and fourth season (Fig. 5). Since the available areas for a spawning grounds closure with an 8 A resolution were very large, covering much more than the core spawning grounds, we implemented partial closures: In the third season, areas 4a1 and 4b2 were half closed (i.e. 50%), area 4b1 was closed to a third (33%) and in the fourth season, area 7d was half closed (50%). As for the 18 A resolution it was possible to completely close the particular areas (Fig. 5). Proportions were determined via spatial analysis in R (packages rgeos, maps, maptools, Version 3.5.2), in which the feature size of each area from the 18 A resolution as well as the size of each area from the 18 A resolution was estimated.

3. Results

3.1. Scenario 1a: Increasing spatial resolution

Under all spatial resolution scenarios, SSB decreased gradually. Differences between one area and eighteen areas were very small (<0.5%) and the general trend was a decrease from 3000 ktons in 2014 to 2240 ktons in 2030 (Fig. 6; Supplementary S.9). This decrease also occurred uniformly in space.

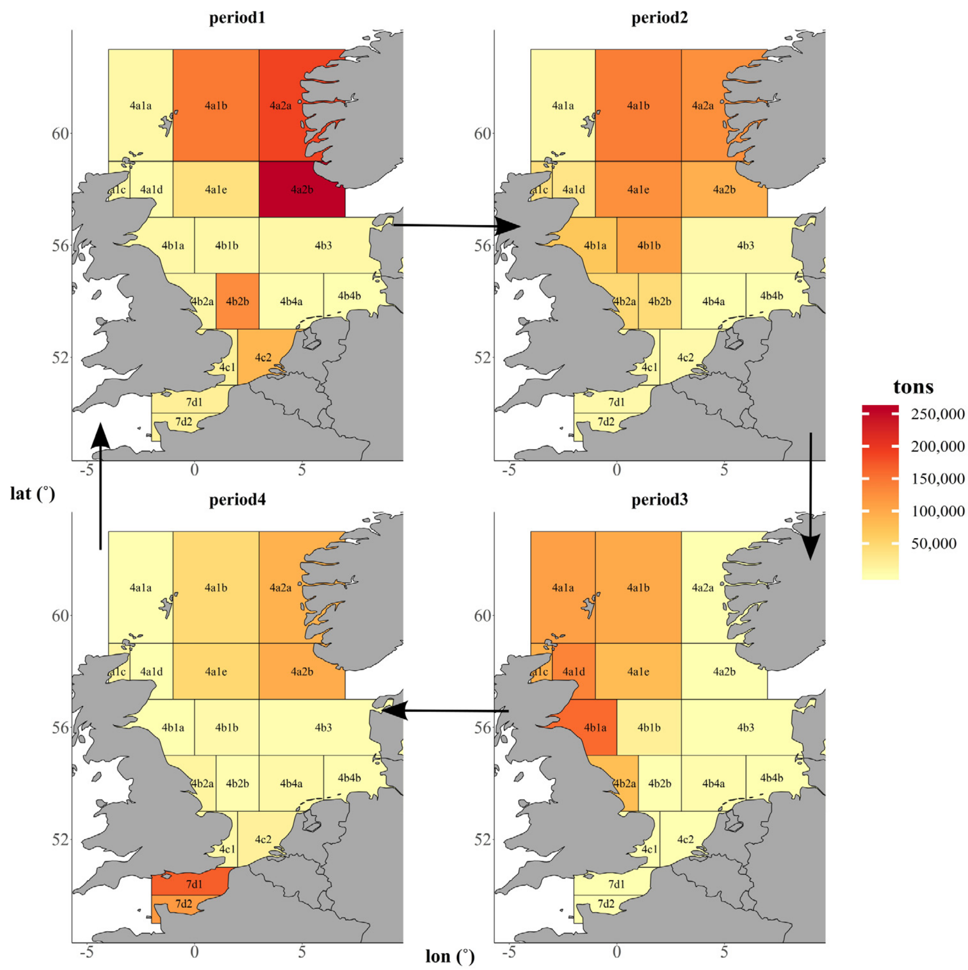

Fig. 4. Initial total stock biomass distribution within the third resolution (18 A) in each season (period 1 to 4) according to Corten (2001, 2013a,b) and Dickey-Collas et al. (2010). A similar overview of the other resolutions can be seen in Supplementary Figures S.6–8.

Table 2
Overview of changes implemented step by step for each of the scenarios. Note: Q3 and Q4 represent the 3rd and 4th season of a year.

Changes	Scenarios		
	1a) Resolution increase	(1b) Increase flexibility	(2) Spawning closure
(a) Resolution	1 (1A) 8 (8A) 18 (18A)	8 (8A_flex) 18 (18A_flex)	8 (8A_clos /8A_flex_clos) 18 (18A_clos /18A_flex_clos)
(b) Additional access to areas	no	yes	yes
(c) Area closures	no	no	yes 8: partial closure of Q3: 4a1 (34%), 4b2 (56%), 4b1 (32%) Q4: 7d (65%) 18: full closure of Q3: 4a1a, 4a1c, 4b1a, 4b2a Q4: 7d1,7d2

The spatial resolution did not have a large impact on effort, catch and profit over time (Fig. 7). When comparing catch over time, differences were very small between the 1 A to 18 A resolution (<0.5%, Fig. 7). In 2030, catch was slightly higher (+0.5%) for the 8 A resolution than for the 18 A resolution (−0.1%).

The variations in effort, and correspondingly fuel costs, were slightly larger: After four years (in 2017), total effort decreased by up to 7% (Danish Pelagic Trawler fleet) under the 8 A resolution compared to 1 A (Fig. 7, left). The remaining fleets varied between −2% and +2%. On the long-term (until 2030), total effort of all fleets increased by up to 10% (Dutch fleet) under all spatial resolutions (Fig. 7, right). When increasing from 8 A to 18 A, on the other hand, most fleets increased total effort, especially the Dutch UK and Danish Pelagic Trawler fleet (Fig. 7, right).

Within the first four years, changes in profit were also very small compared to the 1 A resolution, but on the long-term varied to a slightly larger extent (Fig. 7, right). Especially the German fleet was 11% less profitable on the long-term compared to the 1 A resolution with increasing spatial resolution. The Dutch, UK and Danish Purse Seine fleets showed the least variations in profit

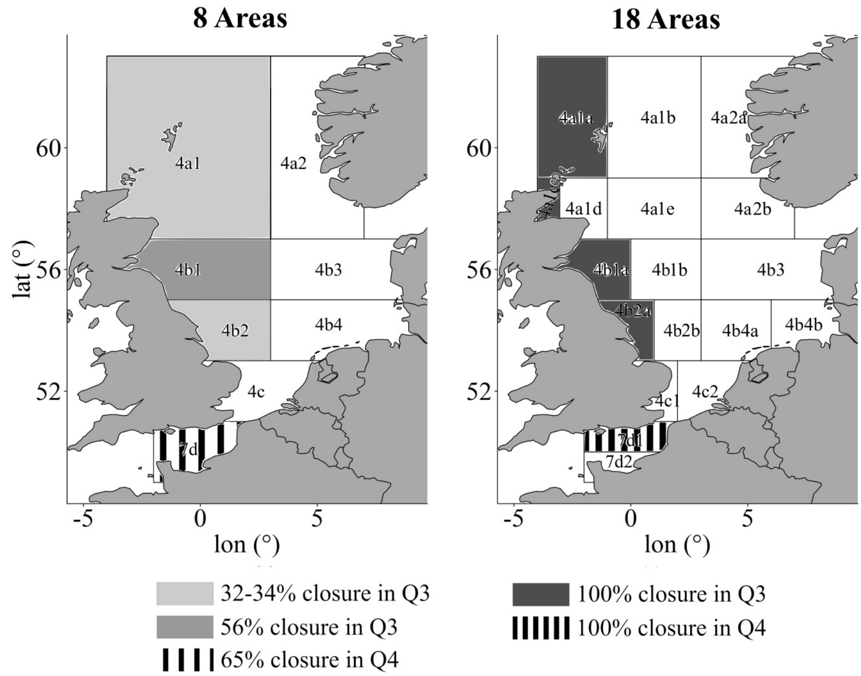

Fig. 5. Closures due to a marine reserve implementation, covering the core spawning grounds during spawning season in the third (Q3) and fourth (Q4) season with 8 A (left) and 18 A (right).

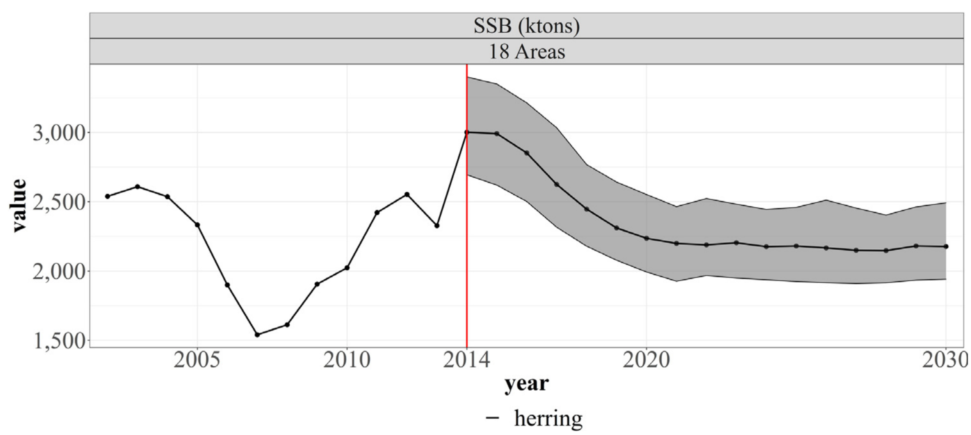

Fig. 6. SSB trend (ktons) of NSAS herring. The historic trend can be seen from 2002 until 2013 (ICES, 2018a) and the modelled trend from 2014 to 2030 of the 18 A resolution. The red vertical line marks the start of the model calculations in 2014.

over time compared to the other fleets, but all were slightly less profitable under the 18 A resolution than under the 1 A resolution scenario (-2% on average; Fig. 7). No fleet had to reduce their numbers of vessels, hence still being profitable over time in general.

Alterations occurred in both space and time. Seasonal effects could also be noticed when increasing the number of areas (Fig. 8). For the 8 A resolution, for instance, fleets reduced their effort and catch in season four rather than in the main fishing season three, whereas with the 18 A resolution they were able to maintain the catch level in season four (Fig. 8). Further, the total catch follows the more stable biomass trend observed after 2020 (Fig. 6).

As an example for fishing effort changes in space, we will present season three and four from the 8 A and 18 A resolution for the German and UK fleet as these were the seasons with the largest changes (Figs. 9 and 10). Again, it can be noticed what was already described before: for the 8 A resolution, the German fleet increased their fishing effort by approximately 15% (2030) around Scotland (4a1 and 4b1) in season three and remained unchanged compared to the initial year 2014 in area 4b2, east of England. In season four, fishing effort remained unchanged in 4a1 but decreased by up to 60% in the southern North Sea (7d; Fig. 9 A/B). In the 18 A resolution, however, the German fleet already decreased its fishing effort by 30% in season three in area 4a1e but could sustain their catch level in all other areas and even increase their effort (and catch) by 10% in area 4b1a. In season four, they did not change any effort in area 4a1e (northern North Sea) but increased their fishing effort in 7d1 (eastern Channel), which is also the time of the valuable herring roe fishery in the English Channel (Fig. 9 C/D; Herrfurth, 1986). Hence, increasing the number of areas from 8 A to 18 A provided the possibility to alter and shift the fishing effort in space rather than season.

Another example for the effects of increasing spatial resolution is the fishing effort distribution of the UK fleet in season three (Fig. 10). For the 8 A resolution, the northern part of the North Sea was not very detailed as the only area, which is available for the fleets, is area 4a1. In this scenario, the UK fleet decreased their

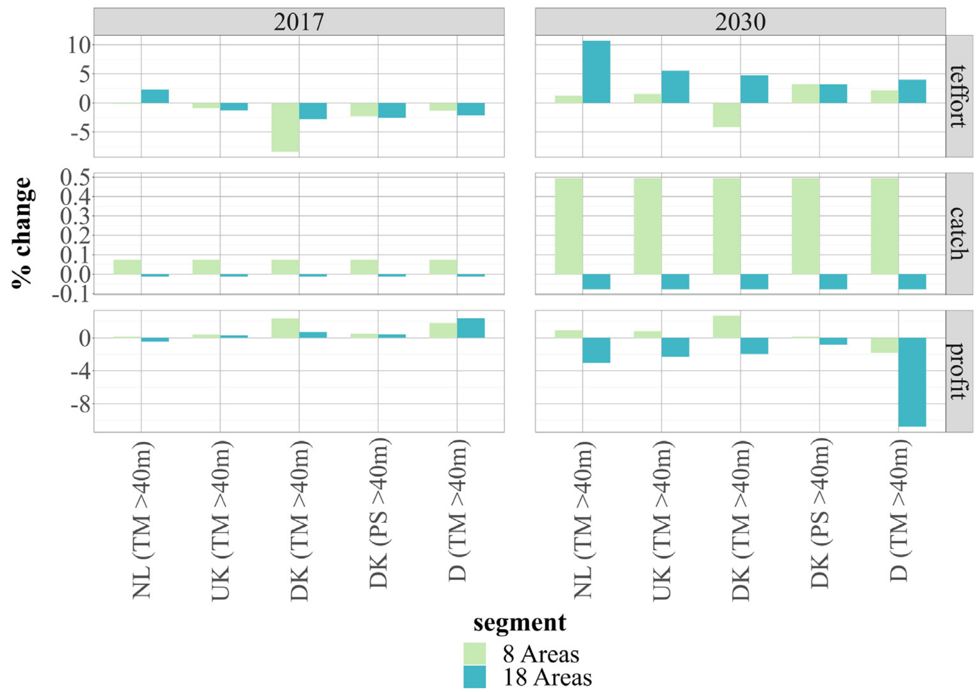

Fig. 7. Total effort (teffort), fuel costs and profit changes (%) of all five fleets in 2017 and 2030 compared to the 1 A resolution under Scenario 1a. Light green for the 8 A and blue for the 18 A resolution.

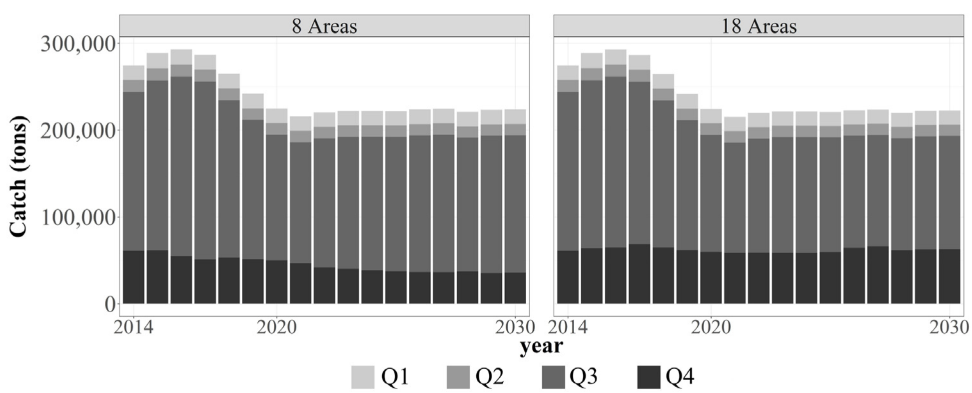

Fig. 8. Seasonal changes in catch (tons) for the 8 A and 18 A resolution from 2014 to 2030 under Scenario 1a. Light grey (top) represents season one (Q1), medium grey is for season two (Q2), dark grey for season three (Q3) and black (bottom) for season four (Q4).

effort by approximately 20% in 4a1 (2030 compared to 2014). When increasing the spatial resolution to 18 A, on the other hand, the UK fleet was able to increase their effort (and catch) in area 4a1d (+10%) and 4a1e (+ 20%) and only decrease fishing effort in 4a1a but in this case by up to 70% (Fig. 10). Again, this illustrates the increase in spatial flexibility of the fleets with a higher spatial resolution.

3.2. Scenario 1b: Increasing fleets' flexibility

Increasing the access to more fishing grounds did not have the expected effects when it comes to applying the approach on different resolutions. The difference between 8 A and 8 A_flex was only <0.1%. When comparing 18 A to 18 A_flex the differences were also very small, except for the German fleet (Fig. 11). When only providing more flexibility without closing any areas, the profit was +10% compared to the 18 A scenario (Fig. 11, right). They also reduced their total effort and therefore fuel costs. At the same time, catch increased in area 4a1b (northern North Sea) and slightly decreased in 4b1a (central North Sea) in 2030. Yet, fleets in general stayed in their historical fishing grounds, which are predefined by the underlying data (i.e. spatial catch rates are based on observed data and for areas without any record of fishing activities in the initial time series for the modelled fleets the catch rate is zero). Therefore, the effects on the stock were also not significant (Fig. 12).

3.3. Scenario 2: Closing the main spawning grounds

When it comes to implementing area closures, the access to additional areas does make a slightly larger difference with a higher resolution (18 A scenarios) on the long-term, again especially for the German fleet (Figs. 10/11). Under 18 A_clos (no additional access), the German fleets' profit was nearly -90% compared to Scenario 1a (18 A; i.e. no additional access or closure) on the long-term (Fig. 11, right), whereas under 18 A_flex_clos (additional access and closure), profit of the German fleet was only -45%. In general, results for all fleets using pelagic trawls (TM) were somewhat more positive, especially on the long-term, when providing the possibility of a higher flexibility than without

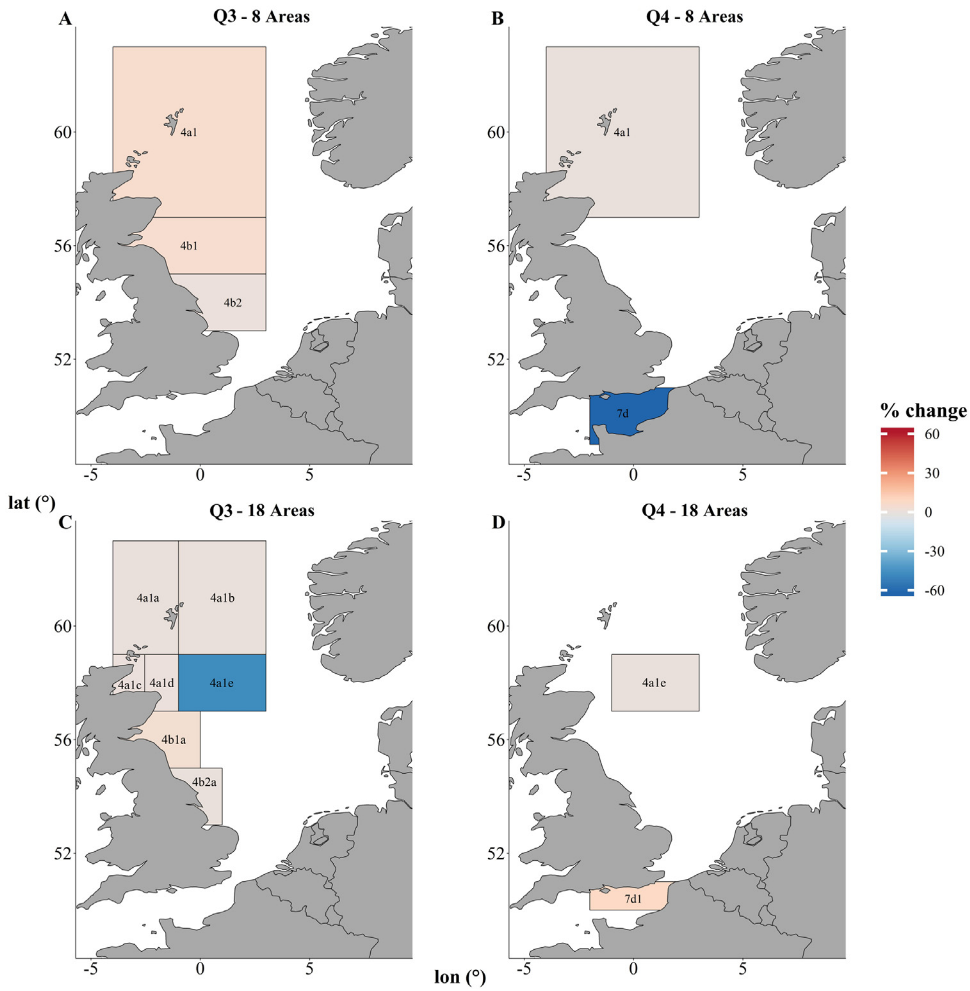

Fig. 9. Spatial perspective of fishing effort variations (% change in 2030 compared to the initial year 2014) of the German fleet for the 8 A (A and B) and 18 A (C and D) resolution for season three (Q3, left) and four (Q4, right) under Scenario 1a. Blue is a negative change compared to 2014, whereas red is a positive change.

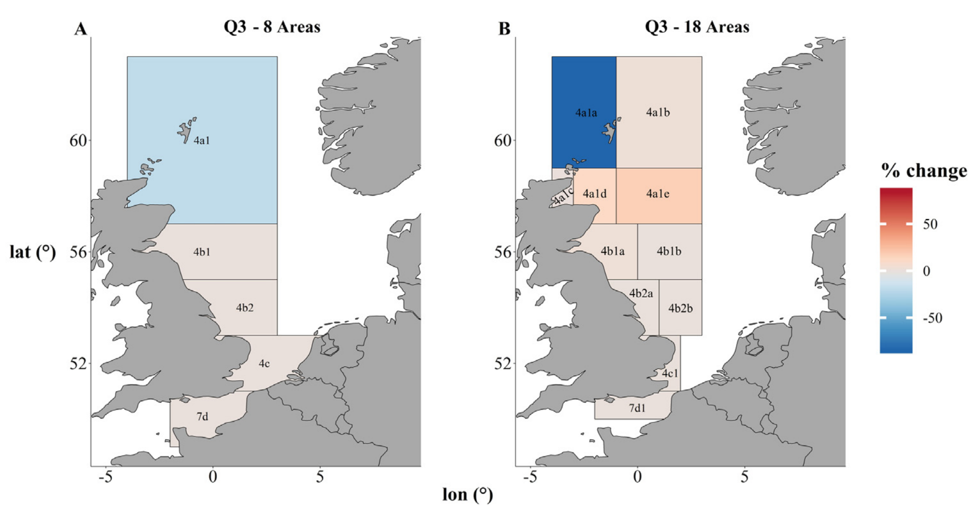

Fig. 10. Spatial perspective of fishing effort variations (% change in 2030 compared to the initial year 2014) of the UK fleet in the 8 A (A) and 18 A (B) areas scenario for season three (Q3, their main fishing season) under Scenario 1a. Blue is a negative change compared to 2014, whereas red is a positive change.

(18 A_flex_clos vs. 18 A_clos). There were no effects of the partial closure with an 8 A resolution (therefore not shown).

The difference in SSB between 18 A_clos and 18 A_flex_clos was small (0.5%) (Fig. 11) and resulted in a difference of 0.75%

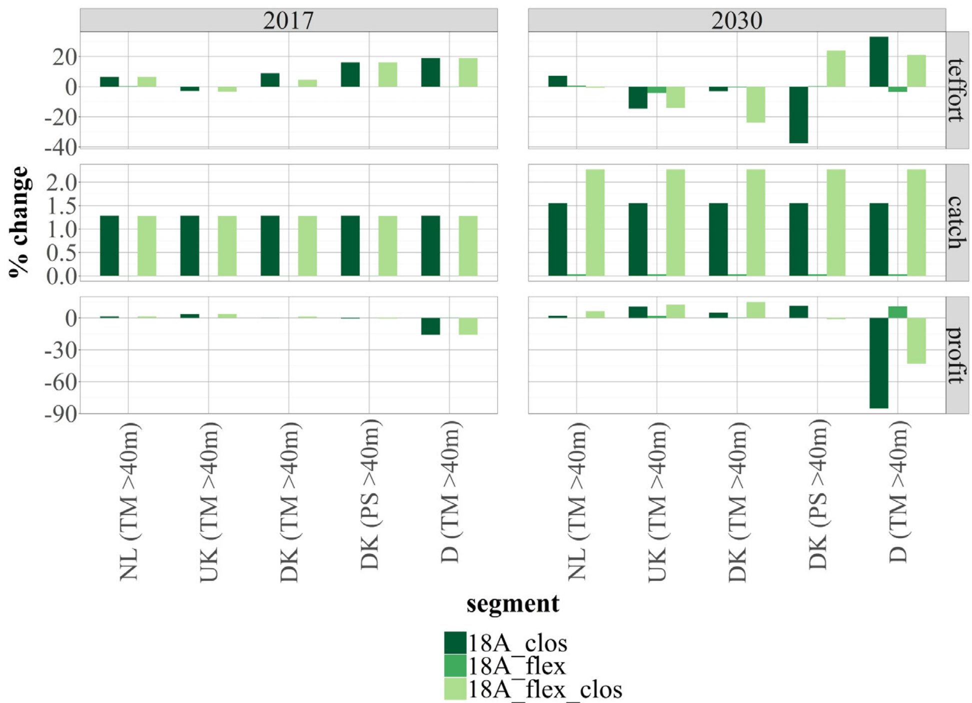

Fig. 11. Total effort (teffort), catch and profit changes (%) of all five fleets in 2017 and 2030 compared to 18 A resolution (Scenario 1a). Medium green: Scenario 1b (18 A_flex), dark and light green: Scenario 2 (18 A_clos, 18 A_flex_clos correspondingly).

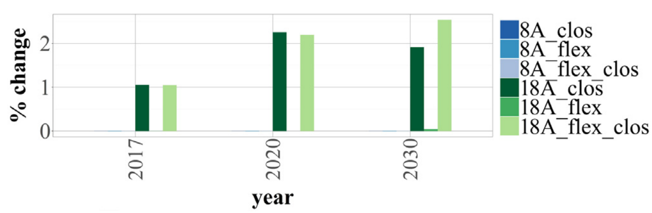

Fig. 12. SSB change (%) in 2017, 2020 and 2030. Results are shown for Scenario 1b (8 A_flex, 18 A_flex) and Scenario 2 (8 A_clos, 8 A_flex_clos, 18 A_clos, 18 A_flex_clos) compared to Scenario 1a (8 A (blue shades), 18 A (green shades) correspondingly). Note: There was nearly no effect resulting from the 8 A scenarios, which is why no blue bars can be seen.

higher catch of all fleets on the long-term when providing more fleet flexibility (Fig. 11).

As the Dutch and German fleet are very similar in terms of fishing technique (both involve large freezer-trawler vessels), similar outcomes could have been expected. On the long-term, the German fleet, however, increased their effort and catch in 4a1b (northern North Sea) in the third season whereas the Dutch fleet increased their effort and catch in 4a1d (east coast of Scotland; Fig. 13).

Both Danish fleets behave very similar when closing the main spawning grounds: On the long-term, they relocate their effort and catch from area 4a1b in season one to 4b1b in the third season, which is closer to their home harbour in Hirtshals (Fig. 13). The Danish fleets are the only catching NSAS herring to such an extent in season one. The UK fleet, on the other hand, completely relocate their effort and catch in the third season from areas 4a1a and 4a1d into 4a1b only, where the German also increased catch (Fig. 13). The other areas are much further away, which would increase effort and hence fuel cost.

4. Discussion

In this study, we adapted the temporal FishRent version of Rybicki et al. (2020) for the pelagic NSAS herring fishery, incorporated spatial explicitness with seasonal migration patterns under different spatial resolutions as well as the possibility to close certain areas to different degrees depending on user settings and research question. In this process, our aim was to illustrate the importance of using a tool that is able to deal with multiple fleets at the same time, operating from different harbours with different seasonal preferences when fishing for specific species. Moreover, we discuss major model limitations generated by the data of European pelagic fisheries used to parameterize the model.

4.1. Scenario 1a: Increasing spatial resolution

In general, introducing a higher spatial resolution first provided the possibility to integrate seasonal migration patterns of NSAS herring, which can be a very significant feature regarding straddling stocks. When using a resolution of 18 A, migrations could be displayed in detail according to Corten (2001, 2013a) and Dickey-Collas et al. (2010). This is an important feature when investigating the fisheries targeting species for which spatial distribution significantly vary within a year. Seasonal, localized high density of fish and therefore high catch rates can drive an entire fishery to operate only at certain season. Using only averaged information (over season and areas) smoothens out the population dynamics of the stock and fails to capture the dynamics of a seasonal fishery. In the NSAS herring fishery, using the highest resolution (18 A) allowed fleets to select the attractive fishing

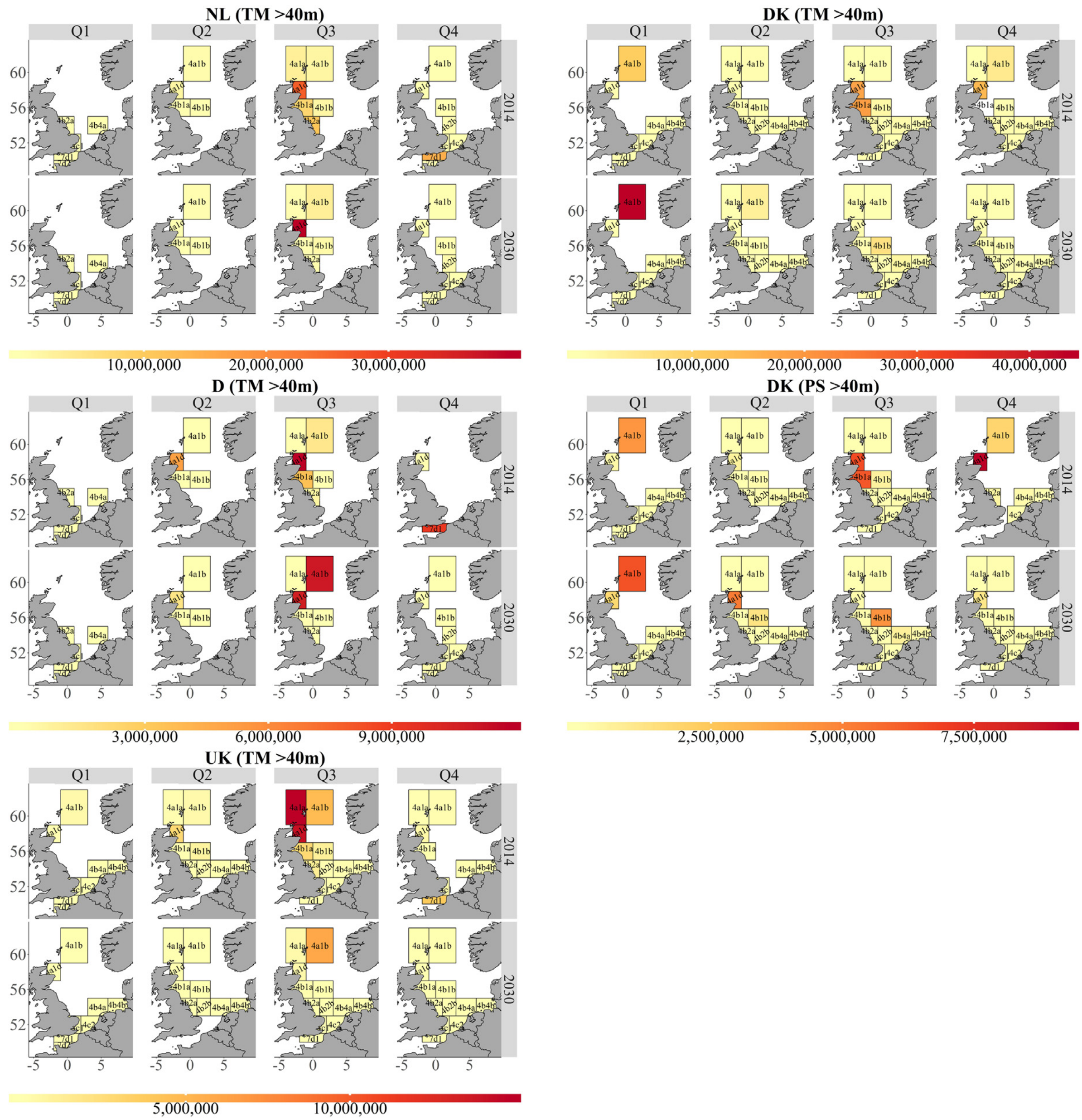

Fig. 13. Catch distribution (kg) in each season for the start year 2014 as well as on the long-term (2030) under Scenario 2 (18 A_flex_clos).

grounds with high catch rates and low costs. In contrast, when using lower resolutions (1 A, 4 A, 8 A), fishing hot spots were hidden/spatially averaged in larger areas.

Effects of increasing spatial resolution on fleet net profit and SSB trends were rather minor, except for the German fleet, for which the 18 A resolution was the least profitable (although the difference between 8 A and 18 A was still only 8%). This suggests that the general trends in the fleet dynamics (how much effort is spent when) and population dynamics is equally well captured by a simple version of the model and that a high degree of resolution is not necessary when being interested in the general development of a population. The general assessment of pelagic species might thus not necessarily need to incorporate the spatial aspect. If the interest is, however, to understand the behaviour of different fleets at the same time, seasonal as well as spatial aspects need to be considered on a higher resolution.

In general, there have been only few attempts though to quantify the effects of different resolutions and the role of matching scale of data when applying bio-economic models. The common view seems to be to use the highest possible resolution without testing for the model performance at other scales (Núñez-Riboni et al., 2021). One study by Hamon et al. (2014) investigated the effects of Tasmanian rock lobster (*Jasus edwardsii*) price changes and climate change on the fishery by applying three different spatially explicit models that each increase in complexity (from static over linear to agent based). Their findings also promoted the usage of the most complex model of all three, implying that the local economic and social impacts can only be realistically captured when including an explicit and detailed representation of economic drivers. Other than this, most studies that engaged in the question of matching scales and different resolutions to the data accessibility and model performance have been conducted in terrestrial habitat modelling exercises. Some claim that the usage of a lower (e.g. Rahbek and Graves, 2001; Luoto et al., 2007; Núñez Riboni et al., 2019) or higher (e.g. Seo et al., 2009; Guisan et al., 2017) resolution produces better results, while others rather highlight the importance of replicating the characteristic scale of the processes of interest when choosing a certain resolution level (Pearson et al., 2004; Bellier et al., 2010; Kärcher et al., 2019). In the end, we argue that the implementation of finer spatial resolution highly depends on data availability and quality as well as the question of interest.

4.2. Scenario 1b: Increasing fleets' flexibility and limitations

When limiting the available fishing areas through area closures, it had to be ensured that every fleet has alternative options. Therefore, the access to the areas where at least one of the fleets fished in the initial data was limited. This step was done because not all fleets visited every area in the initial data, hence this gap was filled using observations of fleets that have visited more areas. The complete access to the whole North Sea was not provided though, because this would most likely induce the modelled fleets to follow the general migration patterns of the NSAS herring stock to the areas where most biomass is available in the model (if this is the most profitable solution also considering expenditures), but where the fleets do not fish in reality due to following reasons: (i) fish size and quality (and therefore price), (ii) fishing for other species.

Fish size, quality and price - A large processing industry is concentrated on manufacturing relatively specific products (e.g. different types of marinated herring sold in cans) of herring, i.a. situated in Neu Mukran, Germany. For those fishing companies, it is very hard to find any substitution products since the quality, fish size and fat content of NSAS herring have to meet specific requirements in order to be able to produce products such as matjes (Stroud, 2001; Nielsen and Olesen, 2008). Usually, the decisions on where to fish best are not only made by the amount of stock biomass available and expenditures to catch this fish but largely depend on fish quality and therefore the fish price. In case of NSAS herring, this changes seasonally, hence the fleets do not always fish herring throughout the year although the abundance may be relatively high (personal communication; Tülsner and Koch, 2010). In this model version, no fat content or quality information is included. Moreover, the weight at age is treated as constant over time and space. Sufficiently detailed data is hard to find and to include into the model. A possibility to handle this problem could be to incorporate fish prices that vary seasonally as well as in space if the available data allows for this. Currently these prices are assumed to be the same for each season and area. This variation depends on the amount of fish available on the market and customer demand. Prices for frozen fish may vary less as they can be kept in a storage for a longer time period (EUMOFA, 2019). This is the case for the German and Dutch fleets targeting NSAS herring but using freezer trawler instead of RSW vessels such as used by the Danish and UK fleets. Yet, as the quality of herring is also seasonal, price seasonality would probably remain the same.

The fact that many bio-economic models assume fixed fish prices was also criticized by Elfoutayeni and Khaladi (2012). They used a bio-economic optimization model and included fish prices depending on the quantity harvested assuming that the price decreases with increasing harvest, but limiting the minimum price to a fixed positive constant. Again, a trade-off between model complexity and data availability had to be made as their model does include dynamic prices, but is not age-structured or spatially resolved.

Fishing for other species - The pelagic fleets included in this model target different species (e.g. Northeast Atlantic mackerel (*Scomber scombrus*), sprat (*Sprattus sprattus*), blue whiting (*Micromesistius poutassou*), horse mackerel (*Trachurus trachurus*) and pelagic redfish (Sebastes spp.)) during different times of the year (ICES, 2019a). Mackerel and horse mackerel, for example, both perform vast migrations, are primarily caught by the same multinational fleets also targeting NSAS herring in the first and fourth season of a year (although separately) and consist of both refrigerated seawater trawler (RSW) and freezer trawlers (ICES, 2019a). Both fisheries take place west of Scotland and northwest of Ireland, to some extent also in Spanish and Norwegian waters. The five modelled fleets catch NSAS herring to 25% on average, hence approximately 75% other species contribute to their total catch (see also Rybicki et al., 2020). When targeting either species, this is considered as a separate fishery. In this model, these "other species" are included as fixed percentage of the revenue. Changes in "other species" biomass, migration patterns, fish prices, etc. are not included as a feedback mechanism in this model version. Therefore, it is not possible for the modelled fleets to switch directly to another species that might be more profitable during the runs themselves and reduces the flexibility of fleet behaviour. Moreover, the pelagic fleets are known to switch relatively spontaneously to another species (e.g. from mackerel to horse mackerel, which may be caught in the same season and a similar area), if catch for one species is unsatisfactory. Including other species that are targeted by the same fleets is possible when data is available, but unfortunately the amount of biological detail is not accessible for all species. Especially biological data for the beaked redfish *Sebastes mentella* is scarce, which is also targeted by the pelagic freezer trawler fleets (stakeholder information; ICES, 2019b).

In the end, although additional areas were introduced to modelled fleets, most remained in their historically observed fishing areas. As before, when increasing spatial resolution, the German fleet was the only changing their behaviour through reducing their total effort and fuel costs by moving slightly closer to their home harbour (more about this is discussed under 4.3). Yet, the static behaviour of the fleets when providing additional access to other areas is a validation of the model producing rather realistic results. Discrepancies may occur to some extent as the model does not include all external factors that might affect fleets behaviour, such as weather conditions, but a drastic change of the fleets would be questionable. Moreover, it confirms that results of Scenario 2 are purely effects of the area closure itself.

4.3. Scenario 2: Closing the core spawning grounds

Spatial explicitness also provides the possibility to test for the effectiveness of marine reserves (Pelletier and Mahévas, 2005) as well as their effects on fleet profitability and stock biomass. The idea of implementing a marine reserve for the core NSAS herring spawning areas was to reduce the fishing pressure when the stock is most vulnerable and hence aid in its recovery. This scenario, however, shows that additional management measures are needed, as closing the main spawning grounds of NSAS herring only slightly increased SSB compared to the non-closure scenario. It suggests that the main focus should indeed be on the decreased of larvae survival. As several studies suggested, NSAS herring larvae survival, growth and hence recruitment success is thought to be impaired by changes in the physical environment and the planktonic community, negatively affecting food availability, metabolic rates and development times (Gröger et al., 2009; Payne et al., 2009; Nash and Dickey-Collas, 2005; Fässler et al., 2011; Corten, 2013a). Moreover, increasing water temperature is thought to reduce habitat suitability in the whole North Sea area (CERES D2.3, 2019). Another possibility might therefore be the introduction of an MPA in the southeastern North Sea, where the nursery area of NSAS herring is situated (Corten, 2013b). Such a management measure does not have a significant effect on the pelagic fleets though as these are not the major fishing areas. The effect on the demersal fleets of such a closure would be much larger and would need to be tested with the demersal FishRent model (e.g. Bartelings et al., 2015; Simons et al., 2015).

Economically, the fleet most affected by the closure scenario was again the German fleet, although a similar behaviour of the Dutch and German fleet might have been expected as they belong to the same company and are both freezer-trawler fleets. The Dutch fleet, for example, continues fishing in 4a4 (western North Sea) whereas the German fleet stays in 4a2 (northern North Sea). Area 4a4 is however closer to the home-harbours of the Dutch fleet (IJmuiden amongst others in the Netherlands) than to the ones of the German fleet (Bremerhaven and Rostock in Germany), for which area 4a2 is closer. Another reason why the impacts on the German fleet are relatively large compared to the other fleets is the small margin between total costs and revenue in the input data. This margin is, for example, twice as high for the Dutch fleet compared to the German. The reason is thought to be due to costs transfers within pan-European operating companies, which makes it possible to transfer subsidiary profits to the parent company (for further description see Rybicki et al., 2020; Gelder and Spaargaren, 2011). Such a profit transition is very hard to capture in this model where fleets but not companies are modelled. Hence, the data available might suggest a large impact on the German fleet whereas in reality this might be an overestimation.

In general, closing the English Channel in the fourth season would have a large impact on the NSAS herring roe fishery, which only takes place in the English Channel within the UK EEZ during December and is of high value. Beattie et al. (2002) already argued that an implementation of marine reserves or MPA's solely with the goal of species protection usually has a negative affect for the corresponding fisheries operating within the North Sea area. In reality, impacts of the English Channel area closure would be much larger as the prices are thought to be higher than the ones for NSAS herring caught during the third season along the UK east coast. For several years, NSAS herring roe has become increasingly important on the Japanese market (Herrfurth, 1986). Those prices are, however, hard to determine and might be higher than the ones employed in this model, again adding to the problem of data availability and possibly underestimating the effects of such a closure.

Another point to mention is the fact that both Danish fleets fish herring in the northern North Sea during season one, but none of the others do. This already occurs in the initial data and then becomes intensified on the long-term during the spawning grounds closure scenario, because this area represents a good alternative for the Danish fleets when fishing activities are prohibited in this region in the third season. In the raw data, a gradually increasing amount of herring catch by the two Danish fleets in the northern North Sea between the Shetlands and Norway in season one could already be observed from 2012 to 2016 (raw data from DCF partner; STECF, 2020). It is yet unclear, which factors promoted this trend as neither the sprat fishery, in which herring occurs as by-catch, nor the Norwegian Spring Spawning herring fishery take place in the first season and in ICES subarea 4a (ICES, 2020a,b,e). Similar to the NSAS herring fishery, the sprat fishery takes place during season three and four in the central North Sea (ICES, 2020a,b). Norwegian Spring Spawning herring is usually targeted further north (e.g. ICES Subarea 2a) and even the occurrence closer to ICES subarea 4a during feeding times would take place in season two and three, not one (ICES, 2020b). In 2017, however, the largest amount of NSAS herring caught by the Danish fleets primarily appeared again in season three and four instead of one (STECF, 2020). Hence, the trend seen in this scenario, where the Danish fleets significantly increase their catch in season one when the major spawning grounds are closed in season three and four, might not be completely realistic. Depending on the underlying reason, the trend to switch completely to season one could be balanced by incorporating seasonal fish prices, with slightly lower herring prices in season one. This might produce more realistic results, but in the end this example shows how large the influence of the data used to parameterize the model on such simulations can be.

5. Conclusion

In general, profit remained nearly unchanged even with higher spatial resolutions. Catch changed seasonally when using a lower resolution, whereas the fleet behaviour was mainly affected spatially with a higher resolution. For the evaluation of changes over time only, the eight-area resolution might even suffice, as the differences between resolution scenarios were relatively small. With the higher resolution of eighteen-areas, however, the migration patterns could be implemented in more detail and spatial effects were more visible, which were spatially more averaged with a lower resolution bearing the risk of misinterpreting fleet behaviour changes.

A major issue of the NSAS herring fishery is the inflexibility of the fleets, which results from the fishing grounds and times being extremely static due to being a spawning fishery. We provided the fleets with a larger access to fishing grounds than the underlying data of each fleet allowed for, which did not lead to significant impacts but validated the model results, as it would have been highly questionable if the fleets would have drastically changed their patterns due to the additional area access. Yet, providing further access to areas where a fleet has not fished in the data used to parameterize the model always comes with trade-offs, of which some are assumptions concerning catchability, effort and activities in other fisheries. Other methods for increasing fleets' flexibility might be to add seasonal prices or other species into the model process. In the end, the model complexity needs to fit the purpose of the modelling exercise and the research question. If the purpose is to understand the behaviour of different fleets with various harbours and target areas, a larger resolution should be considered. In case of pelagic species, the highest degree of complexity (18 A) also provided better results when implementing management measures such as marine reserves. If the interest is the general development of the population over time, a high degree of resolution does not seem to be necessary in case of pelagic species.

CRediT authorship contribution statement

Sandra Rybicki: Conception and design of the study, Wrote and designed the first draft of the manuscript, Manuscript revision. **Katell G. Hamon:** Conception and design of the study, Manuscript revision. **Sarah Simons:** Conception and design of the study, Manuscript revision. **Axel Temming:** Conception and design of the study, Manuscript revision.

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.

Data availability

Detailed economic, catch and effort data analysed in this study was obtained from EU national labs. More data can be accessed from the STECF (open source). Biological data was obtained from ICES assessments and is open access. Requests to access these datasets should be directed to Matt Elliott (MMO, matt.elliott@marinemanagement.org.uk), Arina Motova (Seafish, Arina.Motova@seafish.co.uk), Josefine Egekvist (DTU Aqua, jsv@aqua.dtu.dk), Kim Normark Andersen (DST, KNO@dst.dk), Katell Hamon (WUR, katell.hamon@wur.nl), Jörg Berkenhagen (TI-SF, joerg.berkenhagen@thuenen.de), and Torsten Schulze (TI-SF, torsten.schulze@thuenen.de).

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.rsma.2021.102023.

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