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Implementation of a métier-based dynamic fisheries model in the Atlantis model for Icelandic waters

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1 Introduction

Icelandic fisheries management is one of the most progressive in the world. Iceland was one of the first nations to implement an individual quota system with output controls (i.e., total allowable catches, TACs) in the Atlantic herring (*Clupea harengus*) fishery in 1979 (Jakobsson and Stefánsson 1999). It was also one of the first to implement a harvest control rule in the Atlantic cod (*Gadus morhua*) fishery in 1995 (Anon 2016). The quota system was expanded in 1991 to include essentially all demersal fisheries (Arnason 2005) and is continuously reevaluated to address new concerns.

Despite these strong management controls, Iceland's demersal fisheries suffer from the same concerns found in fisheries worldwide. Since species cannot be fished in isolation, fishing one species impacts others due to interspecific interactions, bycatch, and habitat degradation (Essington et al. 2016). It has therefore become apparent in Iceland and elsewhere that fisheries management systems need to adopt ecosystem-based fisheries management (EBFM, FAO, 2008; Marasco et al., 2007; Ramírez-Monsalve et al., 2016). The goal of EBFM is to develop a more holistic approach by considering these complex interactions and implementing ecosystem-based reference points.

Currently, EBFM has not been implemented for Icelandic waters, as is the case for other nations. While fisheries management in Iceland is mostly based on single species stock assessment models with the precautionary rule (Anon 2023a), species interactions are considered in some cases (ICES 2023). The groundwork for the implementation of EBFM has been laid through several projects including the development of the Iceland Atlantis end-to-end ecosystem model (Sturludóttir et al. 2018). Atlantis includes an oceanographic model, a biological model (which simulates predator-prey interactions and density-dependent effects), and a fisheries model. Atlantis is parameterized with ecological, oceanographic, and fisheries data collected by the Marine and Freshwater Research Institute (MFRI). Atlantis is an extremely detailed representation of marine ecosystem dynamics in waters surrounding Iceland.

End-to-end ecosystem models can characterize marine resource users as a component of the broader social-ecological system. The long history of fisheries management in Iceland is supported by detailed scientific surveys and landings data (Mason, Stedman, and Kleisner 2023) which are invaluable resources in developing a detailed ecosystem model. Landings data are stored in an electronic logbook database collected by the Fisheries Directorate which includes location, time, gear, species, and catch for each haul. These data can be used to elucidate fishing patterns and behavior for inclusion into the ecosystem model. Linking and analyzing these data serves two purposes. First, they inform fisheries management directly by gaining a better understanding of incentives and potential unintended consequences of regulations (Branch and Hilborn 2008; Fulton et al. 2011; Grafton, Kirkley, and Squires 2016; Wilen et al. 2002). Second, they can indirectly inform fisheries management by updating the management model sub-components of Atlantis, which are needed to perform management strategy evaluation (MSE). MSE is currently the gold standard for resolving problems in fisheries management because it combines biological, social, and management models and considers management objectives while evaluating and comparing likely outcomes of multiple management strategies (Punt et al. 2016).

Prior to this study, the harvest in Iceland Atlantis was driven by forced fishing mortality rates where each fleet harvested one species (Sturludóttir et al. 2018). While this approach is an effective means for the initial model development, it is not a platform on which to develop MSE for three reasons. Firstly, the approach does not account for the fact that species are harvested by multiple gear types with spatiotemporal variation. Secondly, the same vessels with the same gear target multiple species. Thirdly, fishing mortality rate is not a directly manageable quantity.

It has been long acknowledged that fisheries management worldwide suffers from a high level of uncertainty both in the complex ecological processes that result in emergent ecosystem properties, as well as in the human dimensions of the system that control the linkages between fish and fisher, given the management system in place (De Young, Charles, and Hjort 2008). It is difficult to assess how management strategies can affect resilience without properly understanding the linkages between the social and ecological components. Therefore, the goal of this report is to provide an update to Iceland's Atlantis marine ecosystem model. The Iceland Atlantis model was extended to a terminal year of 2021. A métiers analysis was used to identify the hauls within the bottom trawl fishery with distinct catch composition and spatiotemporal variation. Harvest from these hauls were then modeled as individual fleets in Atlantis using observed effort from the electronic logbook database.

2 Methods

The Iceland Atlantis model includes 53 polygons, covers the Iceland continental shelf, and extends from the Faroe Islands in the east to Greenland in the west (Figure 1). There are 52 functional groups, some of which are single species (Sturludóttir et al. 2018). Seventeen of these functional groups are fin fishes of which 12 are harvested. This report focuses on the further development of the bottom trawl and longline fisheries in the Iceland Atlantis model. Iceland's bottom trawl fleets accounted for approximately 21% of Iceland's total fisheries landings and 43% of the catch value, while the longline fleet accounted for approximately 8% of the total landings and 16% of the catch value from 2002 to 2022 (Statistics Iceland 2023). Previously, harvest was modeled in Atlantis using forced fishing mortality in eight different fisheries, here we model harvest for much of the bottom trawl and longline fleets using observed fishing effort assigned to the corresponding Atlantis polygon. For the sake of brevity, the fisheries driven by forced fishing mortality will be referred to as "fleets" and those defined by the métier analysis and/or whose harvest will be driven by effort are referred to as "métiers."

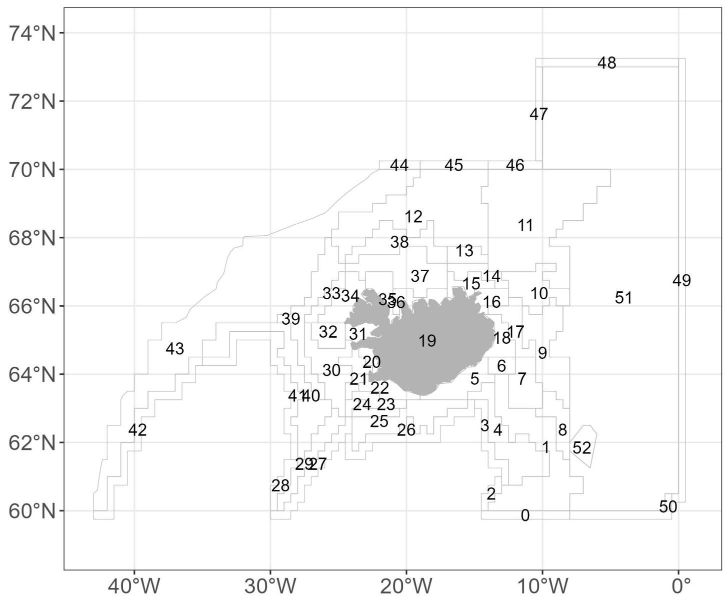

Figure 1: The spatial extent of the Iceland Atlantis model, including the location of the 53 spatial polygons.

2.1 Métier analysis

A métier analysis was conducted using the harvest per Atlantis functional group per haul in the bottom trawl fleet in the years 2016-2020 using the electronic logbook database. The analysis followed the methods used to identify métiers in the Iceland bottom trawl fishery (Baranowska et al. 2024; Oostdijk et al. in review). Briefly, we performed a clustering analysis following a previously reported clustering protocol (Sulanke et al. 2022) to identify métiers. As preliminary analyses defined many clusters based on single hauls, we used Ward's method for hierarchical clustering (Oksanen et al. 2022; Ward 1963). Ward's method is more suitable to find several main clusters of approximately equal size in large, heterogeneous datasets (Ferreira and Hitchcock 2009). The clustering analysis was implemented using the R packages Vegan (Oksanen et al. 2022) and Fastcluster (Müllner 2013) in R (R Core Team 2024).

Fishing activities were classified into distinct clusters with different species mixes. While the main determinants of the clusters are the catch quantities of the functional groups (Table 1), we also included fishing location and day of the year as covariates. While not included in the métier analysis an additional métier, representing the longline fishery, was developed for inclusion in the Atlantis model.

Table 1: Select functional groups in the Iceland Atlantis marine ecosystem model, the maximum age of each group, whether they are fished or not, and whether they were included in the métier analysis.

Functional Group	Max age	Fished	Métiers analysis
Cod (*Gadus morhua*)	16	Yes	Yes
Haddock (*Melanogrammus aeglefinus*)	14	Yes	Yes
Saithe (*Pollachius virens*)	16	Yes	Yes
Redfish (*Sebastes sp.*)	50	Yes	Yes
Greenland halibut (*Reinhardtius hippoglossoides*)	20	Yes	Yes
Flatfish	20	Yes	Yes
Herring (*Clupea harengus*)	20	Yes	Yes
Blue whiting (*Micromesistius poutassou*)	16	Yes	Yes
Other Codfish	20	Yes	Yes
Demersal commercial	20	Yes	Yes
Other demersal fish	10	Yes	Yes
Capelin (*Mallotus villosus*)	6	Yes	No
Sandeel fish	10	No	Yes
Long-lived demersal fish	40	No	Yes
Other mesopelagics	30	No	Yes
Bathypelagic fish	10	No	Yes
Spiny Dogsharks	50	No	Yes
Skates and Rays	30	No	Yes

2.2 Effort data

The métiers identified using the 2016-2020 logbook data were assumed to be representative of the period from 2000-2021 for the purposes of modeling in Atlantis. Harvest and effort per month per polygon for each bottom trawl and longline métier were extracted from the electronic logbook database hosted by the MFRI. The average catch of the most abundant species was used to assign each bottom trawl haul to the appropriate métier. The assignment of these hauls was based on the percentage of cumulative catch of the main species in the métier. If catches of the main species were higher or equal to the cumulative percentage of a main species in a métier the haul was assigned to that métier. Hauls were assigned to a mixed métier if they did not meet the previous criterion. Effort in the bottom trawl fleet was hours towed and in the longline fishery was 1000's of hooks.

2.3 Iceland Atlantis update

The Atlantis update was conducted in a two-step process. First, Atlantis was extended to terminate in 2021 using the existing fleets. As the terminal year for the underlying hydrodynamic is 2012, the hydrological exchanges, salinity, and temperature values from 2003 to 2012 were repeated. Selectivity curves for Atlantic cod and haddock (*Melanogrammus aeglefinus*) were adjusted based on estimated fishing mortality at age time series (Anon 2023c; 2023b). In the second step, six new métiers (five bottom trawl and one longline) starting in 2000 were developed. While the métier analysis included 18 functional groups in the bottom trawl fishery, the five functional groups—Atlantic cod, haddock, redfish (a functional group composed of *Sebastes norvegicus*, *Sebastes mentella*, and *Sebastes viviparus*), Greenland halibut (*Reinhardtius hippoglossoides*), and saithe (*Pollachius virens*)—that contributed to more than 95% of the bottom trawl catch in recent years were selected to be modeled in the bottom trawl métiers. Prior to this update, the harvest of the fish in these métiers was determined by forced fishing mortality. The forced fishing mortality fleets that harvest the species targeted by the new métiers were retained after the year 2000 to account for the remaining harvest that occurs by other gear types (e.g., gillnet, vertical jig). The harvest of the other species was determined by forced fishing mortality and defined in other fleets.

Harvest in the métiers was tuned by modifying fishery selectivity curves, swept area, and catchability. Initial selectivity was parameterized for each métier based on selectivity in the fishing mortality-based fishery to which they most corresponded based on catch composition.

As the métiers operate in different polygons, and the polygons are not the same size, the swept area parameter was adjusted for each métier so that the harvest for each species in each métier was the correct order of magnitude. Subsequently, catchability (fixed value per species per métier) was adjusted. The forced fishing mortality values for species caught in the newly created métiers were decreased accordingly so that the total harvest for each species was similar to that reported. Finally, selectivity and catchability were adjusted in reiterative processes to fine-tune the age composition in the catch.

3 Results

3.1 Métier analysis

The clustering analysis identified five bottom trawl métiers (Figure 2a). Of the functional groups harvested, five (Atlantic cod, haddock, redfish, Greenland halibut, and saithe) contributed to more than 95% of the bottom trawl catch in recent years and were selected to be modeled in the bottom trawl métiers. The mean proportion of catch of the single most prominent species in bottom trawl métiers 1-4 was used as a rule to determine which hauls in the electronic logbook database belong to which métier (Figure 2b). As no single species dominated the catch of métier 5, hauls not assigned to the other métiers were placed into this métier. The longline fishery, which primarily targets Atlantic cod and haddock (82% of catch), was selected as a sixth métier.

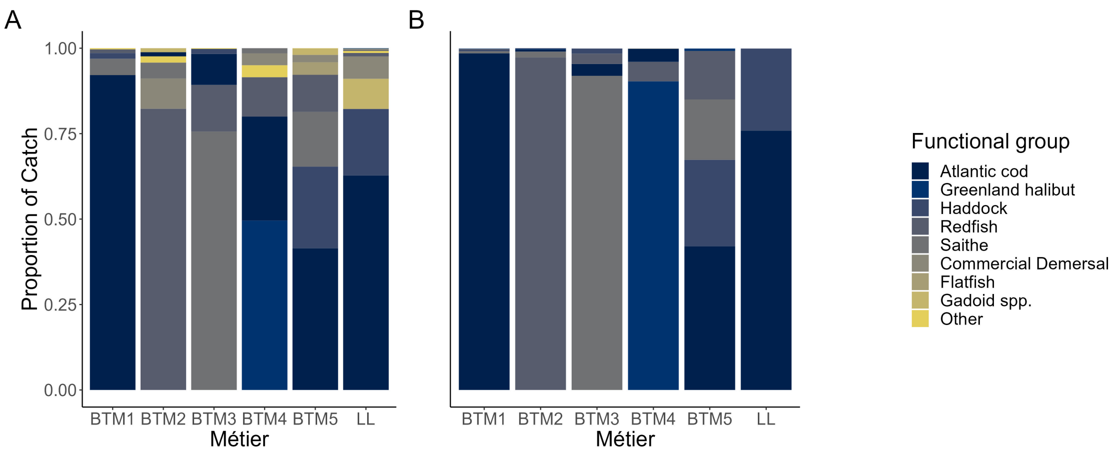

Figure 2: Proportion of catch in each bottom trawl métier (BTM) in Iceland identified by cluster analysis and the longline (LL) métier (A). Proportion of catch in each métier after assigning each haul to a métier (B).

3.2 Effort data

Fishing effort was polygon-specific and varied in each métier and per month (Figure 3). For example, polygon 34 (Figure 1), which is just west of the Westfjords, contained the highest effort for BTM5 and LL and among the lowest effort polygons for BTM2, BTM3, and BTM4. While the effort for most métiers was distributed across many polygons, 69.4% of the effort in BTM4 occurred in polygon 39. Effort also varied by month in each polygon. For example, polygons 23 and 30 have similar effort levels for BTM2, but the effort was much larger in February and March in polygon 30 than in 23 (Figure 3).

3.3 Iceland Atlantis update

The simulated biomass (Figure 4), spawning stock biomass (SSB, Figure 5), and harvest (Figure 6) for the important commercial species, from the first update phase, fit well with the reference indices. While there remain some groups in need of further adjustments, such as Atlantic herring, capelin (*Mallotus villosus*), Greenland halibut, saithe, flatfish, and redfish. These adjustments were saved for the second phase.

The second phase of the Atlantis update was to add the six previously identified métiers. After numerous rounds of tuning, which included modifications to the swept area, catchability, and selectivity curves, the simulated biomass (Figure 7), SSB (Figure 8), total harvest (Figure 9), and harvest per métier (Figure 10) were relatively well fit to the reference estimates. During the process of expanding the métiers, additional parameters were tuned to improve the biomass fits for Atlantic herring and saithe, the SSB fit for capelin, Greenland halibut, and saithe, and the harvest fit for capelin, flatfish, and redfish. The harvest for Atlantic mackerel (*Scomber scombrus*) in the second phase model was not as well fit to the reported harvest as it was in the first phase model. While the SSB of Atlantic cod does not track as well in the final second phase model as the first phase, it is still a relatively good fit and captures the general trend.

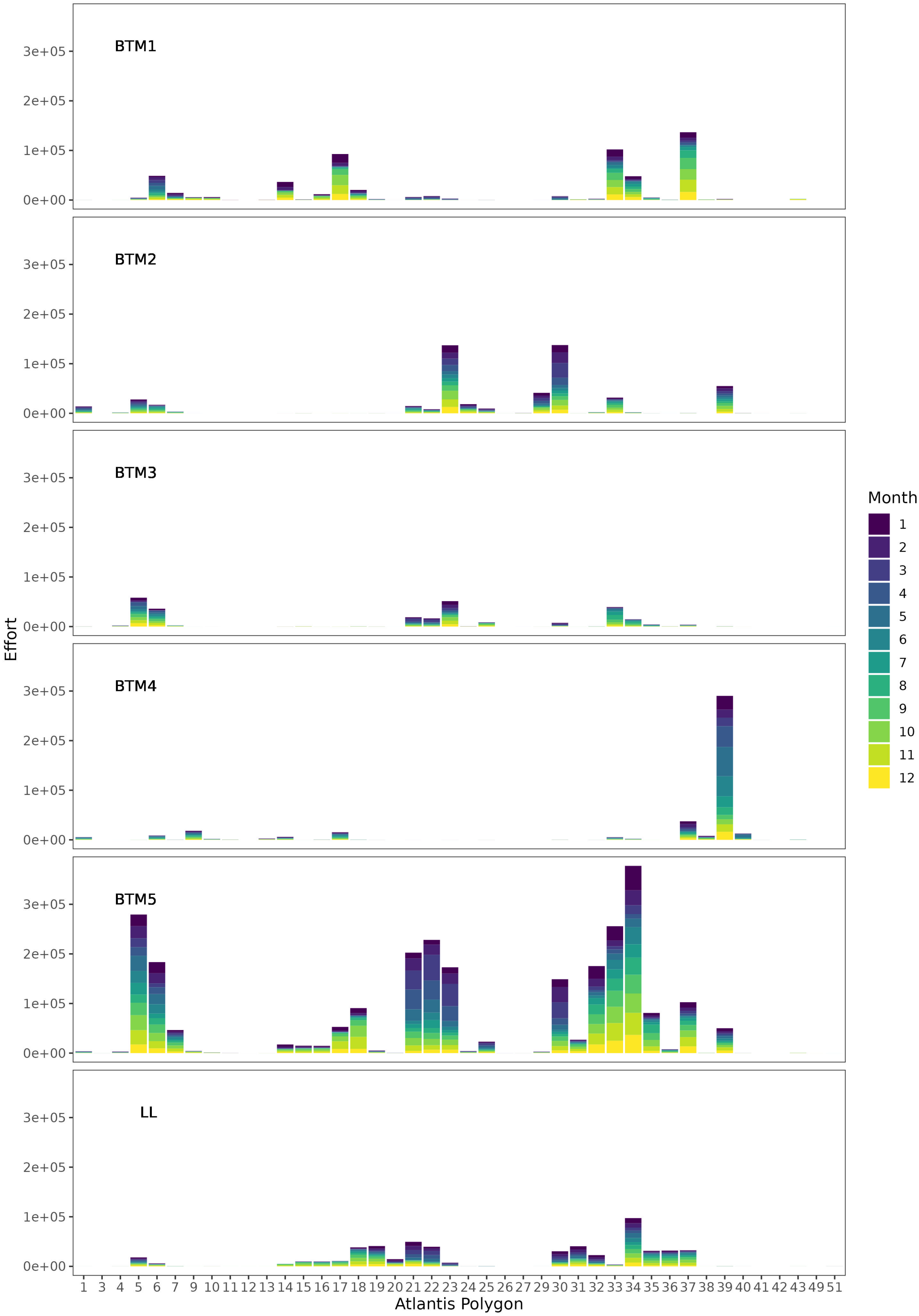

Figure 3: Average monthly effort per box and per métier in the bottom trawl (BTM) and longline (LL) métiers from 2000-2021. Effort in BTM is hours towed and effort in the LL is 1000's of hooks.

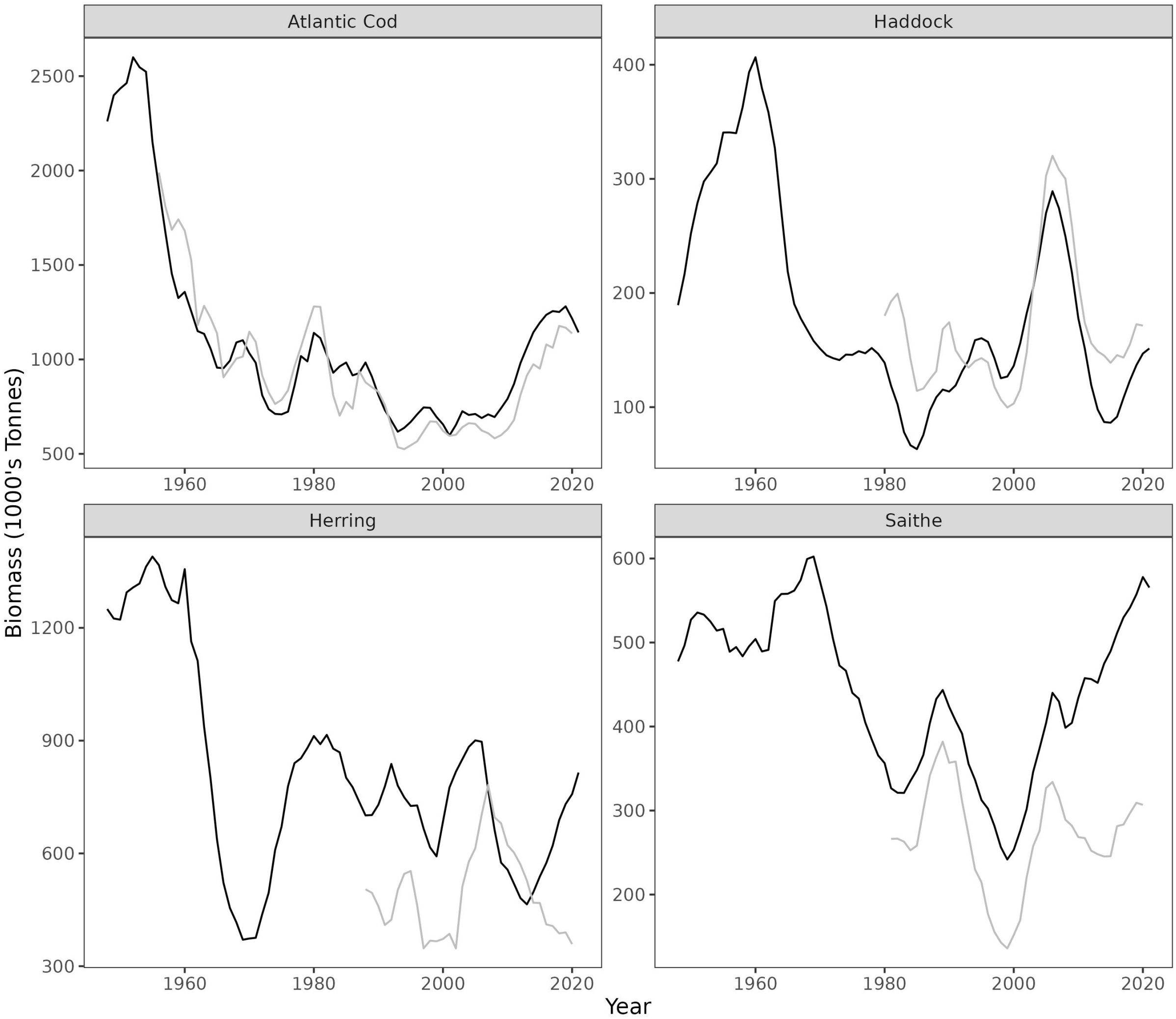

Figure 4: Spawning stock biomass (SSB) indices for some important commercial species in the first phase of the Iceland Atlantis model update. Here the model was extended to run through 2021, but no new métiers were added. Black lines indicate Atlantis estimates and ribbons are reference SSB estimates from the MFRI with 95% confidence intervals.

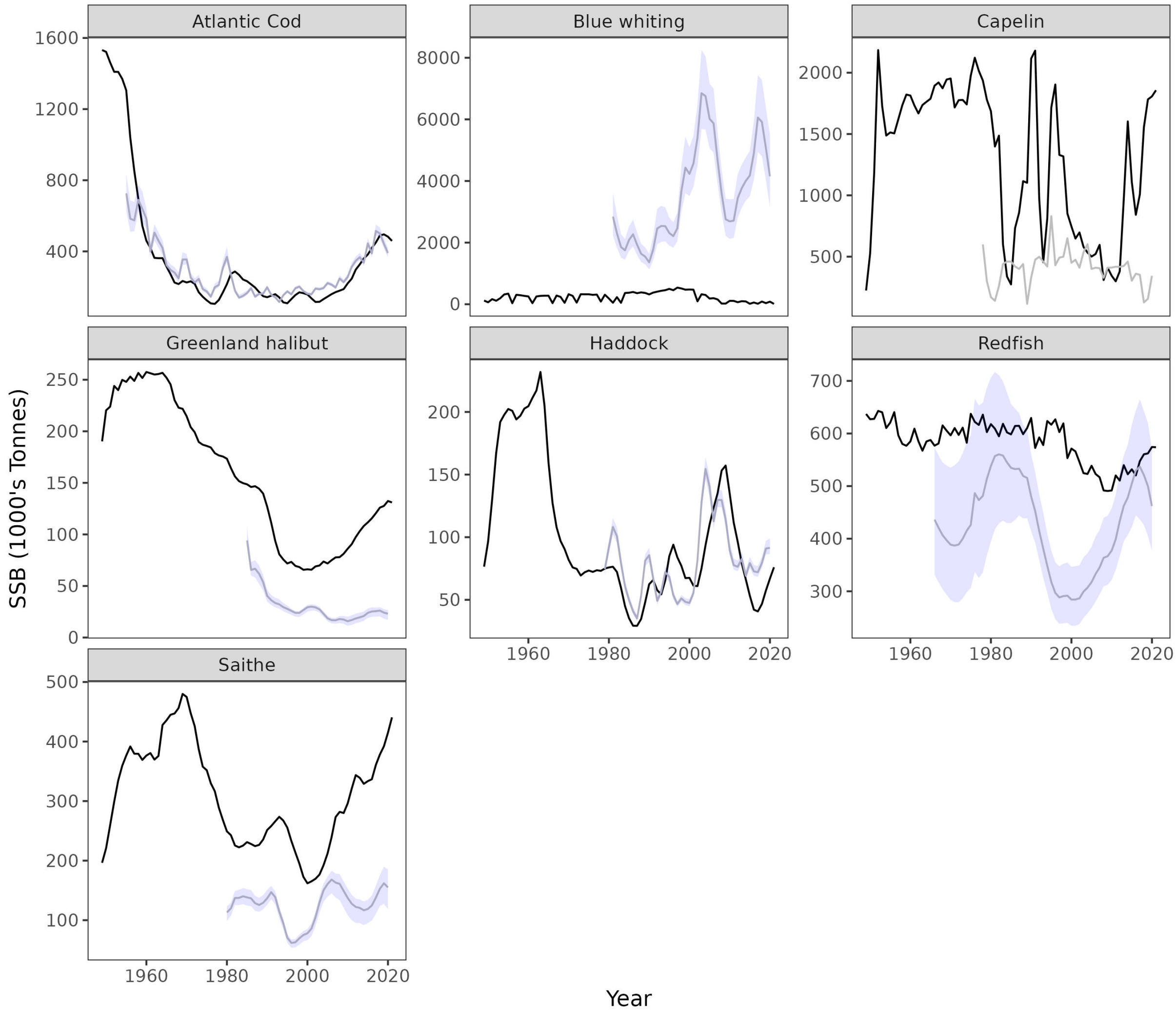

Figure 5: Harvest indices for some important commercial species in the first phase of the Iceland Atlantis model update. Here the model was extended to run through 2021, but no new métiers were added. Black lines indicate Atlantis estimates and grey lines are reference harvest estimates from the MFRI.

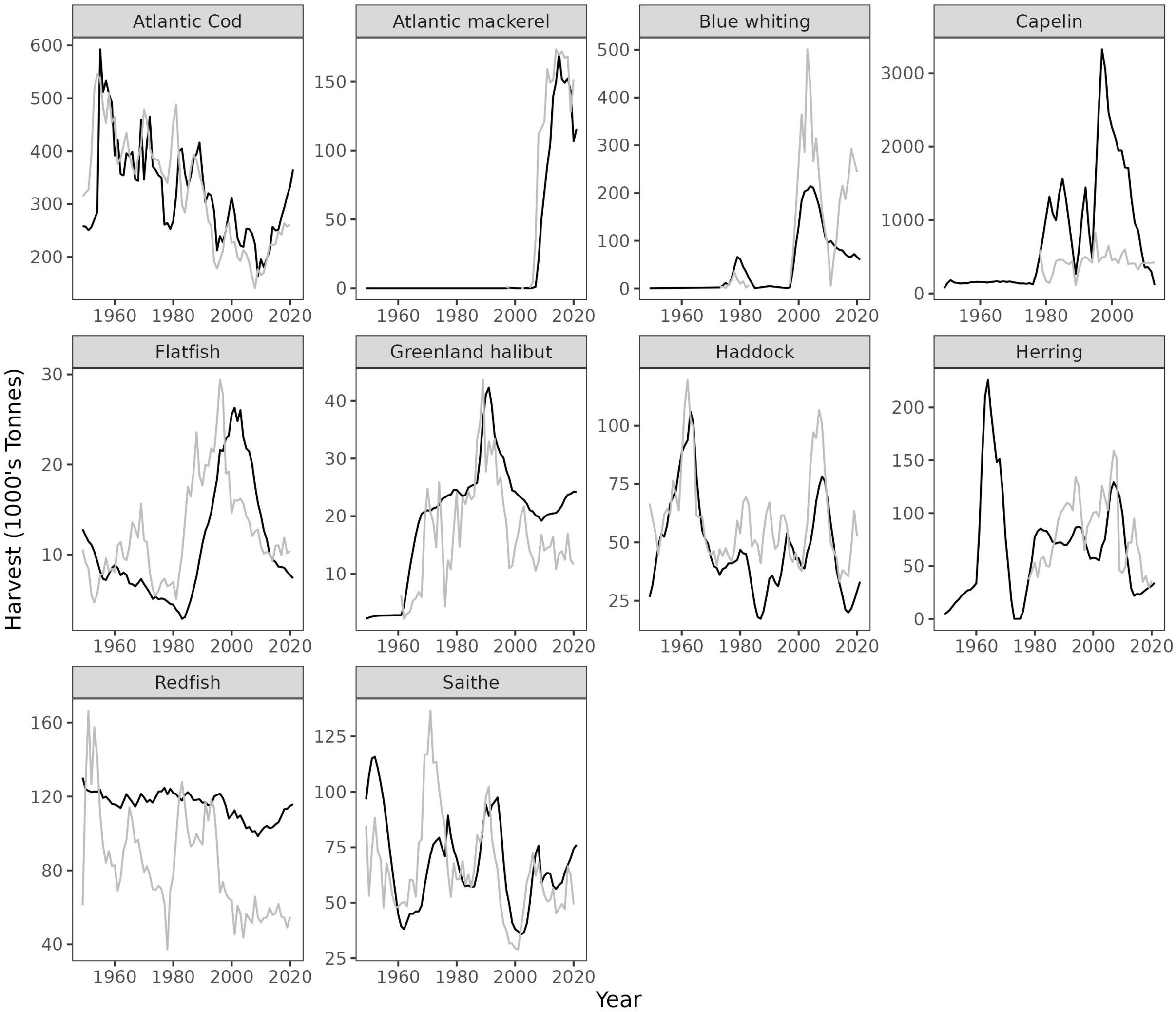

Figure 6: Biomass indices for some important commercial species in the second phase of the Iceland Atlantis model update. Here six new métiers were implemented. Black lines indicate Atlantis estimates and grey lines are reference biomass estimates from the MFRI.

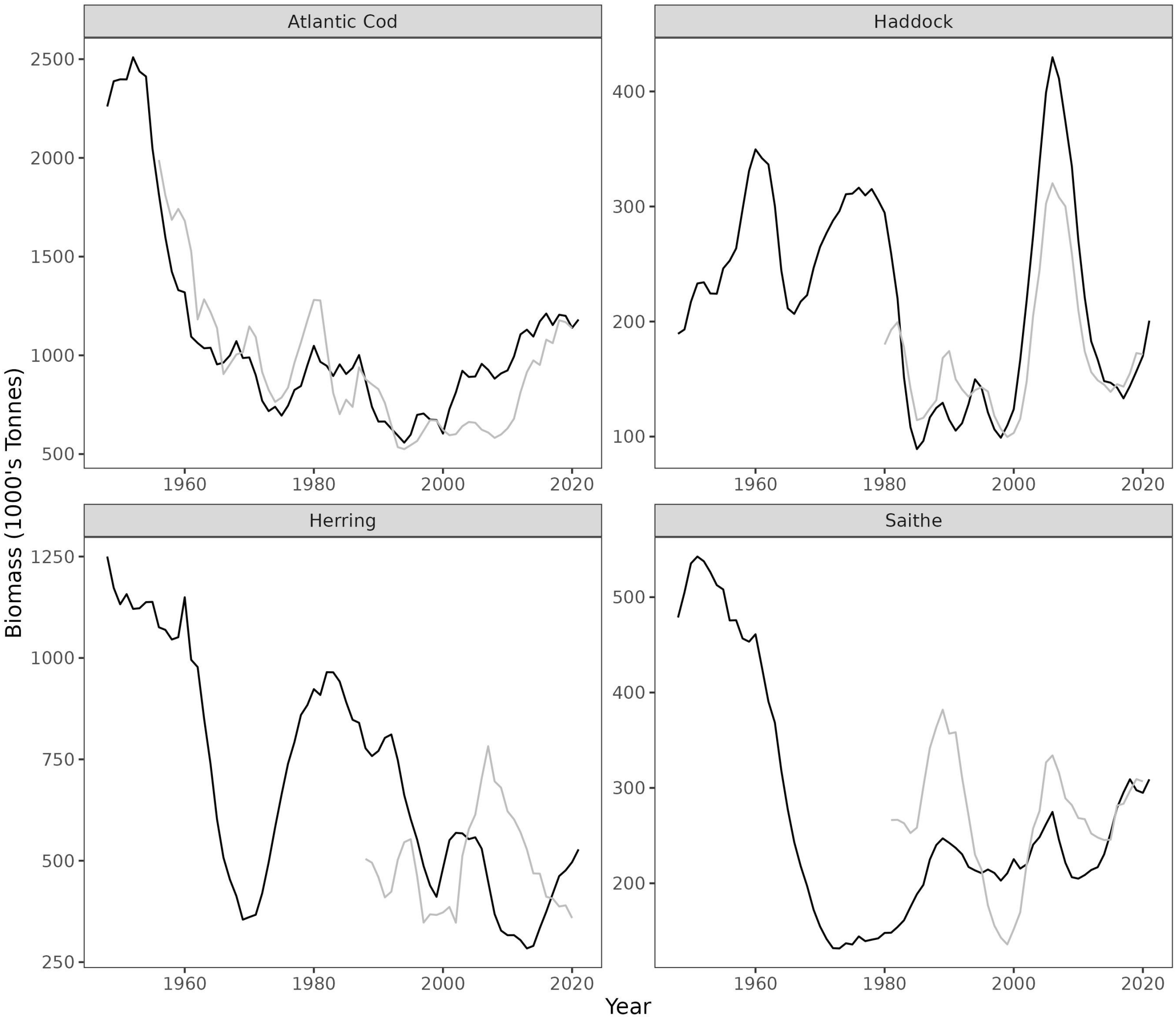

Figure 7: Spawning stock biomass (SSB) indices for some important commercial species in the second phase of the Iceland Atlantis model update. Here six new métiers were implemented. Black lines indicate Atlantis estimates and ribbons are reference SSB estimates from the MFRI with 95% confidence intervals.

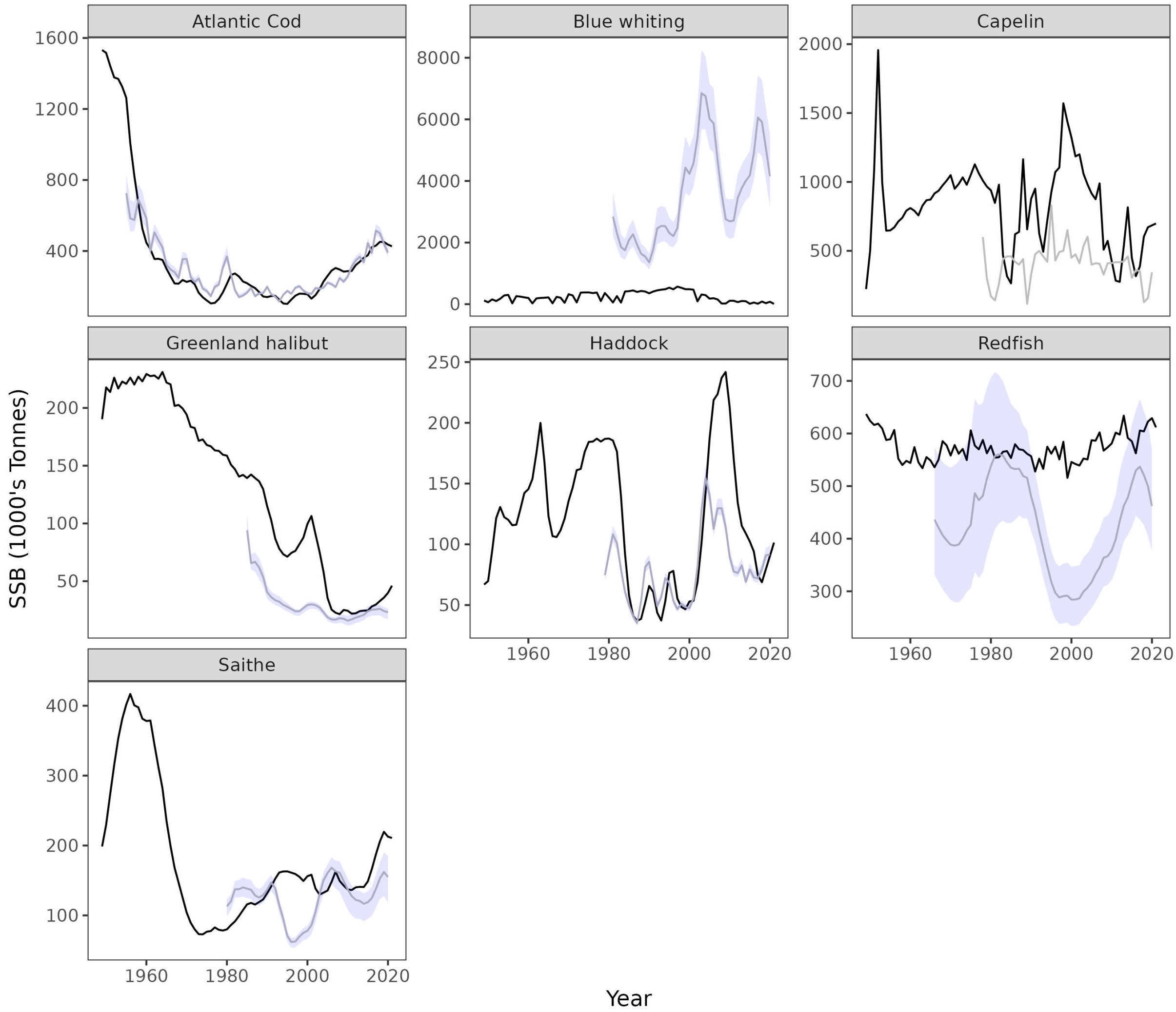

Figure 8: Harvest indices for some important commercial species in the second phase of the Iceland Atlantis model update. Here six new métiers were implemented. Black lines indicate Atlantis estimates and grey lines are reference harvest estimates from the MFRI.

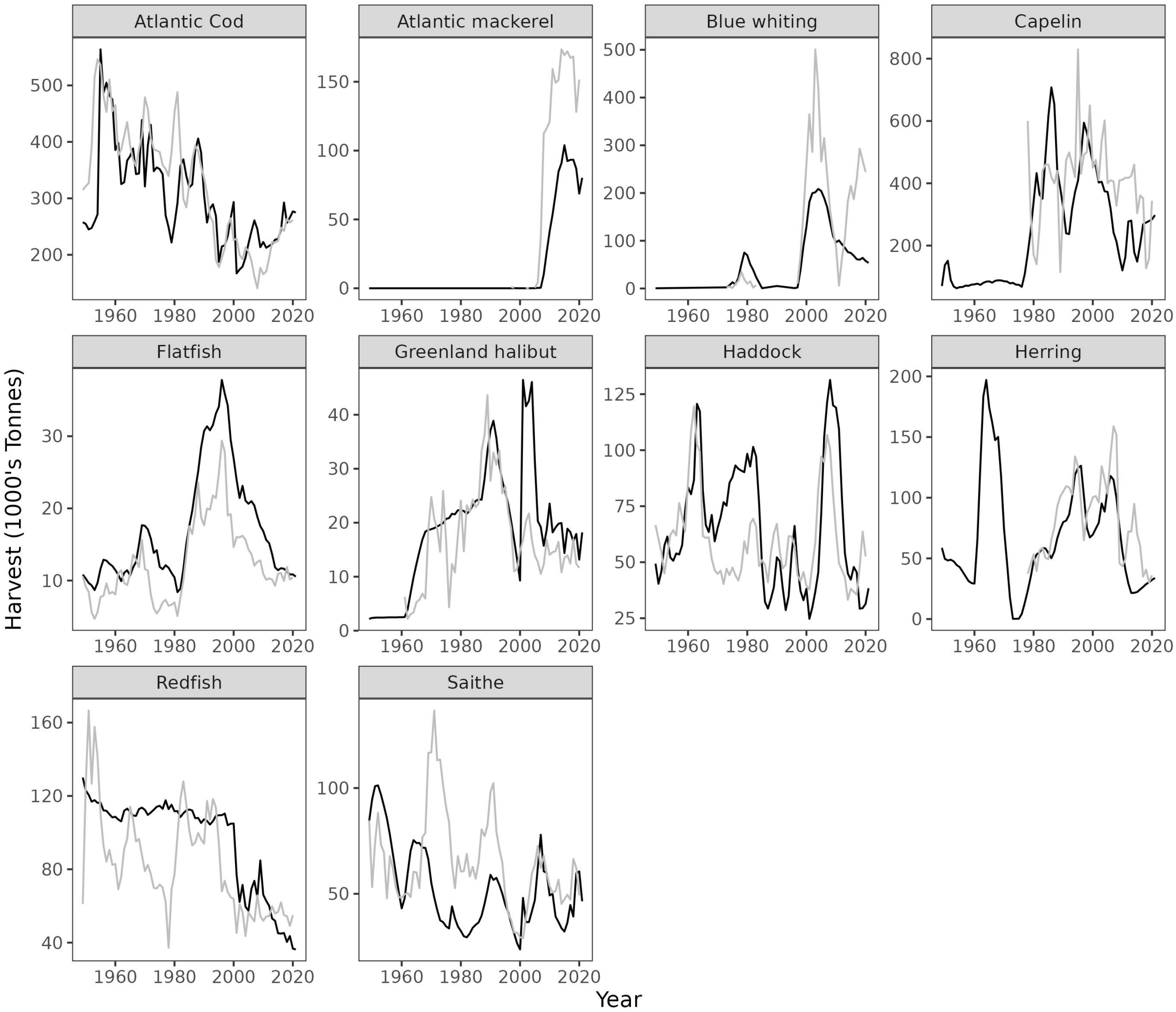

Figure 9: Harvest indices for some important commercial species in the second phase of the Iceland Atlantis model update. Here six new métiers were implemented. Black lines indicate Atlantis estimates and grey lines are reference harvest estimates from the MFRI.

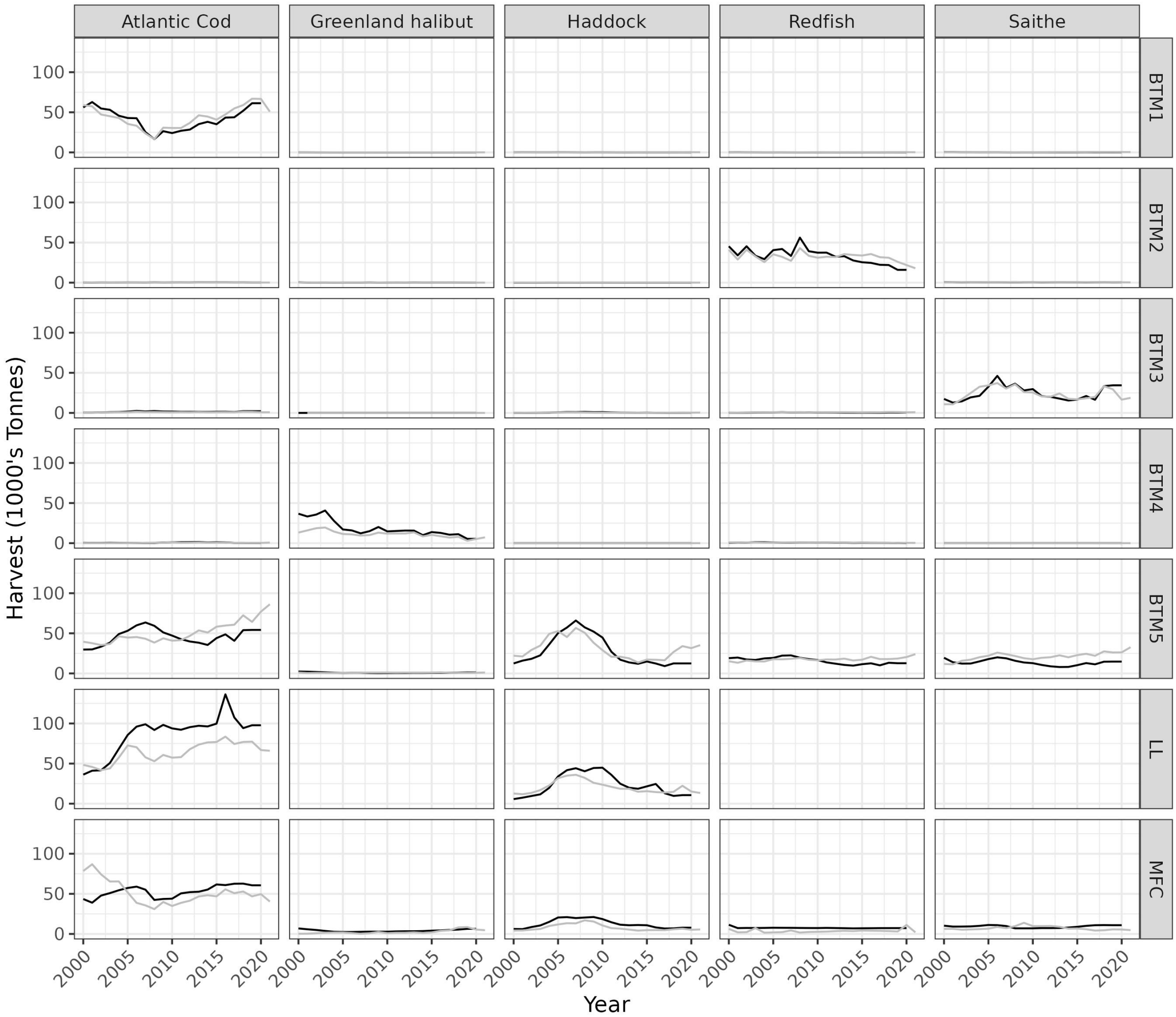

Figure 10: Harvest indices for some important commercial species in the second phase of the Iceland Atlantis model update for each of the new métiers as well as the remaining fisheries for these species for which fishing mortality forced (MFC). Here six new métiers were implemented, five of which were bottom trawl métiers (BTM) and one which was a longline (LL) métier. Black lines indicate Atlantis estimates and grey lines are reference harvest estimates from the MFRI.

4 Discussion

The métier analysis identified five métiers in which the five functional groups of interest were harvested. The effort in these métiers varied spatially and temporarily, considerations not previously addressed in the Iceland Atlantis model. The updates to the Atlantis model occurred in two phases, first the time series was extended through the year 2021 and second, the new bottom trawl métiers and the longline métier were developed within the model.

As previous studies have implemented métiers in Atlantis using varying approaches, our study provides a basis for a unified workflow. The model for the English channel used 20 distinct métiers mainly defined gear and target species (Girardin et al. 2018). Most of the métiers consisted of more than one main species. Effort in this model is spatially resolved, as it is now in the updated version of the Iceland Atlantis model. A similar implementation of fleet segments was done in the Northeast U.S. (Link, Gamble, and Fulton 2011; Olsen et al. 2016) and the Southeast Australian Atlantis marine ecosystem models (Fulton and Gorton 2014). The benefit of our approach, i.e., performing a cluster analysis that is explicitly spatial, rather than manually grouping species into métiers or fleet segments, is that métiers are more realistic and defined by reproducible statistical methods.

The updated Iceland Atlantis model provides a stable foundation to implement management strategy evaluation. There are now six multispecies métiers. Five of which represent bottom trawl harvest and each of these métiers harvest the same five different species, but to varying degrees. The sixth métier represents the longline fishery and targets Atlantic cod and haddock, two of the most important commercial species in Iceland. The extent of the spatial-temporal variation in the effort distribution reflects real choices made by fish harvesters, whether these be due to market concerns or regulatory concerns, such as temporary area closures implemented to protect juvenile fish (Schopka 2007).

There are some limitations in the updated Iceland Atlantis model. Firstly, the underlying environmental model which forces hydrodynamics, salinity, and temperature terminates in 2012. The implemented, and temporary, solution to this problem is to repeat the last 10 years of the data series. This solution is sensible, particularly given that 14 out of 17 fish functional groups experienced a biomass change of less than 5% during a sensitivity test of the forced temperature parameters in the Iceland Atlantis model (Sturludóttir et al. 2018). The exceptions were Atlantic herring, capelin, and Atlantic mackerel. The long-term solution is to change the underlying environmental model to an updated and maintained environmental model, such as Nemo-NAA10 km (Hordoir et al. 2022). Nemo was implemented in the Nordic and Barents Sea Atlantis model (Nilsen et al. 2023), and will be implemented in the Iceland model. Beyond being updated to the current year, the Nemo model has the advantage of easily incorporating downscaled global climate models to simulate the impact of climate change (Nilsen et al. 2023). Another limitation of the updated model is that the métiers were limited to up to five functional groups. This decision to limit the harvested species in the métiers was to simplify model parameterization. While the proportion of harvest is overrepresented for each species that remains in the métiers, the actual harvest values did not change. The major limitation is that with the current model we cannot assess the impact of different management decisions on those functional groups not included in the Atlantis métiers but are harvested in the real-world métiers. Future updates to the Atlantis model should include expanding the functional groups modeled in these métiers to include the commercial demersal, *Gadoid spp*., and flatfish functional groups.

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