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Veiðimynstur íslenska botnvörpuflotans

Elzbieta Baranowska, Maartje Oostdijk, Sandra Rybicki, Bjarki Þ. Elvarsson, Gunnar Stefánsson, Sveinn Agnarsson, Pamela J. Woods

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Ágrip

Botnvörpuveiðar skila alla jafna afla sem samanstendur af fjölda mismunandi tegunda sem veiðast samhliða, þó svo áætlunin sé að ná einungis einni tegund. Til að skoða hvaða fisktegundir eru veiddar saman eru klasagreiningar gerðar á aflasamsetningu en þess konar greining hefur ekki verið gerð hingað til fyrir íslenskan botnvörpuflota. Í þessari skýrslu skoðum aflasamsetningu botvörpuflotans, til að fá fram veiðimynstur (métiers), með því að beita viðurkenndum klasagreiningaraðferðum á aflagögn úr afladagbókum íslenskra togara frá árunum 2016-2019. HAC (Hierarchical Agglomerative Clustering) klasagreiningu var beitt á aflagögnin á togstigi ásamt breytum í tíma og rúmi. Niðurstöður klasagreiningarinnar gefa til kynna tilvist ákveðins veiðimynsturs íslenska botnvörpuflotans sem einkennist af marktegundum á borð við þorsk, gullkarfa, ufsa, grálúðu og djúpkarfa. Einnig komu fram blönduð veiðimynstur sem einkenndist fremur af staðsetningu en marktegund.

Skýrslan er hluti af doktorsverkefni „Flotahegðun íslenskra útgerða á Íslandsmiðum“ sem er einn vinnuhluti stærra verkefnis kallað „Fiskveiðar til framtíðar: Samspil vistkerfis og félagshagrænna þátta við nýtingu sjávarauðlinda“. Háskóli Íslands og Landbúnaðarháskóli Íslands í samstarfi við Hafrannsóknastofnun fengu öndvegisstyrk frá Rannsóknasjóði Íslands – Rannís til framkvæmdar rannsóknarinnar. Verkefnisstjórar eru Erla Sturludóttir, lektor við Landbúnaðarháskóla Íslands og Gunnar Stefánsson, prófessor við Raunvísindastofnun Háskóla Íslands. Þessi hluti verkefnis var gerður í samstarfi við Hafrannsóknastofnun.

Lykilorð: fiskveiðar, botnvarpa, afladagbækur, métiers, klasagreining.

Abstract

Harvests in demersal trawl fleets are of a highly mixed nature, with harvesters often targeting assemblages of species rather than individual species. To study which species are commonly harvested together, clustering analysis is often used. To date, such an analysis has not been performed for Icelandic fishing fleets. Here we explored the catch composition of the Icelandic demersal fishing fleet by analyzing logbook data in a métier analysis from demersal trawl fisheries for the years 2016 to 2019. We applied Hierarchical Agglomerative Clustering (HAC) to catch data and used the outcome from the algorithm to infer fishing operations targeting species assemblages, called métiers. Because we performed the analysis at the haul level, we were able to include spatial and temporal variables which informed métier definition. Results indicated métiers defined based on clusters of hauls were highly associated with the primary target species of Atlantic cod, golden redfish, saithe, haddock, Greenland halibut, and demersal beaked redfish. The métiers were also distinguished by spatial and vertical distributions related to each métier's species composition.

This report is part of a doctoral dissertation titled "Fisher Behaviour and Fleet Dynamics in the Icelandic Demersal Fishing Fleets". It is a section of a larger project, "Fishing into the Future: Operationalizing Linkages in the Ecosystem Approach to Fisheries", funded by the Icelandic Research Fund Grant of Excellence. The project is managed by Erla Sturludóttir, an assistant professor at the Agricultural University of Iceland and Gunnar Stefánsson, a professor at the University of Iceland. This part of the research was carried out in collaboration with the Marine and Freshwater Research Institute.

***Keywords**: fisheries, bottom otter trawl, logbooks, métiers, HAC.*

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1 Introduction

Effective fisheries management needs to consider a significant interplay among biological (i.e. stock sustainability), environmental (i.e. impact of the fisheries on the surroundings), and socioeconomic factors (long-term fishing opportunities and employment) (Selig et al., 2017). Ecosystem-based fisheries management (EBFM) is stated as a pathway towards sustainable, responsible and flexible fisheries in a specific area (Pikitch et al., 2004). This approach can be realized by modifying and refocusing management priorities from a single target species to the ecosystem-based targets. Thus, the goal of EBFM is to establish and maintain a healthy balance among environmental and socio-economic goals (Pikitch et al., 2004, Bastardie et al., 2021. Howell et al., 2021). However, this task is challenging and presents numerous obstacles, even with the best attempts of fisheries scientists to incorporate these factors into existing stock assessment models (Karp et al., 2023). One major obstacle is that fisheries rarely target a single species, and the heterogeneity of the catch can pose challenges in implementing management plans efficiently. The depletion of a single-species Total Allowable Catch (TAC) or quota can produce “choke species” situations, where the filling of quota for a choke species leads to an inability to fully utilize quota for other species and increase missed fishing opportunities (ICES 2022a). This situation can lead to an increase in discards and underreporting (Bastardie et al., 2010, Ulrich et al., 2001), resulting in the depletion of species, despite management efforts consistently focusing on reducing fishing mortality. Thus, single-species/stock TACs alone can fall short in effectively controlling the removal and fishing mortality of other species caught simultaneously (Reiss et al., 2010, Vinther et al., 2004, Ulrich et al., 2011, ICES 2022a). Demersal fisheries also present particular challenges due to the diversity in gear, area, and seasons during which fishing may take place, affecting the expected catch and, consequently, the species composition in the catch (van Denderen 2015). As a result, this complexity of fishing operations makes it difficult to utilize existing information from fisheries, such as logbooks or landings, for management purposes.

Despite these complexities, various methodologies have been explored to integrate multi-species catches into fisheries management plans (Deporte et al., 2012, Ulrich et al., 2012, ICES 2023c). For example, to address the challenges associated with mixed fisheries, coastal countries in Europe have focused on two primary areas: defining fleets and métiers (Ulrich et al., 2012). In support of this task, the International Council for the Exploration of the Seas (ICES) has adopted a typology for organizing vessels into fleets and identifying métiers, which involves categorizing fishing activities into clusters to simplify the interpretation of fishing patterns from data (ICES 2003). The European Data Collection Framework (DCF) defines a “fleet” and “métier” as follows. A fleet (or fleet segment) is described as a group of vessels sharing the same length class and predominant fishing gear throughout the year. While vessels within a fleet segment may engage in different fishing activities during the reference period, they are typically classified under one fleet segment. However, a métier is characterized as a group of fishing operations targeting a specific or similar assemblage of species, using specific gear, within a precise period and/or geographical area, and sharing similar exploitation patterns (EC, 2008, p. 38). Hence, fleets characterize the vessels, while métier(s) delineate the fishing activities in which the fleet is involved (Ulrich et al., 2012). Métiers are identified by utilizing available data on gear group and type, location, time, and catch or landings. This process involves the application of quantitative multivariate statistics on these variables to identify suitable groupings of fishing activities (Deporte et al., 2012, EC, 2008, p. 38, Moore et al., 2019). Métier analysis is a widely practiced method in European waters to comprehend the characteristics of fishing operations and portray catch compositions of target fisheries from extensive harvest datasets (ICES 2023c). Evaluating different métiers and assessing their impact on both living resources and exploited ecosystems are crucial for guiding informed management decisions and enhancing the economic sustainability of fisheries. These fishing strategies serve as vital inputs for management strategy evaluations and monitoring the ecological sustainability of fisheries (Ulrich et al., 2012).

Demersal fisheries within the Icelandic Exclusive Economic Zone (EEZ) are primarily conducted by Icelandic vessels, utilizing a limited set of main gears such as bottom otter trawl, longline, demersal seine, and gillnets (ICES 2022b). These fisheries are mixed, with a handful of leading target species, with Atlantic cod (*Gadus morhua*) being predominant in most of the gear types (ICES 2022b). Additionally, other species such as haddock (*Melanogrammus aeglefinus*), golden redfish (*Sebastes norvegicus*), Greenland halibut (*Reinhardtius hippoglossoides*), saithe (*Pollachius virens*) and demersal beaked redfish (*Sebastes mentella*) are also targeted, along with a few flatfish species (ICES 2022b). The otter trawl exhibits the highest landings rate (~250-300 thousand tonnes yearly or ~56% of all demersal fisheries) and effort (~18.000 1000kW days yearly since 2015) (ICES 2022b) and features a highly mixed species composition, making it the most important gear type in Icelandic demersal fisheries and the focus of this analysis.

This study aims to perform a haul-level métier analysis of Icelandic demersal fisheries carried out with bottom otter trawl by applying verified clustering methods (ICES 2023c, Deporte et al., 2012, Moore et al., 2019). This involved defining fishing patterns of this highly utilized gear type in Icelandic waters and hence provided a deeper understanding of spatio-temporal occurrences of the métiers and giving weight to those variables in the clustering process. Within ICES regions where many countries share the same stocks, métier analysis is often conducted at the trip level due to the unreliable nature of logbook data (Deporte et al., 2012, ICES 2023c, Szynaka et al., 2021). This analysis is therefore unusual in its ability to take advantage of detailed haul-level data and is the first attempt to identify métiers or fishing patterns for the Icelandic trawler fleet.

2 Methods

2.1 Data

This analysis utilized mandatory haul-level electronic logbook data from Icelandic bottom otter trawl fisheries with a minimum 135 mm mesh size in the cod end, collected and registered by vessels themselves and stored by the Directorate of Fisheries (MFAF 2023b). The original dataset, with approximately 166,000 individual logbook entries (with each entry representing one haul) from the years 2016-2019, was used and restricted to the Icelandic EEZ. We decided to focus on bottom otter trawl and not include trawls identified as *Nephrops* and shrimp trawls as those have already a targeted fishery in Icelandic waters and are only used if the fishery is allowed. The logbook data contains numerous variables related to each specific haul, including the towed haul's date, start and end location, towing time, depth, vessel ID, and catch by species, among others.

2.2 Data filtering and alteration

The logbook data underwent pre-evaluation, during which hauls were excluded where they were known to be scientific hauls from Icelandic spring and autumn groundfish surveys, spatially impossible (i.e. on land, in harbor, too deep or shallow for bottom otter trawl to operate within Icelandic waters) or involved excessively large tonnages. In addition, infrequently caught fish and invertebrate species were removed from the dataset. This process resulted in 26 fish species being used in the analysis (Table 1). For several commercial species bound by TACs (which are illegal to discard), a comparison was made between the logbook catch and the landed catch to identify discrepancies. In cases where a significant under- or overshoot was observed, these hauls were looked over in detail by matching the logbook data from this particular trip to the trip's landings data. If the difference was more than 10% under- or overshoot, the hauls were eliminated from the data set. Moreover, dissimilarity between the registered gear in the logbooks and the actual landings were evaluated, and entries for which no likely error correction could be found were eliminated from the dataset.

The remaining dataset of approximately 155,000 distinct hauls was transformed into a catch-profile matrix with hauls as rows, species as columns, and proportions of the total as data. Because the number of species observed in a haul is typically far less than 26, these data were zero-inflated and left-skewed after transformation into proportions. Therefore, we used the geometric Bayesian-multiplicative estimation method to replace any zeros with very small values (zComposition R package, v1.4.1; Palarea-Albaladejo and Martín-Fernández 2015). We assumed the Dirichlet distribution, a generalization of the beta distribution, which acts as the conjugate prior (i.e. the Dirichlet prior) for the multinomial distribution in Bayesian statistics, before continuing analyses (following the procedure described by Parsa et al., 2020). Subsequently, a logit transformation was applied on the adjusted catch-profile matrix to normalize the distributions (boot R package, v1.3-28.1; Canty and Ripley 2024). Additionally, the dates and geographical coordinates for each individual haul were transformed from linear and Cartesian coordinates into cyclical and polar coordinates, respectively and utilized as covariates in the catch-profile matrix (Parsa et al., 2020). Sine and cosine curves are more appropriate than linear dates to reflect the cyclical nature of seasons (i.e., December and January are more similar to each other than their linear month numbers of 12 and 1 indicate). Similarly, polar coordinates are more appropriate and reflect circular distances of locations in the waters that encircle Iceland as an island nation. Transformed day of the haul (doy^T) was then represented as:

$$doy_{sin}^{T} = \sin\left(\left(\frac{doy}{365}\right)2\pi\right)$$

$$doy_{cos}^{T} = \cos\left(\left(\frac{doy}{365}\right)2\pi\right)$$

where the variable *doy* represents the day of the year (1st January = 1 and 31st December = 365). Converting Cartesian coordinates (*X*, *Y*) representing location (longitude and latitude respectively) to polar coordinates (r, θ) was done using the following equations:

$$\bar{X} = \frac{\sum X}{N}$$

$$\bar{Y} = \frac{\sum Y}{N}$$

$$x = X - \bar{X}_{lon}$$

$$y = Y - \bar{Y}_{lat}$$

$$r = \sqrt{(x^2 + y^2)}$$

$$\theta = \arctan\left(\frac{y}{x}\right)$$

Here, r represents the distance from the origin ($\bar{X}$, $\bar{Y}$) to the point (X, Y), and θ represents the angle measured counterclockwise from the positive x-axis to the line segment connecting the origin to the point (x, y). Finally, the Euclidean distance matrix (vegan R package, v2.6-4; Oksanen et al., 2022) was computed on the catch-profile and covariate matrix as input for the cluster analysis.

We decided not to scale our input matrix giving the species with higher standard deviation values (SD-value in Table 1) greater influence when performing the cluster analysis. After comparing the scaled and unscaled approaches, this method yielded more interpretable patterns and was therefore selected for subsequent analyses.

Table 1. Species included in the analysis along with their standard deviation (SD) values calculated form the input catch-profile matrix.

Common name	**Scientific name**	**SD-value**
Arctic wolffish	*Anarhichas denticulatus*	0.7551
Atlantic cod	*Gadus morhua*	2.9388
Atlantic halibut	*Hippoglossus hippoglossus*	0.9650
Atlantic wolffish	*Anarhichas lupus*	1.5792
Black scabbard fish	*Aphanopus carbo*	0.9197
Blue ling	*Molva dipterygia*	1.1672
Dab	*Limanda limanda*	0.7682
Demersal beaked redfish	*Sebastes mentella*	1.5929
Golden redfish	*Sebastes norvegicus*	2.4326
Greater Silver Smelt	*Argentina silus*	1.1998
Greenland halibut	*Reinhardtius hippoglossoides*	1.8457
Haddock	*Melanogrammus aeglefinus*	2.1474

Common name	Scientific name	SD-value
Lemon sole	*Microstomus kitt*	1.3715
Ling	*Molva molva*	1.5699
Long rough dab	*Hippoglossoides platessoides*	0.7849
Megrim	*Lepidorhombus whiffiagonis*	0.9687
Monkfish	*Lophius piscatorius*	1.1413
Norway redfish	*Sebastes viviparus*	0.8761
Plaice	*Pleuronectes platessa*	1.6854
Saithe	*Pollachius virens*	2.3895
Blue skate	*Dipturus batis*	0.8349
Spotted wolffish	*Anarhichas minor*	1.3634
Starry ray	*Amblyraja radiata*	0.8860
Tusk	*Brosme brosme*	0.8882
Whiting	*Merlangius merlangus*	1.1122
Witch	*Glyptocephalus cynoglossus*	0.9886

2.3 Defining the clusters

In our clustering analysis, we generally followed the procedure outlined by Sulanke et al., (2022) for fleet segmentation but adapted the clustering methods to our haul-based dataset. The hierarchical agglomerative clustering (HAC) algorithm was applied on our transformed catch-profile matrix using Ward's linkage (fastcluster R package, v1.2.3; Müllner 2013) (Murtagh and Legendre 2014, Ward 1963; Singh et al., 2011). Various linkage methods within HAC were tested, including complete and average linkage, as well as an alternative clustering approach suitable for large datasets was also explored, the CLARA method (from the cluster R package, v2.1.4; Maechler et al., 2024), which is an extension to partitioning around k-medoids method. After careful consideration, we ultimately opted for the HAC clustering method with Ward's criterion. Even though CLARA gave reasonably similar clusters, it failed to identify some of the distinct fisheries (Fig. A4). In addition, the HAC method allows for tracing the clusters along the clustering tree (clustree R package, v0.5.1; Zappia and Oshlack 2018) and thus for investigating which clusters are more closely related. The complete and average linkage criteria did not perform well with our haul-based dataset, producing one large cluster and many single haul clusters. Ward's linkage is a classical sum-of-squares criterion, producing groups that minimize within-group dispersion at each binary fusion, i.e. when two clusters are combined to one (Ward 1963, Murtagh and Legendre 2014).

The optimal number of clusters was determined using a combination of approaches, including the average silhouette width approach and the Mantel test (Sulanke et al., 2022), visual inspection of the clustering tree generated from the HAC method and expert judgment. These tests for optimal numbers of clusters were run separately for individual years of the data due to memory limitations. Finally, the decision was based on the outcome from the tests, the processing time of the cluster calculations, the insights provided by the clusters, and their perceived utility for ecosystem modelling (Kasper et al., 2023).

Clusters were then defined as métiers and were analyzed for seasonal variation by dividing annual cycles into four quarter periods, defined to align with the typical characteristics of a local gadoid life cycle within Icelandic waters. These seasons were defined as:

- Winter (December-February): this period marks the end of feeding season for typical gadoid fishes and the beginning of the migration towards spawning grounds.
- Spring (March-May): during this time, most gadoids in Icelandic waters enter their spawning season.
- Summer (June-August): onset of the feeding season.
- Autumn (September-November): the feeding season continues through autumn.

All analyses in this report were performed within the R language and environment for statistical computing (v4.2.2) and Rstudio software (v2022.07.2 +576). For data alteration and visual display, the following packages were used: tidyverse (v2.0.0, Wickham et al., 2019) and ggplot2 (v3.5.1, Wickham, 2016).

3 Results

3.1 Clusters

After conducting multivariate analyses, the average silhouette width method and Mantel test suggested a range of 2-15 clusters as the optimal number of clusters (Table A1). We opted for seven clusters as this number frequently emerged as the most suitable and provided a comprehensive description of the fisheries according to the fisheries specialists (Table A1 and Fig. 1). Fewer clusters caused the distinct fisheries of demersal beaked redfish and Greenland halibut to be combined into a single métier, while the fisheries have distinct spatial patterns. More than seven clusters created several more similar clusters with Atlantic cod as a central species, with a lot of spatial and temporal overlap. Further partitioning into informative fishing patterns may be possible within larger main métiers.

The HAC clusters (shown in Fig. 1) are described as following métiers for the bottom otter trawl, named by dominant species and/or spatial characteristic:

1. “Cod”
2. “Shallow-mixed”
3. “Deep-mixed”
4. “Saithe”
5. “Demersal beaked redfish / Greater silver smelt”
6. “Golden redfish”
7. “Greenland halibut”

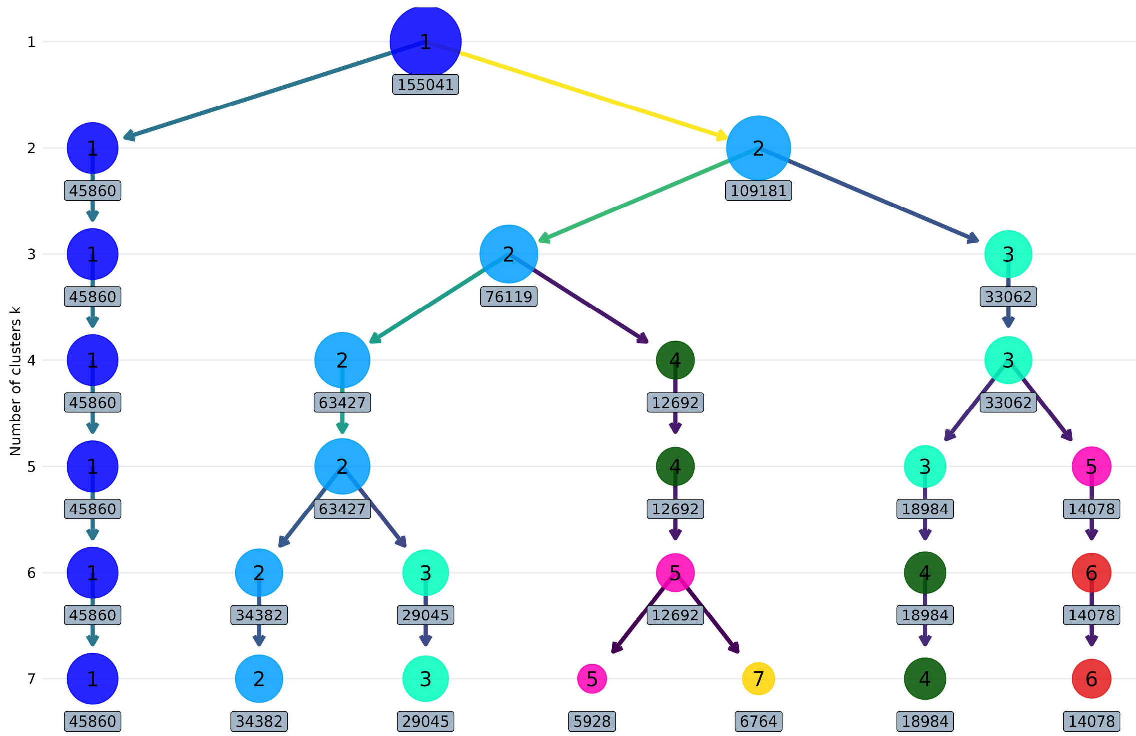

Figure 1. HAC clustering tree. Bubbles show cluster numbers, and boxes underneath show the number of hauls within each cluster. Y-axis shows the number of clusters. Cluster number representing the métier: 1 = "cod", 2 = "shallow-mixed", 3 = "deep-mixed", 4 = "saithe", 5 = "demersal beaked redfish / greater silver smelt", 6 = "golden redfish", 7 = "Greenland halibut".

3.2 Métiers

"Cod"

This métier is characterized by hauls where cod is the dominant species, with little co-occurrence of other species (Figs. 2 and 18). When species co-occurred, these mainly included saithe, redfish, haddock and Greenland halibut. Its spatial distribution exhibits a seasonal pattern, which follows cod migration patterns towards spawning and feeding grounds (Fig. 3). This métier was predominantly caught in the main fishing grounds in the north-west during all seasons. The shift towards primary spawning grounds in the south, near the Selvogsbanki area, becomes visible in the winter (December-February) and peaks in the spring (March-May), indicating migration from the feeding grounds in the north-west and east (Solmundsson et al., 2015). A fishing area strip near Jökuldjúp, deep waters just outside the Faxaflói bay, and the Reykjanes ridge started to become visible in the winter and peaked in the spring, indicating possible cod spawning grounds in those areas (Fig. 3). During summer (June-August) and autumn (September-November), this métier is almost never caught in the south-west, south, and south-east. However, in the colder waters in the east, it is very visible during those months, and a shift north is clearly evident.

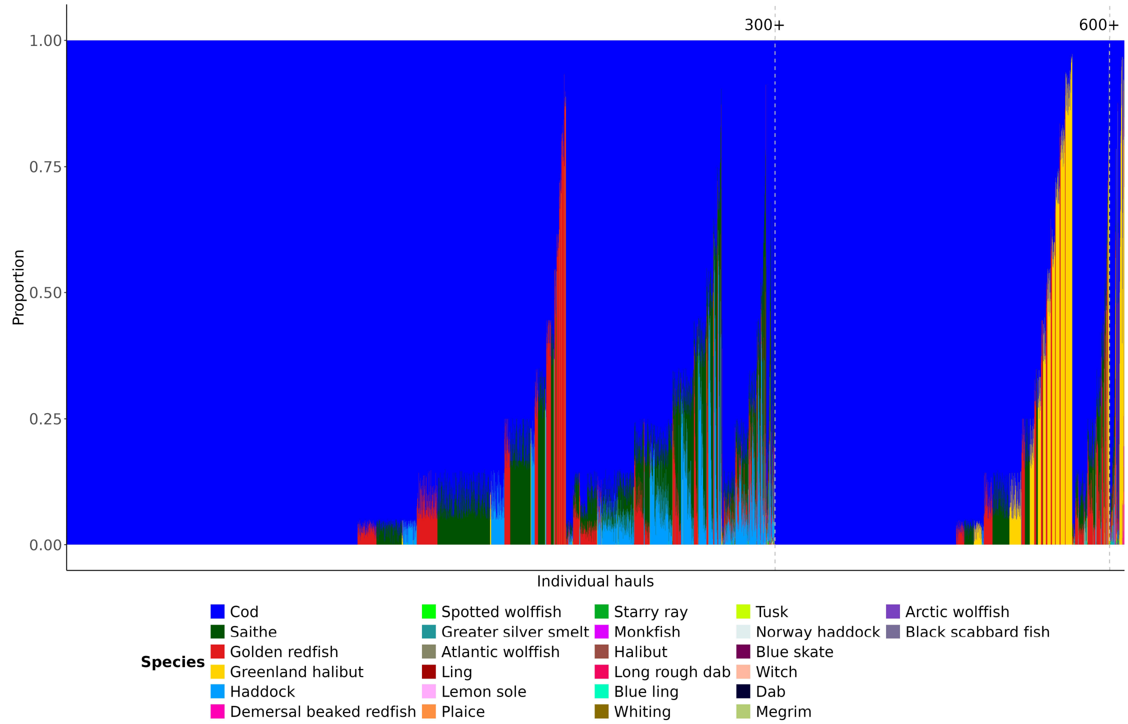

Figure 2. The proportion of species caught within each haul within the "*cod*" métier. The x-axis is organized according to the diversity of species within a single haul, ranging from less diverse to more diverse (one species registered, then two etc.), and in decreasing order of the proportion of cod present in the haul. Notably, a considerable number of "clean" cod hauls are evident in the data. Additionally, the figure highlights the impact of depth, with hauls ranging 0-300 m organized to the left of the 300+ vertical line, 300-600 m between the 300+ and 600+ m lines, and over 600 m to the right of the 600+ line. Hauls with the most species recorded are visible far to the right of each depth bin.

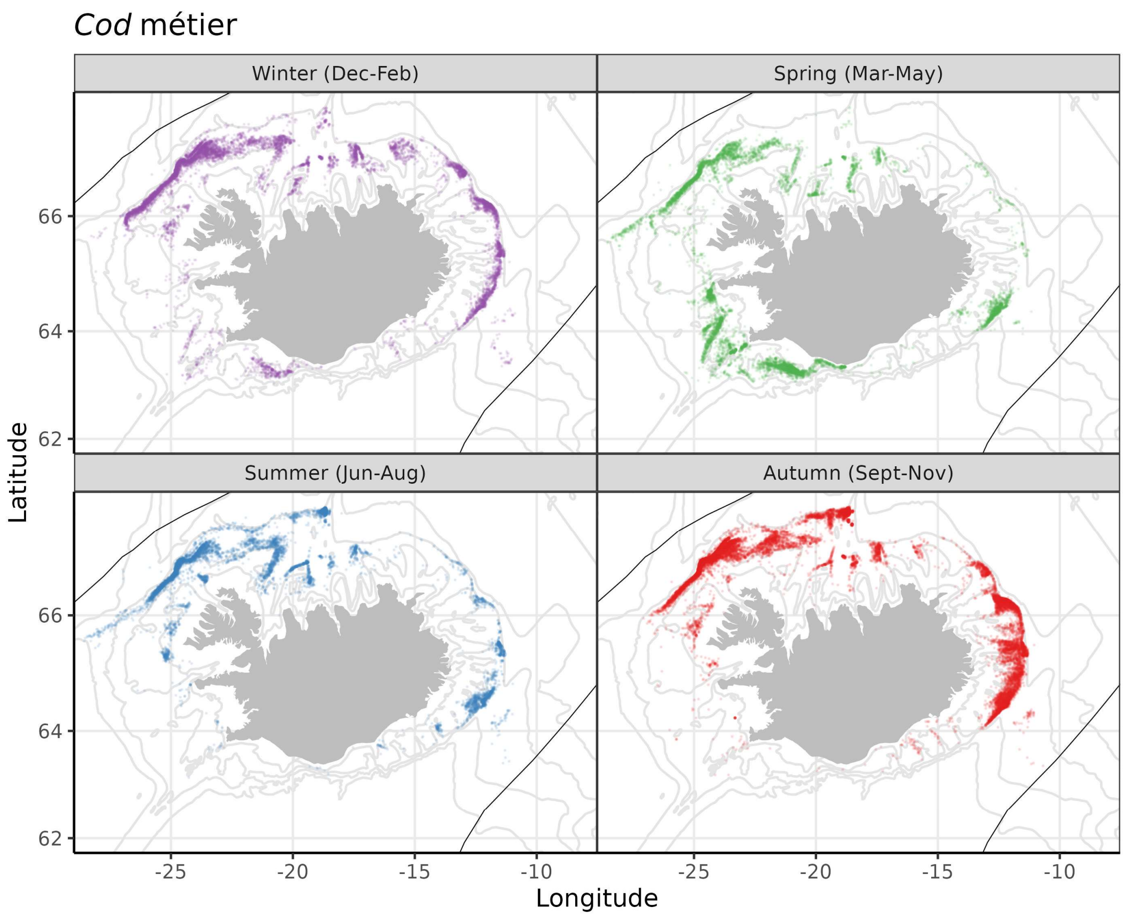

Figure 3. Spatial and seasonal distribution of the hauls classified within the "*cod*" métier.

"*Shallow-mixed*"

Cod, haddock and plaice catches distinguished this métier, with a large proportion of the hauls being divided by the first two (Figs. 4 and 18). There were also hauls where plaice was dominant or constituted a large proportion of the catch. Hauls within this métier were typically caught at shallower depths and closer to the coastline (Fig. 5). This métier exhibited seasonal changes in its spatial distribution, with more hauls towed in the southern region near primary gadoid spawning grounds (Selvogsbanki) during winter, peaking in the spring (Fig. 5). During spring and summer, this métier operated near the shallower edge of the fishing grounds in the north-west and displayed fishing hotspots in various areas in the south and south-east. However, in the autumn, the dispersion of the hauls became more apparent, both in the east and north-west. The depth distribution of the species mix within this cluster was evident, with plaice predominantly caught in shallow hauls (Fig. A1, Fig. 4). Additionally, smaller vessels participated in this métier (Fig. 17).

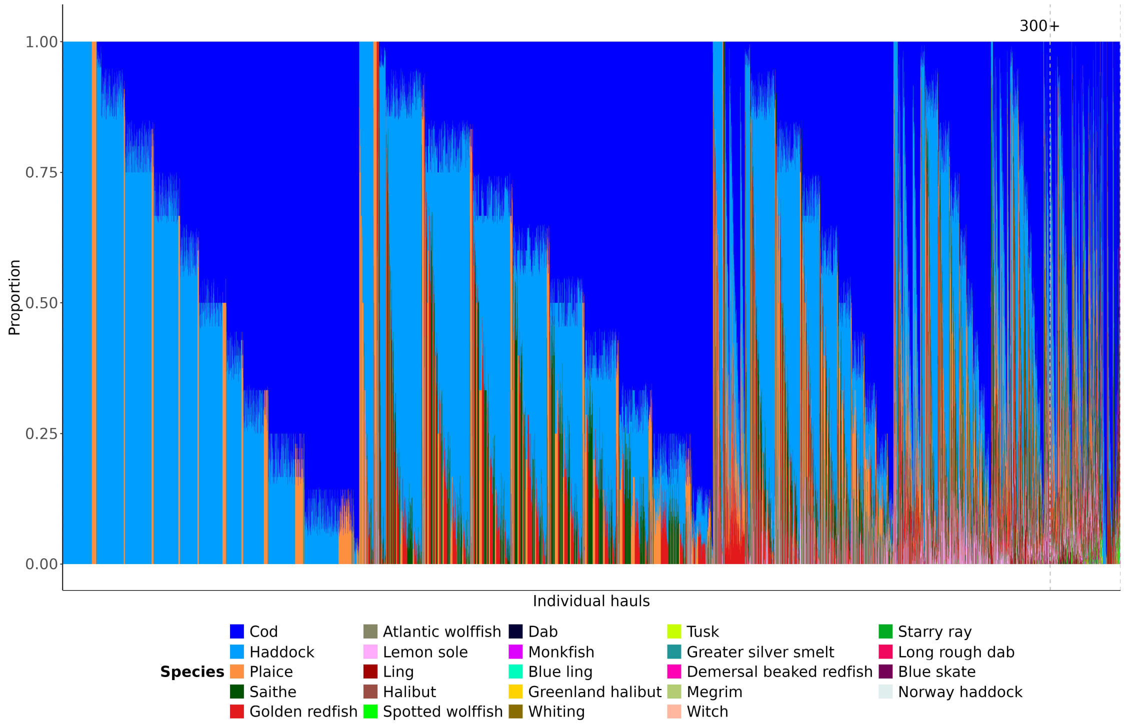

Figure 4. The proportion of species caught within each haul within the "*shallow-mixed*" métier. The x-axis is organized according to the diversity of species within a single haul, ranging from less diverse to more diverse (one species registered, then two etc.), and in increasing order of cod proportion. Far to the left clean haddock hauls are visible and a few plaice hauls. Next are hauls with cod and haddock or plaice. Cod, haddock and plaice are dominant species in this plot. Additionally, the figure highlights the impact of depth, with hauls caught in 0-300 m and 300-600 m ranges lying to the left versus right of the vertical 300+ line. Hauls with the most species recorded are visible far to the right of each depth bin.

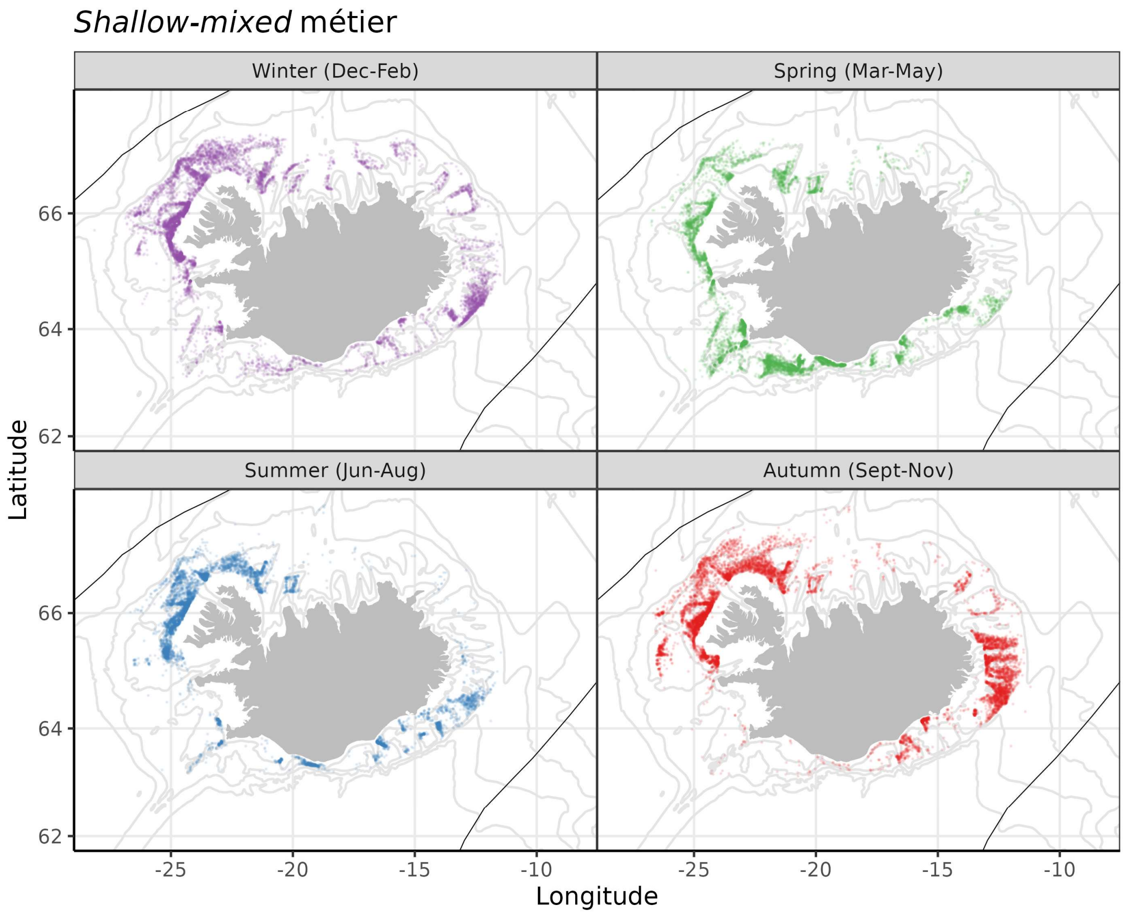

Figure 5. Spatial and seasonal distribution of the hauls classified within the "*shallow-mixed*" métier.

"*Deep-mixed*"

Characterized by cod, saithe, and golden redfish as dominant species (Figs. 6 and 18), this métier captured the hauls in deeper waters near the continental slope in the north-west and in the deeper regions in the south (Figs. 6 and 7). This métier showed spatial shifts, with more captures occurring in the southern areas during winter and spring, the spawning period for most Icelandic gadoid species, but in the summer and autumn, more hauls were taken in the north-west and south-east area (Fig. 7). The Jökuldjúp fishing area, west of Iceland, was also evident in this métier during winter and spring. Specific fishing areas in the south and southeast were much more prominent during autumn and winter. Those areas encompass banks with depths ranging from 100 to 150 m, interspersed with a network of troughs situated approximately at 200-300 m depth. These troughs are common *Nephrops* fishing grounds, including locations such as Skeiðarárdjúp, Breiðamerkurdjúp, Hornafjarðardjúp, and Lónsdjúp (Eiríksson and Jónasson, 2018). As previously mentioned *Nephrops* trawl data was not included in the analysis, but associated areas become visible in this métier, indicating the importance of them during autumn and winter.

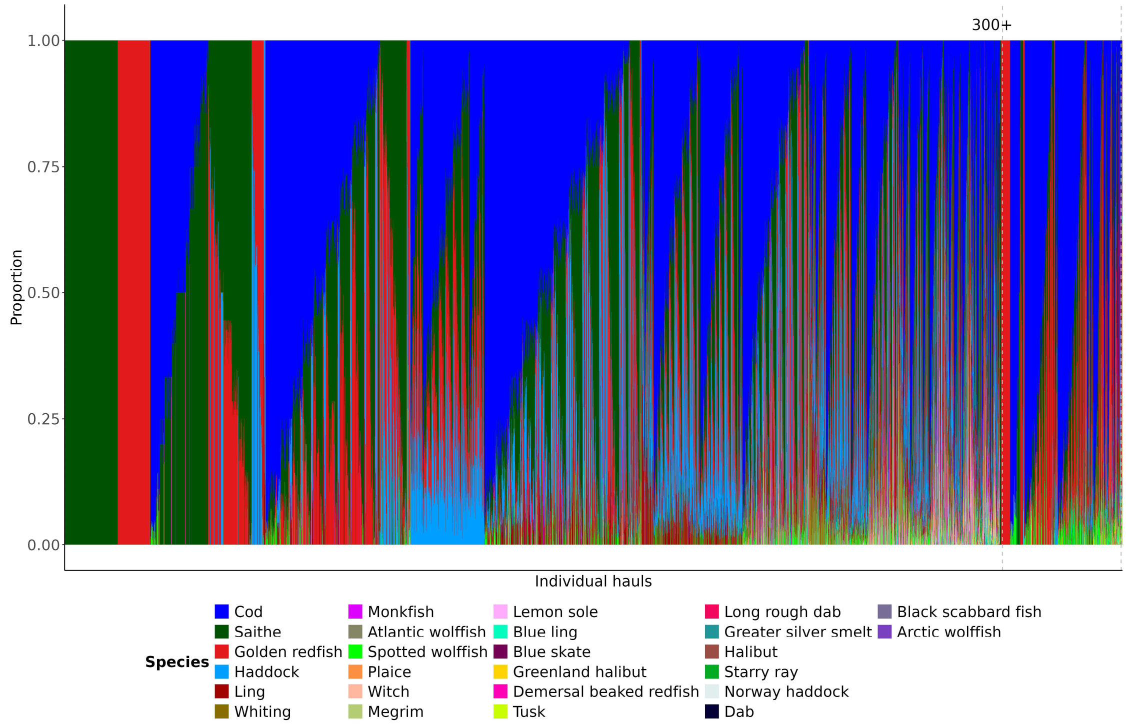

Figure 6. The proportion of species caught within each haul is demonstrated. The X-axis is organized according to the diversity of species within a single haul, ranging from less diverse to more diverse (one species registered, then two etc), and in order of decreasing proportion of cod. Far to the left, clean saithe and redfish hauls are visible. Additionally, the figure highlights the impact of depth, with hauls caught in 0-300 m and 300-600 m ranges lying to the left versus right of the vertical 300+ line. Hauls with the most species recorded are visible far to the right of each depth bin.

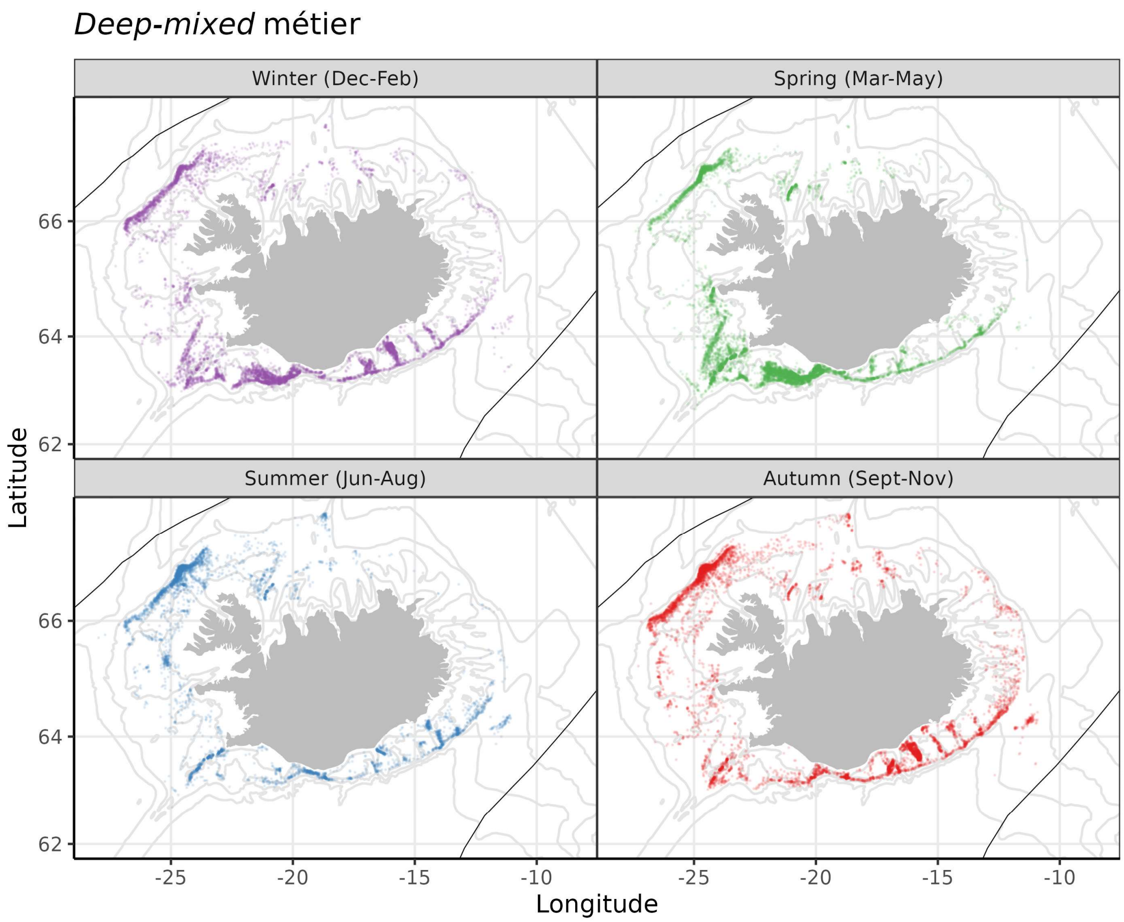

Figure 7. Spatial and seasonal distribution of the hauls within "*deep-mixed*" métier.

"*Saithe*"

The saithe métier was characterized by hauls containing a significant proportion of saithe catch, with clean saithe hauls evident (Figs. 8 and 18). Mixed hauls including saithe, cod, and golden redfish were also observed. However, the majority of hauls within this métier consisted of saithe making up approximately 68% of the catch (Fig. 18). This métier also exhibited a seasonal shift, with hauls being caught around saithe spawning grounds during winter and spring, particularly in the southern region near Selvogsbanki (Fig. 9). During this period, the fishing area near Jökuldjúp also becomes more distinct. In summer and autumn, the catch shifts toward the northwestern and southeastern slope areas. In the summer, hotspots in the south were clearly visible, such as in Lónsdjúp and near Reynisdjúp. However, during the autumn and winter, this métier was more frequently picked up in the *Nephrops* fishing areas, similar to the "*deep-mixed*" métier.

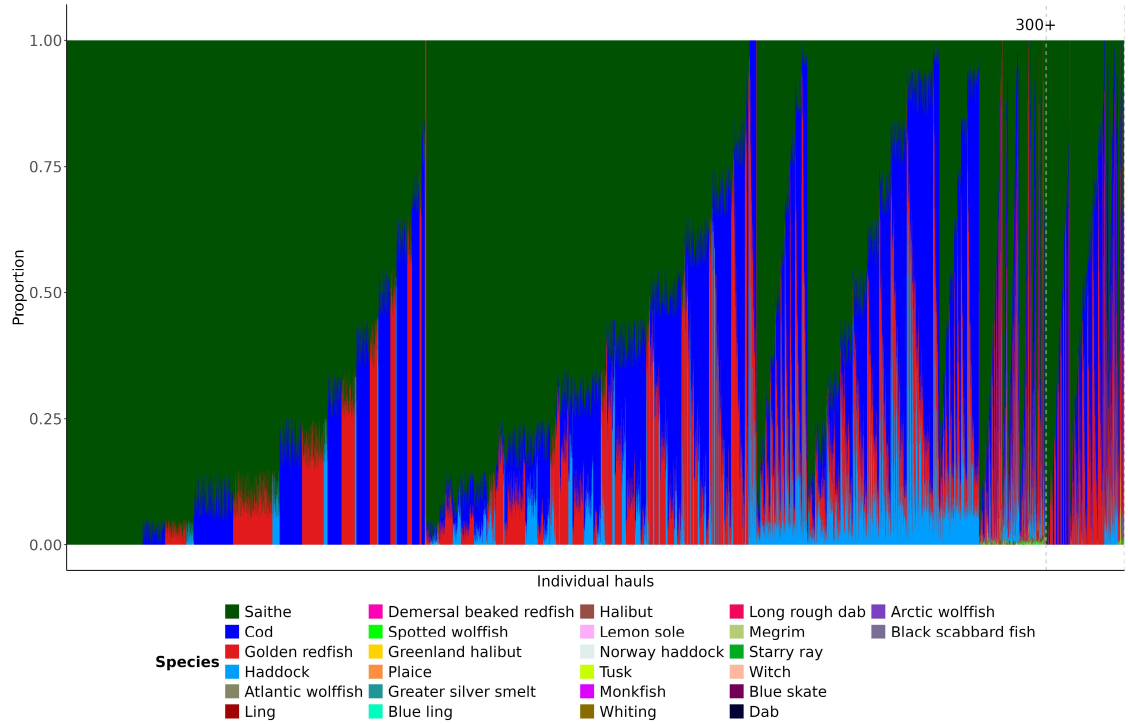

Figure 8. The proportion of species caught within each haul is demonstrated. The X-axis is organized according to the diversity of species within a single haul, ranging from less diverse to more diverse (one species registered, then two etc), and in order of decreasing proportion of saithe. Far to the left clean saithe hauls are visible followed by hauls with saithe and cod or redfish or haddock etc. Additionally, the figure highlights the impact of depth, with hauls caught in 0-300 m and 300-600 m ranges lying to the left versus right of the vertical 300+ line. Hauls with the most species recorded are visible far to the right of each depth bin.

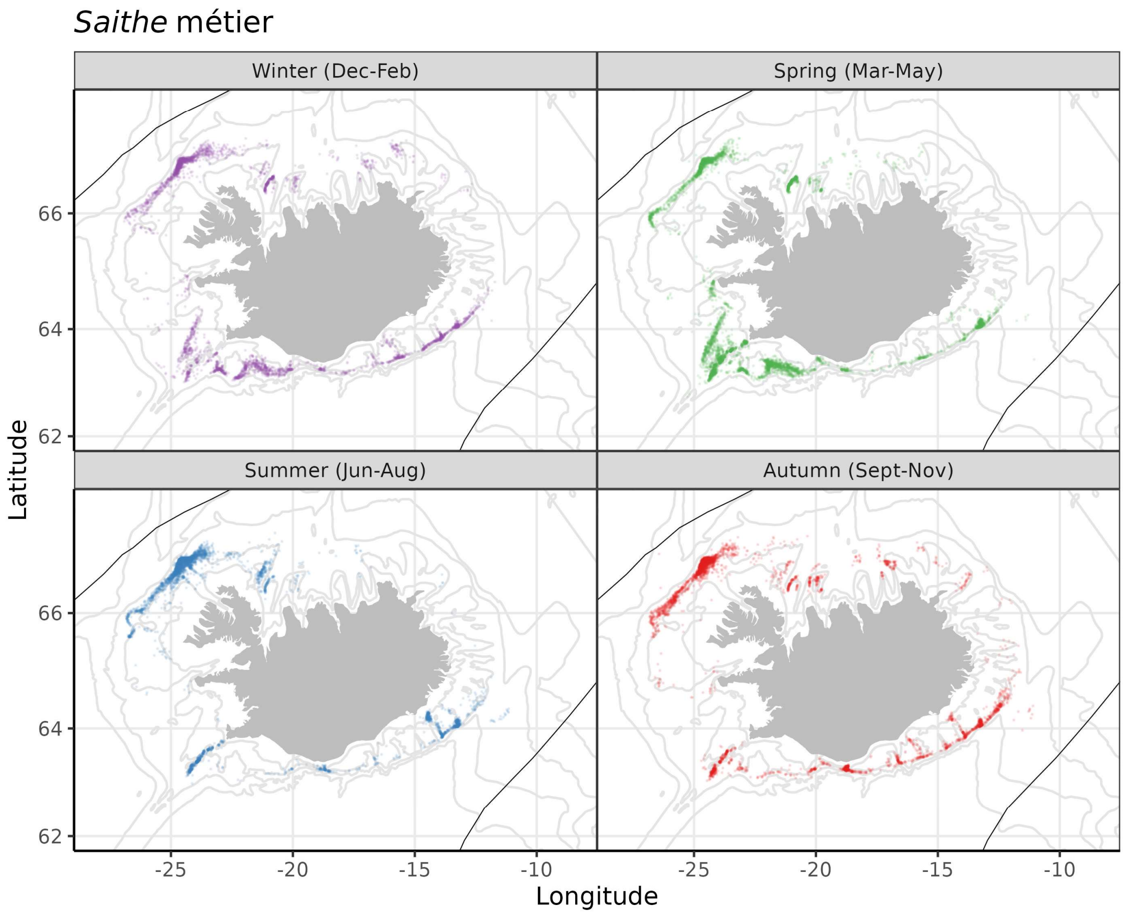

Figure 9. Spatial and seasonal distribution of the hauls within "*saithe*" métier.

"Golden redfish"

This métier contains golden redfish hauls, some mixed with other species, but for the most part clean hauls (Figs. 10 and 18). The golden redfish métier shifts spatially and temporally, with more hauls taken during the spring in fishing grounds west of the Reykjanes Ridge, especially on the edge of the continental slope (Fig. 11). During summer, autumn and winter, this strip in the south-west was not as visible, and more hauls in the main trawling grounds in the north-west were visible, especially during summer and autumn.

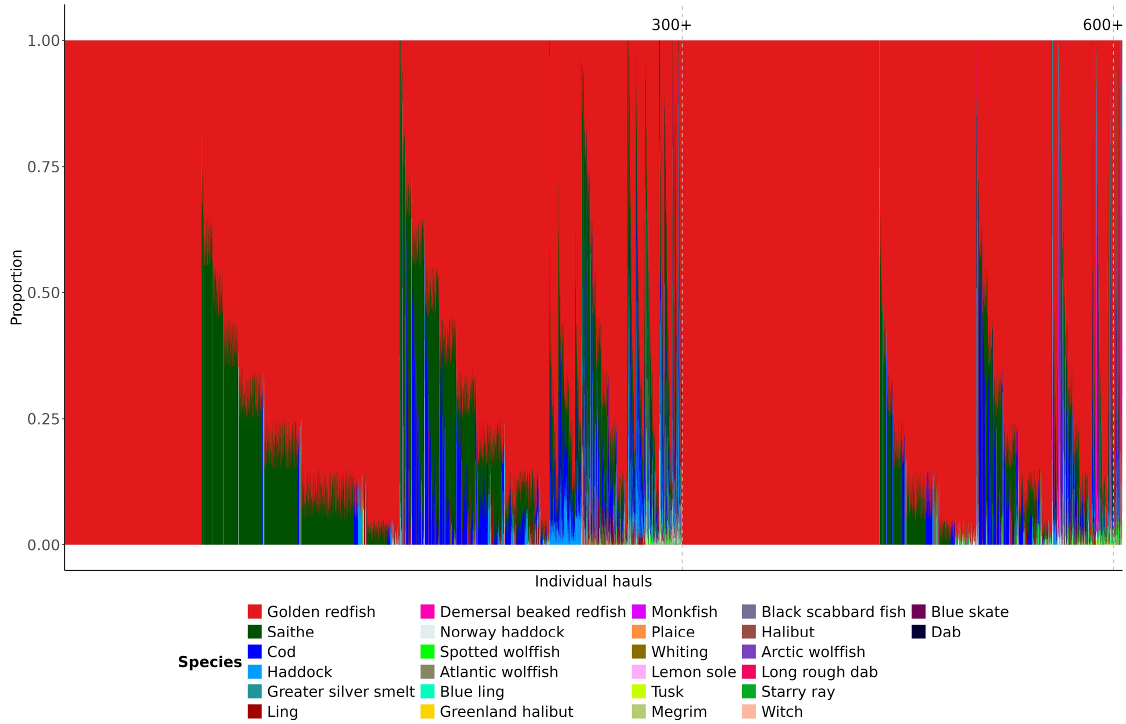

Figure 10. The proportion of species caught within each haul is demonstrated. The X-axis is organized according to the diversity of species within a single haul, ranging from less diverse to more diverse (one species registered, then two etc), and in decreasing order of proportion of golden redfish. Far to the left clean golden redfish hauls are visible followed by hauls with saithe, cod, haddock etc. Additionally, the figure highlights the impact of depth, with hauls ranging 0-300 m organized to the left of the 300+ vertical line, 300-600 m between the 300+ and 600+ m lines, and over 600 m to the right of the 600+ line. Hauls with the most species recorded are visible far to the right of each depth bin.

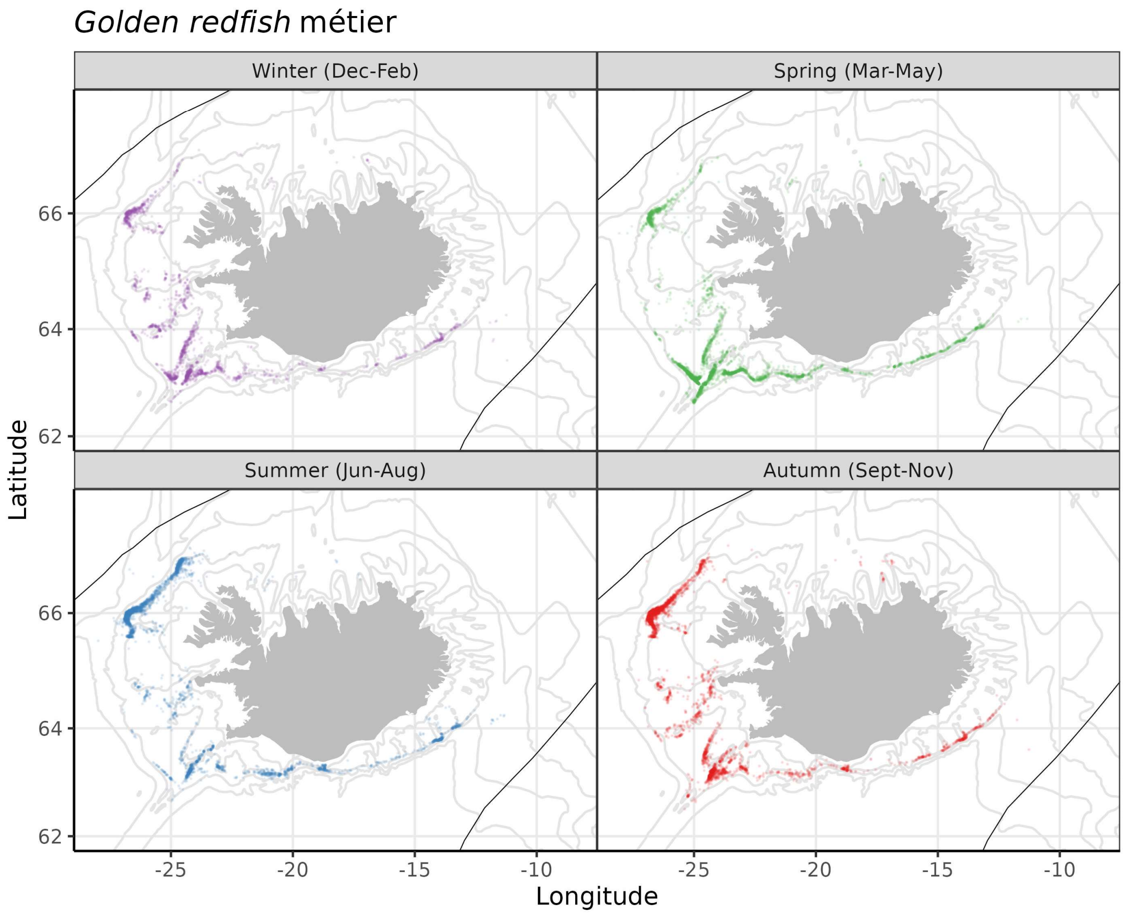

Figure 11. Spatial and seasonal distribution of the hauls classified within the "*golden redfish*" métier.

"Demersal beaked redfish / Greater silver smelt"

Species composition of the hauls within this métier was characterized by a mix of demersal beaked redfish and greater silver smelt, with the latter being more predominant in the deeper hauls due to a ban on fishing greater silver smelt in waters <400 m (Figs. 12, 18 and 1A). No clear shifts were observed in temporal or spatial distribution for this métier except for more hauls in the north-west during spring, summer and autumn (Fig. 13). The spatial distribution of those species in Icelandic waters is more or less connected to the southern parts of the continental slope and Reykjanes ridge.

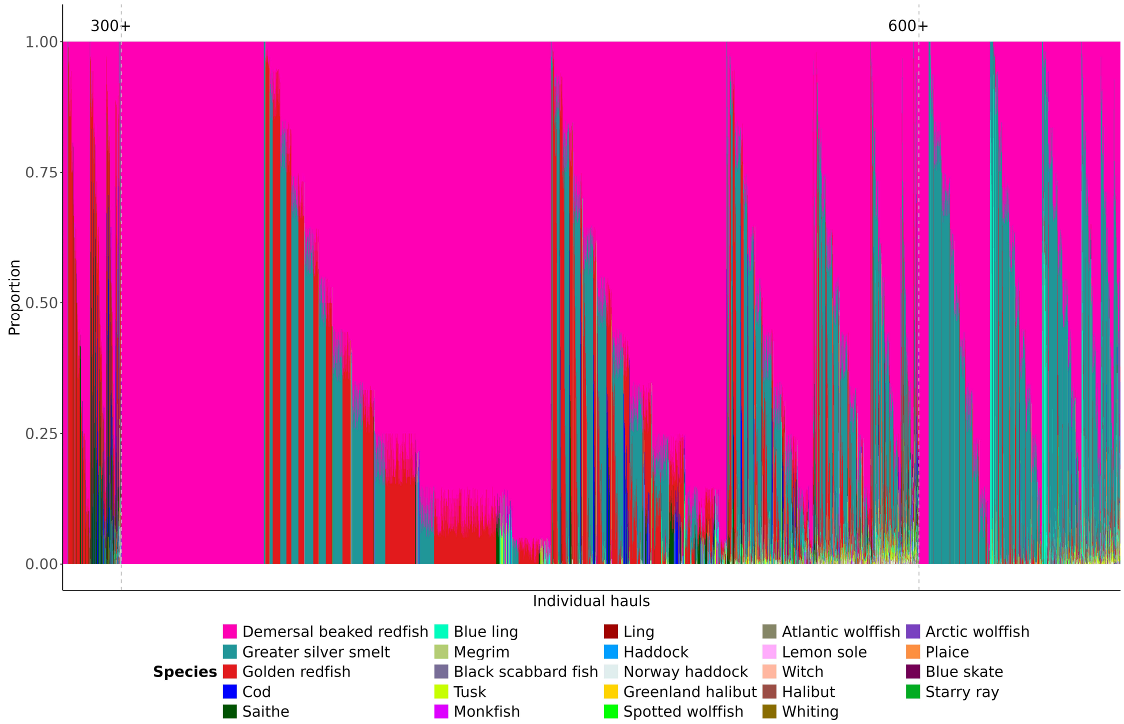

Figure 12. The proportion of species caught within each haul is demonstrated. The x-axis is organized according to the diversity of species within a single haul, ranging from less diverse to more diverse (one species registered, then two etc), and in decreasing order of the proportion of demersal beaked redfish. Far to the left clean demersal beaked redfish hauls are visible followed by hauls with greater silver smelt, redfish, etc. Hauls with the most species recorded are visible far to the right. Additionally, the figure highlights the impact of depth, with hauls ranging 0-300 m organized to the left of the 300+ vertical line, 300-600 m between the 300+ and 600+ m lines, and over 600 m to the right of the 600+ line. Hauls with the most species recorded are visible far to the right of each depth bin.

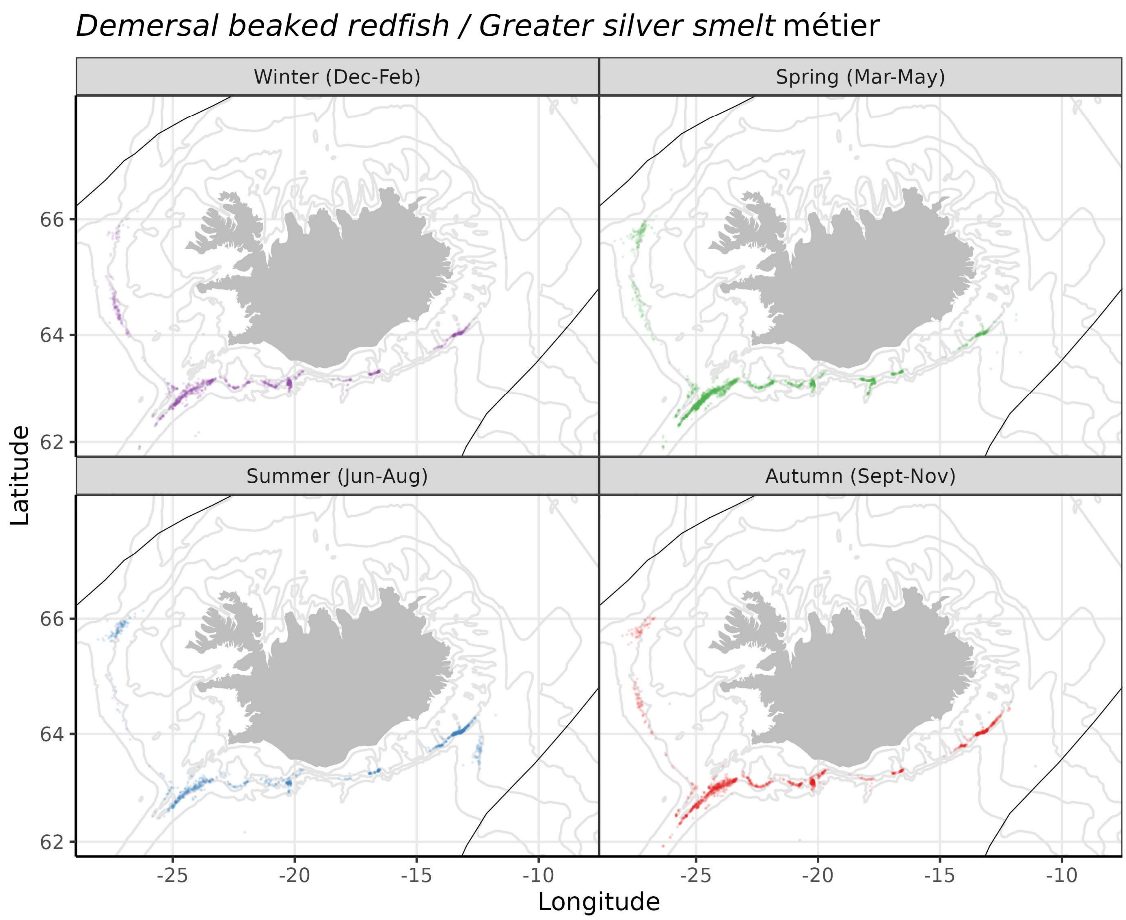

Figure 13. Spatial and seasonal distribution of hauls classified within the "*Demersal beaked redfish / Greater silver smelt*" métier.

"*Greenland halibut*"

The species composition of this métier primarily consists of Greenland halibut (Figs. 14 and 18), mixed with some demersal beaked redfish on the edges of their distribution in the west (Figs. 14, 15 and A2). However, since the hauls are towed for many hours (Fig. 17), there may be more pronounced differences in the depth (Fig. A1) and spatial distribution of species within each individual haul. This métier displays subtle spatial-temporal changes with captures occurring on the edge of the continental slope far from shore (Fig. 15). Notably, a hotspot becomes visible during spring in the north-west near the edge of the EEZ. It remains visible during summer but disappears in the autumn.

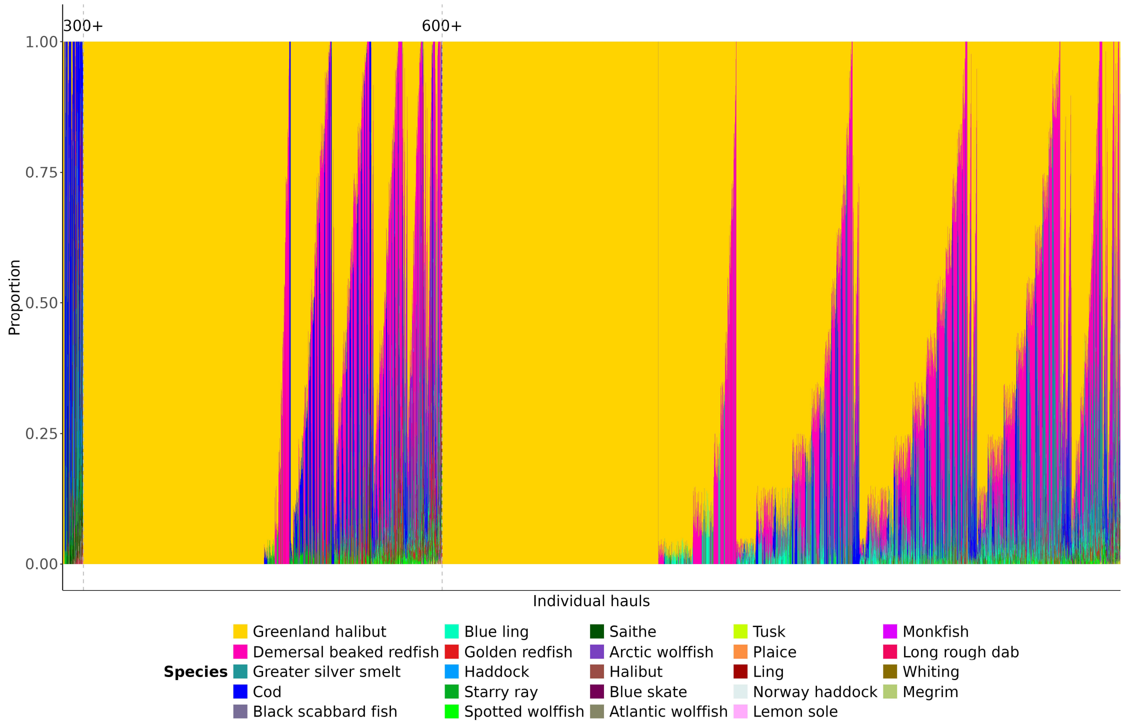

Figure 14. The proportion of species caught within each haul is demonstrated. The X-axis is organized according to the diversity of species within a single haul, ranging from less diverse to more diverse (one species registered, then two etc), and in order of decreasing Greenland halibut proportion. Far to the left clean Greenland halibut hauls are visible followed by hauls with demersal beaked redfish and other species. Additionally, the figure highlights the impact of depth, with hauls ranging 0-300 m organized to the left of the 300+ vertical line, 300-600 m between the 300+ and 600+ m lines, and over 600 m to the right of the 600+ line. Hauls with the most species recorded are visible far to the right of each depth bin.

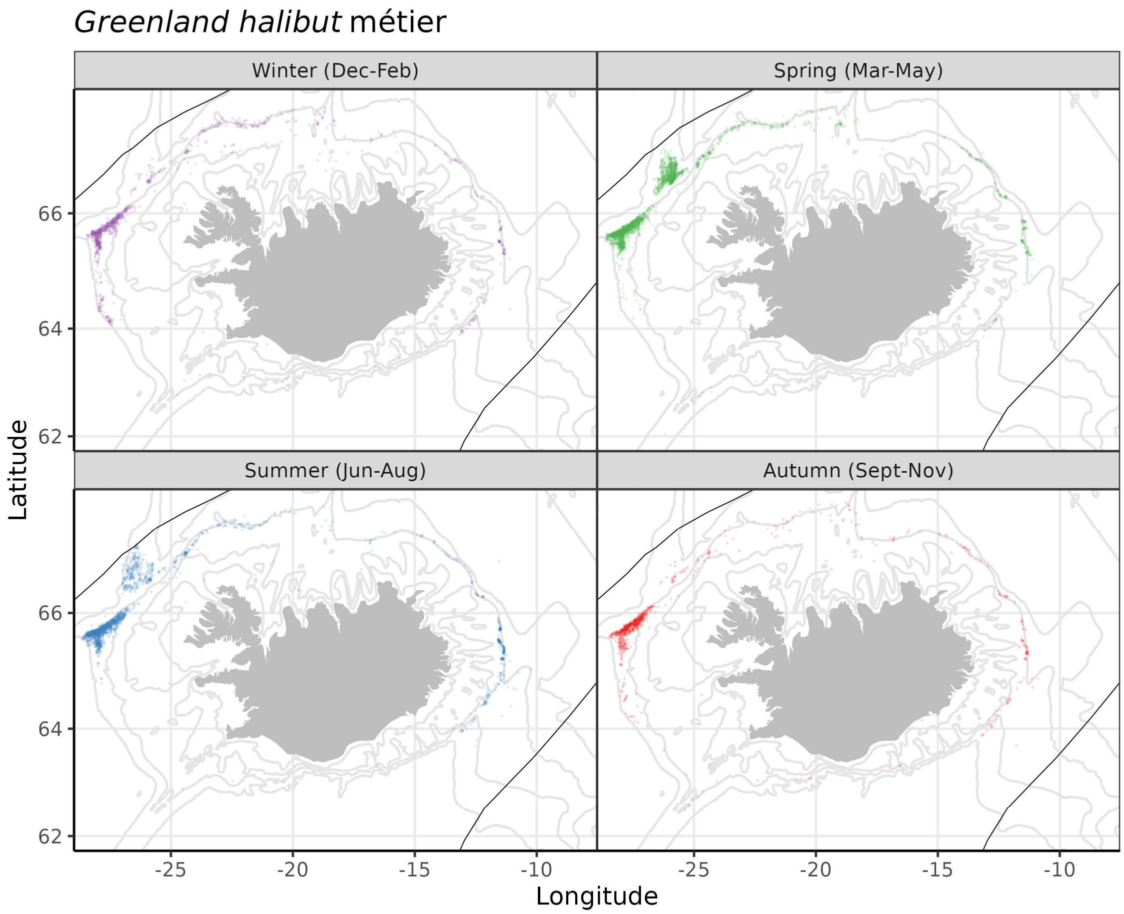

Figure 15. Spatial and seasonal distribution of the hauls classified within the "*Greenland halibut*" métier.

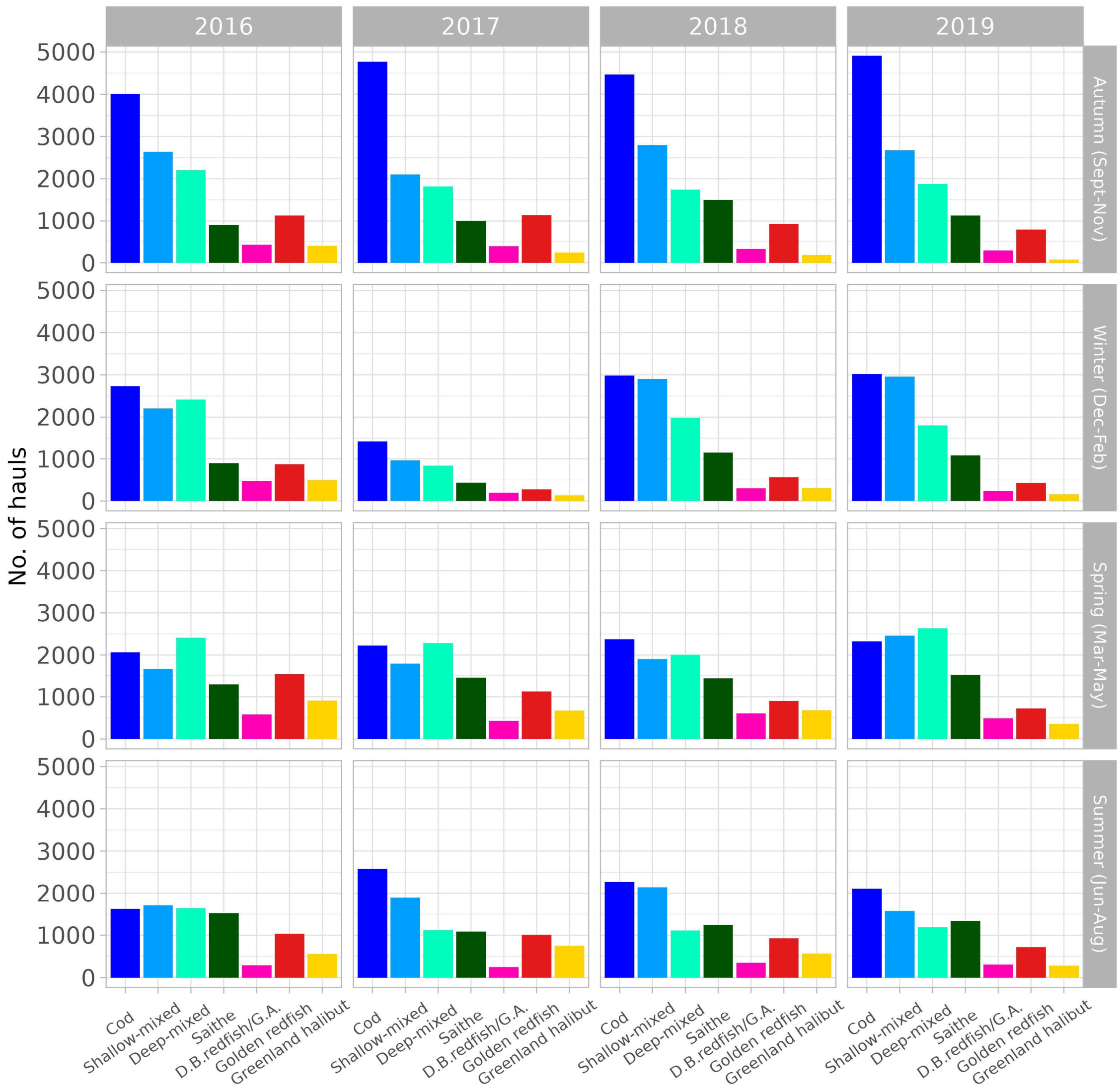

Figure 16. Number of hauls within each métier categorized by year and season.

3.3 Métier characteristics

The distribution of hauls within each métier, categorized by year and season winter (December-February), spring (March-May), summer (June-August), autumn (September- November)), indicated a stable pattern within clusters and seasons over the years of study (Fig. 16). During winter 2017 fishermen's strike occurred in Iceland, resulting in fewer registered hauls during that period in all métiers. The "*cod*" métier recorded the majority of hauls towed during autumn in all years. Both "*mixed*" métiers displayed a consistent pattern among years and seasons, with 1500-3000 hauls per season. The "*saithe*" métier remained relatively consistent throughout seasons and years, with 1000-1500 hauls towed per season, although slightly more hauls appeared in spring and summer. The "*demersal beaked redfish / greater silver smelt*" métier also exhibited stability between years and seasons, with slightly more hauls registered in spring compared to other seasons. A similar steady trend was observed in the "*Greenland halibut*" métier, with more hauls recorded during spring and summer. Lastly, the "*golden redfish*" métier also displayed a steady trend, however, fewer hauls were towed during winter compared to other seasons.

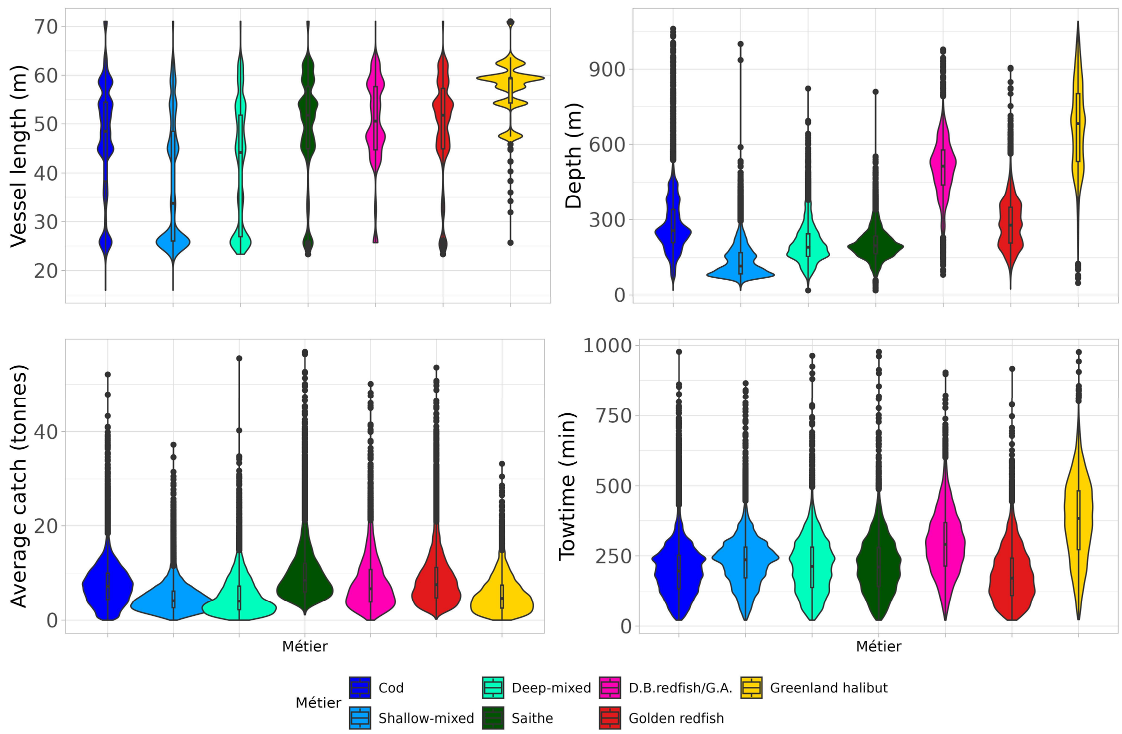

Figure 17. Summary of the métier characteristics from the logbook data. The figure shows the vessel length, the depth towed, the average catch in the haul and towtime of each haul. Hauls under 20 and over 1000 minutes in length were removed from the towtime plot.

Summary statistics for each métier is shown in Table 2 and Figure 17. The largest métier was the "*cod*" métier, comprising 45,860 hauls and yielding a catch of 341,492 tonnes in total over the four-year period (Table 2). This métier was notably distinct from the others, highlighting the significance of cod in trawl fisheries (Fig. 1). The average depth of the hauls within the "*cod*" métier was approximately 274 m (SD = 103) and the average vessel length participating in this métier was 51.2 m (SD = 13.4) (Fig. 17). The average tow time was 198 minutes (SD = 90.5), and the average tonnage within hauls was around 7.45 tonnes (SD = 4) (Fig. 17).

Two other clusters, the "*shallow-mixed*" métier and the "*deep-mixed*" métier, were second and third largest in terms of haul numbers with 34,382 and 29,045 hauls and 162,935 and 149,110 tonnes in total, respectively (Table 2). Although both métiers have hauls composed of mixed species, they exhibited distinct characteristics, including differences in species composition, depth, and potential average distance from shore. The average vessel length in the "*shallow-mixed*" métier was 41.3 m (SD = 14.3) and in the "*deep-mixed*" métier, it was approximately 44.4 m (SD = 14.5) (Fig. 17). Furthermore, the depth of the hauls within métiers differed, with the "*shallow-mixed*" métier primarily operating in shallower parts of the trawling fishing grounds around Iceland, with an average depth of 133 m (SD = 62.1), compared to the "*deep-mixed*" métier, which operated at an average depth of 204 m (SD = 77.2) (Fig. 17). Towing time was similar in both métiers, with the "*shallow-mixed*" métier having slightly longer towing times on average (227 minutes, SD = 84.1) compared to the "*deep-mixed*" métier (213 minutes, SD = 96.6) (Fig. 17). The average tonnage within hauls in "*shallow-mixed*" métier was around 4.7 tonnes (SD = 3.1) and in “*deep-mixed*” was 5.1 tonnes (SD = 3.9) (Fig. 17). The species mixture caught in the tows in mixed métiers varied significantly, with more haddock and plaice caught in the shallow métier compared to a more diverse species mix in the deep métier (Figs. 5 and 7). However, cod was caught in significant quantities in both métiers, accounting for a substantial portion of the catch within the hauls (40% on average for each métier) (Fig. 18).

The "s*aithe*" métier comprised just under 19,000 hauls, yielding a total catch of 186,375 tonnes (Table 2). Larger vessels, averaging 54.4 m (SD = 12.9), were observed in this métier, towing hauls at similar depths as the "*deep-mixed*" métier around 203 m (SD = 61) on average (Fig. 17). The average catch per haul was around 9.8 (SD = 5.6) tonnes, with towing time similar to previously mentioned métiers, averaging 215 minutes (SD = 97.9) per tow (Fig. 17). The "*golden redfish*" métier accounted for 14,078 hauls and a total catch of 124,147 tonnes (Table 2). Vessel sizes participating in this métier were very similar to those in the "*saithe*" métier, averaging 54.7 m (SD = 2.2) in length (Fig. 17). The average depth of the hauls within the "*golden redfish*" métier was approximately 282 m (SD = 93.4), and the average catch was around 8.8 tonnes (SD = 5.7) per tow (Fig. 17). Towing time was also shorter, averaging 182 minutes (SD = 95.4) per tow (Fig. 17). "*Saithe*" and "*golden redfish*" métiers were clustered together in previous steps (Fig. 1) and exhibit similar trends, suggesting that species caught in those two have to some extent similar attributes or have diurnal pattern with golden redfish caught at night and saithe during the day.

The “*Greenland halibut*” métier comprises 6,764 hauls and approximately 37,000 tonnes in total (Table 2). Hauls within this métier differed significantly from the previously mentioned métiers in depth and distance from shore. Hauls were deep, averaging approximately 671 m (SD = 176), and located far from shore near the continental slope (Fig. 15). The vessels participating in this métier were larger compared to other métiers, with an average length of 64.5 m (SD = 5.54), and their towing time was longer, averaging 377 minutes (SD = 146) per tow. The average tonnage within hauls was around 5.5 tonnes (SD = 3.9). Lastly, the “demersal *beaked redfish / greater silver smelt*” métier consisted of just under 6,000 hauls, yielding a catch of 47,800 tonnes in total (Table 2). The depth of the hauls within this métier averaged 505 m (SD = 116). The towing time was longer on average compared to most other métiers, averaging 296 minutes (SD = 116) per tow, although not as long as in the “*Greenland halibut*” métier (Fig 17). Vessel lengths participating in this métier were similar to the “*saithe*” and “*golden redfish*” métiers, averaging around 56.5 m (SD = 10.9) in length on average. The average tonnage within hauls in “*demersal beaked redfish / greater silver smelt*” métier was around 8 tonnes (SD = 5.9).

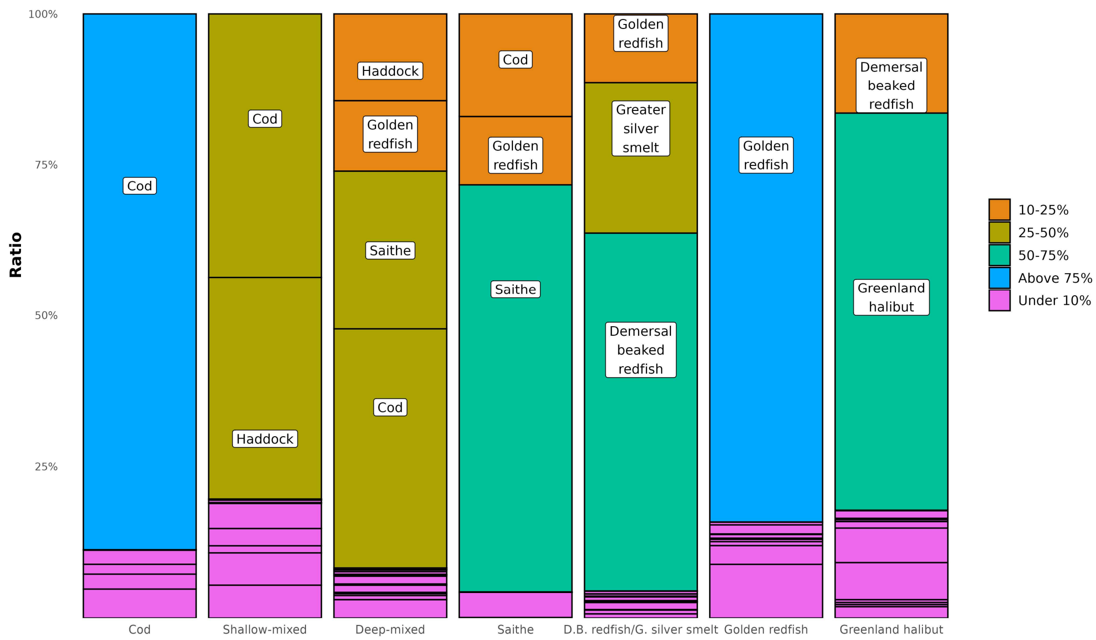

Figure 18. Proportion (%) of the species caught within each métier. "Under 10%" includes many fish species together.

When the average number of species and hauls within the clusters was analyzed at the trip level, with a specific focus on the first, next-to-last, and last hauls within trips (Figs. 19 and 20), it was observed that in both "mixed" métiers, the average number of species tended to be higher in the last haul of the trip with a greater number of hauls registered as the last one. This suggests that bycatch species were predominantly recorded towards the trip's conclusion. Concurrently, fewer last hauls were classified as belonging to métiers with relatively clean hauls (e.g, "*cod*" métier but also "*saithe*" and "*golden redfish*" métiers), relative to first hauls or even second-last-hauls, whereas mixed-species hauls were more frequently registered as last hauls relative to first or second-last-hauls. This pattern of fewer "clean" hauls being registered at the end of a trip (Fig. 20), indicates that clean and mixed métier definitions may partially reflect either a changing strategy through the course of fishing trips, or a tendency to register bycatch species as occurring in the last haul of the trip, rather than in the actual haul in which they were caught.

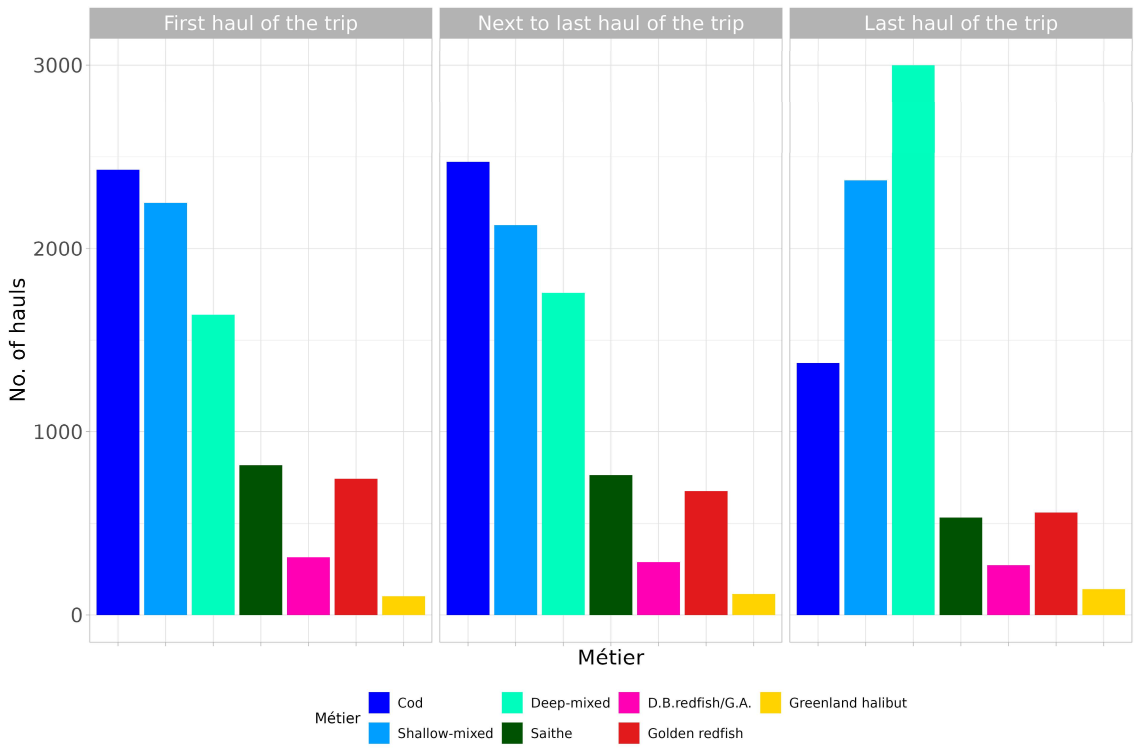

Figure 19. Comparison of the number of hauls within métier in the first haul of the trip (far left), next to the last haul of the trip (middle), and last haul of the trip (far right).

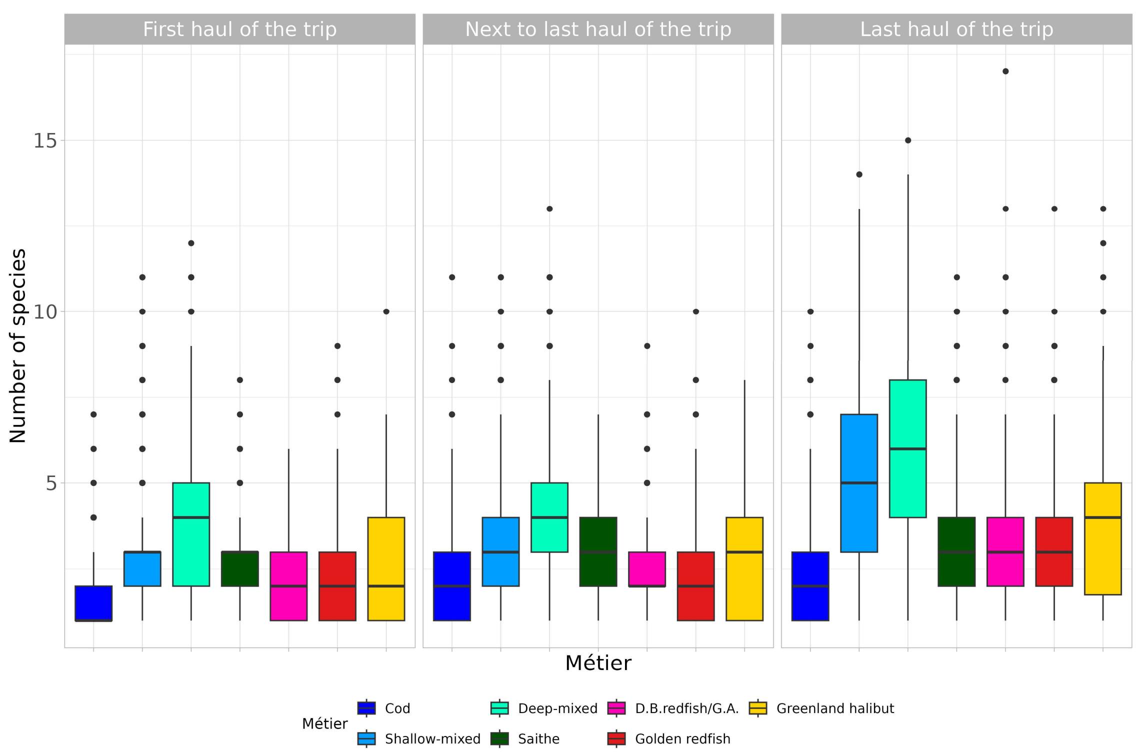

Figure 20. Comparison of the number of species within a métier in the first haul of the trip (far left), and last haul of the trip (far right), and next-to-the-last haul of the trip (middle).

Table 2. Métier overview. The numbers in the columns are summarized per métier for the whole period (2016-2019).

Métier name	No. of tows	No. of vessels	Total catch (tonnes)	Peak season
Cod	45 860	79	341 492	Autumn
Shallow mixed	34 382	77	162 935	Winter
Deep mixed	29 045	80	149 110	Spring
Saithe	18 984	75	186 375	Spring
Demersal beaked redfish/ Greater silver smelt	5 928	52	47 838	Spring
Golden redfish	14 078	71	124 147	Spring
Greenland halibut	6 764	48	36 878	Spring

4 Discussion

This study represents the first systematic attempt to define fishing patterns, referred to as métiers or fishing activities, within Icelandic waters. The focus was directed towards analyzing the demersal fishing gear, bottom otter trawl, which is predominantly used and associated with the highest landing rates (ICES 2022b). In the Icelandic EEZ, demersal fisheries are primarily conducted by Icelandic vessels and regulations regarding logbook data compel them to provide detailed information for each haul, making the use of logbook data highly relevant (MFAF 2023b). The high resolution of the logbook data, coupled with the accuracy of landing data that allows for comparison between datasets, provides a realistic depiction of bottom otter trawl fisheries over the span of four years. Because the analysis was haul-based, the same vessels were observed participating in different métiers, and most engaged in multiple métiers during a single fishing trip (Fig. A3). Vessels that remained at sea for extended periods, such as freezing vessels, transition through particularly numerous métiers over trips lasting up to a month. Fresh fish trawlers also traversed through 1-5 métiers in one trip, likely depending on their quota status and/or the processing factory's requirements. Consequently, the haul-based analysis provides a more detailed picture than métiers derived from landed catch data.

The clustering technique used in this analysis effectively identified the prominent patterns within the bottom otter trawl fisheries in Icelandic waters. Among the seven clusters identified from 2016-2019 logbook data, two were notably diverse in their catches ("*shallow-mixed*" and "*deep-mixed*"), while the remaining five exhibited a single or two main species that the fishers appeared to target, i.e., they are among the most valuable species and vessels returned to those areas to catch species compositions of those métiers (ICES 2022b). The occurrence of the targeted "*cod*" métier is in line with Atlantic cod being the most economically important species in Iceland, as well as its relatively high stock status in recent years (ICES 2023). Spatio-temporal shifts of this métier correlated with known migratory patterns of Atlantic cod (Fig. 3), moving from the feeding areas in the north-west and south-east to major spawning grounds in the south (Selvogsbanki) or to the smaller spawning units inshore during spring (Solmundsson et al., 2015). This pattern also explains the high proportions of cod found in both mixed métiers, reflecting both the widespread distribution of cod in Icelandic waters and high stock status during the research years (ICES 2023b).

Common transitions in métiers within trips were also observed (Fig. A3) by examining which métiers are more frequent in the hauls at the beginning of the trip versus towards the end. It was observed that the "*cod*" métier appeared less frequently in the final hauls compared to the initial ones, as did "*saithe*" and "*golden redfish*" hauls, although to a lesser extent (Fig. 20). In contrast, the "*deep-mixed*" métier increases notably in frequency as the last haul of the trip, along with the "*shallow-mixed*" métier (Fig. 20). Additionally, the number of species in both "*mixed*" métiers sharply increased from the next-to-last haul to the last haul (Fig. 19). These trends signify two possible scenarios. First, fishermen (on fresh fish trawlers) may be aiming to catch shallower species such as haddock, plaice and lemon sole as they head towards shore, driven by the need to maintain freshness of the product and keep fuel costs low. Second, the tendency of fishers to report species in multiples of filled tubs (roughly 350 kg) indicates that the bycatch and unwanted species were likely registered towards the end of fishing trips for convenience, as it can take several hauls to fill a single tub for some less abundant bycatch species. It may thus be the case that the many hauls in the *"deep-mixed*" métier are at least partially attributable to erroneous reporting of landing locations of the many possible bycatch species, and that hauls in the "clean" cod métier may lack small amounts of bycatch species. The spatial overlap of "*cod*", "*saithe*", "*golden redfish*" and "*deep-mixed*" (Fig. A2) métiers could suggest that the latter métier could possibly represent all non-target species caught by vessels targeting the "*cod*", "*saithe*", or "*golden redfish*" métiers, reported as the last haul of the trip. This métier transition within trips might be weaker for "*saithe*" and "*golden redfish*" métiers because species that define these métiers exhibit stronger schooling behavior with diurnal variation and are semi-pelagic (Steele 1963, Gauthier 2001, Froese and Pauli 2024), and therefore are less prone to mixing compared to hauls dominated by cod. Additionally, fish quality considerations further incentivizes fishers to target redfish species separately, as these fish can damage the delicate outer layers of valuable gadoid species, such as saithe and cod, when caught together.

The interplay between depth patterns and species compositions also provide a deeper understanding of complex fishing patterns. Even though "s*hallow-mixed*" and "*deep-mixed*" lack a central 'target' species, they can be partially characterized by their spatial distribution when exploring métiers more closely. The "*shallow-mixed*" métier involves mixed hauls obtained near the shore, where species that occupy shallower depths such as plaice, lemon sole and haddock are present (Fig. 4 and 5) (Solmundsson et al., 2005, ICES 2023d). On the contrary, the "*deep-mixed*" métier consists of a mix of cod, saithe and golden redfish caught in hauls distributed further from the shore, along the continental slope (Figs. 6 and 7). Despite both métiers being heavily mixed in terms of species composition, they represent distinct fishing patterns due to the variety of species caught and their spatial distribution. Vessels targeting species such as Greenland halibut, demersal beaked redfish, or greater silver smelt were instead situated very deep (Fig. 17) and far from the shore at the edge of or on the continental slope (Figs. 13 and 15). Although there is some minor overlap between those fishing activities in both western and eastern areas, they remain notably separate and identifiable by their presence in distinct regions of the northern ("*Greenland halibut"* métier) and the southern slope ("*demersal beaked redfish/greater silver smelt"* métier) (Fig. A2). Large factory vessels, particularly freezer trawlers, primarily target these métiers, operating for extended periods at sea (Fig. 17). Despite the spatial overlap between métiers, the fisheries themselves remain distinct, allowing for the avoidance and separate targeting of these métiers (MFAF 2023a, ICES 2023a).

Fish species that contribute to métiers targeted by freezer trawlers have overall higher catchability (ICES 2023a) and schooling behavior (Planque et al., 2013) and were therefore characterized by slightly higher tonnage per haul and shorter tow-times (Fig. 17). Therefore, when vessels encounter large schools, they can quickly fill the trawl, making relatively clean hauls within these métiers feasible. However, the consumer demand for fresh products, combined with their often more scattered spatial distribution, can make direct targeting less apparent. The complex aggregative behavior and migration patterns, both vertical and horizontal, of saithe, coupled with fleet catchability challenges (ICES 2019), make it intriguing to follow this métier over time and space, as predicting saithe locations is difficult (Fig. 9). Tagging experiments on saithe showed quite complex migratory patterns, with high fidelity to feeding grounds and depth migration between summer and winter (Armannsson et al., 2007, Armannsson and Jonsson 2012). This pattern was observed as "*saithe*" métier disappeared from the saithe fishing grounds along the south coast in the summer in comparison to other seasons, possibly due to shallow-water migrations during that period (Fig. 9), in areas where trawling is not allowed. In recent years the catchability of saithe has purportedly declined, and fishermen often bring up the issue of how difficult it is to find it (ICES 2019). This may contribute to fewer schools or schools of appropriate size-class being found.

The accuracy of fisheries logbook data is pivotal in research such as presented here, given that even in developed countries, self-reported fisheries logbook data contains errors that present challenges to data interpretation and analysis (Hintzen et al., 2012, ICES 2023c). For instance, there can be inaccuracies in registering gears, especially in small-scale fisheries that switch gear classes frequently, and where discards are illegal, as illegal discards are likely not registered (Ulrich et al., 2012). This analysis also indicated that discrepancies between the number of species recorded at the beginning versus the end of trips (Figs. 19 and 20), indicating another potential source of misreporting stemming from inaccurate catch location. Misreporting of the original fishing site of the bycatch species has been previously considered a potential problem associated with the logbook data registration in Icelandic waters (Einar Hjörleifsson, personal communication, April 16, 2024), and creates difficulties regarding identification of métiers and location of bycatch species or species with low catch rates. It would be intriguing to further investigate and attempt to align the outcomes of this clustering analysis with survey data or other reliable sources of species distribution and composition, such as fishing trips with an onboard inspector, to confirm likely fishing locations. It is worth noting that not all métiers are affected by location inaccuracies, particularly those associated with rather clean fisheries such as "*Greenland halibut*", "*demersal beaked redfish / greater silver smelt*", "*golden redfish*", and "*saithe*".

Fleet- or métier-based management could provide a more effective approach for regulating fishing effort and reducing unwanted catch, aiding the transition to multispecies and ecosystem-based fisheries management (ICES 2023c, Briton et al., 2020, García-Rivera et al., 2015, Suuronen & Gilman 2020, Ulrich et al., 2012, Gascuel et al., 2012). Yet, its successful implementation is challenging. It requires accurate data on fleet dynamics, species composition (ICES 2023c) and cooperation among stakeholders. Regulatory changes and enforcement are necessary but can be politically sensitive and resource-intensive (Ulrich et al., 2012). Additionally, the dynamic nature of marine ecosystems and fish stocks means that management approaches must adapt and respond to changes in environmental conditions, stock abundance, and fishing pressures (Woods et al., 2022). While Icelandic fisheries are highly advanced (Marchal et al., 2016) and are integrating ecological considerations into some single-species stock assessments, such as predator-prey interactions (Skern-Mauritzen et al., 2016), they still face challenges related to mixed species catches in demersal trawl fisheries, risking depletion of vulnerable species and introduction of choke species (for example spotted wolffish and recently haddock in some areas of Iceland) (ICES 2012, ICES 2022a). Even with the application of management measures such as area and/or seasonal closures and gear restrictions to protect vulnerable species or age classes, these strategies need intensive monitoring and data flow to be truly effective. Without sufficient information and manpower, maintaining these protective measures becomes challenging, even if they have been successful in the past. As a result, single-species management, even when combined with other management tactics falls short in addressing this problem, making it difficult to control unwanted catches and reduce mortality (ICES 2023c, Reiss et al., 2010, Vinther et al., 2004, Ulrich et al., 2011). Problems related to TAC management, such as discarding (Gisladottir et al., 2021, Sturludottir et al., 2018) and misreporting, continue to persist, although Iceland's quota-transfer system helps mitigate these issues (Oostdijk et al., 2020, Woods et al., 2015a, Woods et al., 2015b).

Ongoing efforts to improve Icelandic fisheries management involve exploring innovative approaches and transition beyond traditional stock assessment models towards a more holistic approach. Because Iceland is an island nation with demersal fisheries almost primarily executed by Icelandic vessels, the integration of mixed fisheries management (e.g. approaches based on fleet or métier classification) could be quite feasible without challenges that involve coordination of fisheries tactics of other nations. Many European countries have long sought to implement métier and/or fleet-based management by establishing working groups and developing models which incorporate those factors into frameworks, such as FCube and FLBEIA, which produce bio-economic evaluations of fisheries management strategies (ICES 2023c). Simultaneously, efforts have been made to integrate ecosystem models such as Atlantis (Fulton et al., 2011, Nilsen et al., 2020, Kasper et al., 2024) and Ecopath with Ecosim (EwE; Christensen and Walters, 2004, Karp et al., 2023, Kell et al., 2024) into single-species fisheries management, where the identification of the fishing strategy based on métiers or fleets is an essential component in the process. This integration, or a full transition to these models, could lead to application of EBFM in Icelandic waters. However, a key step in this process is identifying specific fishing activities associated with the most commonly utilized fishing gear around Iceland, laying the groundwork for the implementation of ecosystem-based fisheries management.

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5 References

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Appendix

Table A1. *Optimal number of cluster index.*

	Indices	*Optimal nr of clusters*	*Index value*	*Year*
1	Average silhouettes	***14***	***0.154***	***2016***
2	Mantel test	***15***	***0.436***	***2016***
3	Davis-Bouldin index	***2***	***1.073***	***2016***
4	SD index	***13***	***0.337***	***2016***
5	Calinski-Harabasz index	***3***	***98.018***	***2016***
6	Average silhouettes	***7***	***0.188***	***2017***
7	Mantel test	***13***	***0.487***	***2017***
8	Davis-Bouldin index	***6***	***0.778***	***2017***
9	SD index	***11***	***0.23***	***2017***
10	Calinski-Harabasz index	***24***	***49.607***	***2017***
11	Average silhouettes	***4***	***0.165***	***2018***
12	Mantel test	***5***	***0.45***	***2018***
13	Davis-Bouldin index	***2***	***0.37***	***2018***
14	SD index	***2***	***0.188***	***2018***
15	Calinski-Harabasz index	***27***	***180.536***	***2018***
16	Average silhouettes	***12***	***0.178***	***2019***
17	Mantel test	***13***	***0.47***	***2019***
18	Davis-Bouldin index	***2***	***0.369***	***2019***
19	SD index	***2***	***0.196***	***2019***
20	Calinski-Harabasz index	***24***	***81.284***	***2019***

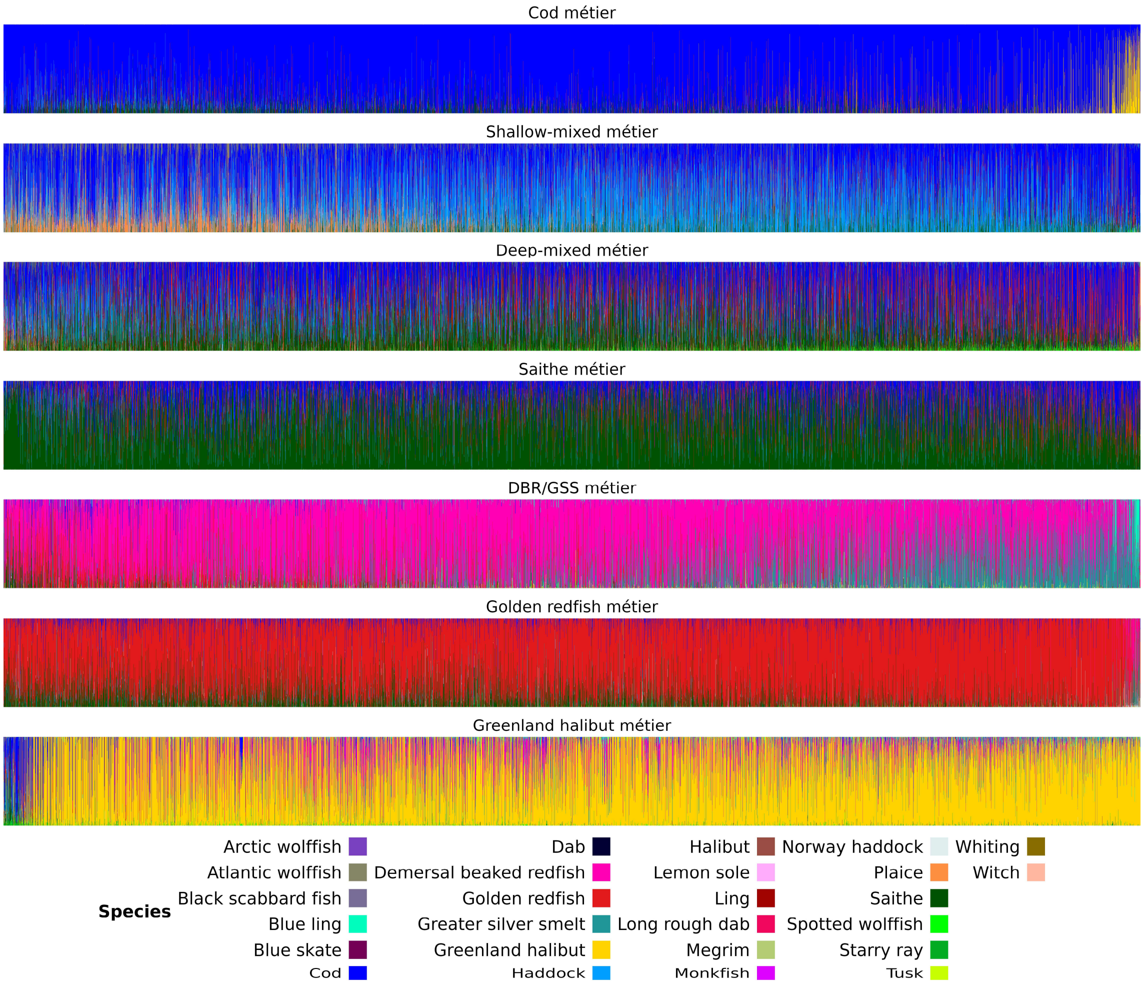

Figure A1. The proportion of the species within each haul is ordered by depth for each cluster/métier. The x-axes show the hauls towed at shallowest depth (to the left) and gradually go deeper towards the right. All métiers have different depth range: "*cod*" (depth range 18.3-1061 m), "*shallow-mixed*" (depth range 18.3-1000 m), "*deep-mixed*" (depth range 18.3-823 m), "*saithe*" (depth range 18.3-810 m), "*Demersal beaked redfish / Greater silver smelt*" (depth range 80.5-978 m), "*golden redfish*" (depth range 23.8-905 m), "*Greenland halibut*" (depth range 47.5-1090 m).

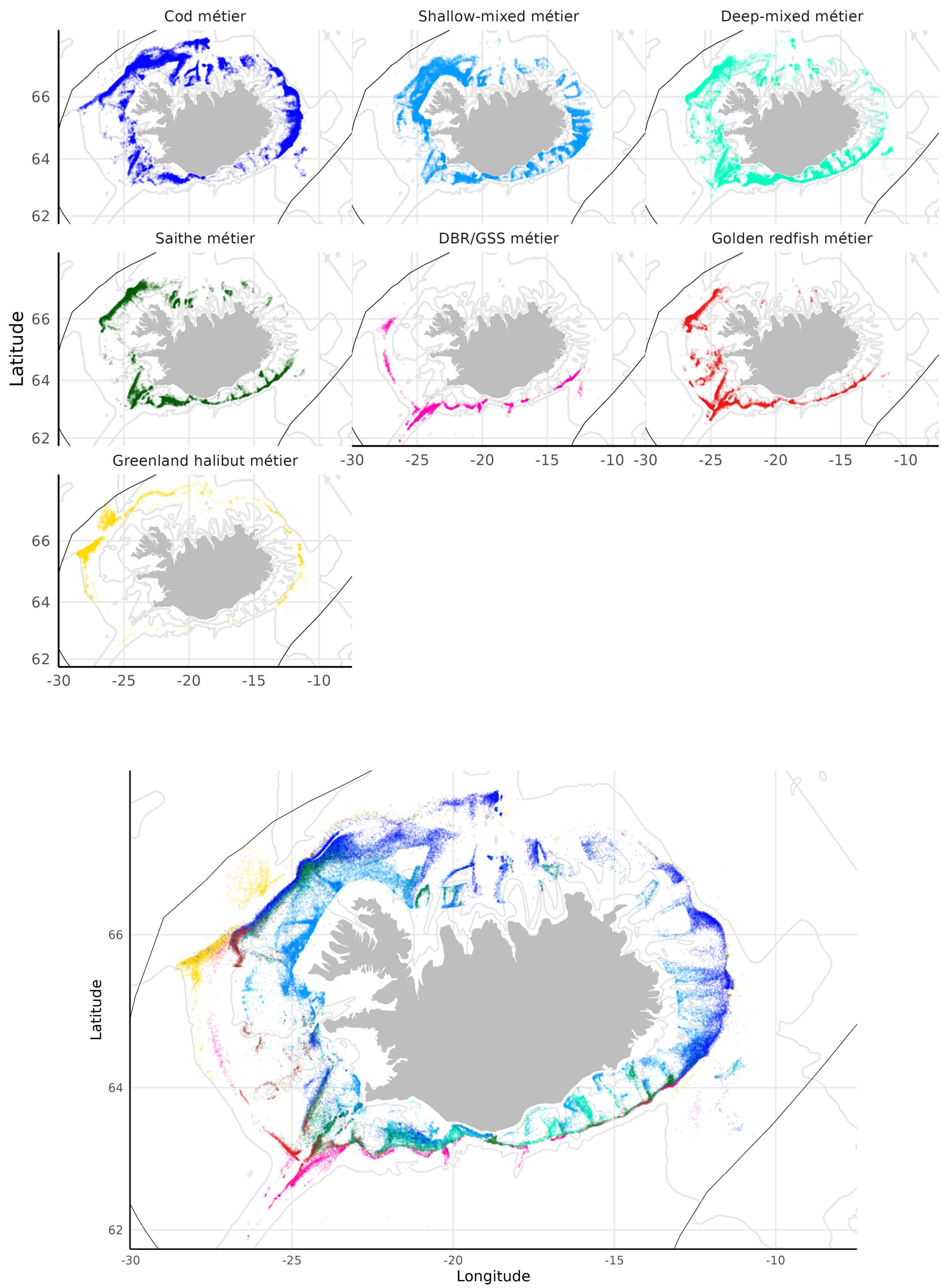

Figure A2. Spatial distribution of the bottom otter trawl fishery, divided by métier (above) versus all métiers together (below).

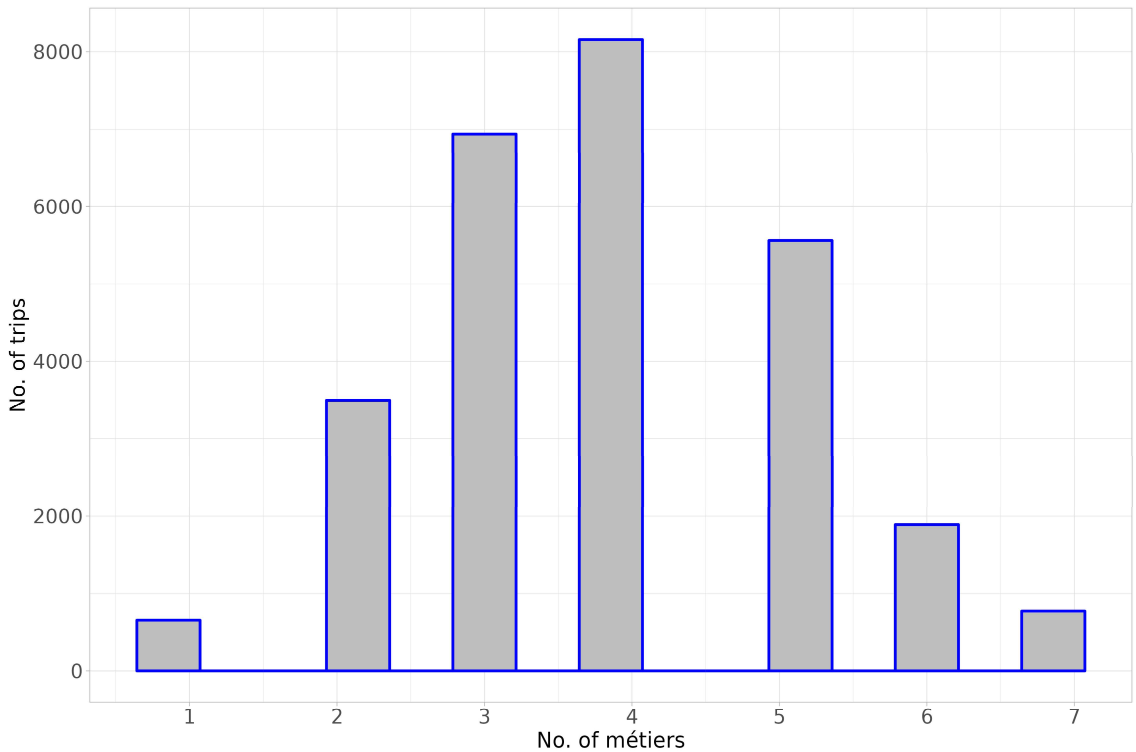

Figure A3. Number of trips according to the number of métiers that the vessel participated in during that trip.

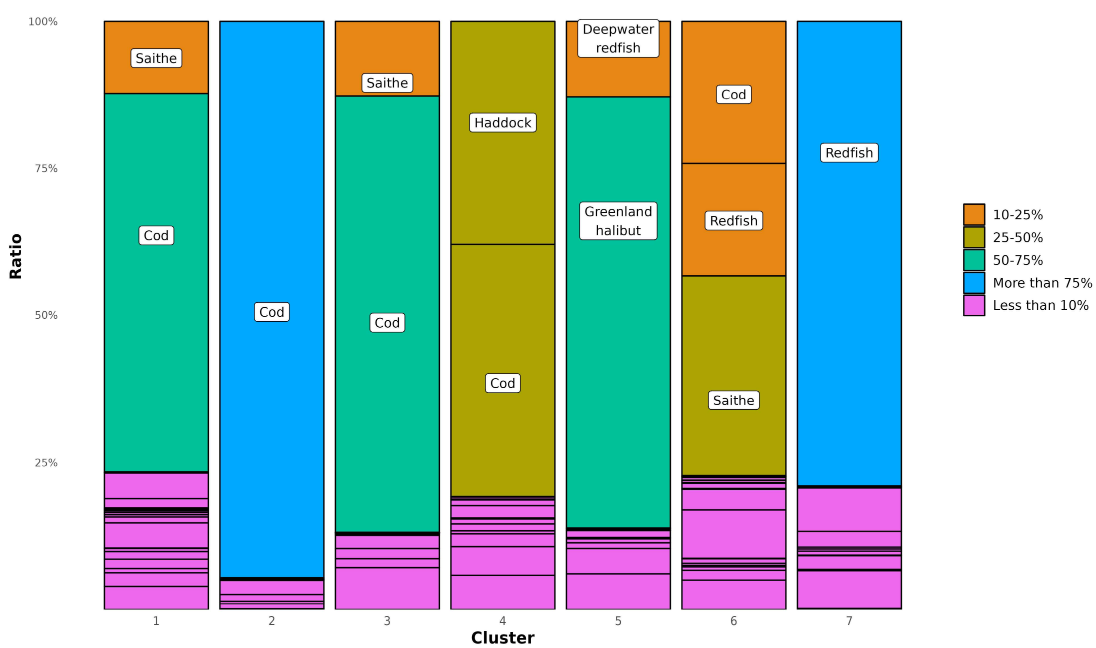

Figure A4. CLARA results. Proportion (%) of species caught within each cluster. “Less than 10%” includes several species. Deepwater redfish in this plot is demersal beaked redfish and redfish, golden redfish.

HAFRANNSÓKNASTOFNUN

Rannsókna- og ráðgjafarstofnun hafs og vatna