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Disentangling complexity of fishing fleets: using sequence analysis to classify distinguishable groups of vessels based on commercial landings

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Abstract

Capturing the diversity of fishing fleets and identifying distinct subgroups is essential for effectively directing research and management efforts. In this study, the German Baltic gillnet fleet was split into distinguishable groups of vessels by applying a stepwise approach. Monthly landing profiles were classified using clustering techniques and arranged as annual landing sequences, as the basis to form groups of vessels with distinct annual landing sequences using sequence analysis. Commercial landings from 1243 vessels across 11 years (2008–2018) resulted in 8031 annual landing sequences, which were clustered into eight groups, each with a characteristic, annually recurring, seasonal landing pattern (cod group, cod-herring group, herring-flounder group, herring group, freshwater fish group, pikeperch group, eel group and port group). The results highlight the heterogeneity of the fleet and a strong adaptation to regional and seasonal resource availability. Studying sequences of landings instead of isolated events in time provides insight into the interlinkage and succession of landings and can aid at classifying fishing fleets and better targeting groups of vessels of interest.

KEYWORDS

annual landing sequence, clustering, fleet classification, seasonal patterns, sequence comparison, small-scale fisheries

1 | INTRODUCTION

Small-scale fisheries cover a great variety of captured species, fishing grounds and seasons (e.g. Castello et al., 2013; Grazia Pennino et al., 2016; Tzanatos et al., 2006). It is estimated that about 90% of employed fishers and fish workers worldwide are engaged in the small-scale fisheries sector (World Bank, 2012), which can be important for shaping place identity of local communities and promoting place attachment and community cohesion, as well as touristic developments (Urquhart & Acott, 2013).

Within the small-scale fisheries, gillnet fisheries contribute the largest share of global catches and catch values (Cashion et al., 2018). They have low seafloor impact (Grabowski et al., 2014; Kaiser, 2014) as gillnets are stationary and temporarily anchored to the ground, and the fish actively swim into the net and become enmeshed. Compared with trawl fisheries, gillnet fisheries are efficient in fuel consumption (Suuronen et al., 2012; Thrane, 2004) and taking into account, inter alia, aspects such as subsidies, fuel consumption, carbon emission and employment, gillnet fisheries can be more beneficial to society than trawl fisheries, despite much lower landings (Crilly & Esteban, 2013).

Gillnet fisheries are very diverse in terms of target species, gear specifications and spatio-temporal dynamics (Andersen et al., 2012; Hentati-Sundberg et al., 2015; Stergiou et al., 2002). Spatio-temporal changes in the activities of a fishery can affect the degree of its potential environmental impact. In the case of gillnet fisheries, one of the pressing issues with respect to environmental impact are incidental bycatches of protected, endangered and threatened species (Gray & Kennelly, 2018). Bycatch rates vary depending on season and area (Sims et al., 2008), mainly due to changes in the spatio-temporal distribution patterns of bycaught species and fishing activities (Murray et al., 2000).

This highlights the importance to gain more insight into the spatio-temporal dynamics of gillnet fisheries. Breaking down gillnet fleets into distinguishable and manageable groups of vessels can improve the understanding of their activities and potentially help to design and direct research effort and management measures, especially if resources are limited.

Thus, the question is whether or not all vessels of a gillnet fleet can be treated as a single homogenous unit, and if not, how different groups can be consistently identified taking into account their heterogeneous activities.

A variety of approaches can be applied to split up fishing fleets into distinguishable groups. Several studies have used different clustering techniques to define catch or landing profiles, and thereby structured and described the activities of various fisheries (e.g. Campos et al., 2007; Castro et al., 2010; Grazia Pennino et al., 2016; Hentati-Sundberg et al., 2015; Marchal, 2008; Pelletier & Ferraris, 2000; Ziegler, 2012). By linking the profiles to fishing location and month, many of these studies gained insight into the spatio-temporal dynamics of a fleet, including seasonality of landings. It was also shown that fishers operate a single vessel to target different species or species assemblages using the same fishing gear or switching between gears during a year and that fishers range in their fishing tactics from specialists to generalists (Ziegler, 2012).

These findings suggest that assessing the interlinkage of landings during a year on the level of single vessel-shipmaster pairings might foster understanding of a shipmaster's action as well as of a fleet's dynamic as a whole. Andersen et al. (2012) showed that choices made by fishers on fishing grounds, gears and target species are primarily influenced by the experiences from previous trips. This highlights the need to study succession of landings as opposed to single events in time, as this takes into consideration that the selection of target species or species assemblage during a year might be interrelated and could be of relevance for characterising a fishing fleet.

Despite landings only indirectly reflecting the objectives of shipmasters (Ulrich et al., 2012) and multivariate methods often being descriptive and indicative in character, grouping vessels based on succession of landings could provide insight into the scope of action a fisher has throughout a year, and allow for a better assessment of consequences by management measures.

Identifying groups of vessels based on distinct landing patterns during a year supports a more targeted selection of relevant vessels and shipmasters. This can aid a variety of research and management topics, for example analysing the ecological and economic performance of each group of vessels, identifying and addressing multi-species fisheries within a fleet, studying the impact of management measures such as time/area closures, evaluating resilience and vulnerability of a fleet, or assessing spatio-temporal fishing effort for each group.

The German Baltic gillnet fishery was used as a case study to classify groups of vessels based on sequences of monthly landings. Clustering techniques were applied to identify monthly landing profiles, which were then arranged as annual landing sequences for each vessel per year. In the second classification step, sequence analysis was used to split the German Baltic gillnet fishery into distinguishable groups of vessels according to the similarity of the annual landing sequences. To the authors' knowledge, it is the first time that sequence analysis based on the concept of optimal matching analysis was applied to fisheries data; a method originally designed for sociology (Abbott & Forrest, 1986; Abbott & Tsay, 2000).

2 | MATERIAL AND METHODS

2.1 | The German Baltic gillnet fishery

In 2018, approximately 80% of the vessels of the German fishing fleet listed gillnets as their main or secondary gear in the EU fleet register (EU, 2020). About 75% of these vessels were registered in ports along the German Baltic coast and the majority of them (98%) was smaller than 12 m, and are thus considered part of the small-scale fisheries in the European Union (EC, 1999).

They operate in one of the largest brackish ecosystems of the world, shaped by decreasing surface salinity from west to east and stratified water bodies in different basins (Snoeijs-Leijonmalm et al., 2017). This strongly affects species distribution and allows the German Baltic small-scale fishery to target marine and freshwater species (Papaioannou et al., 2012). In the Baltic Sea, cod *Gadus morhua* L., herring *Clupea harengus* L., plaice *Pleuronectes platessa* L., Atlantic salmon *Salmo salar* L. and sprat *Sprattus sprattus* (L.) are subject to total allowable catches (TACs) (EC, 2007; EU, 2017). In the German fishery, the quotas, based on the TACs, are attached to a vessel (BLE, 2011) and shipmasters have indirect access to the quota via the vessel.

In the Baltic Sea, logbooks are mandatory for all vessels of the EU (European Union) ≥8 m (paper logbook: 8–12 m, electronic logbook: ≥12 m) (EU, 2011, 2016) and German Baltic vessels <8 m must fill in landing declarations (BLE, 2005). Although this leads to different levels of detail on data of the German Baltic gillnet fleet, data on monthly commercial landings per species are available for all vessels, irrespective of vessel size (BLE, 2005, 2011). Landings contain information on target species and on wanted and landed bycatch but do not account for discards.

2.2 | Data processing

The commercial landing data analysed were from logbooks and landing declarations from German Baltic gillnet vessels covering the

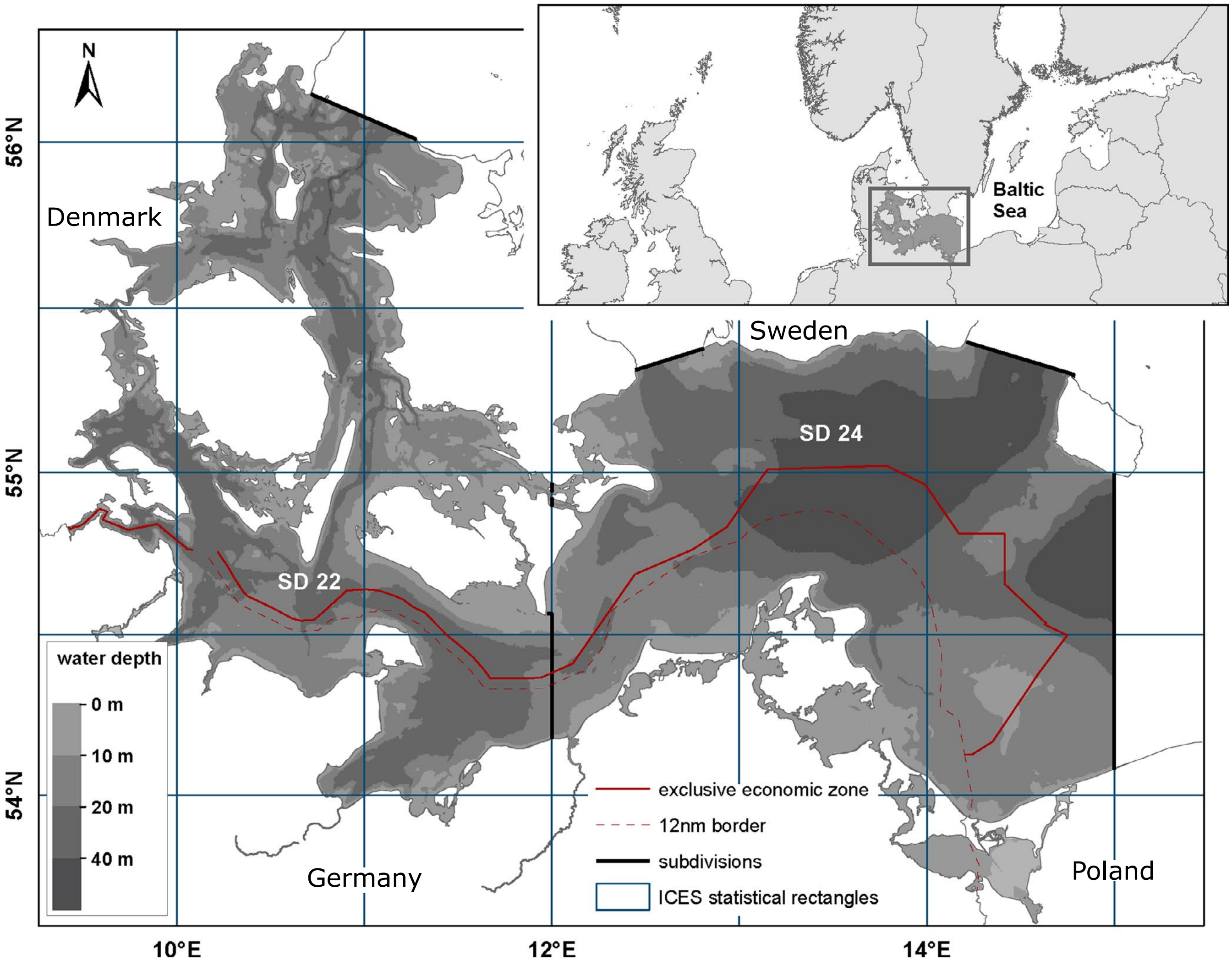

FIGURE 1 Study area, covering the ICES subdivision 22 (SD 22) and 24 (SD 24), including the German exclusive economic zone and 12 nm zone. Landings in logbooks and landing declarations are assigned to ICES statistical rectangles (approx. 30 × 30 nm) [Colour figure can be viewed at wileyonlinelibrary.com]

years 2008–2018, originating from the International Council for the Exploration of the Sea (ICES) subdivision 22 (SD 22) and 24 (SD 24), comprising the German Baltic exclusive economic zone and the 12-nm zone (Figure 1). For the remainder of the study, this area is referred to as the western Baltic Sea. All data handling and data analyses were performed in R 3.6.0 (R Core Team, 2019).

A vessel was considered a German Baltic gillnetter if it flew the German flag, was registered in a port along the German Baltic coast and if gillnet was listed as the main or the secondary gear in the EU fleet register. Unlike for logbooks, the use of gillnets is not recorded in landing declarations and the information from the EU fleet register was taken as the criterion to classify vessels as gillnetters, irrespective of logbook or landing declaration.

The unit for sequences of monthly landing profiles was set to a calendar year per vessel and shipmaster, since this matches the period for which TACs are issued in the Baltic Sea (e.g. EU, 2018) and thus, the planning timeframe for shipmasters with vessels that hold quota.

Gillnet vessels were not included in the analysis if they had a change of shipmaster within a year since the landings would then not have reflected the activity of a specific vessel-shipmaster pairing. Vessels that were retired, sold or decommissioned due to wrecking during a year were excluded from the analyses.

In the German Baltic gillnet fishery, shipmaster and owner of a vessel are often the same person. A shipmaster can own and operate more than one vessel per year, and ownership of a vessel can change between years.

2.2.1 | Data from landing declarations

In landing declarations (vessels <8 m), shipmasters report landings as monthly sums per species and ICES statistical rectangle, which are used for the geographic allocation of the landings and have an approximate size of 30 × 30 nm (ICES, 1977). The low temporal and spatial resolution of the landing declarations sets the limits for the analysis, and thus, landings were evaluated by species and month.

Number of fishing trips can serve as a proxy for fishing effort but are not specified in landing declarations. Instead, the number of vessels with at least one landing event per month was used to describe the activity throughout a year and between years.

2.2.2 | Data from logbooks

In logbooks (vessels ≥8 m), shipmasters report catch and landings per fishing trip, species and ICES statistical rectangle and record the fishing gear used during a trip (EU, 2011). In the European context, a fishing trip is defined as fishing activities carried out by a vessel at sea and starts as soon as a vessel leaves a port and ends once the vessel returns to a port (EU, 2011). Thus, fishing trips reflect how often a vessel went to sea and the number of fishing trips from vessels with logbooks was used to describe their activities during a year and between years.

2.3 | Classification method

The German Baltic gillnet fleet was split up into distinguishable groups through a stepwise approach consisting of three main building blocks (Figure 2). For the first building block, monthly landing profiles were classified for every gillnetter in the respective year. Second, the individual landing profiles were combined into sequences of 12 monthly landing profiles for each vessel and calendar year, leading to annual landing sequences. For the final building block, the annual landing sequences of the individual gillnetters were compared across the different years to form groups of vessels with distinct annual landing sequences.

2.3.1 | Monthly landing profiles—step 1

Monthly landings of each vessel were transformed into relative species composition per month (i.e. landings per species were divided by total landings of all species in a given month). Summed monthly landings from logbooks were only considered if they were from gillnet catches. This excluded landings done with gears other than gillnets (approx. 13% of the trips from vessels with logbooks) and landings that could not unambiguously be linked to a specific gear (< 1% of the trips from vessels with logbooks). A potential reason for the latter could have been trips during which more than one gear was used and reported by the fisher. This differentiation was not possible for vessels with landing declarations due to missing information on the use of gillnets. This bears the risk of landings being considered as landings from gillnet catches but which were actually done with other gears.

The monthly landings lead to a matrix of vessel per month versus the relative contribution per species (Table S1), the input data for calculating the Bray–Curtis coefficients with the R package vegan (Oksanen et al., 2019). The Bray–Curtis coefficient, a distance measure used especially for community analysis in ecology (Bray & Curtis, 1957; Field et al., 1982), is not affected by the joint absence of variables and prioritises abundant variables instead of rare ones (Quinn & Keogh, 2002). This makes the Bray–Curtis coefficient particular appropriate for the landings of the gillnet fishery since different gillnet fisheries have different species that dominate their landings (abundant variables) and at the same time are characterised by the joint absence of other species, that is variables.

The Bray–Curtis coefficients were assembled in a dendrogram based on hierarchical agglomerative clustering applying the unweighted pair group method with arithmetic mean using the R package NbClust (Charrad et al., 2015). The average silhouette width (ASW) was used to decide upon the number of clusters and assisted in evaluating the structure found in the data: ASW = 0.71–1.00, strong structure; ASW = 0.51–0.70, reasonable structure; ASW = 0.26–0.50, weak structure; and ASW ≤ 0.25, no substantial structure (Kaufman & Rousseeuw, 2005; Rousseeuw, 1987).

For the calculation of the ASW, the maximum possible number of clusters, that is number of monthly landing profiles, was set to 50 to exceed the maximum number of landed species observed in each year. The ASWs were rounded to the second decimal place and the number of clusters with the highest ASW were selected, with each cluster representing a monthly landing profile, the first building block. This was done using the R package NbClust (Charrad et al., 2015).

Each monthly landing profile covered the various vessels with a similar relative species composition of the respective year, and was named according to the species that dominated the average landings, for example cod profile (Figure 2). Monthly landing profiles were classified separately for the gillnet vessels of each year (2008–2018).

In case a vessel did not report any landings during a month, the month was assigned the port profile. If a vessel used fishing gear other than gillnets or if it was not possible to link landings unambiguously to a specific gear, the respective month was assigned the no-gillnet/mixed-gear profile. Thus, the port profile and the no-gillnet/mixed-gear profile did not result from the determination of monthly landing profiles using multivariate statistics being based on the landings of known and assumed gillnet catches.

2.3.2 | Annual landing sequences—step 2

For each year in which a vessel was part of the analysis, its 12 respective monthly landing profiles were arranged as an annual landing sequence, the second building block (Figure 2).

2.3.3 | Groups of vessels with distinct annual landing sequences—step 3

Groups of vessels with distinct annual landings sequences were classified across the 11 years between 2008 and 2018, through

FIGURE 2 Three building blocks of the stepwise approach: (a) monthly landing profiles, (b) annual landing sequences and (c) groups of vessels with distinct annual landing sequences. The data are designed for illustrative purpose and do not resemble existing cases [Colour figure can be viewed at wileyonlinelibrary.com]

sequence analysis using the R package TraMineR (Gabadinho et al., 2019). The sequence analysis used in this study was based on the principles of the optimal matching analysis used for comparing protein and DNA sequences. It has been adapted for application in sociology (Abbott & Forrest, 1986; Abbott & Tsay, 2000), where it is used in life course research to study inter alia employment paths and school to work transitions (Dorsett & Lucchino, 2014; Flöthmann & Hoberg, 2017; Pollock, 2007).

Optimal matching analysis measures distances between entire sequences of events and not only between single events, and takes into consideration the chronological order of categories, that is the order of single events in time, within the sequences (Abbott & Forrest, 1986). In this study, the annual landing sequences were equivalent to the sequences and the monthly landing profiles were equivalent to the categories.

The input data for assessing the dissimilarity between sequences was a matrix of vessel per year versus month with the respective monthly landing profile, thus the annual landing sequences (Table S2). The sequences were already normalised in length, given the annual structure of 12 monthly landing profiles per sequence and vessel.

The generalised Hamming distance was chosen as the dissimilarity measure for sequence comparison as it only uses substitutions and no insertions and deletions, and does not allow for shifts of sequences (Gabadinho et al., 2011). This was important as the sequence length was not meant to change and should always represented a calendar year, without a shift in the chronological order of months.

The transition rates between the different monthly landing profiles were used to assign the costs to the different substitutions, which are needed to calculate the dissimilarity measure. Transition rates resemble the probability of one monthly landing profile being replaced by another. If a transition between two monthly landing profiles is likely, the costs are low and inversely; if a transition is unlikely, the costs are high (Gabadinho et al., 2011). Eventually, sequences are more similar the less it costs to make them identical (Abbott & Forrest, 1986; Abbott & Tsay, 2000).

After the costs were set, the generalised Hamming distances between the sequences were calculated (R package TraMineR) and were then assembled in a dendrogram based on hierarchical agglomerative clustering applying the method of Ward (1963) using the R package cluster (Maechler et al., 2019). The final number of groups of vessels with distinct annual landing sequences, the third and final building block, was determined by visual examination of the dendrogram (Gabadinho et al., 2011). Each group was named according to one or two dominating monthly landing profiles, for example herring-cod group (Figure 2).

During sequence comparison, the port profile and no-gillnet/mixed-gear profile were pooled and treated as a single monthly landing profile as the focus was on the landings from known and assumed gillnet catches. These two-monthly landing profiles were then only differentiated in the graphic representation.

For each group of vessels with a distinct annual landing sequence, it was examined how the number of vessels and fishing trips changed over the years and how the groups were distributed along the German Baltic coast based on the ICES statistical rectangles.

3 | RESULTS

3.1 | Structure of the German Baltic gillnet fleet

A total of 1243 gillnet vessels, run by 935 shipmasters, were analysed across the 11 years (2008–2018). Sixty-four taxonomic groups were recorded in the logbooks and landing declarations (Table S3), with a varying number of species landed each year (41 ± 3). The number of gillnet vessels per year represented 78 ± 2% of all German vessels with landings from the western Baltic Sea. During the study period, the number of vessels decreased by an average of 4 ± 1% per year (max: 881 vessels in 2008, min: 580 vessels in 2018) and the number of shipmasters by an average of 4 ± 2% per year (max: 697 shipmasters in 2008, min: 449 shipmasters in 2018).

Not every gillnet vessel was part of the analysis each year, for example, because no landings were reported in the respective year or because of an ownership change (Figure S1a). The majority of the 935 shipmasters operated on average one vessel per year (76 ± 2%) and about one fourth of the shipmasters operated on average two or more vessels per year (24 ± 2%) (Figure S1b).

Out of the 1243 gillnet vessels, 21% were ≥8 m (logbook obligation; maximum length: 14.75 m) and 79% were <8 m (landing declaration obligation; minimum length: 3.75 m). Nine vessels were at times shorter than 8 m and at times longer than 8 m due to modifications to the vessel.

The number of fishing trips (vessels ≥8 m) decreased over the years and showed a similar seasonal pattern each year, with peaks in spring and autumn and a major drop in winter (Figure S2a). The second peak in autumn was not observed for the last three years of the study period (2016–2018), and the number of fishing trips was similar to that in summer.

The number of gillnet vessels with landing declarations (vessel <8 m) that reported at least one landing event per month also decreased over time, with an annual-recurring seasonal pattern, including a major drop in winter (Figure S2b). Peaks in spring and autumn were minor and shifted towards late spring and early autumn compared with the peaks of fishing trips of the larger vessels.

3.2 | Monthly landing profiles

The classification of landings resulted in 36 different monthly landing profiles across the 11 years (20–28 monthly landing profiles per year) with ASWs that ranged from 0.43 to 0.54 (Table S4, Figures S3-S14). For some landings, fisher did not clarify the landed species and reported it as "other," resulting in a monthly landing profile called other profile (Figures S4-S12). In some years, monthly landing profiles had a strongly mixed composition without a dominant species (Figures S7, S8 and S13). They represented <0.5% of all summed monthly landings, and since no dominant species could be identified, they were also assigned to the other profile. This reduced the final number of monthly landing profiles of the three respective years (Table S4). The 36 monthly landing profiles identified by the multivariate statistics were complemented by the port profile and the no-gillnet/mixed-gear profile, resulting in a total of 38 monthly landing profiles between 2008 and 2018 (Table 1 and Table S5). Few monthly landing profiles were composed of a single species, most of them were a combination of several species and the landing compositions of the same monthly landing profile could vary between years (Figures S4-S14).

TABLE 1 Classified monthly landing profiles between 2008 and 2018 sorted alphabetically, their presence (x) and absence (–) within each year and their summed presence across all years. Profiles in italic occurred in all years. Only those monthly landing profiles (20 out of 38) are shown that accounted for at least 1% in any month of the groups of vessels with distinct annual landing sequences. For a complete list of all identified monthly landing profiles, refer to the supporting information (Table S5)

Monthly landing profile	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Total 2008–2018
bream	x	x	x	x	x	x	x	x	x	x	x	11
cod	x	x	x	x	x	x	x	x	x	x	x	11
dab	–	x	–	–	x	–	–	x	x	x	x	6
eel	x	x	x	x	x	x	x	x	x	x	x	11
eelpout	x	x	x	x	x	x	x	x	x	x	–	10
flounder	x	x	x	x	x	x	x	x	x	x	x	11
garfish	x	x	x	x	x	x	x	x	x	x	x	11
herring	x	x	x	x	x	x	x	x	x	x	x	11
mackerel	x	–	x	x	x	x	x	x	x	x	x	10
no-gillnet/ mixed-gear	x	x	x	x	x	x	x	x	x	x	x	11
other	x	x	x	x	x	x	x	x	x	x	–	10
perch	x	x	x	x	x	x	x	–	x	x	x	10
pike	x	x	x	x	x	x	x	x	x	x	x	11
pikeperch	x	x	x	x	x	x	x	x	x	x	x	11
plaice	x	x	–	x	x	x	x	x	x	x	x	10
port	x	x	x	x	x	x	x	x	x	x	x	11
roach	x	x	–	–	x	–	–	x	x	x	–	6
sea trout	x	x	x	x	x	x	x	x	x	x	x	11
turbot	x	x	x	x	x	x	x	x	x	x	x	11
whitefish	x	x	x	x	x	–	x	–	x	x	x	9

3.3 | Annual landing sequences

A total of 8031 annual landing sequences were ascertained for the 1243 gillnet vessels (Figure 3a), and together, they showed a distinct seasonal pattern in the order of monthly landing profiles for the entire German Baltic gillnet fleet (Figure 3b and 3c), which recurred every year (Figure S16). The herring profile was characteristic for spring, mainly in March and April, occurred far less in autumn and winter and was of no importance in summer. The flounder profile was characteristic for summer, observed less in spring and autumn and was not common in winter. The cod profile occurred throughout the year was more common in autumn and winter and had small shares in summer. The plaice profile had very small but consistent shares each month. The turbot and the garfish profiles were most common in late spring and the sea trout profile in winter. The bream, perch, pike and pikeperch profiles were the most dominant freshwater monthly landing profiles and occurred throughout the year. The eel profile was characteristic for summer but must be seen as a false-positive monthly landing profile, as eels are not caught with gillnets but, for example, with traps, longlines and pound nets (FAO, 1970). The port profile occurred every month, with peaks in winter, especially in January and February and the no-gillnet/mixed-gear profile was most often observed from late spring until early autumn.

3.4 | Groups of vessels with distinct annual landing sequences

After examination of the dendrogram derived from sequence analysis and subsequent hierarchical agglomerative clustering, the 8031 annual landing sequences were grouped into eight clusters—the groups of vessels with distinct annual landing sequences (Figure S17). There were three marine groups (cod, herring-cod and herring-flounder), two freshwater groups (pikeperch and freshwater fish), a mixed group (herring), a port group and a false-positive eel group. Each group showed a distinct seasonal pattern in the order of monthly landing profiles (Figure 4 and Figures S18–S25). The port group covered most of the annual landing sequences (26%), followed by the herring-flounder group (18%). The herring, the herring-cod and the eel groups each covered 11% of the annual landing sequences and the cod and the freshwater fish groups each had 10% of the sequences. The pikeperch group was the smallest group with only 3% of the annual landing sequences. It was possible that group

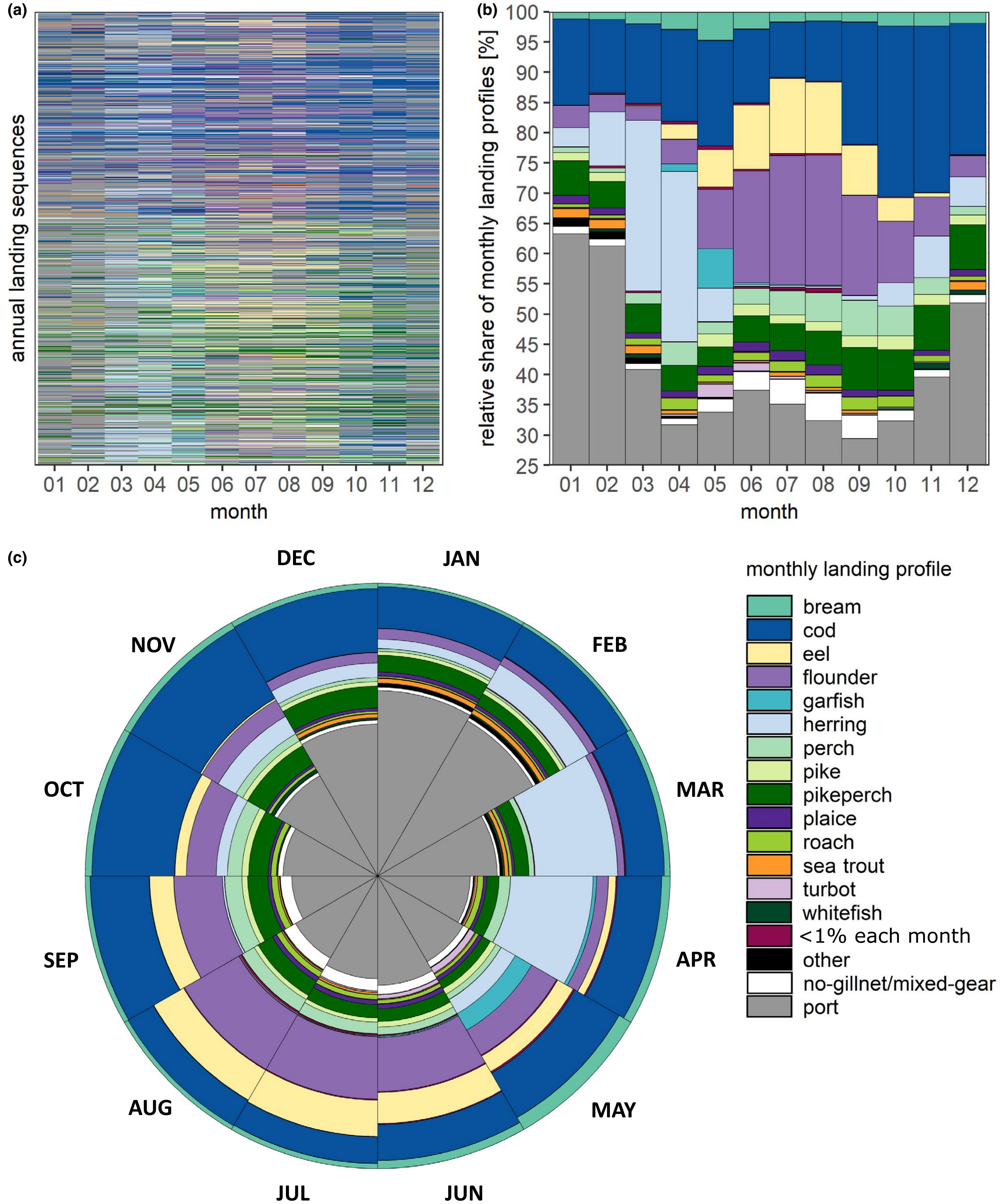

FIGURE 3 (a) Annual landing sequences (*n* = 8031) of the individual vessels from the German Baltic gillnet fleet between 2008 and 2018. Each line represents the annual landing sequence of a single vessel per year. There is more than one annual landing sequence per vessel if it was analysed in more than one year. (b)/(c) Relative share of monthly landing profiles per month across the study period. 25% were covered by the port profile each month. Scale of plot (c): centre = 0%, outer edge: 100%. Monthly landing profiles with a share of less than 1% in every month were summarised as "<1% each month". For complete representation of all monthly landing profiles, refer to the supporting information (Figure S15) [Colour figure can be viewed at wileyonlinelibrary.com]

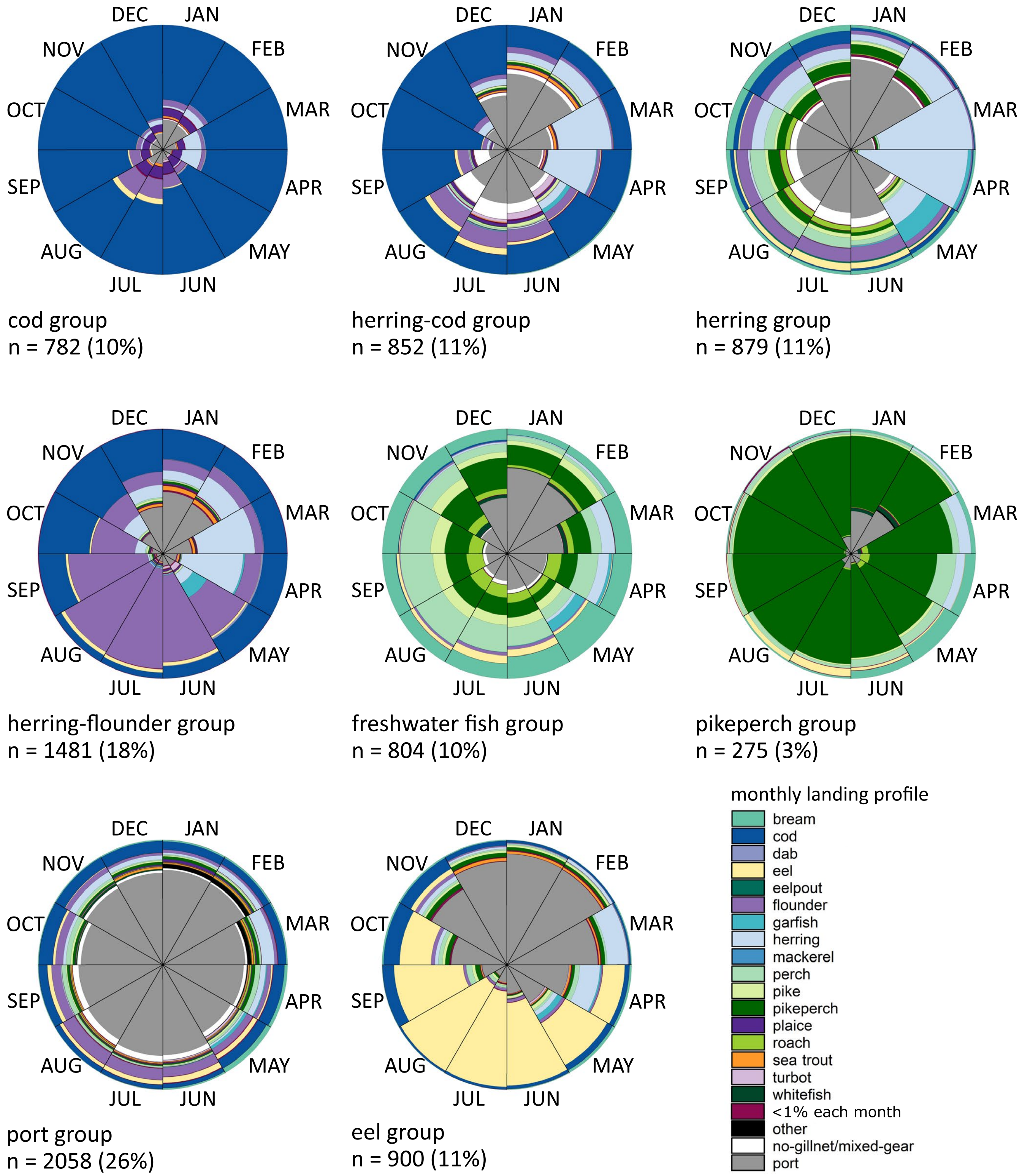

FIGURE 4 Eight groups of vessels with distinct annual landing sequences from the German Baltic gillnet fleet between 2008 and 2018 with the relative share of monthly landing profiles per month across the study period and the number of annual landing sequences per group (entire gillnet fleet: *n* = 8031). Scale of plots: centre = 0%, outer edge: 100%. Monthly landing profiles with a share of less than 1% in a month in the respective group were summarised as "<1% each month". For complete representation of all monthly landing profiles, refer to the supporting information (Figure S18-S25) [Colour figure can be viewed at wileyonlinelibrary.com]

affiliation of a vessel or shipmaster changed between years and by operating more than one vessel per year, shipmasters could participate in different groups within the same year (Figure S26).

3.4.1 | Seasonality

Each group of vessels with a distinct annual landing sequence was associated with a typical seasonal landing pattern (Figure 4). The majority of vessels of the cod and the pikeperch groups reported landings throughout the year and were dominated by either the cod or the pikeperch profile. Compared with all other groups, few vessels of these two groups stayed in port during winter and the seasonal variation in monthly landing profiles was minor.

Unlike any other group, the herring group was strongly dominated by the herring profile in spring, especially in March and April, when almost all vessels were active, and, which was accompanied by the garfish profile in late spring. A mixture of profiles, including different freshwater and marine species, but also vessels that used other fishing gear than gillnets, were characteristic for summer and autumn.

The herring-flounder group was dominated by the herring profile in spring and by the flounder profile from late spring until early autumn, with a pronounced peak in summer, when almost all vessels were active. The garfish profile was again observed in late spring. During winter and early spring, few vessels switched to the sea trout profile, and in late autumn and winter, the cod profile was more common.

The herring-cod group was dominated by the herring profile in spring. The other prominent monthly landing profile was the cod profile, which was present throughout the year, with a small peak in late spring, least common during summer and with a more pronounced peak in autumn and early winter. In summer, a mixture of monthly landing profiles was observed and several vessels stayed in port or used other fishing gear than gillnets. This group had the highest share of the turbot profile, which was most common in late spring and early summer. During winter and early spring, a few vessels switched to the sea trout profile.

The freshwater fish group was characterised by a variety of freshwater fish profiles, including the bream, perch, pikeperch and roach profile and by vessels that stayed mainly in port during winter. In the port group, more than 50% of the vessels did not report any landings in any month. The false-positive eel group was dominated by the eel profile from late spring until autumn, with a strong peak in summer, accompanied by a mixture of other monthly landing

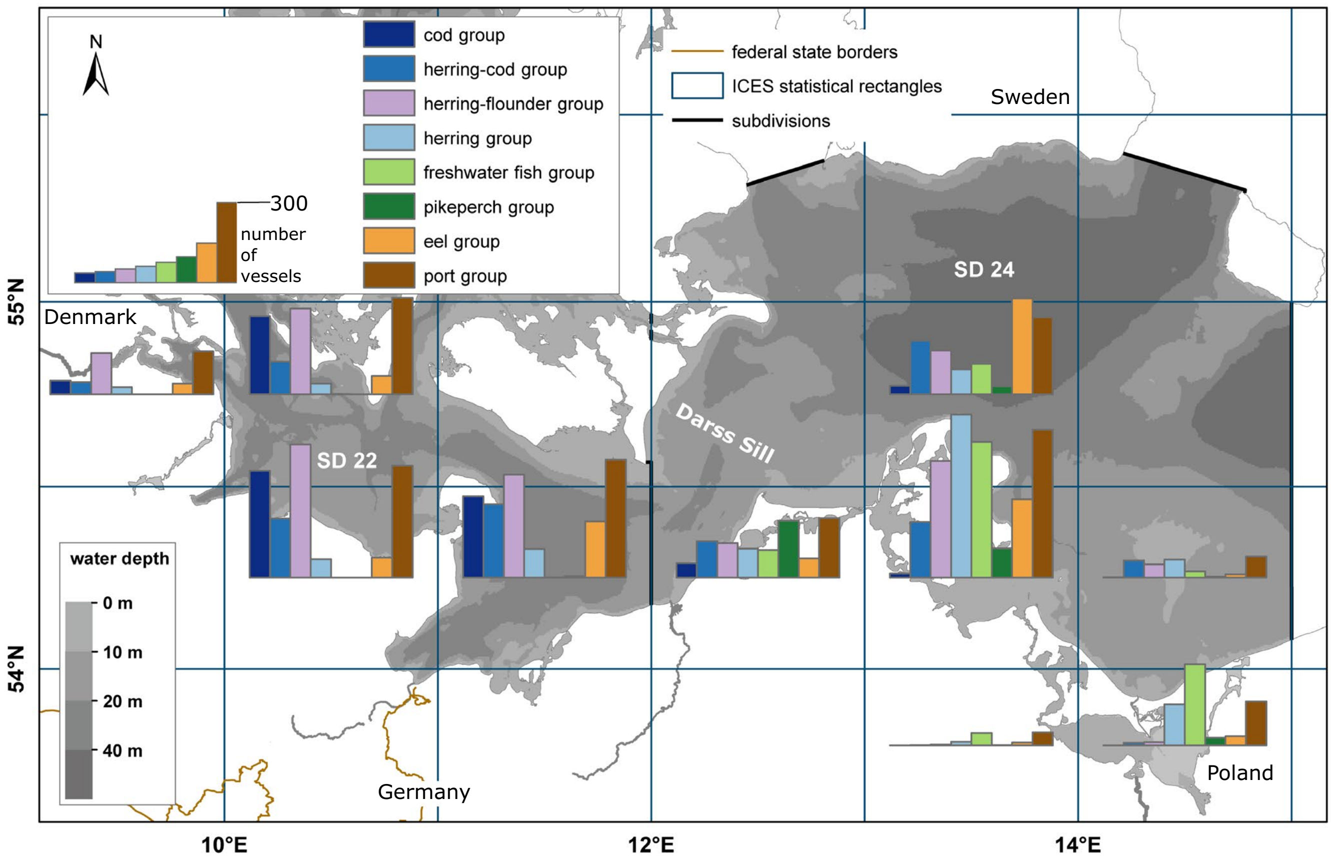

FIGURE 5 Number of German Baltic gillnet vessels per group of vessels with a distinct annual landing sequence and ICES statistical rectangle across the study period (2008–2018). Only ICES statistical rectangles with at least 100 vessels are shown. Some annual landing sequences of vessels covered more than one ICES statistical rectangle, and thus, these vessels were counted multiple times for different ICES statistical rectangles. For complete spatial distribution of all vessels, refer to the supporting information (Figures S28 and S29) [Colour figure can be viewed at wileyonlinelibrary.com]

profiles. From late autumn until early spring, the majority of vessel of the eel group stayed in port.

3.4.2 | Number of vessels and fishing trips

All eight groups of vessel with distinct annual landing sequences were present each year (Figure S27). The number of vessels from the two freshwater groups was stable across the study period and showed little fluctuation, in contrast to the three marine groups (Figure S27a). The herring-flounder and the herring-cod groups decreased in numbers unlike the cod group. The number of vessels from the herring group fluctuated little and decreased steadily over time. The port group covered most of the vessels and declined in numbers, as did the false-positive eel group. Together, the three marine groups covered most of the fishing trips (vessels ≥8 m) in most years (Figure S27b). Their numbers fluctuated across the years and decreased in the case of the herring-flounder and the herring-cod group as opposed to the cod group. The mixed herring group experienced a decline in number of fishing trips over the years, and the number of fishing trips of the two freshwater groups fluctuated little and was stable across the study period. The port group experienced a slight decline in number of fishing trips. No fishing trips were observed for the eel group, implying that this group covered only vessels <8 m.

3.4.3 | Spatial distribution

The majority of vessels reported landings from ICES statistical rectangles close to the German Baltic coast (Figure 5). Three of the groups were spatially more confined (cod, pikeperch and freshwater fish), and the port group was dominant in many areas. The herring-flounder, herring-cod and herring groups were spread along the coast, with the first two were more common in the West and the latter more common in the East. The core area of the cod group was in the West. The freshwater fish group was frequent in the bays and lagoons in the East, and the pikeperch group was most common in the lagoons south and east of the Darss Sill. There was a transition zone between gillnet fisheries primarily influenced by marine species west of the Darss Sill and by freshwater species east of the Darss Sill, which is illustrated by the distribution of the cod, pikeperch and freshwater fish groups.

4 | DISCUSSION

Combining classic clustering techniques with sequence analysis allowed the splitting up of the heterogeneous German Baltic gillnet fleet into distinguishable groups of vessels based on the chronical order of events, represented by the annual landing sequences, as opposed to single and isolated events in time, for example monthly or annual totals. This illustrates how activities are connected across time and suggest that landings were not randomly interlinked with one another during a year but followed specific successions that recurred each year and lead to the formation of specific groups of vessels. This indicates a strong interrelation between fisheries and the seasonal and regional availability of the exploited resources.

4.1 | Data quality

The classification of the false-positive eel group resulted from the assumption that a vessel is a gillnetter if gillnet was specified as the main or secondary gear in the EU fleet register while in fact a different fishing gear was used. This assumption was necessary as no other or more detailed data on the use of gillnets were available at the national level in relation to the monthly summed landings per species and ICES statistical rectangle for single vessels <8 m. To assess the order of magnitude of potential misclassification, conditions for vessels with logbooks were assumed to be equal to those of vessels with landing declarations, that is no information on the gear use would have been available and vessels and their corresponding landings would have been classified as gillnetters and landings from gillnet catches if gillnet was listed as the main or secondary gear in the EU fleet register. Under these assumptions, 16% of the trips and 10% of the vessels would have been misclassified as trips done with gillnets and vessels being gillnetters, respectively, and misclassification would have been substantial. Yet, given the lack of more detailed data on the gear use for vessels with landing declarations, the exact magnitude of misclassification for these vessels cannot be assessed. The indirect definition of German vessels as gillnetters via the main and secondary gear information in the EU fleet register was the best possible option at the time of this study. It is important to acknowledge these data limitations as data gaps remain a recurring issue in the analysis of small-scale fisheries (Papaioannou et al., 2014) and especially given the large amount of vessels without logbooks characterising many national fleets.

Apart from eel, it is not possible to determine unambiguously whether or not other primarily landed species were caught with gillnets. Cod, for example, could also be caught in pots; along the eastern German Baltic coast, pound nets are used to catch pikeperch and herring. Consequently, it cannot be ruled out that only eel catches were misclassified as gillnet landings. However, the no-information-on-the-use-of-gillnets assumption tested for vessels with logbooks (see above) suggests that the majority of landings were from gillnet catches. This also corresponds with what has been observed for Swedish vessels <10 m, which report more detailed data on the type of gear used and primarily used gillnets in the months they went fishing (Hentati-Sundberg et al., 2015).

The logbook information on the gear type used during a fishing trip is presently considered sufficient for EU vessels but concerns have been raised that fishers only report one gear type per trip even if more than one was used (ICES, 2018). The multi-gear behaviour often observed for small-scale fisheries (Castello et al., 2013;

Tzanatos et al., 2006) would then not be well reflected by logbooks. Once more detailed data on the gear use at the level of individual vessels, trips and landings are available for vessels of all size classes, more precise and potentially less biased analyses can be conducted.

It is unclear if the high amount of port profiles is related to under-reporting because detailed data from the vessels with landing declarations are missing. Many vessels <12 m of the German fishing fleet are used as a side business (Anonymous, 2019). Thus, the respective fishers have potentially less need to go fishing all year round, resulting in their vessels spending more time in port.

4.2 | Landings shaped by resource availability

Fishing activities of different target species often overlap regionally and a variety of species are landed almost year round. In many cases, this makes it difficult to detect specific fishing patterns, yet they occur and the typical seasonal patterns of the different groups of vessels with distinct annual landing sequences identified in this study closely match spatio-temporal changes in fish species distribution.

In spring, the western Baltic spring spawning herring, which outside the spawning season inhabit the Skagerrak and Kattegat, enter the river estuaries, shallow bays and lagoons along the coast of the southwest Baltic Sea for spawning (Aro, 1989; Moll et al., 2019) and become accessible to the gillnetters. During this time of the year, the herring profile plays a major role in the herring-cod, the herring-flounder and the herring group, and causes the regular annual peak in number of fishing trips (vessel ≥8 m) in March and April (see Figure S2).

Flounder spawn in the deeper, more saline basins and use coastal waters from spring until autumn (Aro, 1989), when also the flounder profile dominated the herring-flounder group. Flounder is a non-TAC species and hence, available to many shipmasters.

In May, at the end of the herring season and parallel to the increase in flounder profiles, garfish *Belone belone* (L.) enter shallow coastal waters for spawning (Korzelecka et al., 2005) and are targeted by some shipmasters, especially from the herring and the herring-flounder group. Also in May, turbot *Scophthalmus maximus* (L.), a high valued flatfish species, uses shallower coastal waters for spawning (Florin, 2005) and becomes accessible to the gillnet fishers, as seen in case of the herring-cod group. Although turbot is a non-TAC species, turbot fishery is regulated by a time/area closure, which prohibits to fish for turbot from June to July within the 12-nm zone for both federal states along the German Baltic coast (§2 KüFVO, 2018; §5 KüFVO, 2016). The fishery for eel *Anguilla anguilla* (L.), starting slowly in April, is also subject to a time/area closure in the eastern federal state, prohibiting eel catches from October to March outside the limits of 3 nm and from December to February within the 3 nm with rod and line (§5 KüFVO, 2016).

During summer, gillnet fishing activity is reduced and more vessels stay in port or switch to other gears, especially in case of the herring and herring-cod group. This is in response to reduced resource availability with respect to cod and herring and increased occurrence of filamentous algae and jellyfish (Barz & Hirche, 2005; Takolander et al., 2017; Tiselius et al., 2011), which can clog the meshes and impede gillnet fishing. Besides switching to other fishing gear or staying in port, some gillnet fishers reduce the soaking time to cope with these specific conditions in summer (U. Krumme, personal communication with fishers).

The gillnet fishery for cod in the western Baltic Sea is conducted at seasonally changing depth strata, particularly in areas where slopes occur close to the coast, such as in SD 22 (Funk et al., 2020), and allows the targeting of cod year round as demonstrated by the cod group (see Figure 5). For other groups (i.e. herring-cod and herring-flounder group), cod is only of greater interest when they use shallow water areas in spring and particularly in autumn. The absence of a peak in fishing trips in autumn in the last three years (see Figure S2) was most likely due to major reductions in TACs for cod (ICES, 2019). In addition to the cod profile, some shipmasters went for the herring profile in autumn, when minor amounts of autumn spawning herring enter the coastal areas (Aro, 1989).

The cod group on the one side and the pikeperch and freshwater fish group on the other represent two ends of a transition zone marked by the Darss Sill (maximum depth: 18 m), which is also known as a biological boundary to a variety of species (Snoeijs-Leijonmalm et al., 2017; Wasmund et al., 2011; Witkowski et al., 2005). The Darss Sill separates the regions with higher salinity in the west from the more brackish regions in the east, which is reflected by the spatial distribution of the cod group in the west and of the pikeperch and freshwater fish group in the east.

The results of this study demonstrate that the groups of vessels with distinct annual landing sequences in the German Baltic gillnet fleet are closely adapted to the seasonal cycles of species availability (either linked to spawning migrations, e.g. herring, garfish, turbot or feeding, e.g. cod, flounder) and regional particularities (such as the large lagoons in the east providing year-round access to freshwater species).

The different group-specific patterns persisted across the 11 years covered in this study, and this stability in landing patterns reflects the recurring annual distribution patterns of the targeted species. In a Danish gillnet fishery, seasonality was also identified as an important factor that influenced the choice of target species or species assemblage, fishing grounds and fishing gear (Andersen et al., 2012). The consistency of the patterns emphasises the adaptation of the gillnet fishery to the seasonal and regional circumstances and should be acknowledged by research and management.

4.3 | Outlook

Addressing the German Baltic gillnet fishery at large and not differentiating between the various groups can lead to a poor representation and understanding of group-specific fishing impacts, and impede effective research and management. If possible, this should be avoided, for example when working on incidental bycatch of protected, endangered and threatened species, in which case any extrapolation of bycaught individuals requires a thorough understanding of the respective fishery. It is not advisable to merely use the number of registered gillnet vessels or vessels with reported landings to extrapolate bycatch events of a subsample to the entire fleet of a specific area, as has been done in the past (Bellebaum et al., 2013), and risks biasing the results. Instead, difference between various types of gillnet fisheries should be acknowledged. For instance, bycatch rates of harbour porpoises vary depending on target species and thus, vary with differences in, for example, soaking time, net length, mesh size or fishing depth (Bjørge et al., 2013; Vinther & Larsen, 2004). The groups of vessels with distinct annual landing sequences in the German Baltic gillnet fleet identified in this study help to understand which monthly landing profile is important for which group, at what time during the year, and where along the German Baltic coast. This could potentially support more targeted research and management efforts, for example focusing on groups that are more active close to marine protected areas or during bird migration seasons or all year round, when assessing fishing effort and incidental bycatch of the different gillnet fisheries. The extrapolation of incidental bycatch, however, remains highly challenging since bycatches, for example of birds in a Danish gillnet fishery are rare mass events (Glemarec et al., 2020).

The results of this study supported an informed selection of groups and fishers in a downstream research project that identified different fisher types according to their social fishing practises, including the perception and attitude of gillnet fishers towards incidental bycatch of marine mammals and birds in the Baltic Sea (Barz et al., 2020). In the future, the classified groups have great potential to serve as a foundation for a more differentiated and target group-orientated approach in research, monitoring and management; for instance, by (i) addressing the effects of time/area closures, (ii) analysing the competition for space with other stakeholders such as wind farms, recreational fisheries or large-scale fisheries, (iii) studying different livelihood and marketing strategies via socioeconomic data, (iv) estimating bycatch, or (v) evaluating the consequences of protected areas based on group-specific effort data. Furthermore, it is possible to focus on a particular monthly landing profile, independent of the groups, and analyse how it is combined with other profiles and incorporated into the various annual landing sequences and groups of vessels. This will allow a detailed understanding of landing patterns with respect to a specific monthly landing profile.

The characterisation of activity patterns of a fleet is just the beginning of a more in-depth understanding of a fleet's dynamics (Pelletier & Ferraris, 2000). It emphasises the need to consider regional environmental settings and seasonal patterns in resource availability in research, monitoring and management. The approach of annual landing sequences addresses the succession of events in time and offers a more integrated view of the analysis of fishing activities. Sequence analysis can be a useful tool to identify distinguishable groups of vessels and improve the understanding of fleet structures, their dynamics and the underlying processes.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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