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Research Article

How quota cuts, recreational fishing, and predator conservation can shape coastal commercial fishery efforts

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Abstract

Commercial fishing effort often collides with other uses and interests. Fisheries resources might be co-used by recreational fishers (anglers), support populations of nonhuman top-predators, and fishing space might be preserved for conservation purposes. This can affect how commercial fisheries operate. We studied how the spatial distribution of commercial fishing effort among fishing districts is related to quotas, the use of resources by anglers, and the re-emergence of natural predators (the grey seal (*Halichoerus grypus*) and the great cormorant (*Phalacrocorax carbo sinensis*)). Our study area is the small-scale commercial fishery of Mecklenburg-Vorpommern in Germany. We use seemingly unrelated regressions with vessel-level time series of commercial targeting behavior. Spatial shifts in effort shares were related to larger quotas. Further, effort would shift away from areas with high seal densities, but no clear changes with respect to cormorants were found. The relationship between commercial effort share and angling activity was mixed and depended on the type of angler. We found a negative relationship between commercial fishing activity and angling in fishing areas where fishing for trophy pike (*Esox lucius*) and other predator species was popular.

Key words: Germany, great cormorant, grey seal, seemingly unrelated regression, cod, herring

1. Introduction

Human and nonhuman fish predators often pursue the same fish stocks and are thus competitors for a usually limited natural resource. Choosing where to fish under increasing constraints is a key question that commercial fishers ("fishers" from now on) have to answer daily (Bockstael and Opaluch 1983; Smith 2002). This decision may have become more difficult in recent years, particularly for small-scale fishers in Western industrialized countries (Björkvik et al. 2020; Döring et al. 2020), for three key reasons: dwindling stocks of key target species due to overfishing and environmental changes (Stenevik and Sundby 2007; Srinivasan et al. 2010; FAO 2020; Sumaila et al. 2020; Möllmann et al. 2021), societal value changes toward (predator) conservation (Cowx et al. 2010), and an increase in competing uses of fishing sites, e.g., for tourism, recreational fishing (angling[1]), or energy production (Schittone 2001; Berkenhagen et al. 2010; Hall 2021). In particular, small-scale coastal fisheries with limited resources, fishing opportunities, and room to maneuver, are vulnerable to these external shocks (Adger 1999; Salas et al. 2011; Roscher et al. 2022). While these factors can drive the structural change of the commercial fishery, fishers often remain in business despite difficult conditions because fishing is a family tradition and a way of life (Eggert and Lokina 2007), due to lack of other employment opportunities (Ikiara and Odink 1999; Teh et al. 2008), or due to subsidies (Lado 2016; Sumaila et al. 2019). To cope, fishers may adapt their fishing strategy, for example, by focusing on different species, using different types of gear, or fishing in different areas (MacNeil et al. 2010; Lédée et al. 2012; Holbrook and Johnson 2014; Sievanen 2014; Smith et al. 2020).

To prevent overexploitation of fish stocks, quotas are often employed for commercially important species (Branch 2009; Clark 2010; Lado 2016). Individual (transferable) quotas (I(T)Qs) are also meant to reduce inefficiencies and overcapacity in a fishery with derby characteristics (Clark 2010). Setting quota levels is challenging due to substantial data requirements and the difficulty of understanding the ecological system via stock assessments (Melnychuk et al. 2017; van Gemert et al. 2022). Quotas further need proper enforcement to be

[1] **Note:** Throughout the paper, we use the term "angler" and "angling" to describe recreational, not-for-profit fishing. We use the term "fisher" to describe commercial fishers.

effective, which requires public investment (Oliver 1998). Because setting quotas to low levels to help stock recovery is often politically unpopular (Oliver 1998), quotas have historically often been set above scientifically advised levels (Oliver 1998; Möllmann et al. 2021). If a fishery hosts several species and not all of them are quota-regulated, fishing effort can spill over toward areas where nonquota-regulated species are abundant (Squires et al. 1998; Asche et al. 2007; Branch 2009; Koemle et al. 2023). The use of these fish by other sectors, e.g., anglers, can fuel conflicts among fishing sectors (Boucquey 2017; Arlinghaus et al. 2022).

Conservation regulations can also indirectly affect fisheries. The Baltic Sea, one of the largest brackish ecosystems worldwide, is one example for this phenomenon. While populations of fish predators, such as the great cormorant (*Phalacrocorax carbo sinensis*) and the grey seal (*Halichoerus grypus*), have been driven near extinction in the Baltic Sea in the 1900s by hunting and pollution (Harding and Härkönen 1999), subsequent conservation measures instituted through the European Union's (EU's) conservation regulations and reduced pollution levels have helped to stabilize and increase population sizes of these predators. The return of grey seals to the Baltic Sea has caused substantial losses for fishers in Germany (Schwarz et al. 2003), Sweden (Bergström et al. 2022; Jansson and Waldo 2022), and Finland (Varjopuro 2011) though their predation on commercially important species (Bergström et al. 2022), and conflicts between commercial fisheries and seals have been documented in several other contexts (Hammill et al. 2014; Neuenhoff et al. 2019). For example, for Canada, it was found that predation by seals prevented stock recovery of key commercial target species that were once overfished and where a moratorium on fishing was installed, such as the Newfoundland cod (*Gadus morhua*) (Neuenhoff et al. 2019). Seals can affect a fishery through three channels: (1) seals increase the natural mortality of fish directly through predation; (2) fish become less vulnerable to current fishing practices due to avoidance behavior and being chased away; and (3) in gillnet, trap and longline fisheries, seals eat fish directly from the fishing gear and may damage fishing gear (Varjopuro 2011; Blomquist and Waldo 2021). In Finland, attempts have been made to reduce the vulnerability of fishers to seals via technological developments, although success has been limited (Varjopuro 2011). Similar problems have been identified with the return of cormorants in many coastal areas (Bregnballe et al. 2015; Arlinghaus et al. 2021; Ovegård et al. 2021; Herrmann et al. 2022). Cormorants have been reported to particularly damage fish trapped in gillnets (Jepsen and Olesen 2013), but while cormorants have been suspected of contributing substantially to natural mortality of coastal fish, the empirical evidence is inconclusive and varies by fish species (Engström 2001; Arlinghaus et al. 2021; Ovegård et al. 2021). In brackish lagoons (Bodden) around the island of Rügen in Germany in the southern Baltic Sea, cormorants have been found to dominate the extraction of small-bodied freshwater fish (e.g., perch (*Perca fluviatilis*) and roach (*Rutilus rutilus*)) (Arlinghaus et al. 2021), and recent models have shown that they can have substantial impact on coastal predatory fish, such as pike (*Esox lucius*) (Arlinghaus et al. 2023b), pikeperch (*Sander sander*) (Winkler et al. 2015) and cod (Arlinghaus et al. 2021).

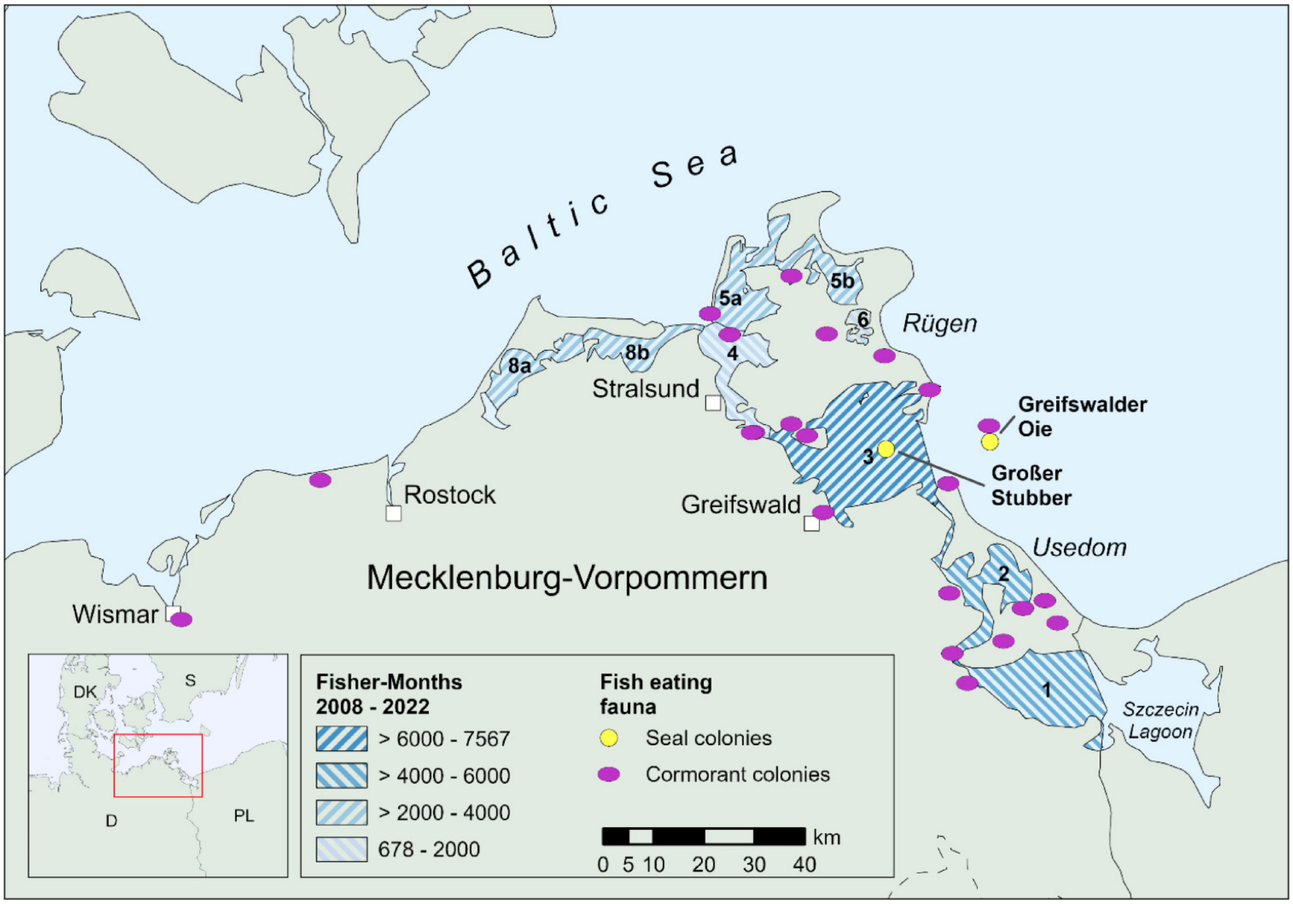
The increased populations of these protected species also have other consequences for commercial fishing. As populations increase, incidental bycatch also increases, with the species becoming entangled in fishing gear (e.g., Tasker et al. 2000; Meyer et al. 2017; Larsen et al. 2021). To counter this, additional restrictions are often placed on fishers, either through regulating the use of bycatch reduction devices or restricting where or when fishers may operate, both of which may affect the economic viability of the commercial fisheries (e.g., Bull 2007; Squires et al. 2021; O'Keefe et al. 2023).

The third channel through which fishers come under pressure is competition from other human uses. Along with economic development, angling in inland and coastal areas has become a frequently pursued activity in many countries (Cowx et al. 2010; Hyder et al. 2018; Arlinghaus et al. 2021). This has resulted in conflict between anglers and fishers, which is well-documented in Europe (Arlinghaus et al. 2022) and elsewhere (Kearney 2001; Brown 2016; Boucquey 2017). Angling has been identified as a relevant source of fishing mortality (Lewin et al. 2006; Ihde et al. 2011), and many studies have been conducted to assess the impact of angling in inland and marine contexts (Eero et al. 2015; Hyder et al. 2018; Radford et al. 2018; Lewin et al. 2019). Anglers have been accused of damaging commercial fishing gear or losing fishing hooks entangled in commercial nets, thereby increasing the risk of injury (Arlinghaus et al. 2023b). Fishers may thus avoid areas with too much angling pressure and vice versa.

Fishers typically allocate their effort based on regulations, past experience and usually based on incomplete information (Bockstael and Opaluch 1983; Smith 2002). Where to fish, and for how long, will, among other things, depend on a fisher's expected profits from that specific location in the short run (Eggert and Lokina 2007; Andersen et al. 2012) as well as on long-term investments such as vessels, gear, and fishing rights (Bockstael and Opaluch 1983; Girardin et al. 2017). Fishers may redirect their effort if changes in quota require them to target other species in different areas. Fishers may also expect that damage from seals on their gear or catch is greater than the potential profit, causing them to fish in areas where they expect lower predator activity. When fishers expect long-term changes to the fishery, they may make larger changes in their business by, e.g., acquiring rights to new fishing locations, purchasing new gear or vessels, relocating their equipment, or even resulting in industry entry/exit decisions (Bockstael and Opaluch 1983). When fishers re-allocate their effort, there may be immediate crowding effects; that is, due to exploitative and interference competition (Poos and Rijnsdorp 2007) between fishers (if more fishers are fishing in the same area), catches and (or) revenues could decrease despite higher effort (Koemle et al. 2023).

The goal of this paper is to estimate how recent quota cuts in key commercial species, in addition to the consequences of conservation policy (i.e., the re-emergence of grey seals and cormorants) and alternative uses of the fishery (i.e., angling) have shaped the spatial commercial fishing effort distribution, using the small-scale coastal fishery of Mecklenburg-Vorpommern (MV) in northeastern Germany as a case study

Fig. 1. Map of the study area showing different fishing districts in the brackish lagoons (Bodden) of Mecklenburg-Vorpommern indicating the total number of fisher-months over the time-period 2008–2022. (1) Stettiner Haff, (2) Peenestrom, (3) Greifswalder Bodden, (4) Strelasund and Kubitzer Bodden, (5a and 5b) Westrügen, (6) Kleiner Jasmunder Bodden, (8a and 8b) Darß-Zingst Bodden Chain. Data sources: Fisher-months—LALLF (2023*a*), Cormorant colonies—LUNG (2008–2022), Seal colonies—German Maritime Museum (2023); Basemap: Natural Earth, Projection: UTM Zone 33N, Datum: ETRS 1989, EPSG code: 25833, Coordinates = UTM.



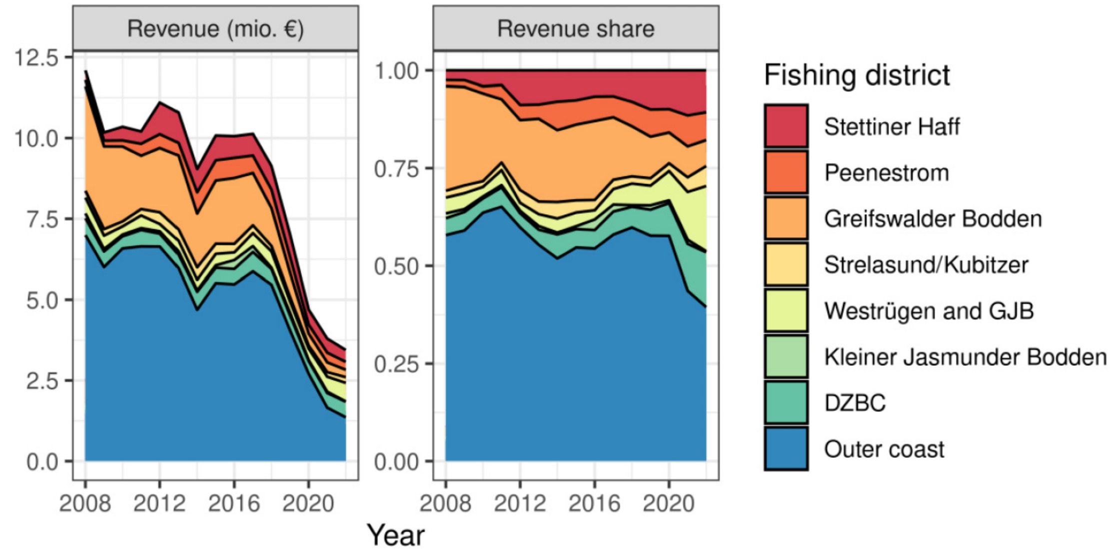
system. The main commercial target species, historically, have been Atlantic herring (*Clupea harengus*) and Atlantic cod, where the fishery has been hit particularly hard by reductions in spawning stock biomass and associated quota cuts (Möllmann et al. 2021; Lewin et al. 2023*a*). The area also hosts a suite of freshwater and diadromous fish as targets within the brackish lagoons close to the island of Rügen and Usedom, where pikeperch, perch, pike, or eel (*Anguilla anguilla*), among many other species, are targeted (Lewin et al. 2023*a*). The fishery has also been subject to strong increases of anglers as well as seal and cormorant populations in recent years (Arlinghaus et al. 2021, 2023). We hypothesize that, in response to quota cuts, fishers will spatially adjust their fishing effort toward fishing areas where nonquota regulated fish can be targeted instead of the quota-regulated herring (H_{1a}) and cod (H_{1b}). Furthermore, we hypothesize that fishers will adjust their effort away from concentrations of seals (H_{2a}), cormorants (H_{2b}), and there may be a bi-directional avoidance between fishers and anglers (H_{2c}). We expect the dislodgement effect to be stronger in seals than in cormorants, as seals also damage gear and remove fish from gear types such as gill nets, which is perhaps more prevalent than in cormorants. We follow Smith's (2002) aggregate approach by estimating seemingly unrelated regression (SUR) and explaining the effort shares by quotas, predator counts, and angling effort.

2. Study area and background

2.1. Commercial fishery

The coastal commercial fishery of MV currently (2023) consists of approximately 300 full-time or part-time fishers. It has been subject to structural change, having hosted more than 1000 fishers in 1990, and today many fishers are over the age of 60 years (Arlinghaus et al. 2023b). The fishery of MV can be separated into two distinct parts: a coastal/marine fishery targeting mainly marine species (historically dominated by cod and herring), and a brackish water fishery in the lagoons close to the island of Rügen (Fig. 1) (Döring et al. 2020; Meyer and Krumme 2021). These lagoons are fed by both freshwater discharge from several rivers such as river Odra, Barthe, Peene or Sehrowbach, as well as saltwater inflows from the Baltic

Fig. 2. Total revenues and revenue shares produced in the respective fishing districts (data source: LALLF 2023*a*). GJB = Großer Jasmunder Bodden; DZBC = Darß-Zingst Bodden Chain.



Sea, but annual mean salinities are less than 10 PSU. As such, the lagoons host a wide variety of freshwater and diadromous species but also provide important spawning grounds for the spring- and autumn-spawning Western Baltic herring.

Key commercial species (herring, cod, plaice (*Pleuronectes platessa*), salmon (*Salmo salar*), and sprat (*Sprattus sprattus*)) are managed using quotas under the Common Fisheries Policy (CFP) of the EU, which is also responsible for fleet management using structural measures. The cod and herring fishery in the Western Baltic Sea has been subject to quotas for many decades, first under the International Baltic Sea Commission (Bekiashev and Serebriakov 1981) and then within a bilateral agreement between the EU (subject to the CFP) and Russia. While the International Council for the Exploration of the Sea (ICES) publishes annual advice on the setting of quotas, the size of the quota remains a political decision negotiated by the EU member states.

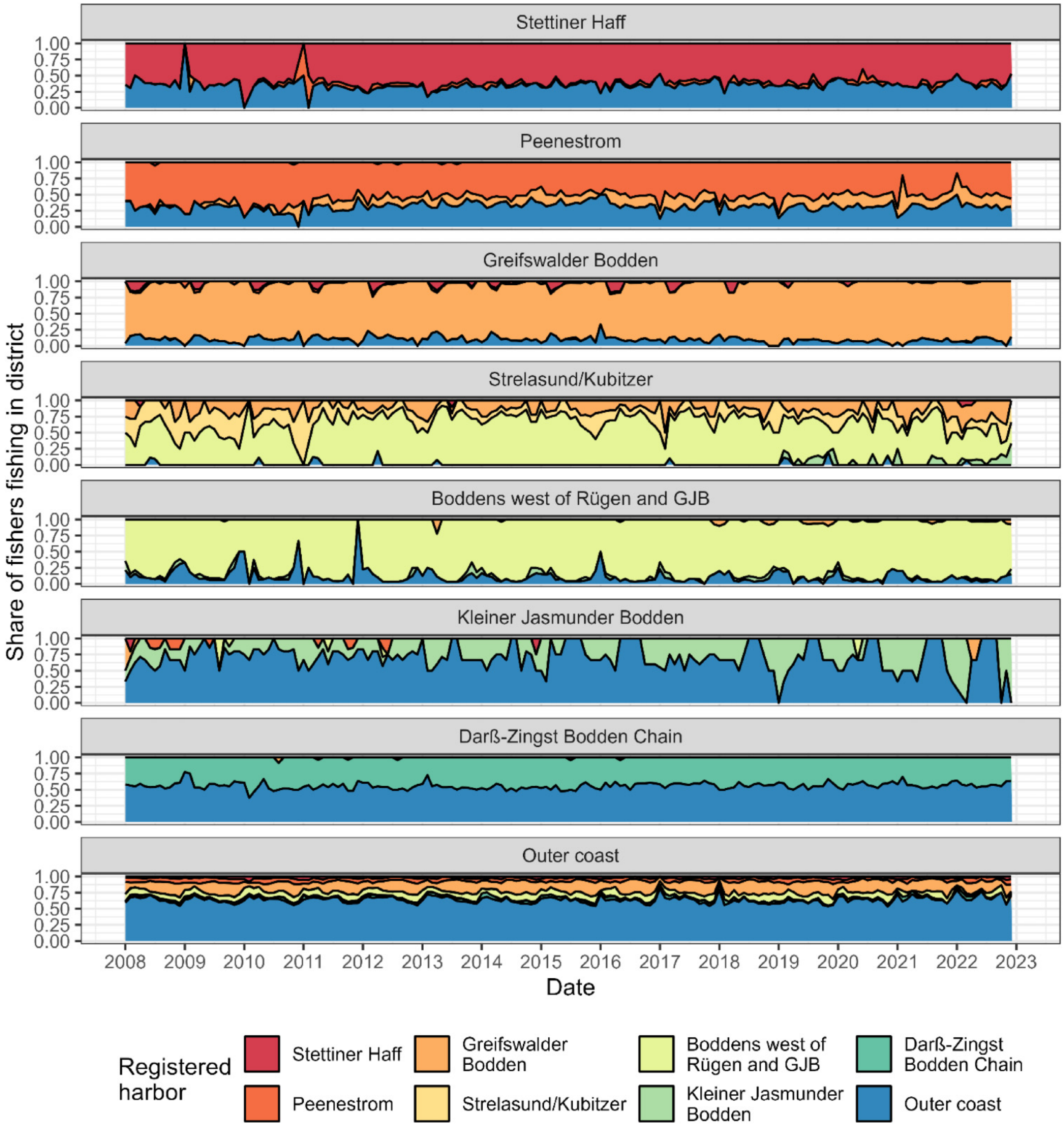
For species outside the scope of the CFP, including the lagoons, the state coastal fisheries directive (SCFD, "Küstenfischereiverordnung" in German) regulates access to, and fishing rights in, coastal waters. The lagoons are separated into 10 fishing districts (Fig. 1). Within these districts, in principle, fishers are free to choose their target species. The SCFD includes limits on inputs, as well as regulations on what, when, and where fish can be harvested. In the lagoons, only passive gears such as gillnets, longlines, eel traps, and fyke nets are allowed, apart from some limited wind-powered trawling with historical vessels. The total amount of gillnets, longline hooks, and eel traps is also limited by the SCFD for each fishing district. Each fisher is assigned the maximum length of gillnet he or she can set within a certain fishing district. This means that fishers have limited flexibility in where to fish. Nevertheless, there is no constraint on the total time that these nets can be deployed in the respective fishing district. Similarly, fyke net locations need to be registered with the fisheries authority. Currently, there are 994 registered fyke net sites in the study area, although the amount of active use of each site is unclear. Fyke nets are registered with their time of use, particularly spring fyke nets (38, active from 1 March to 30 June each year), autumn fyke nets (35, active from 1 August to 30 November each year), and all-year fyke nets (913, active all year). Three fyke nets are registered for spring or autumn use, and for the remaining, there was no information available. Different specialized types of fyke net exist in the area. Most fyke nets are of the normal fyke net type (724), with fewer of the larger Kummreuse type (197, similar to pound nets), which are open on top, swimming fyke nets (47), and shrimp fyke nets (25). A total of 903 of these fyke nets are not accessible by land. Due to confidentiality, the positions of these fyke nets are not shown in Fig. 1.

On the output side, there exist species-specific minimum length limits (e.g., 50 cm for pike) as well as closed seasons (e.g., 1 March to 30 April for pike). The fishing districts were reorganized in 2013, particularly splitting District 5 (including the lagoons West of Rügen and the Großer Jasmunder Bodden (GJB)) into two separate districts (5a and 5b) and similarly splitting District 8 (the Darß-Zingst Bodden (DZB) Chain) into districts 8a and 8b. The districts are characterized by different species compositions (Lewin et al. 2023*b*).

We separated seven different fishing districts that differed in their species composition and the total revenue produced over time. To a large extent, the fishery has relied on catches from the outer coast/marine areas (>60% of revenues) and the largest of the lagoons, the Greifswalder Bodden (∼25% of revenues) (Fig. 2).

Fishers are typically registered to a single harbor. To clarify, in the following we separate the terms "*home district*" and "*fishing district*". The home district is the district where the fisher is registered. We assigned fishers who were located on narrow strips of land between a brackish and open water, and thus had direct access to both sides, to the brackish fishing district. The fishing district is the district where

Fig. 3. Share of fishers fishing in a certain fishing district. Fill colors show the fishing district of the harbor to which a fisher's vessels were registered (data source: LALLF 2023*a*). GJB, Großer Jasmunder Bodden.



the fisher actively fished in a given month. By separating the two, one can obtain an impression about how fishing activity in various districts is driven by fishers whose home district is inside or outside the fishing district (Fig. 3). The fishing districts can be characterized as follows (summarized in Table 1):

- *Stettiner Haff* (District 1): The Stettiner Haff is fed directly by the river Odra, and it is shared between Germany and Poland. Given its eutrophic state, the catch is dominated by freshwater species that are striving for high nutrient loads, particularly pike-perch (*Sander lucioperca*), perch, bream (*Abramis brama*), and eel (Fig. 4). The area has 251 registered fyke net locations. The effort is mainly driven by local fishers, as well as fishers registered along the outer coast (Fig. 3). This distribution remained relatively stable over time.
- *Peenestrom* (District 2): The Peenestrom is the connecting estuary between Stettiner Haff and the Bodden lagoons. The fishing district includes a larger side waterbody named the "Achterwasser". The fishery is dominated by the same species as the Stettiner Haff, i.e., pike-perch, perch, bream, and eel (Fig. 4). A total of 255 fyke net locations are currently registered here. While effort was initially dominated

Table 1. Summary of characteristics of the fishing districts along the coast of Mecklenburg-Vorpommern coast (data source: LALLF 2023*a*).

Fishing district	Main target species	Number of fykenets	Avg. number of fishers registered (2008–2022)
Stettiner Haff	Pike-perch, perch, bream, eel	251	28
Peenestrom	Pike-perch, perch, bream, eel	255	34
Greifswalder Bodden	Herring, garfish, eel, perch	109	82
Strelasund and Kubitzer Bodden	Herring, pike-perch, perch, pike, eel	17	2
Westrügen and Großer Jasmunder Bodden	Roach, pike, and pike-perch, eel	71	45
Kleiner Jasmunder Bodden	Pike-perch, roach	14	2
Darß-Zingst	Pike-perch, eel	39	16
Outer coast/open Baltic Sea	Cod, herring, European flounder European plaice, eel	238	163

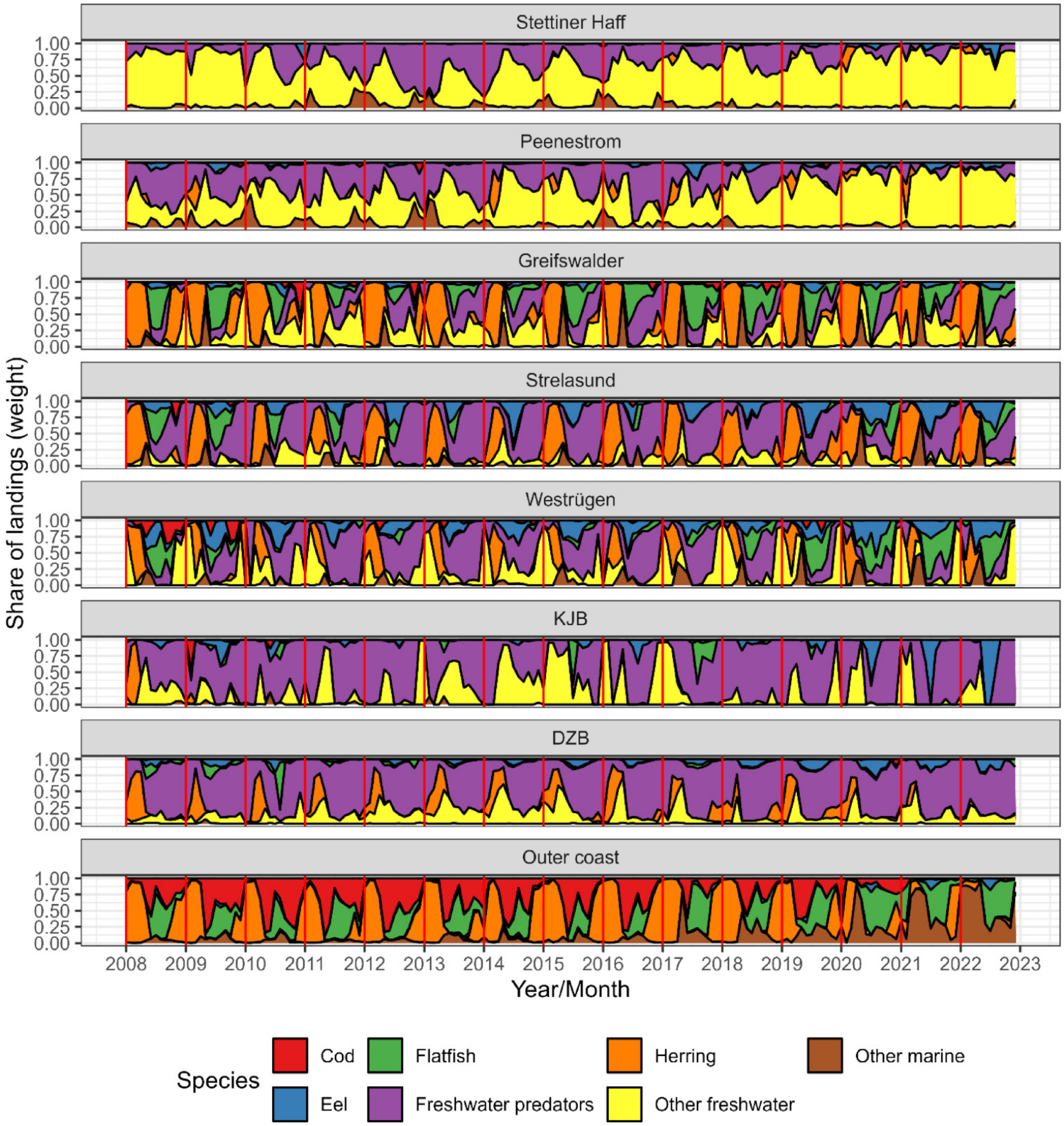
by local fishers, it is increasingly shared with fishers registered on the outer coast, as well as the Greifswalder Bodden (Fig. 3).

- *Greifswalder Bodden* (District 3): The Peenestrom feeds into the Greifswalder Bodden. Here, the key target species, historically, is spring-spawning herring (Subklew 1955), which uses the waterbody for spawning in spring and, to a lesser extent, in autumn (Fig. 4). The Greifswalder Bodden is directly connected to the open Baltic Sea in the east. However, with recent quota cuts, the revenue shares of other species such as garfish (*Belone belone*), eel, and perch have increased (Fig. 4). Seals have been monitored on a sandbank named the "Großer Stubber" within the Greifswalder Bodden as well as on the small island "Greifswalder Oie" just outside the Greifswalder Bodden. Seal abundances are greatest in the Greifswalder Bodden and are much lower in the other lagoons. One hundred nine fyke net locations are registered here. The effort in the Greifswalder Bodden is dominated by local fishers, with a decreasing share of seasonal fishers from the Stettiner Haff (for the herring season) and the outer coast.
- *Strelasund and Kubitzer Bodden* (District 4): Going west from Greifswalder Bodden follows a narrow waterbody named the Strelasund between the German mainland and the Island of Rügen. Seventeen fyke net locations are registered here. The fishing district also includes the mesohaline Kubitzer Bodden, which forms the border between the Westrügen Boddens to the North and the DZB Chain to the East. In the Strelasund, apart from herring (which is still dominant), fishers also target pike-perch, perch, and pike, along with eel (Fig. 4). This fishing district is dominated by fishers registered to the Westrügen and GJB districts, with a smaller share of fishers coming from the Greifswalder Bodden and the remaining fishers being locals. While showing some fluctuations in effort shares over time, the years 2021 and 2022 seem to have shown a reduction in effort shares by the Westrügen fishers.
- *Westrügen and GJB* (District 5): The mesohaline Boddens to the west and north of Rügen are largely dominated by freshwater species (specifically, roach, pike, and pike-perch) and eel, although some cod and herring fishing has been conducted in previous years (Fig. 4). Twenty-five fyke nets are registered in Westrügen and 46 are registered in GJB. The effort in this district is dominated by local fishers but shows some seasonal influx from the outer coast.
- *Kleiner Jasmunder Bodden* (District 6; KJB): The polytrophic and less saline KJB forms the end of a series of lagoons and is well-known to host pike-perch, although other freshwater species such as roach have produced larger revenue streams in the past (Fig. 4). Fourteen fyke nets are registered here. The effort is dominated by outer coast fishers, and to a lesser extent by locals (Fig. 3).
- *Darß-Zingst* (District 8, DZB): The DZB Chain is another well-known waterbody for pike-perch fishing (especially in the western more eutrophied and less saline area, and less so in the eastern less eutrophied, mesohaline area), with eel making up larger revenue shares as a second species. Other freshwater species (pike, perch, or roach) played only a minor role in the past (Fig. 4). Thirty-nine fyke net locations are registered here. The effort shares roughly showed a 50–50 split between locals and outer coast fishers and remained relatively stable over time with seasonal fluctuations.
- *Outer coast/open Baltic Sea*: The outer coast and the open Baltic Sea were the prime locations for cod and herring fishing (Fig. 4), but the revenue shares of these species have decreased in favor of flatfish such as European flounder (*Platichthys flesus*), European plaice, and eel. The remaining 238 fyke net locations are registered along the outer coast. The effort shows a seasonal pattern, which is dominated by outer-coast fishers as well as fishers from the Greifswalder Bodden and Westrügen to a smaller extent.

2.2. Seals and cormorants

Seals and cormorants in the Baltic Sea have re-emerged over the past three decades (Fig. 5) after the species were almost extinct (Harding and Härkönen 1999; Schwarz et al. 2003). Along with heavy hunting up until 1980, grey seals reproductive ability was reduced due to run-off of phosphorous and pollutants before comprehensive protection measures were instated in many countries along the Baltic coast. Anecdotal sightings of seals are reported in the entire study area (Herrmann 2012; Arlinghaus et al. 2023b). However, two areas where seal colonies have been observed in recent years are the Großer Stubber (a rock formation in the Greifswalder

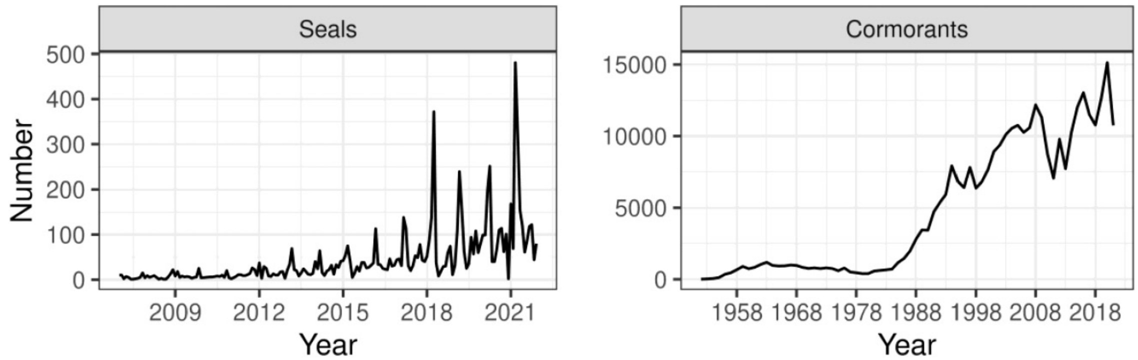
Fig. 4. Share of landings of species groups over time by fishing district (data source: LALLF 2023*a*). KJB, Kleiner Jasmunder Bodden; DZB, Darß-Zingst Bodden Chain.



Bodden) as well as the island "Greifswalder Oie", located just west of the Greifswalder Bodden in the Baltic Sea (Fig. 1). For these two locations, monthly seal counts have been conducted since 2007. Overall, sightings of seals have increased sharply since 2007. The sightings fluctuate throughout the year, with peaks in February and March during the herring spawning season (Nordheim et al. 2019) (Fig. 5, left panel).

Like seals, cormorants were hunted to very low levels in Europe due to their impact on fish stocks (Rauschmayer and Weiss 2013). Since the 1980s, bird conservation regulations within the EU have allowed cormorant populations to recover (Herrmann et al. 2018), with several colonies now nesting along the coast of MV (Fig. 5, right panel), although their population size may have suffered in cold winters (Herrmann et al. 2022), such as in 2009/10 (Herrmann et al. 2018). Monthly counts of breeding pairs from the year 2018 suggest that the size of colonies varies throughout the year, with peaks occurring in March and September (Herrmann and Zimmermann 2019). Several large colonies have been observed,

Fig. 5. Counts from monthly grey seal monitoring on the Großer Stubber and the Greifswalder Oie in Mecklenburg-Vorpommern (MV) from 2007 to 2022 and annual breeding pairs of cormorants along the coast of MV from 1952 to 2021 (data sources: Seals—German Maritime Museum (2023); Cormorants—LUNG (2008–2022).



particularly in the lagoon areas around the island of Rügen. The largest single colony hosting over 4000 breeding pairs was observed close to the Stettiner Haff; several colonies of approximately 1000–2000 breeding pairs were observed in various conservation areas, e.g., along the Peenestrom, on the island "Heuwiese" in the Kubitzer Bodden, or in the center of Rügen in 2020. A lower bound of fish removals by cormorants within the lagoons have been estimated to be roughly 2400 t per year in 2011 and 2012, to a large extent feeding on perch (24%), roach (24%), and smaller sizes fishes (e.g., threespined stickleback (*Gasterosteus aculeatus*), gobiids (*Gobidae*), ruffe (*Gymnocephalus cernua*); Winkler et al. 2015), although removals including migratory cormorants are potentially higher. To prevent excessive damage to inland fisheries, cormorants can be managed with an exceptional permit. Management actions such as oiling of eggs, the destruction of nests, or shooting of adult birds have been taken in several countries including Sweden and the Baltic states. The only intervention in MV colonies has been trial harassment with laser pointers from 2008 to 2012, in addition to shooting cormorants outside the breeding season (Herrmann et al. 2018). Conflict between these predators and fishers has been well-documented along the MV coast (Vogt 2020) and also in the Nordic countries (Koningson et al. 2010; Varjopuro 2011; Hammill et al. 2014; Holma et al. 2014).

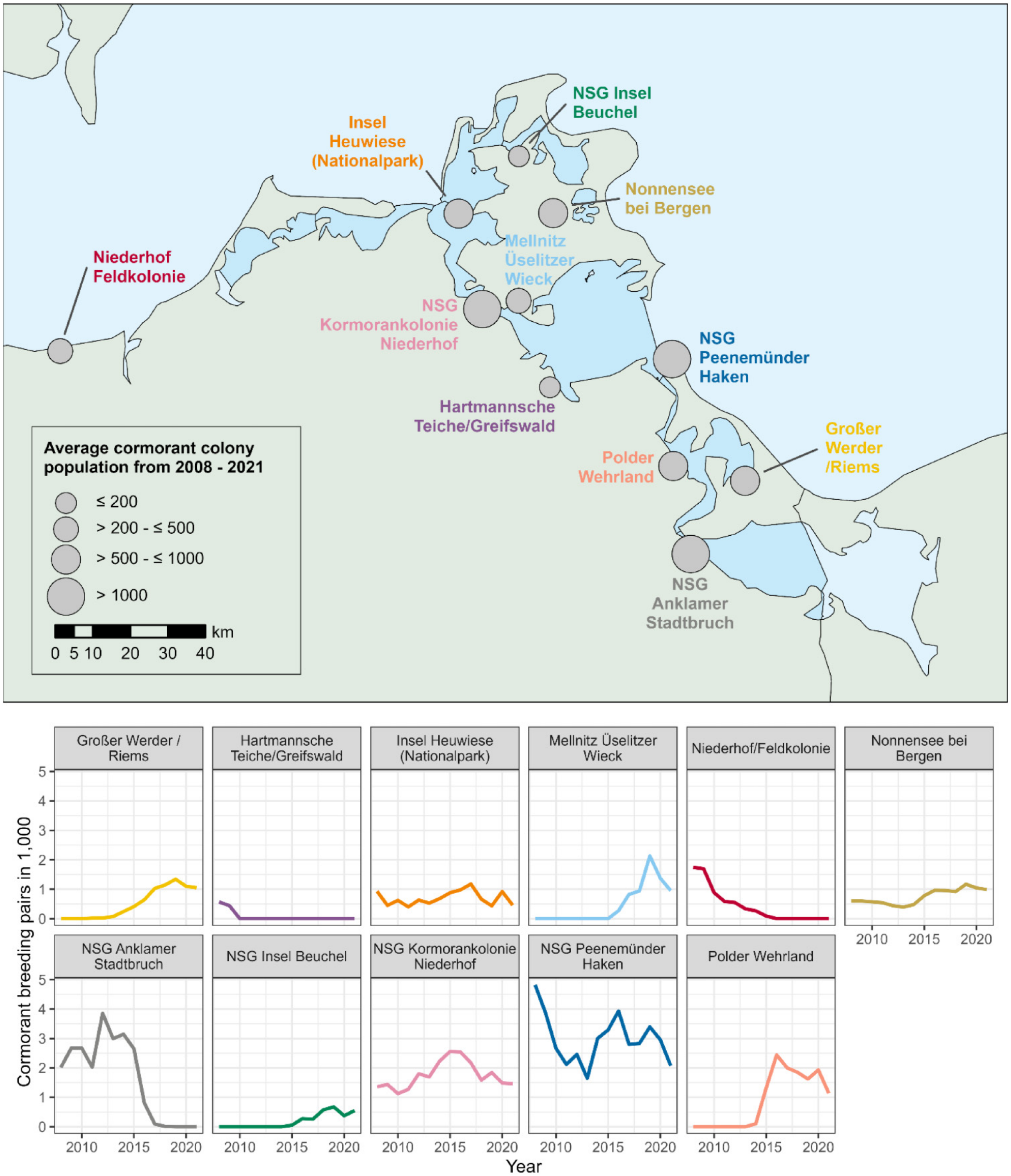
While seals occur relatively concentrated in the area and may be easier to avoid for some fishers, large cormorant colonies are distributed throughout the study area and may be more difficult to avoid. The sizes of colonies have also changed drastically over the past 14 years, with some colonies having decreased in size and subsequently ceased to exist (e.g., Niederhof/Feldkolonie, Anklamer Stadtbruch), while others have increased in size (e.g., Großer Werder/Riems, Nonnensee bei Bergen) (Fig. 6).

2.3. Recreational fishing (angling)

Recreational fishing in the coastal areas of MV has particularly increased after the German reunification (Weltersbach et al. 2021; Arlinghaus et al. 2023a), and the coast of MV has become a popular fishing site for various marine, freshwater, and diadromous species (Winkler 1989; Haase 2000; Strehlow et al. 2012). On the outer coast of MV, cod, flatfish, herring, sea trout (*Salmo trutta*), salmon, and garfish are the most popular recreational target species (Weltersbach et al. 2021). The brackish lagoons (Bodden) have been well-known for catching trophy pike (Fuhrmann and Balkow 2013; Arlinghaus et al. 2021) and other freshwater predatory species such as pikeperch and perch, as well as herring and garfish, particularly in spring (Weltersbach et al. 2021). Anglers are required to purchase a coastal fishing permit to fish in the coastal areas of MV, at the cost of 6€ (daily), 12€ (weekly) of 30€ (annual permit). Annual permits for persons below 18 years or disabled persons cost 10€. The permit numbers strongly increased to about 60 000 annual permits up to 2013, along with increases in weekly and daily permits peaking just below 40 000 each (Fig. 7). For all three permit types, recent years have shown a decline in sales.

On the outer coast, angling is carried out from beaches, piers, and jetties (land-based fishery) and from small private or rental boats and to a lesser extent from larger charter boats (Strehlow et al. 2012; Lewin et al. 2023c). In the Bodden, most anglers fish from small boats (either self-organized or with a guide), or from harbors or the shore (Arlinghaus et al. 2021; Koemle et al. 2021). An important target species for anglers in the Bodden waters is pike, which is targeted by around 50% of recreational lagoon fishing (either singly or as one among several species) (Arlinghaus et al. 2021). A recent survey conducted by the authors in 2020/21 (see Koemle et al. 2022, 2024 for details) among lagoon pike anglers asked the question: "Which waterbody on the Bodden was your main angling site for pike?" Responses from 2145 anglers suggested that the main fishing districts for pike for were the Bodden waters West of Rügen including the GJB (33%), and Strelasund/Kubitzer (32%); fewer chose the Greifswalder Bodden (17%) and the DZB Chain (10%) or Peenestrom (5.7%), and only a small number of respondents (1%), respectively, chose either the Stettiner Haff or the KJB for pike fishing. Thus, the increase in anglers and their concentration in specific districts may have led fishers to adjust their fishing strategies (particularly in the tourist-heavy seasons) by fishing in different places, adjusting their fishing times, or targeting different (less profitable) species.

Fig. 6. Locations of the main cormorant colonies indicating the average colony size 2008–2021 and results of monitoring (breeding pairs over time) in the study area (data sources: Cormorants—LUNG (2008–2022); Basemap: Natural Earth, Projection: UTM Zone 33N, Datum: ETRS 1989, EPSG code: 25833, Coordinates = UTM).



Unpublished data from a telephone-diary survey conducted by the Thünen Institute of Baltic Sea Fisheries (see Weltersbach et al. (2021) for a description of the survey) reveal that the different permit types are bought by distinctly different types of anglers (Table 2). On average, age of the owners of different permits were similar although anglers with annual coastal fishing permits were typically more avid (on average 15 fishing days/year) than were daily and weekly permit holders (6–7 days/year). Similarly, Bodden and Baltic Sea fishing trips were more frequent among annual permit holders

Fig. 7. Number of annual, weekly, and daily coastal angling permits sold annually in the state of Mecklenburg-Vorpommern (data source: LALLF 2023*b*).

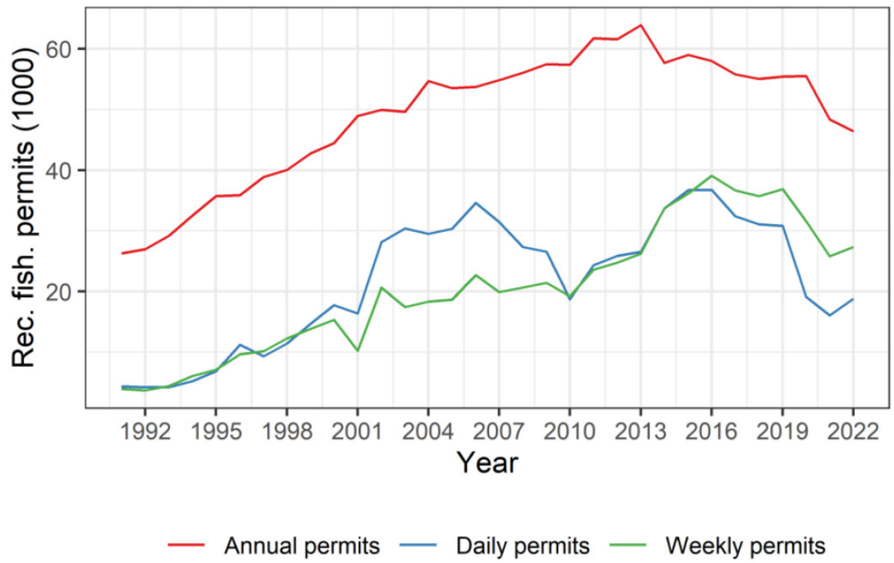


Table 2. Age, avidity, and number of fishing days of anglers holding different coastal angling permits in Mecklenburg-Vorpommern (Source: Thünen Institute of Baltic Sea Fisheries).

Variable	Type of coastal angling permit	Mean	SD	Min	Max
Age	Annual permit	49.7	12.9	14	84
	Daily permit	48.7	15.3	14	80
	Weekly permit	45.3	11.3	23	74
Number of Bodden days	Annual permit	3.0	7.6	0	92
	Daily permit	0.5	1.3	0	10
	Weekly permit	1.0	2.3	0	16
Number of Baltic Sea days	Annual permit	4.8	8.0	0	65
	Daily permit	1.9	4.0	0	24
	Weekly permit	1.6	3.1	0	20
Avidity	Annual permit	15.7	20.0	1	180
	Daily permit	6.1	10.4	1	70
	Weekly permit	6.9	5.3	1	30

(3.0 and 4.8 fishing days, respectively) compared to 0.5 and 1.9 fishing days for holders of other permits, respectively.

3. Data and methods

3.1. Data

Data for this study were combined from several sources. As we only used secondary (administrative) data, no ethics approvals were required. Confidential fisher-level landings declarations for 2008–2022 were provided by the local fisheries authority (Landesamt für Landwirtschaft, Lebensmittelsicherheit und Fischerei Mecklenburg-Vorpommern - LALLF) for research purposes.

- Data on the commercial fishery were generated from self-reported monthly landing declarations. Coastal fishers in MV are required to fill out monthly declarations detailing the landings and revenues generated from each species separated by vessel and fishing district and submit them to the fisheries authority, where they are double-checked and compared to purchase data from fish buyers (e.g., wholesalers). These monthly landing declarations were available for the period January 2008 to December 2022. From these landing declarations, we computed the number of fishers active per fishing district and month as our effort indicator. Note that no data on species-targeted effort existed, so all effort in this analysis is total effort. Given that the majority of fishers is small-scale and uses passive gear, this constituted the best available proxy of effort compared to other measures that are frequently used in industrial-scale fisheries such as engine power. The share of fishers active in a fishing district in a given month constituted the dependent variable in subsequent analyses. We also computed the total revenues produced in each district and month, to be used in calculations of revenue differentials (see below) as a first set of explanatory variables. All revenues were deflated to 2015 price levels using a German consumer price index (CPI).

- Annual quotas for ICES areas 22–24 for cod and herring were published by the state fisheries authority of MV (LALLF) on their website. These represent the Total Allowable Catch (TAC) for German vessels fishing in the area.
- Data on the number of seals in an area were produced by the German Maritime Museum in Stralsund through monthly aerial counts from 2007 onwards. We computed an index for seals in each fishing district as $S_{i,t} = \sum_j \frac{1}{d_{i,j}^2} Seals_{j,t}$, where *Seals* was the number of seals counted at a particular time *t* at monitoring site *j* and $d_{i,j}^2$ is the squared distance between the centroid of fishing district *i* and monitoring site *j* in km.
- The number of cormorant breeding pairs in several areas along the coast of MV has been monitored through annual programs since the 1950s for several sites along the MV coast (Fig. 5). In addition, in 2018, cormorants were counted monthly (Herrman and Zimmermann 2019). We thus used the numbers from the monthly counts to create monthly varying numbers of cormorants for each year. Analogous to seals, we computed an index for cormorants as $C_{i,t} = \sum_j \frac{1}{d_{i,j}^2} \text{Cormorants}_{j,t} * \text{weight}$, where weight is a monthly weight according to the 2018 monthly counts. Like for seals, $d_{i,j}^2$ is the squared distance (in km) between the colony and the centroid of the fishing district.
- Angling effort was measured by the sales of coastal angling permits in MV obtained from the state fisheries authority (LALLF). To create a spatially differentiated index of angling effort, we used data from our recent survey (Koemle et al. 2022, 2024) on pike fishing, as described above ("Which waterbody on the Bodden was your main angling site for pike?"). We used the share of anglers as a weight when assigning the number of recreational coastal fishing permits to each fishing district. While there are three types of coastal angling permits as described above, weekly and daily permits showed a high correlation of 0.83. Therefore, we removed weekly permits from the analysis and only estimated parameters for annual and daily permits. As mentioned above, weekly and daily permits were used by anglers of similar avidity.
- The price of diesel has been found to influence where fishers fish: if prices are too high, fishers tend to stay closer to their home harbor than when prices are low (Pascoe et al. 2020). Monthly prices of diesel were obtained from the Federal Statistical Office of Germany. Similar to revenues, we deflated our time series of monthly diesel prices using the German CPI to the 2015 price level.
- Physical data (water temperature) were measured in various measuring stations distributed throughout the research area and provided by the Federal Agency for Environment, Nature Protection and Geology (German abbreviation: LUNG) in MV.

3.2. Estimation strategy

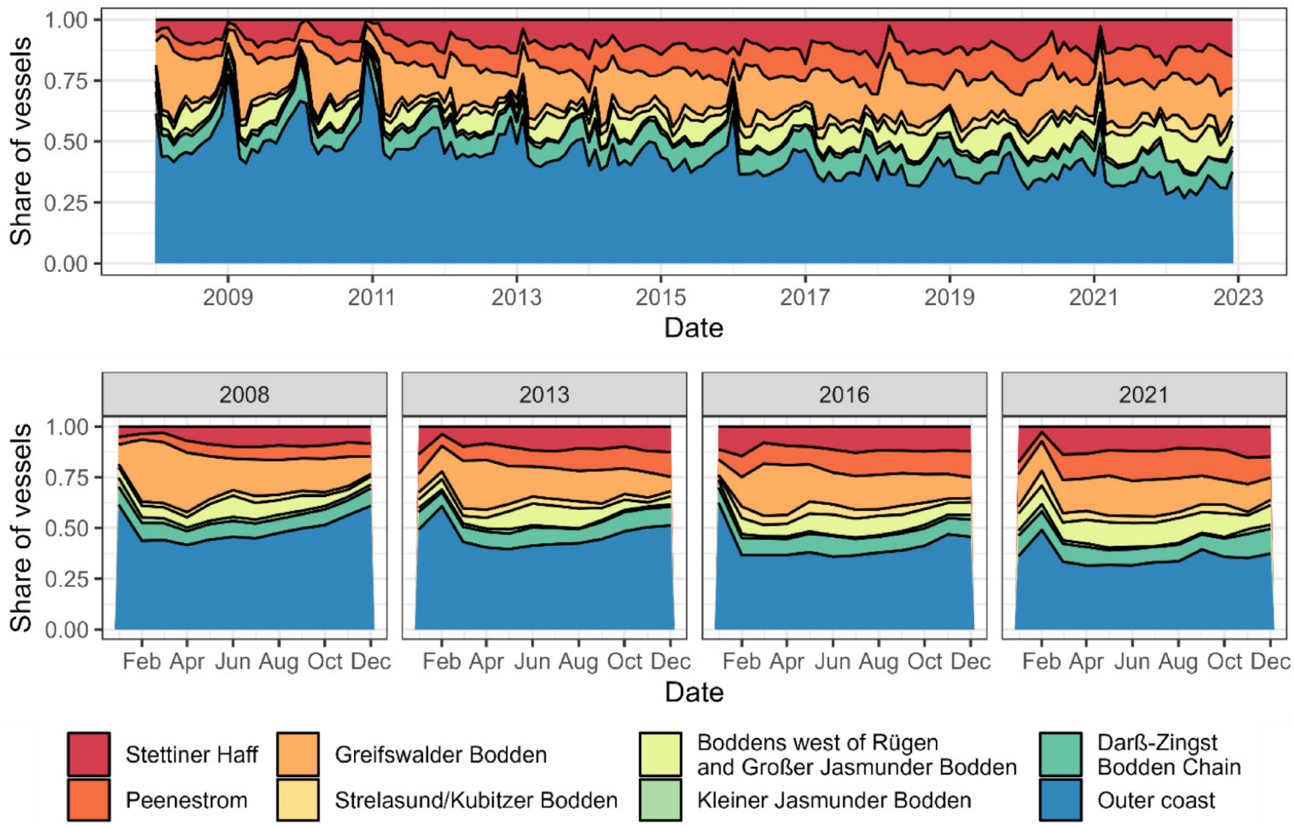
Estimation of effort distribution can be done at the individual as well as the industry level (Smith 2002). Individual-level analyses typically require observations of trip-level decisions on where a fisher had fished at a certain point in time (Smith and Wilen 2003, 2004; Wilen et al. 2002). In our case, only monthly-aggregate data were available, meaning that the individual trip-level decision of a single fisher was not observed; thus, the use of random-utility-based individual models would be impractical and inappropriate. In addition, using a macro-level approach can increase the quality of model predictions (Smith 2002). We thus closely follow the strategy devised by Smith (2002) and more recently applied in Pascoe et al. (2020), where relative total industry effort distribution was explained through a systems of equations (SUR) approach. Effort distribution share s_i was measured as the number of active vessels in a single fishing district *i* divided by the total number of active-vessel-area combinations in a given month, such that $\sum_i s_i = 1$. Given the current restrictions fishers have regarding where to fish, changes in the relative effort level can be driven by (1) fishers switching to a different fishing district, or (2) fishers deciding not to fish at all if they cannot fish somewhere else. Effort distribution is often assumed to be driven by net revenue differentials across different fishing sites (Sanchirico and Wilen 1999; Smith 2002). Due to the lack of data on costs, gross revenue has been used as a proxy for profit in the literature (e.g., Smith 2002; Pascoe et al. 2020). Given that the fishery mostly uses passive gear and consists mainly of one-person businesses, (variable) operating costs (e.g., diesel, labor) may not factor too much into the decision of individual spatial effort allocation compared to larger trawling vessels. In addition, fixed costs (such as mortgage payments) are typically not part of operating decisions in the short run. Therefore, gross-revenue differentials ($\Delta R_{i,j}$) were computed for each fishing district separately.

The estimated share equation is given as

$$s_i = \alpha_i + \sum_{i \neq j} \gamma_{i,j} \Delta R_{i,j} + \beta_i X + \delta_1 \text{year} + \delta_2 \text{month} + \varepsilon_i$$

As in Smith (2002) and others (e.g., Pascoe et al. 2020), the response to changes in revenue differentials is assumed to be symmetric, i.e., $\gamma_{i,j} = \gamma_{j,i}$, where *i* and *j*, respectively, index fishing districts. *X* is a vector of external influences on the fishery, that were selected based on the research questions given our own in-depth understanding of the fishery, including aggregated quotas for herring and cod (which historically have provided most of the revenue), the number of coastal angling permits (annual and daily), the number of seals and cormorants, diesel prices, and water temperature. Because the COVID pandemic substantially changed the opportunities of the fishery, we included a dummy that was one when the COVID pandemic happened (2020, 2021, 2022). Further control variables included a time trend (*year*) and monthly dummy variables (*month*) to control for seasonality in the availability of fish as well as individual and collective experience of fishers. The parameters γ, β, and δ were estimated for each fishing district. Given the linearity of the model, parameter interpretation is straightforward as marginal effects; i.e., a change in one unit of X is associated with a change in β_i in the percentage of aggregated effort. In contrast to Smith (2002), we only focus on the marginal effects of the three drivers (quotas, anglers, predators) on the relative effort distribution, and leave studying the absolute effects to future research. The model was estimated with the R (R Core Team 2022) package systemfit (Henningsen and Hamann 2008) us-

Fig. 8. Share of active vessels in a given fishing district along the coast of Mecklenburg-Vorpommern, Germany (data source: LALLF (2023*a*)).



ing SUR, which exploits the contemporaneous correlation of error terms across equations. Importantly, independence over time is assumed, i.e., no autocorrelation. Model fit was computed by McElroy's $R^2 = 1 - \frac{U'WU}{Y'VY}$, where U is a stacked vector of residuals, **W** is the variance–covariance matrix, and Y is the stacked vector of dependent variables (McElroy 1977). Different specifications were tested, including leaving out the time trend and month dummies; the best-fitting specification was kept and is presented below.

4. Results and discussion

4.1. Descriptive results

The largest number of fishers ($n = 167$, 53%) exclusively fished in the outer coast and marine areas and produced the largest share of total revenue (33%) in the time period under study. This includes open water trawlers, as well as fishers along the western coast and those in the east who do not have permits to fish in the inner lagoon waters. The second largest share of revenue (9%) came from fishers fishing exclusively on the Greifswalder Bodden, the Peenestrom, and the outer coast/marine areas, closely followed by those fishing on the Greifswalder Bodden and outer coast, and those fishing on the outer coast and DZB Chain (5% of total revenue). In total, 99.3% of the fishers fished in four or fewer fishing districts and captured 98% of the revenue.

Intra-annually, the effort distribution showed a repeated pattern but with an overall decreasing trend of the effort shares along the outer coast (Fig. 8, top panel). This decrease can be explained by general decreasing quotas (with some intra-annual fluctuations) for the main marine target species, i.e., western Baltic cod and western Baltic spring-spawning herring, in the past years (ICES 2023*a*, 2023*b*). Effort shares along the outer coast were highest in winter and gradually decreased toward summer, particularly after the herring season was over in May. The effort on the Greifswalder Bodden is also particularly visible from February to April, although shares also remained higher during the summer months and then decreased until December.

However, when considering different years of the study period, some changes are noticeable (Fig. 8, bottom panels): particularly, while we found a distinct seasonal pattern, with high effort shares on the outer coast in winter (years 2008, 2013, and 2016), the effort shares remained relatively stable in the year 2021 apart from a bump in outer-cost fishing in February, likely due to cod fishing. This could be driven by structural change (with cod trawlers exiting the industry over time) or by climate change, allowing fishers to fish the inshore areas even in winter when there is no ice.

4.2. Estimation results and discussion

In the estimated SUR model, a time trend showed a positive sign in most fishing districts, except for the KJB (where it was negative) and in Greifswalder Bodden (where it was insignificant) (Table 3). This suggests that overall, relative effort has increased in the inshore lagoon areas and thus decreased on

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Table 3. Estimation results of a seemingly unrelated regression relating effort shares to quotas, anglers, and predators.

Parameter	Stettiner Haff	Peenestrom	Greifswalder	Strelasund	Westrügen	KJB	DZB	Outer coast (recovered)
Intercept	**−0.1106****	**−0.0817****	**0.1813*****	−0.0115	**0.1195*****	**0.0368*****	0.0426	
	(0.0554)	(0.0366)	(0.0583)	(0.0196)	(0.0307)	(0.0136)	(0.0337)	
Year	**0.0048****	**0.0044*****	0.0017	**0.0017****	**0.0032*****	**−0.0011****	**0.0026****	
	(0.0019)	(0.0013)	(0.0019)	(7e-04)	(0.001)	(4e-04)	(0.0012)	
Temperature	3e-04	2e-04	0.0011	−5e-04	−2e-04	**−6e-04****	4e-04	
	(0.0012)	(8e-04)	(0.0012)	(5e-04)	(6e-04)	(3e-04)	(7e-04)	
Diesel price	**0.0353***	**0.0329****	0.0145	**0.0158****	−0.0067	0.0013	0.012	
	(0.0196)	(0.013)	(0.0196)	(0.007)	(0.0106)	(0.0046)	(0.0115)	
COVID	**0.0222****	0.0076	0.0035	0.001	−0.0011	**0.0061****	−4e-04	
	(0.0109)	(0.0072)	(0.0108)	(0.0038)	(0.0059)	(0.0025)	(0.0063)	
Quotas								
Quota Herring	0.001	−5e-04	**0.0017****	0	7e-04	0	**8e-04***	
	(8e-04)	(5e-04)	(7e-04)	(3e-04)	(4e-04)	(2e-04)	(5e-04)	
Quota Cod	−0.0024	−0.0038	−0.0047	0.0027	−0.0011	−3e-04	−6e-04	
	(0.0052)	(0.0034)	(0.005)	(0.0018)	(0.0027)	(0.0012)	(0.003)	
Conservation								
Seals	**0.2148****	−0.0306	**−0.1116*****	**0.1062****	**0.1097***	−0.0154	−0.2077	
	(0.1063)	(0.0231)	(0.0262)	(0.0419)	(0.0585)	(0.0118)	(0.1653)	
Domestic cormorants	0.0016	2e-04	7e-04	2e-04	−3e-04	**3e-04***	−7e-04	
	(0.0012)	(2e-04)	(9e-04)	(2e-04)	(5e-04)	(2e-04)	(0.0034)	
Recreational fishing (angling)								
Annual coastal angling permits	**0.1559***	**0.0254****	−0.009	−8e-04	**−0.0041*****	−0.0169	0.0038	
	(0.0867)	(0.0105)	(0.0056)	(0.001)	(0.0015)	(0.0213)	(0.0055)	
Daily coastal angling permits	**0.1541****	**0.0162***	−0.0035	**0.0015***	−7e-04	0.0063	5e-04	
	(0.0667)	(0.0084)	(0.0043)	(8e-04)	(0.0012)	(0.0162)	(0.0044)	
Revenue differentials								
Stettiner Haff		1e-04	−7e-04	2e-04	**0.0011***	5e-04	−7e-04	−6e-04
		(0.0013)	(6e-04)	(7e-04)	(6e-04)	(3e-04)	(0.0011)	(9e-04)
Peenestrom	1e-04		**−0.0012****	7e-04	**−0.0011****	2e-04	0	8e-04
	(0.0013)		(5e-04)	(7e-04)	(5e-04)	(3e-04)	(0.0013)	(6e-04)

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Table 3. (*concluded*).

Parameter	Stettiner Haff	Peenestrom	Greifswalder	Strelasund	Westrügen	KJB	DZB	Outer coast (recovered)
Greifswalder	−7e-04	**−0.0012****		**−7e-04***	0	0	**−8e-04***	−9e-04
	(6e-04)	(5e-04)		(3e-04)	(3e-04)	(1e-04)	(5e-04)	(8e-04)
Strelasund	2e-04	7e-04	**−7e-04***		2e-04	−3e-04	0	−4e-04
	(7e-04)	(7e-04)	(3e-04)		(7e-04)	(3e-04)	(9e-04)	(3e-04)
Westrügen	**0.0011***	**−0.0011****	0	0		0	−5e-04	**−0.0011****
	(6e-04)	(5e-04)	(3e-04)	(3e-04)		(2e-04)	(4e-04)	(5e-04)
KJB	5e-04	2e-04	0	0	0		**−5e-04****	0
	(3e-04)	(3e-04)	(1e-04)	(1e-04)	(2e-04)		(2e-04)	(2e-04)
DZB	−7e-04	0	**−8e-04***	**−8e-04***	−5e-04	**−5e-04****		−2e-04
	(0.0011)	(0.0013)	(5e-04)	(5e-04)	(4e-04)	(2e-04)		(5e-04)
Outer	−6e-04	8e-04	−9e-04	−4e-04	**−0.0011****	0	−2e-04	
	(9e-04)	(6e-04)	(8e-04)	(3e-04)	(5e-04)	(2e-04)	(5e-04)	
Adj. R-squared	0.48	0.71	0.77	0.52	0.83	0.29	0.23	
Observations	180	180	180	180	180	180	180	

Note: McElroy R-squared was 0.72 (KJB = Kleiner Jasmunder Bodden, DZB = Darß-Zingst Bodden Chain, Strelasund includes Kubitzer Bodden, Westrügen includes Großer Jasmunder Bodden and lagoons between Rügen and Hiddensee; for month parameters, see Fig. 9). "*" $p < 0.1$, "**" $p < 0.05$, "***" $p < 0.01$; McElroy R-squared: 0.72.

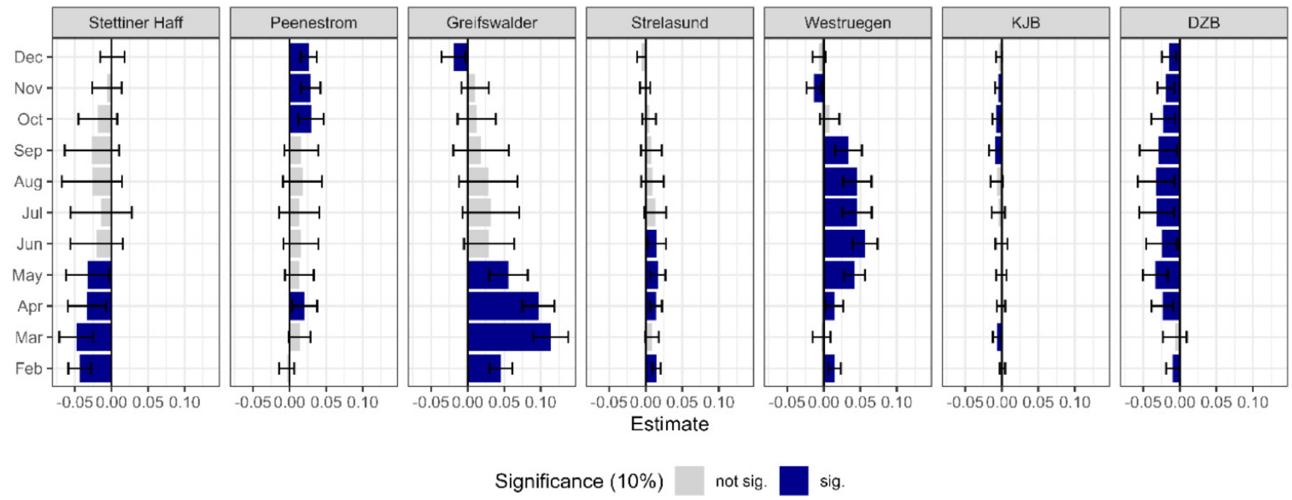
the outer coast. With respect to temperature, only the small and shallow KJB showed a negative and significant sign. This may be related to poor fishing conditions with higher temperatures leading to more anoxic conditions. Additionally, at higher temperatures the fish flesh deteriorates more quickly leading to poorer quality and revenue, particularly in gill net fisheries.

For the diesel price, we found positive effects for the Stettiner Haff and the Strelasund. Diesel prices have been found to affect effort distribution in other studies as well, e.g., in the Australian prawn fishery (Pascoe et al. 2020). Both of these districts are mainly used by fishers who are local to the area but also by those who fish along the outer coast; it is therefore likely that higher diesel prices encourage fishers to switch toward inshore fishing when diesel prices become too high. The KJB showed a negative sign, indicating that fishers may avoid the area when diesel prices become too high. As the KJB is at the end of a lagoon, it may be too costly to reach if diesel prices are high. Overall, for the passive gear fishery, diesel prices may be less relevant compared to a trawl fishery.

The prime fishing locations changed throughout the year. Month effects (capturing the average availability of fish throughout the year, as well as seasonal differences apart from temperature) were dummy-coded, with January serving as the base (Fig. 9). The most obvious changes occurred in the Greifswalder Bodden, particularly for the main herring season in March and April. Effort shares increased sharply in these months. After this, effort shares were mostly not significantly different from the January effort shares. In contrast, effort shares in the freshwater area Stettiner Haff drop in the winter months (likely due to ice coverage and the unavailability of fykenet fishing), whereas the Peenstrom fishery is particularly more active around February and around September–December. For the Westrügen lagoons, interestingly, effort shares significantly increase over the summer months. This may be related to shifts in effort after the herring season; as fishers with permits in Westrügen may increase their effort in this inshore area. Results in the DZB were somewhat in contrast to those in the Westrügen/GJB area, with lower revenue shares in spring and summer.

While most of the parameters on revenue differentials were nonsignificant, those that were significant had a negative sign, which is consistent with the theory; i.e., effort tends to be allocated to those fishing districts with the best economic opportunities (the exception being the pairing Westrügen and Stettiner Haff). This finding partially contrasts with the empirical findings of Smith (2002) but is well in line with findings by Pascoe et al. (2020). In particular, negative relationships were found for the pairings of the neighboring Greifswalder Bodden with Peenestrom, Strelasund, and DZB. We also found a negative relationship between the outer coast and Strelasund as well as the Westrügen lagoons. Somewhat puzzling were the negative relationships between DZB Chain and KJB, where the distance is quite far, and similarly, the negative relationship between Westrügen and Peenestrom.

Fig. 9. Plot of month parameters by fishing area (base = January) from the seemingly unrelated regression model. Error bars show 90% confidence intervals. KJB, Kleiner Jasmunder Bodden; DZB, Darß-Zingst Bodden.



4.3. Quotas for cod and herring

Turning to the policies under study, the quota for herring showed the expected result (in line with H_{1a}) that an increase in quota would also increase the effort share in the Greifswalder Bodden, i.e., the major spawning area of Western Baltic spring-spawning herring, as well as positive effects in Stettiner Haff and DZB. Shares were related only to the cod quota in the Strelasund fishing district (H_{1b}). As all signs of the quotas were positive in these regions, our results suggest merely an increase (decrease) in fishing in these areas when quotas increase (decrease). However, we did not find substantial changes in effort distribution in other regions (which would be indicated by negative signs); that is, a reduction in effort in certain districts would be indicated when quotas increase (and vice versa), which could be driven by changes in target species (e.g., freshwater vs. marine species). While previous research has suggested that quota-driven changes in target species occur (Asche et al. 2007), our evidence suggests that effort increases and decreases with the quota in areas where the species occurred, but we found no evidence of shifts in target species away from areas where the quota species were less important. While the introduction of ITQs has been shown to increase trawl intensity (Larcombe et al. 2001), our results are consistent with findings in the same fishery (Koemle et al. 2023), where landings related to quotas were found to shift toward species in similar habitats (i.e., other marine species and flatfish rather than freshwater species). A reason for this may be the effective regulation of permitted fishing sites: as mentioned above, fishers are restricted in which districts they can fish. Furthermore, adjustment costs (Asche 2009) may prohibit fishers from switching target species and target areas in the short run.

4.4. Seals and cormorants

Turning to the impact of predators in the area, we find support for our hypothesis that increases in grey seal counts were related to a shift in effort away from the Greifswalder Bodden, supporting H_{2a}. This is not surprising, as the main seal colonies are located within and close to the Greifswalder Bodden (Fig. 1). More interestingly, our results suggest that effort may have shifted toward the Strelasund (i.e., the neighboring fishing district) as well as the Westrügen district. As we have mentioned in our discussion of local versus imported effort (Fig. 3), effort shares from outsiders have decreased in the Greifswalder Bodden, particularly during the herring season, while the Greifswalder Bodden fishers have increasingly fished in the Strelasund area, potentially replacing fishers from the Westrügen area. Thus, a cascading effect may have been observed, which was likely driven by both quota cuts, particularly for herring, as well as the presence of seals in the Greifswalder Bodden. While some authors have suggested that "the extent of the conflict can be represented by seal-induced catch losses" (Holma et al. 2014), catch losses occur from both seals eating fish directly from the nets, as well as fishers avoiding areas with high seal activity and thus fishing in areas with lower fish abundance. This may be accompanied by higher transaction costs, for example, for searching fish, learning how to catch them and adjusting gear. Therefore, just measuring direct seal losses (e.g., the number of damaged nets or damaged fish) produces an inadequate measure of the total economic losses incurred. This also makes paying adequate compensation payments more difficult, because the counterfactual (i.e., the situation where fishers do not adapt to the presence of seals) is unobserved. Several countries (e.g., Finland) have therefore introduced active management of seals by hunting (Varjopuro 2011) as an alternative strategy to compensation.

With regard to cormorants, we find no relationship of cormorant numbers and effort shares, thus rejecting H_{2b}. A key reason for this may be that cormorants are distributed throughout the whole fishery (Fig. 6) and thus it may be impossible for fishers to avoid them. Given the hunting behavior of cormorants, their presence may also be more difficult to predict for fishers and they may simply "try their luck". A more pragmatic explanation is that cormorants interact less with the fishing gear than seals and as such the fishers do not respond to local densities.

4.5. Recreational fishers (anglers)

Annual coastal angling permits were associated with a higher commercial fishing effort share in the Peenstrom and a lower effort share in the Westrügen lagoons. In contrast, daily angling permits were associated with a higher commercial effort in the Peenestrom and Strelasund but with lower commercial effort in the KJB. It is important to note that the causal relationship may be somewhat ambiguous. The Westrügen lagoons are well-known for angling of trophy pike, and our results suggest that some displacement of fishers may have taken place. Alternatively viewed, anglers may fish less in Westrügen as commercial fishing effort rises. As the data presented in Table 2 show, more avid anglers purchase annual licenses. Thus, particularly the Westrügen area may be frequented by these anglers—causing a shift of fishers away from these fishing grounds or, conversely, anglers avoiding fishers. Positive relationships may be driven by fishers and anglers going after the same locally abundant stocks without displacing each other. However, this may point toward potential (future) conflicts between the two user groups, which are already present in the area, e.g., related to fishing for pike and other predatory fish (Arlinghaus et al. 2022).

5. Limitations

Our analysis of the observational fisheries data has several limitations. The most obvious one is that our study relies on self-reports and that the effort indicator is relatively rough; even if a fisher only went fishing once in a certain district (e.g., to try it out), it counted as effort. We further do not capture effort redistribution within the same district (e.g., specifically targeting certain spawning areas rather than open waters). Limited flexibility due to fishers being only able to fish in a limited number of districts could not be captured from the data, but biases were likely small at the aggregate level. Better data are not available, but would be important to obtain a more nuanced picture of the relationship. Furthermore, the current data could mask several aspects of fisher behavior. For example, various studies showed that not only economic reasons influence fishing behavior and that non-monetary motives, such as tradition or nature experience, might cause commercial fishers to continue fishing even if there are economic reasons for not doing so (Young et al. 2016; Holland et al. 2020; Barz 2022; Lewin et al. 2023*a*). This may also influence effort distributions and could not be captured by our model.

Regarding cormorants, a fisher may decide after a few trials in a month to stop fishing in a district due to the current cormorant pressure. The reduction in effort is therefore masked by the data availability. Similar strategies may be applied in the presence of seals, although here the risk of gear damage may be higher and thus avoiding the area altogether may be a more effective strategy. Regarding quotas, a fisher may have his or her quota full in a single outing if the quota is very small. This means that if the quota was larger before, but he still fished it out in 1 month, the effort of the fisher will not change according to our indicator (i.e., while the real effort has changed (from several days to just 1 day in the fishing district), our analysis does not capture this).

Finally, our results may suffer from reverse causality or simultaneity issues. As mentioned above, this may be particularly true for the angler-fisher relationship and the underlying unobserved variables such as local stock sizes that drive the behavior of both groups.

6. Concluding remarks and implications

The relationship between fishers and external pressures is complicated. Particularly for users who are after the same target (i.e., fish), the key drivers of fishing effort remain poorly understood. We have attempted to shed some light on this topic. Our key findings were that:

(1) Quota size increases effort in areas where the quota species are typically abundant but does not decrease effort in other areas (and vice versa). Likely, quota reductions may mainly reduce the amount of fishing that occurs. Thus, our results suggest that, for the time-period under analysis (2008–2022), arguments for increased conflict between fishers and anglers (i.e., effort shifts due to quota reductions; Arlinghaus et al. 2022, 2023) does not have a solid empirical basis. With further restrictions in commercial fishing opportunities, such as the closure of the directed cod fishery in 2024, this may however change.
(2) Indeed, from the external pressures examined in this study, effort shifts seem to be driven mainly by the presence of seal colonies in a certain fishing area. In contrast, effort distribution does not seem to be related to cormorant densities. The evasion behavior of fishers should be closely monitored and considered when seal management options are discussed. If policy makers are to protect fishers from seal damages, managing the population size of seals, in line with other conservation goals, may be appropriate.
(3) When anglers target the same species as commercial fishers, some competition and displacement (e.g., in Westrügen with annual license holders) may occur. Potential conflicts in these areas should be closely monitored and managed if deemed necessary. For example, managers could try to spatially separate the two interest groups by zoning. However, angling can also coexist with commercial fishing: as our results have shown, going to the same areas does not necessarily mean displacement.

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