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Change points in marine recreational fisheries – The impact of stock status and fisheries regulations: A case from the western Baltic Sea

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ABSTRACT

Marine recreational fisheries can be viewed as social-ecological systems in which sudden biological changes can affect interconnected social components. The Baltic Sea underwent various regime shifts, and the stock of western Baltic cod (*Gadus morhua*), a commercially and recreationally important target species, collapsed in 2016/17. This resulted in the first-time introduction of a bag limit in the recreational cod fishery. An eleven-year time series of recreational fisheries data was used to identify change points in the number of German cod anglers and in their catch and harvest rates, which may have occurred corresponding to the stock collapse. The number of anglers as well as their catch and harvest rates showed pronounced intra- and inter-annual fluctuations and the share of large cod in the catch decreased. Nonetheless, catch rates corresponded only weakly with cod stock biomass, suggesting that this fishery-related indicator was more responsive to the introduction of the bag limit than to the stock status. The study underlines the importance of long-term monitoring programs at appropriate spatial and temporal scales as a prerequisite for identifying change points in recreational fisheries and as an integral component of fisheries management to improve management in the future.

1. Introduction

Recreational fisheries are characterized by tight interactions between the aquatic ecosystem and the human subsystem including its economic, political, and social components (Berkes, 2011; Hunt et al., 2013). These types of social-ecological systems are characterized by nonlinear dynamics and are prone to sudden, unexpected, and possibly long-lasting changes in structure and function, known as regime shifts (Arlinghaus et al., 2017). Regime shifts occur when critical thresholds (change points or tipping points) are reached (Muradian, 2001; Milkoreit et al., 2018) and can have significant ecological, social, and economic implications.

Regime shifts have been observed in several marine ecosystems including the Baltic Sea (Dippner et al., 2012; Rocha et al., 2018; Sguotti et al., 2019; Perälä et al., 2020). One relevant trigger has been the overfishing of top predators in combination with eutrophication and global warming (Möllmann et al., 2009; Möllmann and Diekmann, 2012; Bossier et al., 2020).

Large top predators are the preferred target species of anglers, and recreational fishing can substantially contribute to the total fishing mortality for these species (Lewin et al., 2019 for review). Conversely, the stock size of the target species influences catch rates and angler behaviour (Solomon et al., 2020). The catch rates, however, do not necessarily reflect the stock size, because the relationship between both parameters can be disproportional and non-linear (Erisman et al., 2011). The most common form of disproportionality is hyperstability characterised by stable catch rates at declining stock sizes (Harley et al., 2001; Dassow et al., 2020). Hyperdepletion, on the other hand, can occur when consistent differences in fish behaviour among individuals leads to selective harvesting (Alós et al., 2019 and literature therein). The relationship between angler catches and stock size is a matter of ongoing debate and is unknown for many fish stocks (Harley et al., 2001; Ward et al., 2013; Arlinghaus et al., 2017). Given the complex feedbacks and interactions inherent in recreational fisheries (Arlinghaus et al., 2013), there is a need to understand the relationship between catch rates, fishing effort, and the corresponding target fish stock in order to develop

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appropriate management measures and predict their outcomes (Camp et al., 2016).

One relevant top predator in the Baltic Sea is Atlantic cod (*Gadus morhua*), which is also an important target species for commercial and recreational fisheries (Link et al., 2008; Hyder et al., 2018). In the Baltic Sea, two genetically distinct stocks of Atlantic cod occur, the western and the eastern Baltic cod located in ICES (International Council for the Exploration of the Sea) subdivisions 22–24 and 24–32, respectively (Eero et al., 2014; Hüssy et al., 2016). Both stocks have experienced large fluctuations due to unsustainable fishing, climate change, oxygen depletion, and habitat loss (ICES, 2019a,MacKenzie et al., 2007; Bartolino et al., 2017; ICES, 2019b, 2021; Orio et al., 2020). The spawning stock biomass (SSB) of western Baltic cod strongly decreased since the late 1990s (Fig. 1). Although declining in recent years, the fishing mortality (F_{MSY}) exceeded sustainable levels since the 1990s and the western Baltic cod stock collapsed in 2016 (Möllmann et al., 2021; Receveur et al., 2022).

After the collapse in 2016, an 88% quota cut for the commercial fishing sector was proposed, which would have resembled a moratorium of the directed cod fishery, as considerable amounts of cod are caught as bycatch in other fisheries (European Union, 2016). In 2017, a daily bag limit of three cod per angler and day during February and March and five cod per angler and day for the rest of the year was introduced for the first time to reduce the recreational fishing mortality (2019: 28% of the total catch, ICES, 2020; Fig. 1) and to share the burden of stock rebuilding between the commercial and recreational fishing sectors (European Union, 2016). Until then, the German marine recreational fishery was open access and regulated only by minimum-size limits and a license requirement. In 2019, the daily bag limit was raised to seven cod per angler and day for the whole year before it was restricted again to 5 cod per angler and day and 2 cod per angler and day during the spawning season in 2020 and 2021, respectively (Haase et al., 2022). Nevertheless, despite a short recovery phase due to a single strong year class in 2016, the stock continued to decline because of the low recruitment (ICES, 2022). In 2022, the recreational fishing regulations for western Baltic cod were further restricted, including the reduction of the bag limit to 1 cod per day and angler and the introduction of a fishing closure during the spawning season from mid-January to the end of April (Haase et al., 2022). Because the recreational cod fishery is largely consumptive (Bronmann et al., 2022), the bag limit implementation has caused social conflicts within some angler groups, who have lobbied against the bag limit or for more liberal levels. Indeed, bag limits are known to reduce the attractiveness of the fishery and to affect fishing effort in consumptive freshwater fisheries (Beard et al., 2003; Johnston et al., 2011). Accordingly, parts of the angling industry claimed that fewer angling tourists came to the coast and that booking numbers for charter boats have declined since the introduction of the bag limit. This was underlined by the fact that the travel distances of Baltic Sea charter boat anglers initially declined immediately after the bag limit was implemented, indicating that at least some nonresident anglers left the fishery in response to the new regulation (Lewin et al., 2021a).

Although scientists and fisheries managers widely agree that better scientific information is needed to support fisheries management processes (Ostrom, 2007), data on marine recreational fisheries in particular are still limited in many areas of the world (Hyder et al., 2018; Potts et al., 2020). Against this background, the present study investigated changes in the German recreational western Baltic Sea cod fishery that accompanied the collapse of the western Baltic cod stock.

First, we hypothesized that the collapse of the western Baltic cod stock in 2016, along with the implementation of the bag limit, might have been associated with corresponding declines in the numbers of charter boat anglers and anglers using private boats (hereinafter referred to as boat anglers), as well as declining cod catch (CPUE) and harvest rates (HPUE). To identify possible change points, nonparametric change point analyses (CPA) were applied to an 11-year time series of the numbers of boat anglers and the CPUE and HPUE of boat and charter boat anglers.

Second, to clarify knowledge gaps regarding the relationship between catch rates and cod stock size, we applied power regression analyses to assess whether the recreational western Baltic cod fishery is showing signs of hyperstability.

Third, we applied correlation analyses to investigate whether there is a relationship between the catch and harvest rates of boat and charter boat anglers and the introduction of the bag limit.

Finally, because changes in the length and age structure of the target fish stock may be reflected in the length and age composition of angler catches, we tested whether the proportion of smaller and younger cod in the catches increased over the study period.

2. Material and methods

2.1. Study area

The Baltic Sea is a large brackish water body in north-eastern Europe with salinities decreasing from outer to inner coastal waters and from the west to the east (Andersen et al., 2015). Including inner coastal

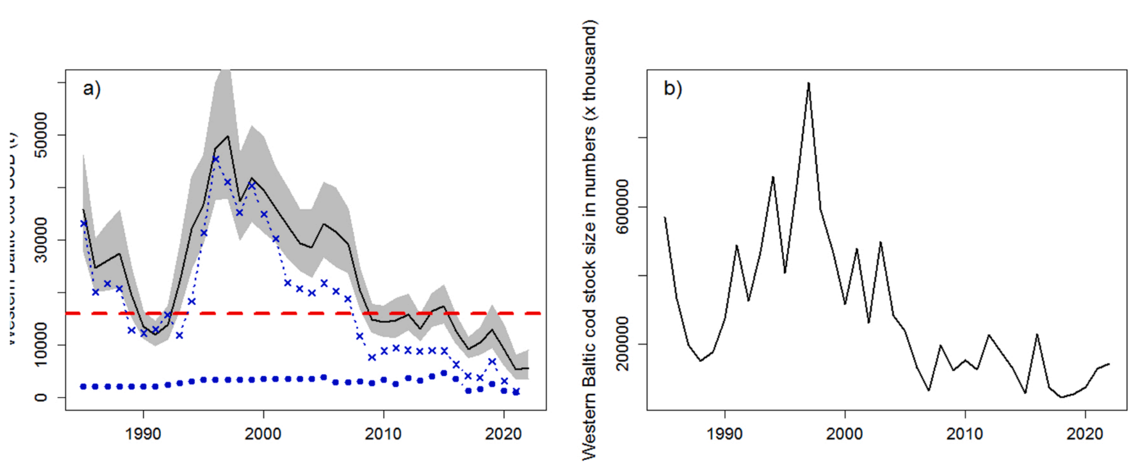

Fig. 1. Development of the western Baltic cod (*Gadus morhua*) stock between 1985 and 2021. a) Spawning stock biomass (SSB) (black line). The shade displays the lower and upper estimates of SSB. The dashed red line shows the current biomass limit reference point B_{lim} beyond which the stock reproduction is at high risk. The blue dots indicate the recreational removals (harvest + dead releases) and the blue crosses the commercial landings (including discards since 1994), b) stock size in numbers (x 1000). Data
Source: https://stockassessment.org/results.php?token= 752eae1f28d4dc7544e669a5fb3b00ea, last accessed August 2022).

lagoons and backwaters, the German coastline extends for over 2000 km and belongs to the two federal states Schleswig-Holstein (SH) and Mecklenburg-Western Pomerania (MWP). Minimal tidal currents and a diverse shoreline attract anglers from all over Germany (Lewin et al., 2021a). For 2014/15, the number of German Baltic Sea anglers was estimated at 161,000 spending approximately 1.2 million fishing days per year (Weltersbach et al., 2021). Recreational fishing is carried out from beaches, piers, and jetties (land-based fishery) and from small private or rental boats and larger charter boats (Strehlow et al., 2012). Anglers need a valid German fishing license. In MWP, a coastal fishing permit is also required, which can be purchased as a daily, weekly, or annual permit.

2.2. Data collection

The recreational fishery-related data were collected through an on-site access point intercept survey that was conducted within the German marine recreational fisheries data collection program. The on-site survey has been conducted annually since 2009, and data collection followed a multiannual survey design. The coastline was divided into five spatial strata, with harbours and beaches serving as access points (Fig. 2) and fishing days as the primary sampling unit. Within each spatial stratum, access points and sampling days were randomly selected. Sampling was divided by month, day type (weekday/weekend/holiday), and fishing method. It was evenly distributed throughout the year covering all 12 months, with increased sampling effort for sea-based fishing methods and for weekends and holidays when anglers fish most frequently (Strehlow et al., 2012). Fishing methods were grouped into shore fishing (shore/surf angling and wading), boat fishing (including float tubes and kayaks), and charter boat fishing. Anglers fishing from float tubes and kayaks were not included in a separate category because they fished in the same locations and with the same gear as boat anglers. Although the number of float tubes and kayaks has increased in the past 15 years, their numbers have remained small compared to the number of angling boats (pers. comm. survey agents A. Gebel, T. Jankiewicz, F.-M. Conrad).

This study focussed on sea-based angling (boat and charter boat angling) on the outer Baltic coastline because most cod are caught in waters with salinities > 10 PSU and the sea-based angling methods accounted for the majority of recreational cod catches (about 85% in Germany; Strehlow et al., 2012; Eero et al., 2014). Shore anglers were encountered comparatively rarely and the corresponding time series of fishing effort and harvest data had large gaps. Therefore, shore anglers were not included in this study. Further, recreational fishers using gear other than rod and line were also not included in this study because this group is very small (< 1%) compared to the angler population and available data are limited (Strehlow et al., 2012). From 2009–2019, survey agents averaged 318 (± 56 S.D.) sampling days per year, for a

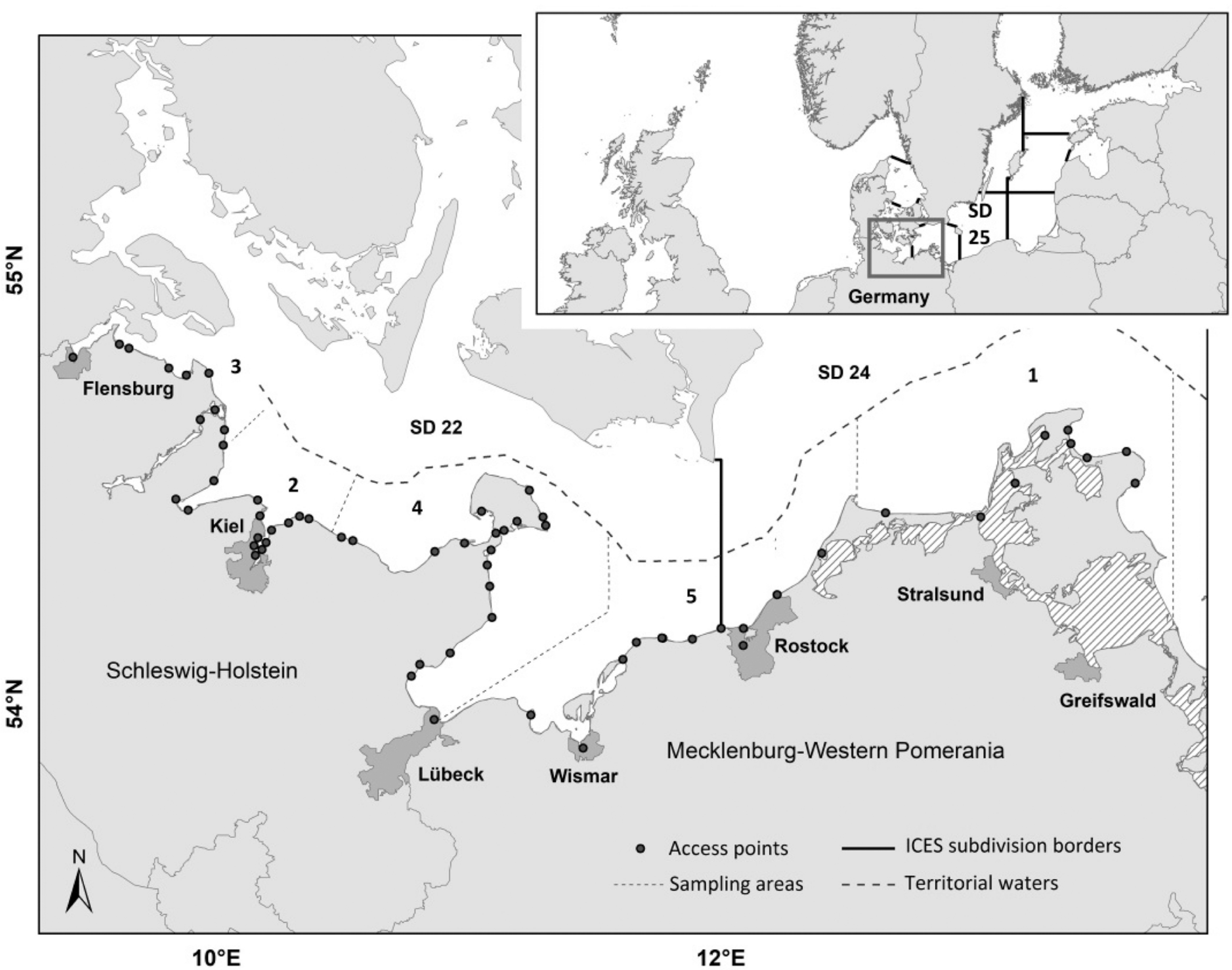

Fig. 2. Map showing the locations of the access points used for the on-site access point survey between 2009 and 2019 along the German Baltic Sea coast, the federal states, and the ICES subdivisions (SDs). The numbers indicate the sampling areas.

monthly average of 26 (± 5 S.D.) sampling days per month.

The following data were collected from the anglers encountered: angling platform (shore, boat, charter boat), fishing site and date, number of caught, harvested, and released fish by species, gender, age, place of residence (zip code), and avidity (number of days fished in the Baltic Sea in the last 12 months). The numbers of fish caught, harvested, and released per species has been collected since 2009, and anglers' age and avidity have been systematically collected since 2012. Catch, harvest, and release rates for cod were calculated as the number of cod caught (CPUE), harvested (HPUE), and released (RPUE) per angler per day. Release rates were calculated as the difference between catch and harvest rates. Resident anglers were those residing in the coastal states SH and MWP, while nonresident anglers were those residing in other states. The present study used only data from completed fishing trips provided by survey participants over 14 years of age. Refusal rates were very low (between 1% and 2%) and were not considered in the analyses.

There were up to 60 anglers on the charter boats. Due to time limitations of the anglers and the survey clerks, only a subsample of these anglers could be interviewed during a certain sampling assignment. These anglers were randomly selected from the crowd leaving the charter boat. This approach allowed the calculation of charter boat angler catch and harvest rates. Because the total number of anglers per charter boat could not be reliably estimated, it was not possible to determine the trend in the number of charter boat anglers over the study period. Instead, a time series of the annual number of anglers who booked a fishing trip on charter boats in Heiligenhafen, Germany from 2000 to 2019 was used. Heiligenhafen, which has been the main charter boat harbour in Germany, is located on the mainland south of the island of Fehmarn in the federal state SH. Charter boat skippers reported the number of anglers who boarded their charter boats to the port authority. These data were provided by the regional economic development agency ("Entwicklungsgesellschaft Ostholstein mbH EGOH").

Stock size (total number) and SSB estimates for western Baltic cod were downloaded from the stockassessment.org website (https://stockassessment.org/results.php?token=752eae1f28d4dc7544e669a5fb3b00ea, last accessed April 2022).

Length data were only available from the recreational charter boat fishery where scientific observers measured the total lengths of caught cod during monthly random on-board samplings (Strehlow et al., 2012; Weltersbach et al., 2019). Age-length data from commercial fishery samples and the Baltic International Trawl Survey (BITS) (ICES, 2014) based on otolith readings were used to assign the age corresponding to the length-age proportion of a given recreationally caught cod. Charter boats and commercial fishers operated primarily nearshore in the same areas (ICES subdivision (SD) 22 and 24). Data from the BITS survey included additional length data from Arkona basin (ICES SD 25). Length distributions were calculated separately for the first and second halves of the year to account for potential seasonal differences.

2.3. Data analysis

CPUE and HPUE data were standardized prior to the change point and regression analyses to reduce potential biases resulting from spatio-temporal patterns of the data (Maunder and Punt, 2004; Mateo and Hanselman, 2014). The input data and the various analyses are presented in a conceptual diagram (Fig. 3).

2.4. Standardisation of catch and harvest rates

Standardization was done using boosted regression tree (BRT) models that automatically account for nonlinear interactions between variables and handle different types of predictor variables and missing data (Elith et al., 2008). They improve the performance of single tree models by combining the algorithms of decision trees and a boosting procedure that adaptively builds and combines a large number of tree models (De'Ath, 2007; Elith et al., 2008). Furthermore, they include stochasticity into the model by maintaining a bag fraction, which is the fraction of a random subset of the data that is selected at each step. Here, a bag fraction of 0.5 (50% of the data are randomly drawn from the full training set at each iteration), a maximum number of 5000 trees, a tree complexity of three, and a learning rate of 0.01 were used to build the models with the default ten-fold cross-validation (Elith et al., 2008). Year, quarter, angler avidity, age, and place of residence were used as potential explanatory variables. Fishing area and day of week were included as spatio-temporal fixed effects to account for the stratified sampling design. Federal state was included as a dichotomous variable because the minimum landing sizes differ between the federal states SH and MWP (35 cm in MWP and 38 cm in SH, respectively, Weltersbach et al., 2019). Non-integer CPUE and HPUE values were rounded to the nearest integer and the Poisson distribution was applied to the BRT

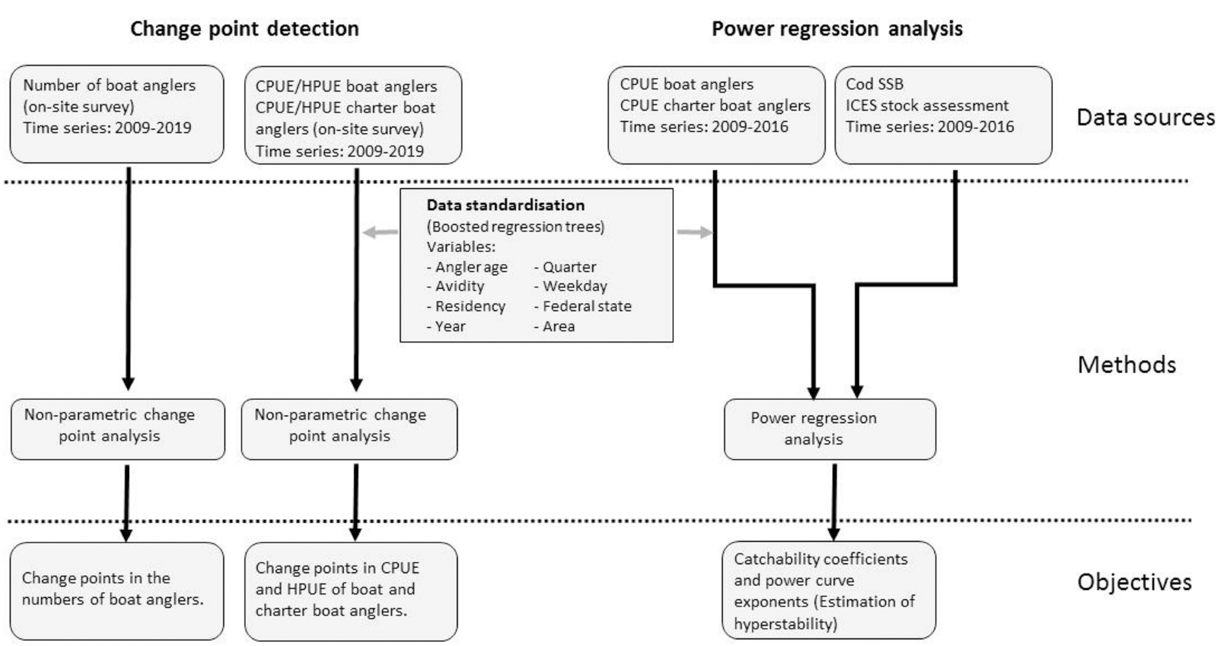

Fig. 3. Conceptual diagram showing the statistical methods and corresponding input variables as well as the objectives of the methods used in this study.

models. The CPUE and HPUE values standardised by means of the BRT analyses were then subjected to the change point analyses.

2.5. Change point analyses

Change point analyses (CPAs) identify time points in an ordered sequence of data between which the statistical properties of the data differ. CPAs have been applied in a variety of fields, including climatology and ecology (Beaulieu et al., 2012; Snickars et al., 2015). Over the years, several algorithms have been developed to detect multiple change points, including sparsified binary segmentation (SBS, Cho and Fryzlewicz, 2015), optimal partitioning (OP, Jackson et al., 2005), and pruned exact linear time (PELT, Killick et al., 2012). Basically, CPAs use recursive algorithms to identify change points by repeatedly partitioning a time series into segments with constant different statistical properties (e.g., mean, variance, or periodicity). Because the data were characterised by high and unequal variances over time, nonparametric change point analysis was applied using the cpt.mean function (R package "changepoint.np", Haynes and Killick, 2020). Within the function, the PELT algorithm was used because it has been shown to be accurate and fast compared to other methods (Wambui et al., 2015). PELT is based on optimal partitioning (Jackson et al., 2005) and searches for an optimal partition of the time series by minimizing a cost function using a nonparametric maximum likelihood approach (Haynes et al., 2017). PELT incorporates an additional pruning step to reduce the computational cost of the method without compromising the accuracy of the results (Killick et al., 2012). To avoid overfitting or underfitting, the PELT algorithm requires a penalty that controls the segmentation size. The modified Bayesian information criterion (Zhang and Siegmund, 2007) was used as a penalty term. Seasonality of the time series data was removed by differentiating the data sets prior to the CPAs (Holmes et al., 2021). Change points analyses were applied to monthly mean boat angler numbers and boat and charter boat anglers' catch and harvest rates.

2.6. Power regressions to investigate the relationship between CPUE data and cod stock size

Power regression analyses were applied to investigate the relationship between charter boat anglers and boat anglers' CPUE values and cod stock size. We only used catch data from 2009 to 2016 because CPUEs were different before and after the introduction of the bag limit, and the available data did not allow us to separate the effects on CPUEs resulting from low stock status or management changes (introduction of the bag limit in 2017).

The power curve was used to model the proportionality between CPUE and cod stock size N at time t as follows:

$$CPUE_t = qN_t^{\beta}, \tag{1}$$

where q is the catchability coefficient and β is the exponent of the power curve. When $\beta \neq 1$, catchability changes with abundance. When $\beta < 1$, CPUE decreases more slowly than abundance N (hyperstability in catch rates). When $\beta > 1$, CPUE decreases faster than abundance (hyperdepletion, Harley et al., 2001, Erisman et al., 2011).

2.7. Statistical tests

Mann Whitney U and Chi^2 tests were used to detect differences in CPUE, HPUE, and RPUE data and sociodemographic parameters between charter boat and boat anglers. Mann-Kendall trend tests were used to investigate trends in age and avidity of boat and charter boat anglers over time.

Partial Spearman correlations accounting for the presence of the bag limit were used to investigate the relationship between CPUE and HPUE of boat and charter boat anglers before and after the bag limit was introduced.

To detect trends in total lengths of cod caught over time, Mann-Kendall trend tests were applied in the case of annual mean values, and seasonal Mann-Kendall trend tests were applied in the case of monthly mean values. Prior to the trend tests, missing monthly mean cod total lengths were replaced by interpolation using the seasonal Kalman function (Moritz et al., 2015).

2.8. Statistical software

All statistical analyses were performed using R statistical software version 4.0.2 (R R Core Team, 2017). The package "gbm" (Ridgeway, 2020) and additional functions provided by Elith et al. (2008) were used for the BRT analysis. The package "imputeTS" (Moritz and Bartz-Beielstein, 2017) was used to interpolate the time series of length data, and the packages "changepoint" (Killick and Eckley, 2014), "changepoint.np" (Haynes and Killick, 2020), "trend" (Pohlert, 2020), and "Kendall" (McLeod, 2011) were used for the change point analyses and trend tests. The packages "nlstools" (Baty et al., 2015) and "basicTrendline" (Mei et al., 2018) were used to calculate the power regression functions. The partial Spearman correlations were conducted using the package "correlations" (Makowski et al., 2020).

3. Results

3.1. Socio-demography of cod anglers

A total of 21,656 cod anglers were encountered and interviewed during 3495 sampling visits. On 29% of the sampling assignments, no anglers were encountered. The majority of interviews were with charter boat anglers (69%), 20% with boat anglers, and 11% with shore anglers. Most anglers were middle-aged men. Charter boat anglers were slightly but significantly older than boat anglers (Table 1) and their mean age increased slightly over the study period (Mann-Kendall trend test: tau = 0.17, z = 2.37, p = 0.02). In contrast, the mean age of boat anglers showed no trend over the years (Mann-Kendall trend test: tau = 0.1, z = 1.3, p = 0.2). The avidity of charter boat anglers ranged from 0 to 280 fishing days per year with an overall mean of 6.4 (± 13.9 S.D.)

Table 1
Summary showing medians, means, standard deviations, and numbers as well as the results of Mann-Whitney-U tests and Chi^2 tests for German charter boat and boat angler characteristics (age, avidity, gender, and residency) and catch (CPUE), harvest (HPUE), and release (RPUE) rates including periods of available data. p values < 0.05 indicate significant differences between charter boat and boat anglers.

	Charter boat	Boat	MW-U test, Chi^2-test
Age (years) Data 2012–2019	48, 47.3 (± 15.1) n = 8649	46, 45.7 (± 13.2) n = 2752	$U = 1.2 \times 10^7$, p = 0.0001
Avidity (days during the last 12 months) Data 2012–2019	2, 6.4 (± 13.9) n = 8775	5, 12.3 (± 18.1) n = 2782	$U = 8.4 \times 10^6$, p = 0.0001
Gender (%) Male/female Data 2009–2019	96/4 n = 8946	95/5 n = 3868	Chi^2 = 4.0 p = 0.05
Residency (%) Nonres./res Data 2009–2019	71/29 n = 14,016	54/46 n = 3868	Chi^2 = 435 p = 0.0001
Catch per angler and day (CPUE) Data 2009–2019	4, 5.4 (± 5.7) n = 14,600	2, 4.2 (± 6.0) n = 4219	$U = 2.4 \times 10^7$, p < 0.0001
Harvest per angler and day (HPUE) Data 2009–2019	2, 3.4 (± 4.1) n = 14,600	1, 2.5 (± 3.8) n = 4218	$U = 2.5 \times 10^7$, p = 0.0001
Release per angler and day (RPUE) Data 2009–2019	1, 2.4 (± 3.3) n = 9839	1, 2.5 (± 3.7) n = 1891	$U = 9.1 \times 10^6$ p = 0.08

fishing days per year and increased slightly over the years (Mann-Kendall trend test: *tau* = 0.16, $z = 2.36$, $p = 0.02$) (Suppl. Fig. 1). With a mean number of 12.3 (± 18.1 S.D.) and a range between 0 and 200 fishing days per year, encountered boat anglers were more avid than charter boat anglers. No temporal trend in their avidity was apparent. Most of the charter boat and boat anglers encountered were non-residents, and the proportion of nonresidents was significantly higher among charter boat than among boat anglers (Table 1). Consequently, the ratio of nonresidents to residents was higher for charter boat than boat anglers, ranging from 2 (2014) to 3.8 (2019) and 0.7 (2009) to 1.7 (2011), respectively. The ratio of nonresidents to residents was subject to some seasonal variation and was highest during the summer months for both angling platforms.

3.2. Number of boat and charter boat anglers

The np-CPA distinguished three main periods in the time series of the number of boat anglers. The highest numbers of boat anglers per access point visit occurred between September 2009 and January 2012. The subsequent period from 2012 onwards was characterised by comparatively stable mean angler numbers and little fluctuation, but was interrupted by a short period (February/March 2017) when comparatively high number of boat anglers were encountered (Fig. 4).

The numbers of charter boat anglers in Heiligenhafen significantly decreased by approximately 81% from over 90,000 anglers per year in 2000 to approximately 17,000 in 2019 (angler numbers from 2000 to 2019, Mann-Kendall trend test: $z = 5.5$, $p < 0.0001$; Fig. 5).

3.3. Results of standardisation of CPUE and HPUE data

Standardisation of the CPUE and HPUE data using the BRT models showed that inter-annual differences explained most of the variance in the data. Fishing during the summer months and in the eastern coastal areas (area 1) resulted in higher CPUE and HPUE values for both angling platforms. CPUE and HPUE increased slightly with the avidity of individual anglers, although the relative importance of the predictor was low. Charter boat anglers harvested more cod in MWP than in SH, while federal state had little effect on boat angler harvest rates (Suppl. Figs. 2–5).

3.4. Change points in boat angler catch, harvest, and release rates

Annual mean CPUEs of boat anglers encountered during the on-site survey ranged from 2.8 to 5.8 cod per angler and day (Suppl. Fig. 6). The np-CPAs identified two change points in the boat angler CPUE time series (Fig. 6). The highest CPUE was reached between August 2015 and July 2016. The following period was characterized by lower values with catch minima in summer and autumn 2016. In 2017, CPUE values initially increased before decreasing again in 2019 and the catch rates fluctuated strongly. The introduction of the bag limit in 2017 was not reflected in separate change points (Fig. 6). Over the entire study period, 37% of boat anglers caught no cod during their fishing day, while 27%

Fig. 5. Annual number of charter boat anglers in the harbour of Heiligenhafen, Germany from 2000 to 2019. The black arrow indicates the first-time introduction of a daily bag limit in the western Baltic cod fishery in January 2017.

caught more than five cod per fishing day.

The annual mean HPUE of boat anglers ranged from 0.6 to 3.8 cod per angler and day and closely matched those of CPUE (Suppl. Fig. 7). The time series of HPUE data was separated by four closely spaced change points (Fig. 6). The period from 2009 to April 2015 was characterised by fluctuating but stable harvest rates. Some high harvest rates were recorded in the following year before HPUE dropped sharply in 2017 and remained at lower levels in subsequent years. The lowest harvest rates were observed between May and December 2017. Thereafter, harvest rates increased slightly without reaching baseline levels.

3.5. Change points in charter boat anglers catch, harvest, and release rates

The overall mean cod CPUE of charter boat anglers was significantly higher than the CPUE of boat anglers (Table 1). The annual mean CPUE of charter boat anglers varied between 3.7 and 7.7 cod per angler and day (Suppl. Fig. 6). The time series of catch data showed four change points (Fig. 7). CPUE initially increased and was highest between April 2013 and December 2015, while the following period was characterized by low CPUE values with a minimum in autumn 2016. In 2018, charter boat angler CPUE values initially increased before decreasing again in 2019. There was no change point at the time the bag limit was introduced. Throughout the study period, 16% of charter boat anglers caught no cod during their fishing day, while 38% of the interviewed charter boat anglers caught more than five cod per day.

The overall mean cod HPUE of charter boat anglers was significantly higher than the HPUE of boat anglers (Table 1). The annual mean HPUE of charter boat anglers ranged from 1.5 to 5.1 cod per angler and day (Suppl. Fig. 7). The HPUE data were characterized by five main periods, and the change points occurred slightly delayed compared to the time series of the CPUE data. Corresponding to the CPUE values, HPUE values were highest between February 2014 and December 2015 and lowest between June 2016 and April 2018. Thereafter, charter boat angler

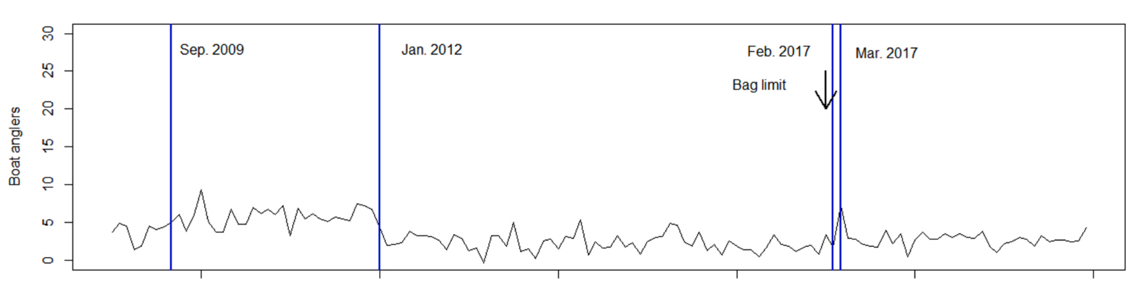

Fig. 4. Change points (vertical blue lines with dates) in mean and variance of the numbers of encountered boat anglers from 2009 until 2019 as identified by nonparametric change point analyses. The black arrow indicates the first-time introduction of a daily bag limit in the western Baltic cod fishery in January 2017.

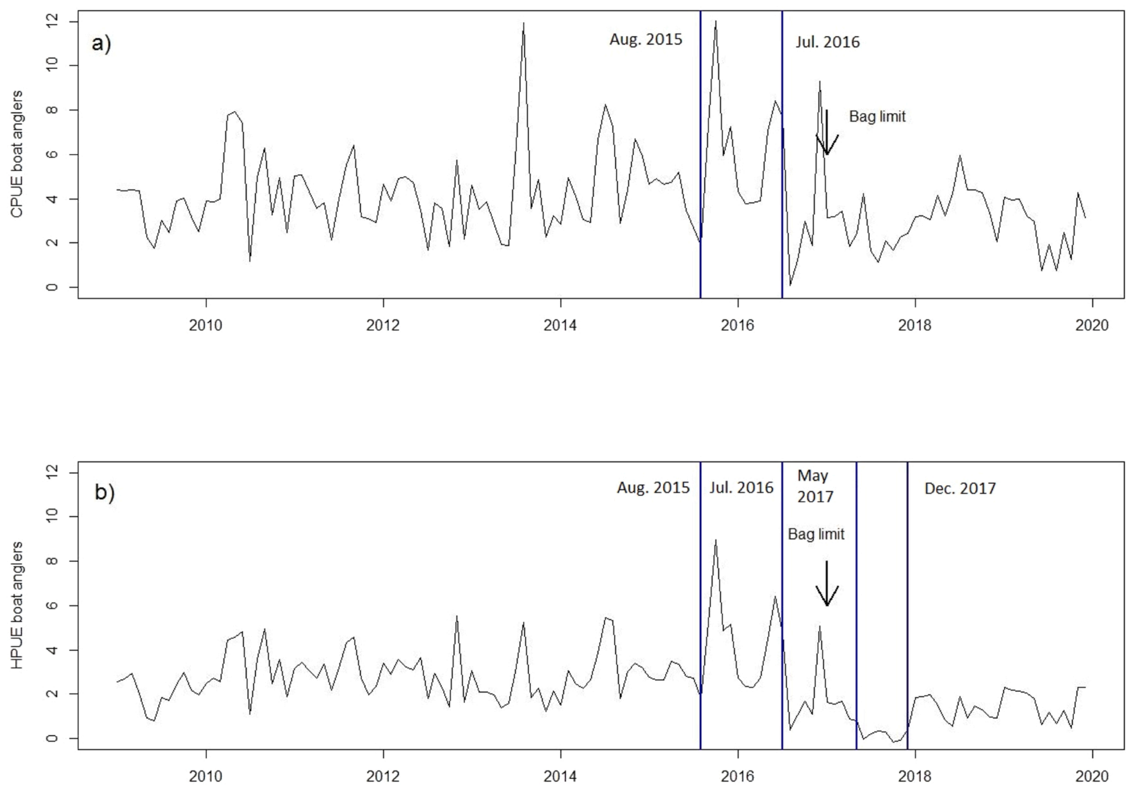

Fig. 6. Time series with change points (vertical blue lines with corresponding dates) of a) cod catch rates (standardized monthly means) and b) cod harvest rates of German boat anglers from January 2009 to December 2019 as identified by nonparametric change point analyses. The black arrows indicate the first-time introduction of a daily bag limit in the western Baltic cod fishery in January 2017.

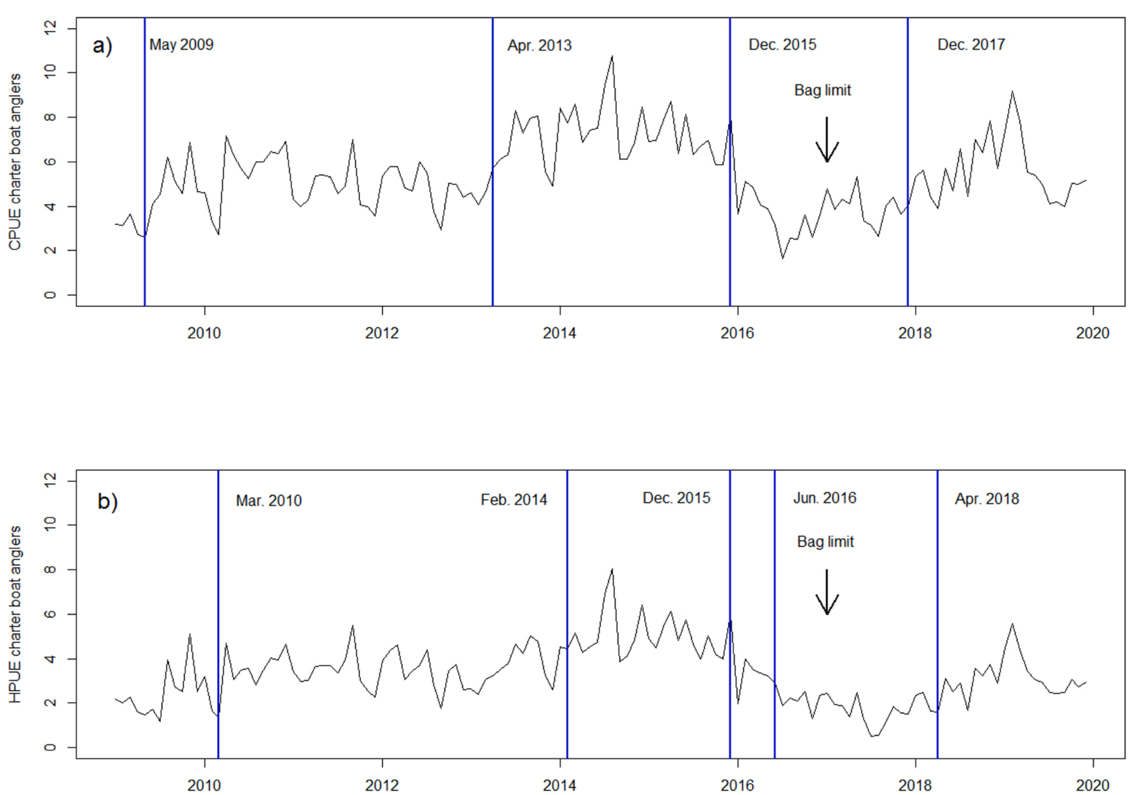

Fig. 7. Time series with change points (vertical blue lines with corresponding dates) of a) cod catch rates (standardized monthly means) and b) cod harvest rates of German charter boat anglers from January 2009 to December 2019 as identified by nonparametric change point analyses. The black arrows indicate the first-time introduction of a daily bag limit in the western Baltic cod fishery in January 2017.

HPUE values increased before declining in 2019 (Fig. 7).

3.6. Evidence of hyperstability

According to the ICES stock assessment, both the estimated stock size (total numbers) and SSB of western Baltic cod declined sharply from 1985 to 2020, by about 86% and 74%, respectively. Stock size and SSB reached minima in 2017 and 2018 (Fig. 1). For both angling platforms, the period of low CPUE values between December 2015 and December 2017 corresponded to the low stock size estimates for western Baltic cod. However, the nonlinear regression did not show a significant relationship between CPUE and stock size for either charter boat anglers ($R^2 = 0.3$, $p = 0.2$) or boat anglers ($R^2 = 0.2$, $p = 0.2$). Neither the estimated catchability coefficients nor the corresponding power curve exponents β were significant, indicating inadequate model fits (Fig. 8).

3.7. Correlation between catch rates and bag limit introduction

Catch and harvest rates were strongly correlated for both angling platforms (partial Spearman correlations: boat anglers: $r = 0.9$, (0.89, 0.91 CI), $S = 134$, $p = < 0.001$, charter boat anglers: $r = 0.86$, (0.85, 0.86 CI), $S = 199$, $p < 0.001$). Boat and charter boat anglers released between 0% and 100% of the cod caught per fishing day, with charter boat anglers (mean ± S.D.: 36% ± 35% S.D) releasing a slightly higher proportion of cod on average than boat anglers (mean ± S.D.: 35% ± 35% S.D., MW U test: $U = 1.6 \times 10^7$; $p = 0.04$). Both mean CPUE and HPUE of boat anglers were significantly higher in the period before the bag limit introduction than in the period after the introduction of the bag limit (CPUEs mean ± S.D.: 4.9 ± 7.7 vs. 3.1 ± 5.0, MW U test: $U = 5.6 \times 10^5$; $p = 0.0001$; HPUEs mean ± S.D.: 3.3 ± 5.1 vs. 1.3 ± 2.1, MW U test: $U = 5.0 \times 10^5$; $p = 0.0001$). Release rates increased from 30% ± 30% (mean ± S.D. 2014–2016) before to 51% ± 38% (mean ± S.D. 2017–2019) after the introduction of the bag limit (MW U test: $U = 1.3 \times 10^5$; $p = 0.0001$).

For charter boat anglers, mean CPUEs were not significantly different three years before and three years after the introduction of the bag limit (mean ± S.D.: 6.0 ± 6.5 vs. 5.3 ± 4.7, MW U test: $U = 5.0 \times 10^6$; $p = 0.2$). In contrast, mean HPUEs were significantly higher for the same periods before the introduction of the bag limit (mean ± S.D.: 4.2 ± 4.9 vs. 2.5 ± 2.4, MW U test: $U = 4.2 \times 10^6$; $p = 0.0001$). Accordingly, the proportion of fish released increased significantly from 29% ± 30% (mean ± S.D. 2014–2016) before to 48% ± 33% (mean ± S.D. 2017–2019) after the introduction of the bag limit (MW U test: $U = 3273$, $p = 0.0001$). In 2017 and 2018, the HPUE of more than 99% of boat anglers and 97% of charter boat anglers did not exceed the daily bag limit.

3.8. Length and age composition of cod catches

Overall, the total lengths of cod caught by charter boat anglers ranged from 10 cm to 101 cm (42.9 ± 5.3 cm, mean ± S.D.). Most cod were 30–50 cm long, with no significant differences between the first and second half of the year ($Chi^2 = 2548$, $p = 0.7$). Average monthly total length ranged from 28.5 to 57.1 cm and varied between years with no significant trend evident during the study period (seasonal MK trend test: $z = -1.0717$, $p = 0.3$). The proportions of length classes in the catch also differed between the years without a clear trend. Nevertheless, the proportion of cod over 70 cm in the catch over the whole study period ranged from 0.5% to 5% and decreased significantly during the study period (MK trend test: $z = -2.8026$, $p = 0.005$). Most of the cod caught with total lengths between 30 and 60 cm belonged to age groups 2 + and 3 + . In eight of the 11 years, the proportion of old fish (≥ 6 +) in the catch was less than 1%, with the highest proportion of 2.7% observed in the first year of the study. In 2018, the catch consisted primarily (62%) of 2 + cod. In the following year, the catch consisted almost exclusively of 3 + cod (Fig. 9, Suppl. Table 1).

4. Discussion

The objective of this study was to examine the relationship between the recreational cod fishery in the western Baltic Sea and the corresponding fish stock, focusing on the occurrence of change points in the time series of angler numbers, catch rates, and harvest rates associated with cod stock development and the first-time introduction of a bag limit.

4.1. Change points in boat and charter boat angler numbers

The cod anglers encountered during the on-site survey were similar in age and gender distribution to those from other parts of Germany and beyond (see Arlinghaus, 2004; Schroeder et al., 2006; Gundelund et al., 2020). Several studies have observed a high proportion of nonresidents, particularly among charter boat anglers, as was the case in this study (Dorow and Arlinghaus, 2011; Vølstad et al., 2020; Lewin et al., 2021b).

Originally, we had assumed that the decline of the cod stock and the corresponding introduction of the bag limit would be reflected in the

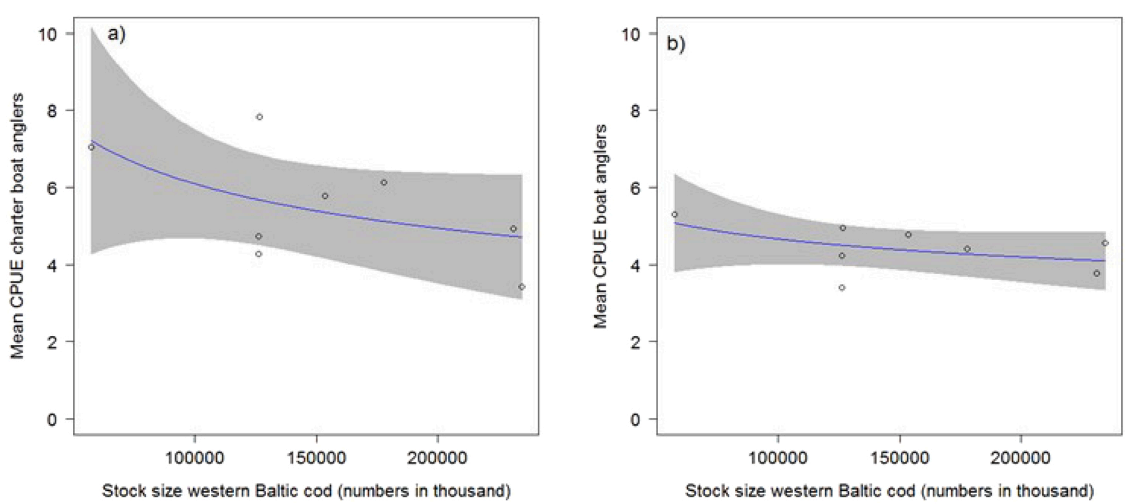

Fig. 8. Relationship between the stock size (estimated numbers) of western Baltic cod and the CPUE of a) charter boat anglers and b) boat anglers from 2009 to 2016. The figures show the regression lines with 95% confidence intervals (grey shades). Charter boat anglers: catchability coefficient 196 ± 416 S.E., $p = 0.6$; $\beta = -0.3 \pm 0.2$ S.E., $p = 0.2$; $R^2 = 0.3$, $p = 0.2$. Boat anglers: catchability coefficient = 26.8 ± 33.4 S.E., p = 0.5; β = −0.15 ± 0.1 S.E., p = 0.2; $R^2 = 0.24$ $p = 0.2$.

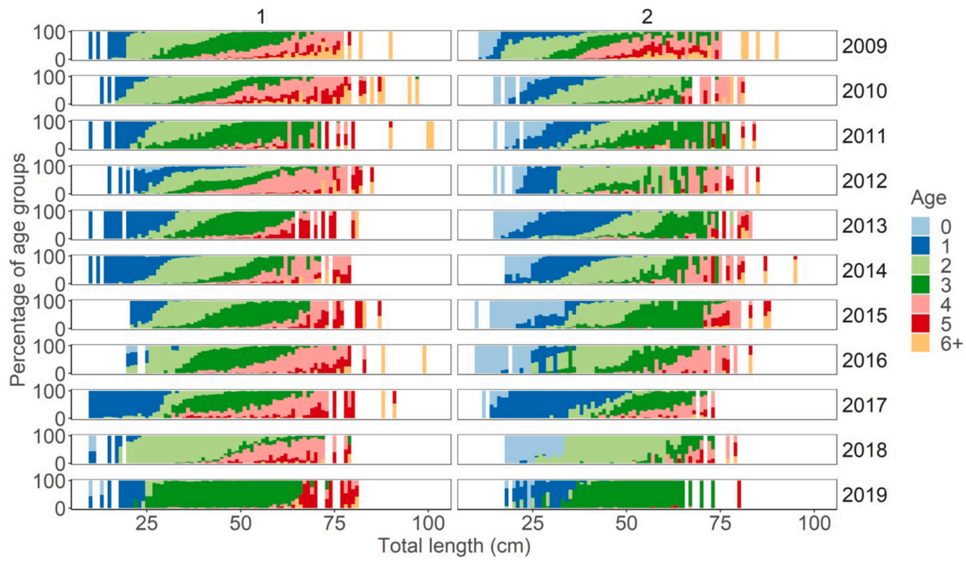

Fig. 9. Annual age-length composition of German recreational charter boat cod catches from the western Baltic Sea from 2009 to 2019 for the first (1) and second (2) half year. The different colours show the age groups: light blue: 0 + age group, blue: 1 + age group, light green: 2 + age group, green: 3 + age group, pink: 4 + age group, red: 5 + age group, apricot: 6 + and older age group.

number of cod anglers participating in the fishery, as angler dynamics change over time in response to the stock status of the target species, fishing regulations, and travel costs (Abbott and Fenichel, 2013; Camp et al., 2018). However, the number of boat anglers remained stable during the observation period and did not exhibit a change point that could be attributed to the stock collapse and the introduction of the bag limit. In contrast, the number of charter boat anglers in Heiligenhafen declined more sharply after the introduction of the bag limit, but a general decline had already been observed since 2000. The stronger response of charter boat anglers may be due to the fact that they are more catch-oriented than other angler groups (Graefe and Fedler, 1986; Ditton et al., 1991; Holland and Ditton, 1992) and may be less likely to fish when the harvest is restricted (Johnston et al., 2011; Whitehead et al., 2011; Hunt et al., 2019). However, the total number of active charter boats along the German Baltic coast including the harbour of Heiligenhafen also declined from 87 in 2005–29 in 2019, suggesting that the decline in charter boat anglers is most likely related to these structural changes. Although an interaction between local supply and demand cannot be ruled out, there has been evidence from other coastal regions that rising operating and vessel costs, complex regulatory requirements for safety and harvest, changing demographics and lifestyles, and competition from other expanding tourism opportunities are also responsible for the decline in charter boat fishing (Hales, 2006; Mueller et al., 2008; Waldo and Paulrud, 2012; Bachman et al., 2017; Williams et al., 2020). The slightly increasing age of charter boat anglers observed in the present study could support the assumption of socio-demographic changes among German charter boat anglers.

The stable number of boat anglers may be partly attributed to the high proportion of residents among them. Residents may have compensated for the low daily catches by making repeated fishing trips, as the one-time travel costs and organisational effort are lower compared to nonresident charter boat anglers. Moreover, boat anglers' avidity, which can be considered an indicator of commitment (Beardmore et al., 2013), was about twice that of charter boat anglers. These anglers may have been willing to continue fishing regardless of catch rates because low access costs or low crowding provided sufficient compensatory utility (Beardmore et al., 2015; Hunt et al., 2019). In addition, both the availability and equipment of small motor boats have improved over the past 10–20 years. In 2012, the German license requirement for recreational boating was changed so that small motorboats with an engine power of up to 15 h.p. (11.03 KW) and a length of less than 15 m on federal inland waters and coastal waterways do not require a boating license (BGBL, 2012). Furthermore, the daily mean CPUE of boat anglers was below the bag limit, while the CPUE of charter boat anglers was slightly higher (Table 1). Consequently, the new bag limit regulation may have had less effect on boat anglers than on charter boat anglers.

The weak relationship between the number of anglers and the size of the western Baltic cod stock is consistent with a study by Camp et al. (2016), who concluded that either the diversity of anglers' motives targeting the same species or the dominance of non-catch-related motives could explain the relationship. Accordingly, motives such as the pleasure of boating or the desire to experience nature may have additionally stabilized the number of boat anglers (Sutton and Ditton, 2001; Beardmore et al., 2011; Hunt et al., 2019; Lewin et al., 2020).

4.2. *Change points in catch and harvest rates and hyperstable catch rates*

The generally lower CPUE values of boat anglers compared to charter boat anglers may be due to the large charter boats with experienced skippers being able to access offshore fishing grounds that are inaccessible to small boats. Western Baltic cod concentrate in deep-water areas in winter and early spring to spawn (Hüssy, 2011) and in summer to avoid high water temperatures (Funk et al., 2020).

The change point analyses identified periods of very low catch and harvest rates. Periods of very low catch and harvest rates corresponded to a period of very low stock abundance. Comparatively high catch and harvest rates occurred when western Baltic cod stock sizes were high, suggesting that recreational catch and harvest rates are somewhat related to cod abundance.

The power regressions found no statistical evidence for the presence of hyperstability. Hyperstability has been demonstrated for other recreational fisheries, but most studies have focused on fisheries in spatially restricted freshwater environments (Dassow et al., 2020; Tsuboi et al., 2021; Mosley et al., 2022). Hyperstability threatens fish stocks because stable catches mask stock declines, so management actions may not be taken until the stock eventually collapses (Post, 2013; Ward et al., 2013). It is caused by several interacting mechanisms, including effort sorting, technological innovations, angler behaviour, and habitat heterogeneity, and is most likely to occur when fisheries are able to target fish aggregations or fish species with high site fidelity (Reubens et al., 2013; Van Poorten et al., 2016; Dassow et al., 2020; Mosley et al., 2022).

4.3. Effects of the bag limit introduction

Correlation analyses suggest a relationship between the introduction of the bag limit and increased cod releases in the primarily consumptive cod fishery. However, release rates were also likely influenced by increased catches of undersized cod, which are the most common reason of cod releases in the Baltic Sea (Dorow and Arlinghaus, 2011; Ferter et al., 2013). Indeed, the proportion of undersized cod (cod $\leq$ 38 cm total length) in charter boat angler catches reached a maximum in 2017, which was probably due to the strong 2016 western Baltic cod cohort that entered the fishery (ICES, 2019c). Furthermore, some anglers may have also voluntarily released fish that could have been legally harvested (comp. Arlinghaus et al., 2007).

5. The length and age composition of charter boat catches

The age and length composition of cod catches suggests that the size and age distribution of the cod stock is reflected, at least in part, in the recreational cod catches, indicating that substantial changes in the target stock status may affect recreational fisheries. For example, the age composition of recreational charter boat catches in 2018 corresponded well withthe age composition of commercial cod landings in 2018, with the majority of commercial landings consisting of age group 2 of the large 2016 year class (ICES, 2019c). This strong year class also dominated recreational charter boat catches in 2019, which may reflect low cod recruitment in 2017 (ICES, 2019c). The proportion of large cod (cod $>$ 70 cm) in the catches declined from about 7% in 2009 to 0.4% in 2019. This observation was in accordance with many other studies showing declining numbers of old and large fish in heavily commercially and recreationally exploited fish stocks (Richardson et al., 2006; Bellquist and Semmens, 2016; Barnett et al., 2017).

6. Study limitations

Several limitations should be considered when interpreting the study results. First, the statistical analyses conducted in this study provided evidence of statistical relationships between cod abundance and recreational fishing, but this does not imply causality. Further research is needed to identify additional factors that may have influenced the recreational cod fishery and to shed light on the complex relationship between cod stock, management measures, recreational catch and harvest rates, and the size composition of the recreational catch.

Moreover, the time series may have lacked contrast. The on-site survey allowed calculations of monthly CPUEs whereas the ICES stock assessment provided only annual estimates of the cod stock size. Furthermore, the cod stock assessment was conducted at a large scale and the results lack high spatial resolution. Stock size estimates from the stock assessment were based primarily on commercial catches and fishery-independent bottom trawl surveys conducted twice a year. Most trawling occurred in offshore areas inaccessible to recreational fishers (ICES, 2014) and covered a limited range of habitat, as hard bottom structures in water depths $<$ 20 m (e.g., boulders and rocky structures) were generally avoided to prevent gear damage (Funk et al., 2020). Finally, the short 11-year time series provided limited insight into the temporal dynamics of the recreational fishery (Cooke and Cowx, 2004; Lynch, 2014), particularly because angler numbers and CPUE estimates were not available for the period of high western Baltic cod stock sizes (in the 1980s). In general, small numbers of paired observations lead to difficulties in calculating β estimates (Dunn et al., 2000).

Data obtained from on-site surveys are susceptible to avidity biases resulting from an increased selection probability of more avid anglers who go fishing more often or stay longer at their fishing sites (Thomson, 1991; Bellanger and Levrel, 2017). Furthermore, angler self-reports may introduce additional bias and obscure relationships between variables (Van de Mortel, 2008; McCormick et al., 2013). On-site surveys, however, are considered reliable for estimating catch and harvest rates in recreational fisheries, not least because individual anglers' catches can be directly inspected by survey agents and the non-response bias is usually low, especially if survey agents are familiar with the local recreational fishery (Strehlow et al., 2012; Griffith et al., 2013; Herfaut et al., 2013). In a recent study that also provided data for the present study, sociodemographic variables, catch and release rates of German Baltic charter boat and boat anglers encountered during the on-site survey were compared to those of participants and non-participants in a diary survey (Lewin et al., 2021b). The latter were recruited from a representative off-site telephone survey conducted simultaneously. Overall, the results of the study showed that anglers interviewed from the on-site survey were broadly representative of the general angler population and that catch and release rates of diarists and on-site anglers were in a similar range for boat and charter boat anglers (Lewin et al., 2021b).

The possibility that individual anglers were contacted more than once during the study period could not be completely ruled out. However, the probability can be considered very low since the survey covered 11 years and the entire German Baltic coast, which attracts approximately 161,000 anglers annually from all over the country (Lewin et al., 2021a; Weltersbach et al., 2021). Furthermore, although survey agents did not officially record these numbers, they very rarely reported repeatedly encountered anglers.

Finally, BRT models are generally well suited for standardising catches (Serghini et al., 2018), but several factors that may have additionally influenced catch and harvest rates were not captured during the on-site survey. Previous work in freshwater fisheries, for example, has shown that a self-reported skill index systematically related to catch rates. It is possible that age and avidity were not optimal for capturing individual variation in the catches of anglers (Monk and Arlinghaus, 2018). This uncertainty underlines the conclusions of previous studies that management of marine recreational fisheries should continue to expand its focus on angler behaviour and aspects of the human dimension (e.g. Ward et al., 2016).

7. Management implications and open research questions

A fisheries management for mixed commercial-recreational fisheries requires sound knowledge of the status of recreational fisheries in terms of the spatial and temporal scales of effort, catch, and harvest to reduce the risks of crossing change points, avoid inter-sectoral conflicts, and minimize discrepancies in resource allocation, responsibilities, and participation (MacKenzie and Cox, 2013; Selkoe et al., 2015; Serrao-Neumann et al., 2016; Hyder et al., 2020(Arlinghaus et al., 2019)).

This study found evidence that the poor status of the western Baltic cod stock (Bryhn et al., 2022) was only weakly reflected in the catch and harvest rates of recreational fishers. The data also suggested that the recreational catches did not contribute significantly to the stock decline during the period of high SSB (comp. Fig. 1). Since we did not observe stable catch rates following the stock decline, the risk of collapse of the western Baltic cod stock due to recreational fishing appeared to be low. Nonetheless, the increasing proportion of the recreational catch to the total catch of the commercial and recreational fishery at low stock status indicates that recreational fishing must be considered in fisheries management.

The low abundance of large fish in the western Baltic cod stock is of particular concern not only because it may reduce the attractiveness of the fishery to anglers (Dabrowska et al., 2017; Birdsong et al., 2021; Bronmann et al., 2022) but more importantly because it affects recruitment to the stock. Large individuals have high fecundity and total reproductive energy (Barneche et al., 2018), and an uniform age composition reduces the resilience of fish stocks to variable environmental conditions (Planque et al., 2010; Oomen and Hutchings, 2015).

The introduction of a daily bag limit appears to have had the intended effect of reducing individual harvest rates, although the increasing proportion of juvenile cod from the 2016 year class in the catches may have additionally contributed to the observed increase in release rates. Despite conflicting results from other studies (Cox et al., 2002), a significant change in fishing effort (changes in the number of recalled fishing days per angler and year) was not detectable following the introduction of the bag limit. Accordingly, a more recent study showed that the number of coastal fishing permits sold in MWP decreased by only 4.3% after the introduction of the bag limit (Haase et al., 2022). The small effect of the bag limit on the fishing effort was likely attributed to the fact that the different angler groups may have responded differently to the bag limit (comp. Fenichel et al., 2013). Prior to the introduction of the bag limit, an average of 37% of boat and 16% of charter boat anglers caught no cod at all, and 36% of boat anglers and 47% of charter boat anglers caught one to five cod during a fishing day. These observations suggest that only a fraction of anglers may have perceived the new bag limit regulation as binding and may have stopped fishing for cod in the western Baltic Sea. It further underlines that psychological factors such as, e.g., the perceived loss of freedom in harvesting decisions may have had a greater influence on angler behaviour than actual restrictions (Bronmann et al., 2022). However, the tightening of the bag limit regulation in 2022 could have a strong impact on angler numbers. Nonetheless, the study results suggest that the majority of cod anglers are coping well with the new harvesting limits, while a possible avidity bias in the on-site survey data cannot be ruled out. Future surveys should therefore include complementary off-site surveys to control for biases and assess the reliability of the information obtained from the on-site surveys.

Aside from a bag limit, limiting fishing effort is another strategy to protect fisheries and fish stocks that are prone to hyperstability (Dassow et al., 2020). A recent simulation study of the recreational western Baltic cod fishery showed that liberal bag limits, supplemented with landing size regulations and seasonal closures, are best suited to ensure sustainable exploitation of the western Baltic cod stock while maintaining angler utility (Haase et al., 2022). Accordingly, BRT analyses showed that a higher minimum landing size (38 cm and 35 cm in the federal states SH and MWP, respectively, Weltersbach et al., 2019) reduces harvest rates more efficiently (Suppl. Fig. 5) so harmonization of federal regulations should be considered.

When considering the release of fish, it should be kept in mind that the release of angled fish is often associated with some mortality (Bartholomew and Bohnsack, 2005). The post-release mortality of western Baltic cod angled from charter boats, for example, ranged from 0% to 27.3% (mean 11.2%) (Weltersbach and Strehlow, 2013). Furthermore, bag limits may increase the risk of high-grading, in which anglers discard small cod they catch to replace them with more valuable, larger specimens. Although high-grading could not be ruled out, the HPUEs between 2009 and 2016 exceeded the later introduced bag limit on only about 24% of individual sea-based fishing days (Haase et al., 2022). Because catch rates were even lower as of 2017, high-grading is not likely to have been a major problem in this fishery.

The issue that the stock size resulting from ICES stock assessments may not reflect the cod stock available to anglers remains and limits the validity of the relationship between stock size and catch rates. The recreational cod fishery in the western Baltic management area is assumed to consist entirely of western Baltic cod (ICES, 2019c), an assumption that should be verified by future research. Recreational fishing for cod also occurred in ICES SD 24, where mixing of eastern and western Baltic cod stocks occurs (Hüssy et al., 2016), and it cannot be completely ruled out, that eastern Baltic cod influenced catch and harvest estimates and length composition analyses. Moreover, more high-resolution information on the spatial and temporal distribution of western Baltic cod in coastal areas is required to estimate the proportion of cod affected by marine recreational fishing, not least because fishable marine areas are becoming smaller due to increasingly diverse usage demands.

Furthermore, the simultaneous introduction of the bag limit and the stock collapse made it difficult to separate the effects of the two factors on catch and harvest rates. This finding indicates that further research is needed to investigate the underlying mechanisms and underlines the importance of long-term recreational fisheries monitoring programs as a prerequisite for identifying change points in recreational fisheries and as an integral component of fisheries management.

CRediT authorship contribution statement

Wolf-Christian Lewin: Conceptualization, Formal analysis, Writing – original draft. **Marc Simon Weltersbach:** Conceptualization, Writing – review & editing. **Kevin Haase:** Writing – review & editing. **Robert Arlinghaus:** Conceptualization, Writing – review & editing. **Harry V. Strehlow:** Funding acquisition, Conceptualization, Writing – review & editing, Supervision.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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Supplementary material

The following supplementary material is available online: i) Box plots showing the time series of age and avidity of charter boat and boat anglers, ii) the partial dependence plots from the BRT analyses for the variables used to predict the cod CPUEs and HPUEs of charter boat and boat anglers, iii) violin plots showing the standardized and log transformed catch and harvest rates of boat and charter boat anglers, and iv) a table showing the age composition of western Baltic Sea cod catches by German charter boat anglers from 2009 to 2019.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fishres.2022.106548.

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