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Article

Integrative spatial assessment of status and trends in a commercial–recreational coastal fishery for Northern Pike, with implications for management

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Abstract

***Objective*: Competition over resource access can drive conflict between commercial fishers and recreational anglers, especially when fish stocks are declining. This study presents a spatially explicit integrative assessment of Northern Pike *Esox lucius* fisheries across five major brackish lagoons around Rügen Island (Germany) in the southern Baltic Sea, combining social and ecological indicators of status and trends.**

***Methods*: We combined an extensive mark–recapture-based approach with catch-curve analysis to estimate spatially differentiated, user-group-specific fishing mortality rates, as well as natural mortality rates acting on the coastal pike across five lagoons. Using surveys, we assessed the preferences of fishers and anglers for different lagoons as a measure of their social desirability. Additionally, we examined long-term commercial landings as a coarse indicator of stock trends. Finally, we formed a composite index combining spatially explicit social–ecological use and status indicators to provide an integrative perspective.**

***Results*: Current fishing pressure on pike as assessed by captures was similar for anglers and commercial fishers, with an annual potential instantaneous fishing mortality rate *F* of 0.10 (~9.5% per year) for each sector. However, when considering only retained fish due to widespread catch-and-release practices by anglers, commercial fishers removed approximately twice as many pike as anglers did during the study period (2020–2022). Spatial analyses revealed pronounced differences in fishing and natural mortality rates among lagoons, while the long-term trend in commercial landings suggested a declining pike population. Integration of the various indicators revealed that the largest lagoon in the study area, the Greifswalder Bodden, exhibited the largest number of threats.**

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***Conclusions*: Our findings suggest that a combination of lagoon-specific management measures tailored to either commercial or recreational fisheries, embedded in an ecosystem-based management approach, may be necessary to recover the pike fishery, which is currently showing strong stock declines. Implementing such measures can reduce conflicts between user groups, protect and recover pike stocks, and ensure sustainable benefits for both commercial and recreational fisheries.**

Native language abstract–German
Zielsetzung

Konflikte zwischen Berufsfischern und Anglern um begrenzte fischereiliche Ressourcen werden durch rückläufige Fischbestände verschärft. Die vorliegende Studie präsentiert eine räumlich explizite, integrative Bewertung von Zuständen und Trends der Fischerei auf den Hecht *Esox lucius* in fünf großen Boddengebieten rund um die Insel Rügen (Deutschland) in der südlichen Ostsee.

Methoden

Basierend auf einer umfangreichen Fang-Markierung-Wiederfangstudie kombiniert mit einer Fangkurvenanalyse wurden räumlich differenzierte, nutzergruppenspezifische fischereiliche sowie natürliche Sterblichkeitsraten von Hechten in den fünf Boddengebieten quantifiziert. Ergänzt durch Umfragen wurden die präferierten Hauptfangebiete von Berufsfischern und Anglern ermittelt. Zeitserien zu berufsfischereilichen Hechtanlandungen in den Bodden dienten als Indikator für Bestandstrends. Aus den sozialen und ökologischen Indikatoren wurde ein integrativer Index zum Zustand des Hechtbestandes und der fischereilichen Entwicklungen entwickelt.

Ergebnisse

Die aktuellen Fangraten von Hechten durch Angler und Berufsfischer bewegen sich in ähnlichen Größenordnungen, bei einer jährlichen potenziellen fischereilichen Sterblichkeitsrate F von 0,10 bzw. 9,5% pro Sektor. Werden angesichts weit verbreiteter Catch-&-Release-Praktiken unter Anglern nur entnommene Fische betrachtet, entnahmen Berufsfischer im Studienzeitraum (2020–2022) etwa doppelt so viele Hechte wie Angler. Räumliche Analysen zeigten deutliche Unterschiede in der fischereilichen und der natürlichen Sterblichkeit zwischen den Boddengebieten. Die Langzeitentwicklung der kommerziellen Anlandungen deutete auf einen stark rückläufigen Hechtbestand hin. Die Integration der verschiedenen Indikatoren ergab, dass insbesondere der Greifswalder Bodden das größte Gefährdungs- und Konfliktpotential aufwies.

Schlussfolgerungen

Die Erkenntnisse legen nahe, dass eine Kombination aus lokalen, boddenspezifischen Managementmaßnahmen, zugeschnitten auf die Berufs- und Angelfischerei, eingebettet in einen ökosystembasierten Ansatz über das gesamte Boddennetzwerk, notwendig ist, um den Boddenhechtbestand wiederaufzubauen, ihn nachhaltig zu nutzen und Konfliktpotenziale zwischen Nutzergruppen abzuschwächen.

Keywords: fishing mortality rate, mark–recapture, mixed-use fishery, pike, stock status

Lay summary

Northern Pike in German Baltic Sea lagoons face fishing pressure from anglers and commercial fishers, but impacts vary by lagoon. Lagoon-specific regulations that consider the ecosystem could reduce conflicts, help pike recover, and ensure long-term benefits for both user groups.

Introduction

In systems where fisheries conflicts are prevalent, effective governance requires a comprehensive understanding of the underlying social–ecological dynamics. Under spatially varying fisheries productivity, competition for access to shared fishing grounds can become a regular source of conflict between commercial fishers (hereafter, "fishers") and recreational anglers (hereafter, "anglers"), especially when fish stocks are declining (Arlinghaus et al., 2022; Bavinck, 2005; Harrison & Loring, 2014; Kearney, 2002). The key structuring role of space (Lorenzen et al., 2010) necessitates spatially explicit fishery assessments to understand sector-specific spatial exploitation patterns and their potential impacts on metapopulations and user benefits in light of equity concerns. Expanding from a single-population paradigm to managing spatially structured fish populations as metapopulations (Hanski, 1999) has been increasingly emphasized (Bradford & Braun, 2021; Hutchinson, 2008; Kritzer & Sale, 2004; Lamarins et al., 2025; Radici et al., 2023; Schtickzelle & Quinn, 2007). Examples highlighting the need for spatially explicit management are emerging in a wide range of managed marine and freshwater ecosystems (Hayden et al., 2015; Kritzer & Sale, 2006; Robichaud & Rose, 2004; Ying et al., 2011).

One example of a spatially structured, conflict-prone fisheries system is the coastal Northern Pike *Esox lucius* (hereafter, "pike") fishery in the brackish lagoons of the southern Baltic

Sea around the German island of Rügen (so-called "Boddens"; Arlinghaus, Braun, et al., 2023; Arlinghaus, Koemle, et al., 2023; Arlinghaus, Rittweg, et al., 2023). The network of Boddens—different lagoons that vary in trophic state and that have an average salinity low enough to allow colonization by primary freshwater fishes (Arlinghaus, Rittweg, et al., 2023; Schubert & Telesh, 2017)—constitutes distinct fishing grounds connected by movements of fish, natural fish predators, fishers, and anglers. The Boddens are well known among anglers for having a high abundance of trophy pike; this reputation laid the foundation for the development of angling tourism in the region (Koemle et al., 2021, 2022). Around Rügen Island, pike have traditionally also been a relevant target of a small-scale commercial multispecies fishery (Arlinghaus, Rittweg, et al., 2023) that primarily uses passive gear types (e.g., gill nets, longlines, and fyke nets) to catch a variety of freshwater predatory fish, such as pike, Zander *Sander lucioperca*, and European Perch *Perca fluviatilis*, as well as seasonally available Atlantic Herring *Clupea harengus* (Arlinghaus, Rittweg, et al., 2023; van Gemert et al., 2022; Winkler, 1991). Commercial pike landings around Rügen Island have strongly declined from 200 to 300 metric tons of annual pike yield in the 1950s (Porada, 2009; Schlumpberger et al., 1966) to less than 50 metric tons in recent years (Arlinghaus, Rittweg, et al., 2023). Reasons include a restructuring of the commercial fishery after the German reunification in 1990 (Arlinghaus, Rittweg, et al., 2023; Fitzgerald et al., 2023; Olsson et al., 2023; van Gemert et al., 2022). Anglers, angling guides, and fishers have also observed a decline in the Bodden pike metapopulation, indicated by decreasing catch rates and decreasing mean sizes of caught pike (Arlinghaus, Rittweg, et al., 2023; van Gemert et al., 2022). The declining trend in pike catches in the Bodden lagoons has fueled an allocation conflict between fishers and anglers, reflected in intense debates among user groups about the core drivers and possible solutions going forward (Arlinghaus et al., 2022). Following reports of the decline of the Bodden pike fishery, the recreational tourism sector has also experienced a reduction in activity in recent years, with an increasing number of angling guides and boat rental businesses withdrawing from the market.

The spatial structure of the coupled social–ecological system affects the ecology of the lagoon pike metapopulation around Rügen Island. Pike benefit from seasonal migrations of Atlantic Herring, which enter the lagoons in large numbers during the spring (Winkler, 1987). However, declining Baltic herring stocks (International Council for the Exploration of the Sea, 2025) may have reduced prey availability for pike in the Boddens. Since 1990, abundance of natural predators such as great cormorants *Phalacrocorax carbo* and gray seals *Halichoerus grypus* has increased, although their numbers vary widely among the lagoons (Arlinghaus, Braun, et al., 2023; Arlinghaus, Rittweg, et al., 2023), possibly creating spatial variation in predation pressure and natural mortalities in the lagoon network. Importantly, although pike may disperse along fitness gradients among different localities (Haugen et al., 2006), recent biotelemetry studies and genetic and genomic studies have documented sedentary pike behavior (Dhellemmes et al., 2023) and limited exchange of individuals between different lagoons around Rügen Island (Lukyanova et al., 2024). The localized movement patterns result in primarily localized population dynamics, underlying the development of behaviorally and genetically differentiated ecotypes (Rittweg, Trueman, Wiedenbeck, et al., 2024; Roser et al., 2023). Despite the spatial structure in its population dynamics, the data-poor Bodden pike stock is currently managed as one homogeneous unit with, for example, minimum length limits (for fishers and anglers) and daily bag limits (for anglers) applying uniformly in all lagoons (Arlinghaus, Braun, et al., 2023; Arlinghaus, Rittweg, et al., 2023). However, the low ecological connectivity and mainly localized movements of Bodden pike restrict their potential for recolonizing different lagoons and increase their vulnerability to local overfishing and depletion in specific lagoons, which challenges the current spatially homogeneous lagoon management policy (Lukyanova et al., 2024).

Multiple causes have been proposed as contributing to the decline of Baltic Sea pike stocks (Olsson et al., 2023), including environmental changes, such as warming (Berggren et al., 2022) and loss of aquatic macrophytes through eutrophication (Lehtonen et al., 2009; Winkler & Debus, 2006), natural predation by great cormorants and gray seals (Arlinghaus et al., 2021; Bergström et al., 2022), egg and larval predation by a rising Threespine Stickleback *Gasterosteus aculeatus* population that spatially overlaps with spawning pike in spring (Bergström et al., 2015; Byström et al., 2015; Nilsson et al., 2019), loss of spawning habitats through coastal development and obstruction of tributaries used for spawning (Engstedt et al., 2018; Psuty et al., 2023; Roser et al., 2023), and overfishing (Fitzgerald et al., 2023; van Gemert et al., 2022). However, scarce monitoring in many coastal areas of the Baltic Sea has hindered a meaningful pike stock assessment (Olsson et al., 2023). A crucial step enabling managers to address commercial–recreational fishing conflicts is to conduct a spatial assessment of status and trends and to gain spatially explicit knowledge about fishery sector-specific fishing mortality rates (Walters & Martell, 2004). Past research has shown that the Bodden pike stock at large is slightly growth-overfished (Fitzgerald et al., 2023; van Gemert et al., 2022), but knowledge about the relative contributions of the commercial and recreational fishing sectors at the lagoon level is lacking.

Here, we develop a spatially explicit assessment of social–ecological status and trends in the mixed commercial–recreational coastal fishery for pike in the southern Baltic Sea of Germany using a range of ecological and social indicators. We quantified these indicators for five major coastal lagoons (i.e., Bodden areas, Figure 1) as geographical units, and we addressed spatial differences in (1) user-group-specific pike fishing mortality, (2) natural mortality of pike, (3) spatial use preferences by fishers and anglers, and (4) trends in pike landings. By relying on an extensive mark–recapture study, recognized to provide reliable direct estimates of instantaneous fishing mortality rates (F) in inland, coastal, and marine systems (e.g., Allen & Hightower, 2010; Pine et al., 2003; Simpfendorfer et al., 2005; Walters & Martell, 2004; Williams et al., 2002), we estimated F acting on pike separately for fishers and anglers for each Bodden area. We also estimated

Bodden area-specific natural mortality (*M*) for local pike substocks, derived from a geographically distributed catch-curve analysis. To capture the social importance of Bodden areas for specific user groups, we analyzed extensive survey data from fishers and anglers to identify which Bodden areas were preferentially targeted by each group. Finally, we evaluated stock status and trends by comparing current fishing mortality estimates with reference points and analyzing a time series that encompassed over 50 years of commercial landings within each Bodden area. All spatial indicators were integrated into an overall assessment of spatial differences in use, exploitation, and status of the pike stock around Rügen Island to inform ongoing local fisheries management reform and to help address fisher–angler conflicts.

Methods

Study area

The Bodden waters are shallow, productive, soft-bottom estuarine lagoons located around the German islands of Hiddensee, Rügen, and Usedom, and the Fischland-Darß peninsula in the southern Baltic Sea (Schubert & Telesh, 2017; Figure 1). The entire lagoon area covers approximately 2,000 km², of which 1,600 km² are within German territory. For subsequent analyses, we distinguish five geographic subunits (hereafter, "Bodden areas") that differ along environmental gradients in nutrient status, turbidity, salinity, and predation pressure by great cormorants and gray seals, as well as having differential local use and associated fisheries pressure: Darß-Zingst Bodden Chain (DZBC), Western Rügen Bodden Chain (WRBC), Northern Rügen Bodden Chain (NRBC), Greifswalder Bodden (GB), and Peenestrom/Achterwasser (PAW; Figure 1).

The lagoons receive freshwater inflow from connected streams and rivers but have limited hydrodynamic exchange with the adjacent Baltic Sea (Kjerve, 1986; Schubert & Telesh, 2017), resulting in year-round average oligohaline to mesohaline (3–9-psu) conditions that are suitable for a range of freshwater and marine species (Arlinghaus, Braun, et al., 2023). All lagoons are shallow (mean water depth = 2–6 m), polymictic ecosystems characterized by high primary productivity (eutrophic to hypertrophic; 40 μg/L to over 100 μg/L total phosphorus content), soft-bottom substrates, and low to medium macrophyte coverage (Arlinghaus, Braun, et al., 2023; Roser et al., 2023). There is a salinity gradient from the western (oligohaline) to the eastern (mesohaline) DZBC and from the northwest (higher mesohaline levels in the WRBC and NRBC) to the southeast (lower mesohaline levels in GB and oligohaline levels in the PAW) subunits (Figure 1). The PAW and the most hydrodynamically isolated western DZBC are hypertrophic in response to extensive past nutrient inputs, while the other Bodden areas are currently mesotrophic to eutrophic (see Arlinghaus, Braun, et al., 2023; Arlinghaus, Koemle, et al., 2023; and Arlinghaus, Rittweg, et al., 2023 for detailed background data).

Study species

The phytophilic Northern Pike, the focal species of this study, is a circumpolarly distributed freshwater piscivore in the Northern Hemisphere (Craig, 1996; Skov & Nilsson, 2018), where it inhabits most lentic and slow-flowing freshwater and

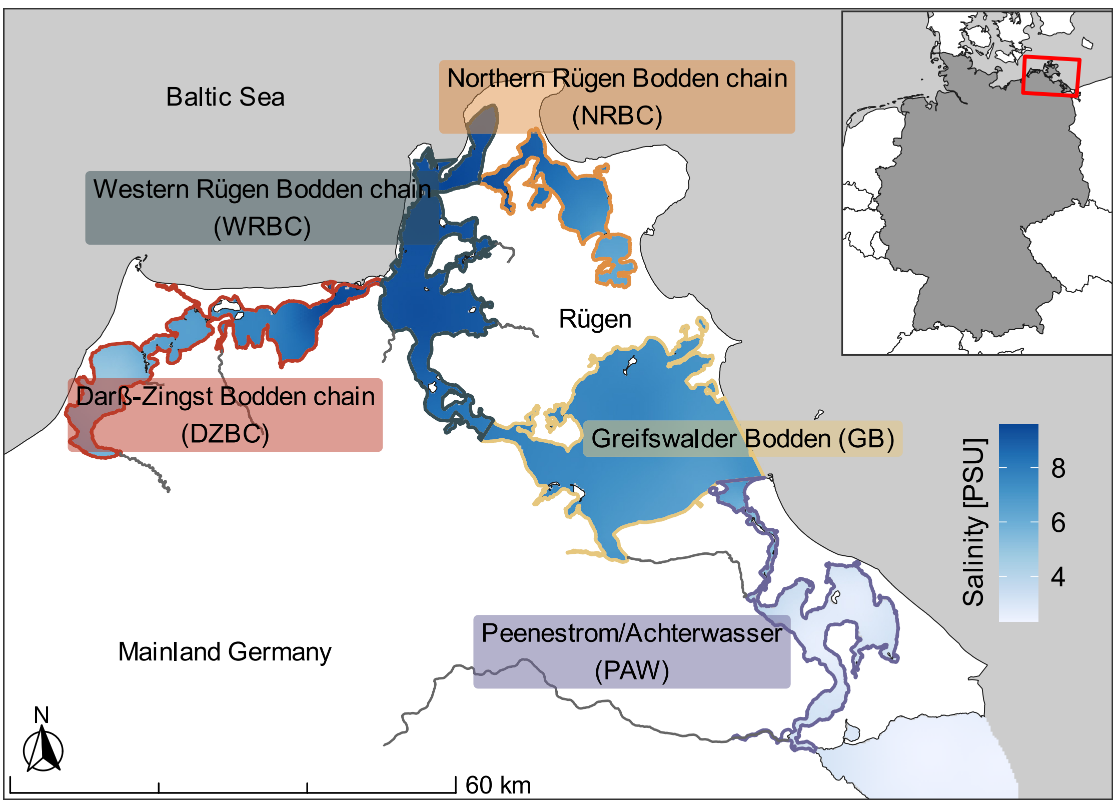

Figure 1 Bodden lagoons around the German island of Rügen in the southern Baltic Sea. Colored lagoons refer to spatially differentiated Bodden areas as used in the analyses.

inshore coastal water bodies up to an average salinity of 10 psu (Skov & Nilsson, 2018). Despite being considered a freshwater species, pike are able to tolerate, spawn in, and recruit in mesohaline brackish conditions in vegetated inshore areas of the Baltic Sea (Arlinghaus, Rittweg, et al., 2023; Larsson et al., 2015; Rittweg, Trueman, Wiedenbeck, et al., 2024; Sunde et al., 2022). Pike have colonized all five Bodden areas, with the greatest abundances observed in the less eutrophicated WRBC, NRBC, and GB (Arlinghaus, Braun, et al., 2023). Across the study area, pike constitute a target of recreational and commercial fisheries (Arlinghaus et al., 2021; van Gemert et al., 2022; Winkler, 1991). In recent years, approximately 50,000 Bodden anglers dedicated roughly 200,000 angling days/year exclusively to pike fishing (Weltersbach et al., 2021) over a lagoon area of about 1,600 km^2. Half of the total angling effort is exerted by 75% of tourist (nonresident) anglers who also contribute local economic revenue (Strehlow et al., 2025). Many tourist anglers who target pike are highly involved and seek large-sized pike (Koemle et al., 2022, 2024). Angling tourism is facilitated by the provision of infrastructure, including boat rentals, lodging, and guide services. There is also a relevant demand for pike fishing by resident anglers, who are often more harvest oriented than tourist anglers (Koemle et al., 2022, 2024). In the regional commercial fisheries, pike are primarily caught in a multispecies gill-net fishery that targets several freshwater fishes (Arlinghaus, Rittweg, et al., 2023).

Current fisheries regulations for pike in the Bodden areas include a minimum length limit of 50 cm, a minimum mesh size of 100 mm (stretched mesh) for gill nets targeting pike in the commercial fishery, and a daily bag limit of 3 pike/angler. There is no quota for pike in the commercial fishery. Regulations also include a seasonal closure of the pike fishery from March 1 to April 30 and several restricted-access zones, such as no-take zones, spawning reserves (April–May), winter refuges, and other nature conservation areas, where fishing is either fully or seasonally prohibited or permitted only for fishers with special licenses. Furthermore, commercial fishing effort is limited by fisher and lagoon, including capping the total length of gill nets allowed for a given fisher in a given area (Arlinghaus, Braun, et al., 2023; Ehrlich, Bath, et al., 2023).

Social importance: Spatial use preferences by anglers and fishers

We designed and administered surveys to assess which lagoon areas were preferential fishing environments for fishers and anglers. Between November 2020 and April 2021, an online survey was conducted among 1,846 German pike anglers (14 years of age or older) who targeted predatory fish species (e.g., pike, European Perch, or Zander) in the Bodden waters. This sample of anglers was generated using multiple recruitment channels, including contacting a list of anglers who previously had indicated their willingness to participate in scientific studies in the coastal region of the study area, as well as advertising campaigns on social media platforms, in printed fishing journals, and in angling shops. Fieldwork was carried out by a professional polling institute (imug, Hannover, Germany) based on questionnaires designed by the authors. Compared with the unknown population of anglers, the online sample was potentially biased toward more active anglers; therefore, respondent weights were assigned in accordance with known distributions of key characteristics (avidity in terms of fishing effort, gender, age, school education, vocational education, employment status, household size, and residency) that were derived from a random sample of German coastal/Bodden anglers (Weltersbach et al., 2021). We report weighted data that are assumed to be representative of the targeted angler population and thereby compensate for the self-selection bias associated with online surveys. Every respondent was incentivized with a €10 voucher for an online angling shop and participation in a lottery for high-quality angling gear (for details, see Arlinghaus, Braun, et al., 2023; Koemle et al., 2022; Slaton et al., 2023). The survey asked a series of questions about demographics, fishing styles, area preferences, and other topics. For this paper, we analyzed angler responses to a question asking for the main Bodden area used for pike fishing over the past 5 years. Data were analyzed separately for (1) anglers with residency in Mecklenburg-Western Pomerania (Mecklenburg-Vorpommern; hereafter, "resident anglers"), the state bordering the lagoons, and (2) anglers originating from other German states (hereafter, "tourist anglers"). In addition, a mail survey was carried out between November 2021 and April 2022 among all 316 commercial fishers registered in Mecklenburg-Western Pomerania who fished the state's coastal and Bodden waters. Completed questionnaires were received from 118 of these fishers (a 37% response rate). Survey data from fishers were not weighted in subsequent analyses, as there were no independent reference values for key variables describing this population of fishers. However, given the high response rate, we assumed that the data were representative of the fisher population. To obtain a spatially distributed picture of commercial fishing activities, the fishers were asked to indicate the Bodden areas that they usually targeted. Survey data were then aggregated to the spatial level of the five geographic Bodden areas represented in Figure 1. Responses that indicated other preferred fishing areas not covered by our study area (e.g., Stettiner Haff) were not included in the analysis.

Estimating total mortality from catch-curve analyses

In many fished stocks, the adult-stage natural mortality M and fishing mortality F additively contribute to total instantaneous mortality ($Z = F + M$; Ricker, 1975), which also holds for adult pike (Allen et al., 1998). For a continuous fishery system where M and F operate concurrently (type 2 fisheries; Allen & Hightower, 2010; Ricker, 1975), estimating area-specific Z from catch data via the sequential decline in cohorts of fish (Miranda & Bettoli, 2007; Ogle, 2016) in combination with mark–recapture-based exploitation estimates allows for disentangling F from M (see below). Catch-curve analyses (Miranda & Bettoli, 2007; Ogle, 2016) were performed to estimate Z within each Bodden area. Each catch curve represents a frequency distribution of the sequentially declining number of fish per age-class beyond a minimum age (i.e., above the selective size limit of the sampling gear). This pattern suggests a consistent annual mortality rate across ages and time (Chapman & Robson, 1960), with the slope of the catch corresponding to Z.

We used length data available for the 4,619 pike that were sampled for a mark–recapture experiment between 2020 and 2022 with a multitude of gears (angling, gill nets, and fyke nets), which were assumed to be nonselective for adult pike larger than 50 cm total length (Arlinghaus et al., 2009; Pierce et al., 1994). These data were used to generate separate catch curves for each Bodden area. The total length of each pike was translated into an age-class based on sex-specific length–age keys. Length–age keys were developed for a subsample of 932 pike ($n = 439$ males; $n = 493$ females) sampled from the Bodden lagoons between 2019 and 2022 based on age assignments from scales ($n = 812$ individuals) and otoliths ($n = 120$ individuals, corroborated via oxygen isotope ratios; Rittweg, Trueman, Ehrlich, et al., 2024). Body length measurements ranged from 143 to 1,240 mm total length and were categorized into 50-mm bins. The sex-specific probability tables $P(\text{age}|\text{length})$, based on observed data from 932 pike, were smoothed across adjacent length-classes using generalized additive models to reduce sampling noise and avoid zero probabilities prior to individual age assignment (Supplementary Figure 3). We used the alkIndivAge() function from the R package FSA (Ogle et al., 2023) for individual age assignment based on sex-specific, smoothed age–length keys, describing the conditional probability $P(\text{age}|\text{length})$. To propagate uncertainty associated with this probabilistic assignment, the 4,619 pike belonging to the unaged sample were repeatedly assigned to age-classes by sampling from a probabilistic age distribution conditional on length. This procedure was repeated for 1,000 iterations, resulting in 1,000 realized age data sets. Subsequently, for each realized data set, we fitted catch curves using generalized linear mixed-effects models with a negative binomial distribution (Mainguy et al., 2024) and catch data as response:

$$C \sim \text{age} + b + (\text{age} \times b) + (1 \mid y) + (1 \mid y \times b),$$

where C = catch (number of individuals), age = age-class, and b = specific Bodden area. Sampling year $(1|y)$ and its interaction with Bodden area $(1|y \times b)$ were included as random effects to account for varying overall catch sizes across years and areas (i.e., year- and area-specific intercepts of the catch curve). The interaction term age $\times\, b$ allowed us to differentiate for varying slopes in the catch curves across different Bodden areas. For the catch-curve regressions, only sampling years with a sample size greater than 50 individuals were considered. Furthermore, only age-classes of 5 years or older were included, representing fish that are fully susceptible to the fishing gears employed. Additionally, age-13 and older fish were excluded from the analysis, as these age-classes represented the upper limit in the length–age keys, potentially causing confusion by grouping age-13 and older fish into a single class.

Following repeated catch-curve calculations, Z-estimates were extracted from each model iteration ($n = 1{,}000$) as marginal slopes of the age effect using the emtrends() function from the R package emmeans (Lenth & Piaskowski, 2026). Slopes were estimated separately for each Bodden area. Subsequently, Z-estimates were averaged across iterations for each Bodden area, and corresponding 95% confidence intervals (CIs) were calculated to represent uncertainty propagated from the probabilistic age assignment to the catch-curve fitting.

Estimation of fishing mortality and natural mortality rates from combining catch-curve analysis with mark–recapture data

To estimate spatially explicit F and M, the catch-curve analysis was complemented by direct estimations of the fisheries exploitation rates (u; percentage of pike harvested per unit of time, usually per year) through a mark–release–recapture approach (Allen & Hightower, 2010). By comparing the recaptured individuals to the number of marked fish (after controlling for underreporting, tagging-induced mortality, and tag loss; see below), mark–recapture studies allow for estimating fishing removals and quantifying F with relatively good precision, provided they are informed by adequate sample sizes and recapture rates (Allen & Hightower, 2010; Ricker, 1975). Mark–recapture approaches require extensive field efforts to capture, individually mark, and monitor recaptures of fish (Pine et al., 2003), which can only be realized in large coastal areas if users participate in monitoring and reporting programs.

From January 2020 to the end of 2022, 4,735 pike were externally marked with individual Floy tags (Floy Tag & Manufacturing Inc., Seattle, Washington, USA) by the research team in collaboration with specially trained angling guides and a contracted fisher (Figure 2). On average, 132 pike (standard deviation [SD] = ±131) were tagged per month (Supplementary Figure 1). The number of tagged pike varied across the Bodden areas, ranging from 256 in the PAW to 2,204 in the WRBC (Supplementary Table 1). Variations in these tagging numbers reflect differences in habitat suitability and sampling effort across the Bodden areas, with the WRBC representing our prime study area. Fishers and anglers who recaptured marked fish were encouraged to report tagged-pike recaptures and their corresponding capture locations via a dedicated website or by calling a project telephone number printed on each tag. The project was extensively advertised in the region through media reports, signs at harbors, fishing shops, a project website, social media, podcasts, and local seminars. To facilitate tag-reporting rate estimation, a high-reward study component was added (Pollock et al., 2001, 2002). Approximately 8% ($n = 389$) of the pike were tagged with a high-reward tag, which was visually distinct (white) from the standard tags (orange) and had a different reward label printed on it (Supplementary Table 1; Figure 2). Individuals who reported a pike with a high-reward tag earned €100. We initially assumed a 100% reporting rate of fish with this tag (see Pollock et al., 2001, 2002). In subsequent analyses, we relaxed this assumption and adjusted reporting rates for high-reward tags due to anecdotal reports and direct observations of recaptures of high-reward tags on social media that were not reported (see below). Pike that were recaptured during scientific sampling with angling gear outside the closed season (Roser et al., 2025), where ordinary anglers were part of the sampling efforts, were treated similarly to regular angler catches in subsequent analysis of u. By contrast, scientific recaptures from other study-related efforts (such as electrofishing in streams, scientific fyke-netting, and

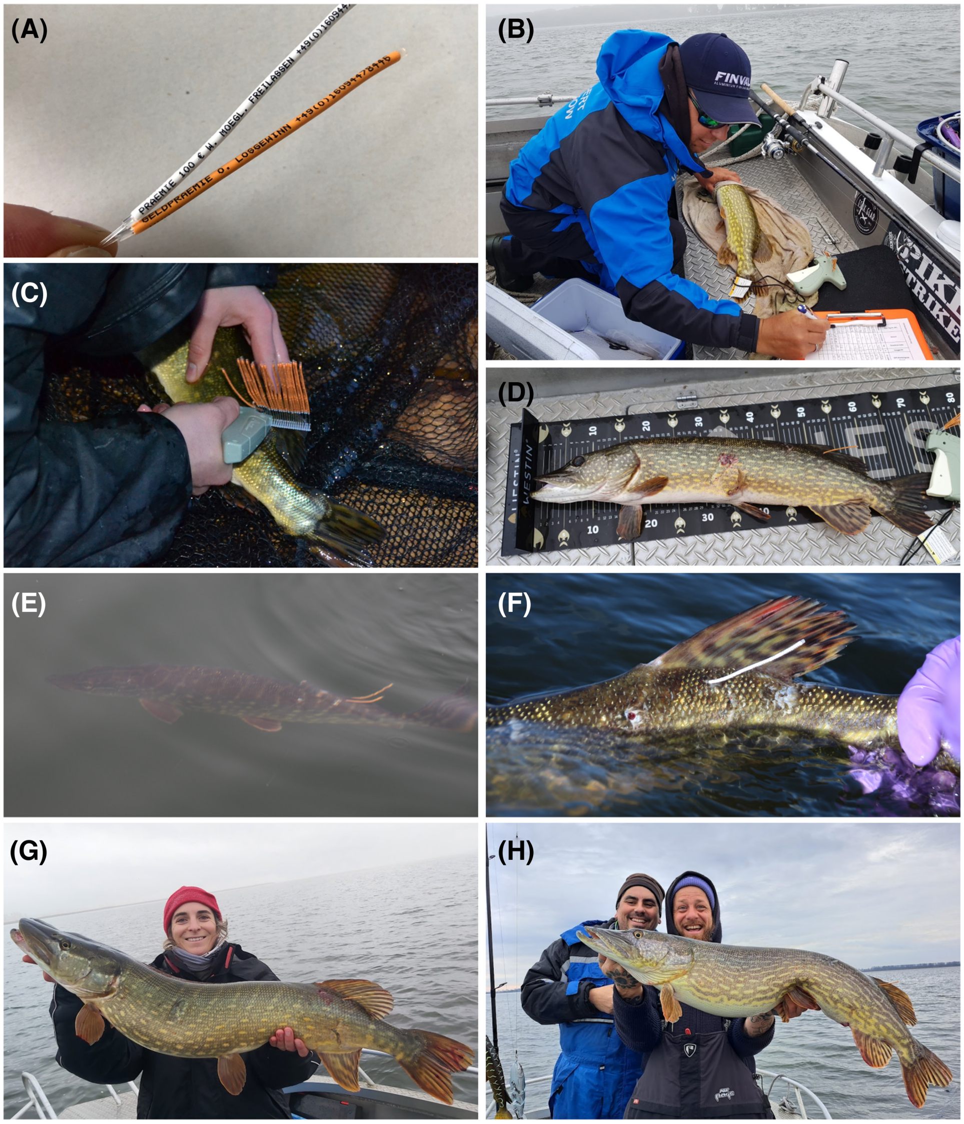

Figure 2 Northern Pike were (A)–(D) marked with external standard tags (orange) and high-reward tags (white) and (E), (F) released. (G), (H) Commercial fishers and recreational anglers could report recaptures of the tagged Northern Pike and their respective capture locations. (Photos by D. Niessner [A, C, E, and F], R. Balkow [B], and IFishMan/Boddenhecht [D, G, and H].)

scientific angling during the closed season) were separated and not included in the estimation of u.

The exploitation rate (u) was calculated from the collective mark–recapture data for the entire study area as well as separately for single Bodden areas (b) and was stratified by user groups (g; recreational anglers [rec] and commercial fishers [com]) based on equations reported by Allen and Hightower (2010):

$$u_{b,g} = \left(C_{b,g} \times \lambda.corr_g\right) / T.corr_b,$$

where $C_{b,g}$ = number of reported recaptures per user group and area, $\lambda.corr_g$ = corrected reporting rate for each user group, and $T.corr_b$ = number of tagged fish in each area (T_b) available for recapture, including correction for potential tag loss (Tl), tagging mortality (Tm), and hooking mortality (Hm; for recreationally angled and released pike). Specific parameter values for Tl, Tm, and Hm are described below. Given the restricted movement and exchange of pike across lagoons as revealed by acoustic telemetry (Lukyanova et al., 2024), the effects of migration on the tags available to be recaptured were not considered in the estimation of u. The value $T.corr_b$ was calculated as (Gwinn, 2014)

$$T.corr_b = T_b \times (1 - Tl) \times (1 - Tm) \times (1 - Hm).$$

Tag reporting rates (λ), which refer to the proportion of recaptured fish that are reported (Pollock et al., 2001, 2002), were calculated for the entire study area and separately for fishers and anglers based on the number of released and reported tags of two different types (the orange, standard tag and the white, high-reward tag; Figure 2):

$$\lambda = \left(C_s / T_s\right) / \left(C_h / T_h\right),$$

where C_s = number of reported fish with standard tags, T_s = total number of fish with standard tags, C_h = number of reported fish with high-reward tags, and T_h = total number of fish with high-reward tags. Tag reporting rates are known to depend on tag type and visibility as well as angler/fisher willingness to report (Pollock et al., 2001, 2002). Although high-reward tags are commonly used to incentivize reporting (Pollock et al., 2001, 2002), a 100% reporting rate cannot be guaranteed, as some anglers and fishers may not report fish, regardless of the reward, or the tags may be overlooked. Therefore, the reporting rate for €100 high-reward tags was conservatively estimated to be 80% based on a previously reported reward–return relationship and by back-calculating the equivalent of a €100 reward in 2022 using the Consumer Price Index (Henry, 2003; Nichols et al., 1991). Consequently, the calculated tag reporting rates were adjusted as

$$\lambda.corr = \lambda \times 0.8.$$

To account for uncertainties in tagging mortality, tag loss, hooking mortality, and reporting rates, a resampling approach was applied to these model input parameters (Gwinn, 2014). Specifically, repeated model calculations ($n = 1{,}000$ iterations) of u were conducted in which a value for these potential uncertainties was determined from a descriptive probability distribution (Supplementary Figure 2). We set the annual tag loss rate to a mean value of 12.5% (95% CI = ±11.7%; Hühn et al., 2014), and average tagging mortality was assumed to be 10% (95% CI = ±5%; Hühn et al., 2014). Time since tagging (d) for each individual fish was calculated to estimate the probability of tag loss. Hooking mortality rate was informed by Hühn and Arlinghaus (2011) and was set at a mean of 7.1% with an SD of 13% (equivalent to the reported standard error of 5.3%). The correction factor for the reporting rate was described using a triangular probability distribution with a mode of 0.8 and a range of 0.5–1.0 (i.e., assuming a maximum reporting rate between 50% and 100% for high-reward tags).

To calculate user-group-specific values of u, particularly angler-specific u_{rec}, two scenarios were considered. In scenario A (potential exploitation), all anglers' recaptures, regardless of subsequent live release, were treated as removals because study participants were encouraged to release tagged pike to ensure continued data provision, potentially influencing them to release fish that they might have otherwise removed. In scenario B (actual exploitation), released pike were excluded from the calculation of u, but the delayed hooking mortality Hm (mean = 7.1%; Hühn & Arlinghaus, 2011) was accounted for in the calculations.

As part of the repeated model calculations, values of u were transformed into estimates of F by considering the relationships that apply to systems where M and F operate concurrently (type 2 fisheries; Allen & Hightower, 2010; Ricker, 1975). For a mixed continuous fishery with F-estimates for anglers and fishers, the total instantaneous mortality (Z) per year and the annual total mortality rate (A) can be expressed as

$$Z = F_{\text{rec}} + F_{\text{com}} + M,$$

$$A = 1 - e^{-\left(F_{\text{rec}} + F_{\text{com}} + M\right)}.$$

Here, Z was assumed constant over the period represented by the data that were used to fit the underlying catch curves (~13 years). The u for a specific user group g is defined as (Pine et al., 2003; Ricker, 1975):

$$u_g = \frac{F_g \times A}{Z} = \frac{F_g \times \left[1 - e^{-\left(F_{\text{total}} + M\right)}\right]}{F_{\text{total}} + M}.$$

Because Z was estimated externally through a catch-curve analysis (see the previous section), the equation can be rearranged to solve for user-group-specific F:

$$F_{\text{rec}} = \frac{u_{\text{rec}} \times Z}{A},$$

$$F_{\text{com}} = \frac{u_{\text{com}} \times Z}{A}.$$

Consequently, M can be estimated as a residual component:

$$M = Z - \left(F_{\text{rec}} + F_{\text{com}}\right) = Z - \frac{\left(u_{\text{rec}} + u_{\text{com}}\right) \times Z}{A}.$$

Following the repeated model calculations, results of instantaneous F_{com} (fishers), F_{rec} (anglers; separately for scenarios A [$F_{\text{rec-A}}$] and B [$F_{\text{rec-B}}$]), and M were averaged, and the corresponding 95% CIs were calculated to account for uncertainty inherent in the input parameters.

Pearson's correlations were calculated to link F_{rec} and F_{com} in each Bodden area to the spatial use preferences (in percentage of each user group preferring a specific lagoon area) of each user group for that specific Bodden area. Additionally, the proportion of fishing mortality induced by recreational angling on total fishing mortality ($F_{\text{rec}}/F_{\text{total}}$) within each Bodden area was correlated with the preferences of anglers for a specific Bodden area. We also assessed whether the estimated F by Bodden area exceeded maximum sustainable yield (MSY)-based reference points following Zhou et al. (2012), who found in a meta-analysis that optimal sustainability was achieved when F was less than $0.87M$.

Trend indicators of commercial pike landings

A time series of annual commercial pike landings spanning from 1968 to 2022 was collated based on data from the State Office for Agriculture, Food Safety, and Fisheries (Landesamt für Landwirtschaft, Lebensmittelsicherheit und Fischerei Mecklenburg-Vorpommern; 1976–2022); data from Winkler (1991; 1968–1975); and data from annual fisheries reports published by the Institut für Hochseefischerei und Fischverarbeitung Rostock of the former German Democratic Republic (van Gemert et al., 2022). The data set only included landings (kg) reported by commercial fishers per fisheries district and did not cover any angling catches. To ensure compatibility with further analyses, yearly landings were aggregated to the spatial units of the Bodden areas (Figure 1). However, the WRBC and NRBC have been treated as a single spatial unit in the landings statistics (Fisheries District 5: water bodies between Hiddensee and Rügen islands) and therefore were considered a combined spatial unit (NWRBC) in subsequent analyses. Bodden-specific pike landings were expressed as relative landings per unit area (kg/ha). For each Bodden area, the long-term trend of the area-standardized landings was estimated using the slope of a linear regression (landings ~ year). Additionally, to assess the current pike landings status within each Bodden area, the current Bodden-specific mean landings over the three most recent years (2020–2022) were calculated as a relative share of the overall Bodden-specific long-term mean (1968–2022), analogous to Hilborn et al. (2020). Furthermore, the current Bodden-specific mean landings were categorized relative to their historic maxima (Kleisner et al., 2013; Supplementary Table 3). Following Kleisner et al. (2013), the current status of each Bodden area was considered "fully exploited" when current area-specific landings (over the study years 2020–2022) exceeded 50% of their long-term maximum (from 1968 to 2022). The landings status was categorized as "overfished" when current landings were between 10% and 50% of the historic maximum, and the status was designated as "collapsed" when current landings were below 10% of the historic maximum (Froese & Kesner-Reyes, 2002; Kleisner et al., 2013). We recognize the limitations of using landings statistics as a surrogate for stock status, given the absence of appropriate effort data (e.g., number of pike gill nets deployed) matching the temporal and spatial resolution of the catch time series. Accordingly, we interpret landings-based indicators as comparative measures of yield status among lagoons within a common analytical framework rather than as direct indicators of fishery status.

Composite index of spatial social–ecological use and status of lagoon pike

We developed a composite assessment index to facilitate a comparative, qualitative benchmarking of the five Bodden areas given their relevance to users, status, and varying pressures. For each Bodden area, the user-group-specific fishing mortalities (F_{rec} and F_{com}), the natural mortality rate (M), F_{total} relative to M, the use preferences by anglers and fishers (as social indicators), and the long-term trend of the pike landings were normalized into indices ranging from 1 to 5:

$$x_{scaled} = 1 + \frac{(x - x_{min})}{(x_{max} - x_{min})} \times 4.$$

The landings indicator, which compares the current status to the historical maximum, follows the original classification into five classes by Kleisner et al. (2013) as described above (see Supplementary Table 3). In all indicators, larger values reflect more severe conditions (such as higher F and steeper landings declines). A visualization of the composite index of pike use with its underlying indicators (similar to Halpern et al., 2012) served to address Bodden-specific factors contributing to the ongoing fisheries conflict and to derive potential management recommendations. Areas where all indicators show high values would indicate areas with particularly strong conflict potentials (high social importance but also a high rate of exploitation) and current threats.

Results

Spatial use preferences by anglers and fishers

The different lagoon areas varied in their attractiveness to tourist anglers, resident anglers, and fishers. Of the five studied Bodden lagoons, the WRBC was the area most preferred by both resident anglers (40%) and tourist anglers (44%) for pike fishing over the past 5 years, as revealed from the angler survey (Figure 3). The PAW was the Bodden area least sought after by anglers (residents: 9%; tourists: 6%). The importance for angling in the WRBC and NRBC was somewhat greater for tourists (44% and 22%, respectively) compared with resident anglers (40% and 14%, respectively), while the other Bodden areas were comparably more preferred by resident anglers (e.g., GB: residents [25%] vs. tourists [17%]; Figure 3). Fishers mostly fished in GB (36%), while the DZBC was the Bodden area that was least intensively used by fishers (10%; Figure 3).

Fishing mortality rates

By the end of 2022, 618 of the 4,735 tagged pike were recaptured and reported, with 46 pike being recaptured multiple times (up to three times), resulting in a total number reported and identifiable recapture reports of 668 pike. Pike were recaptured and reported during scientific fieldwork ($n = 73$ recaptures), by anglers ($n = 407$ recaptures), and by fishers ($n = 181$ recaptures; Supplementary Figure 1). A few individuals ($n = 7$) were reported as dead recoveries and therefore could not be attributed to any specific user group. The emigration rates from each Bodden area (i.e., recaptures in areas other than the initial tagging area) were generally low, ranging from 0% (recaptures outside the PAW area) to 6.2% (recaptures outside the WRBC). The average number of reported recaptures per month was 19 pike (SD = ±11; Supplementary Figure 1).

The calculation of reporting rates was based on 4,272 pike marked with standard tags and 353 fish marked with high-reward tags. Assuming 100% reporting of high-reward tags, we estimated a 40% tag reporting rate for fishers (32 reported high-reward tags; 155 reported standard tags) and a 77% rate for anglers (38 reported high-reward tags; 353 reported standard tags). Thus, anglers reported substantially more marked pike than were reported by fishers. Assuming an adjusted reporting rate of only 80% for high-reward tags (Henry, 2003; Nichols et al., 1991; see *Methods*), coupled with uncertainties (Supplementary Figure 2), we estimated user-group-specific reporting rates to be 31% (95% CI = 23–38%) for fishers and 59% (95% CI = 43–72%) for anglers.

Values of Z derived from catch curves varied across Bodden areas from 0.37 per year (95% CI = 0.20–0.54) for the PAW to 0.60 per year (95% CI = 0.49–0.70) for the WRBC (mean Z across all Bodden areas = 0.50 per year, 95% CI = 0.43–0.57; Figure 4; Supplementary Table 5). The potential instantaneous F across the entire study area and period, estimated from exploitation rates based on all reported recaptures (with 80% reporting of high-reward tags) without considering releases and combined for both user groups, was 0.20 per year (95% CI = 0.14–0.30; Table 1). For a 100% reporting rate for the

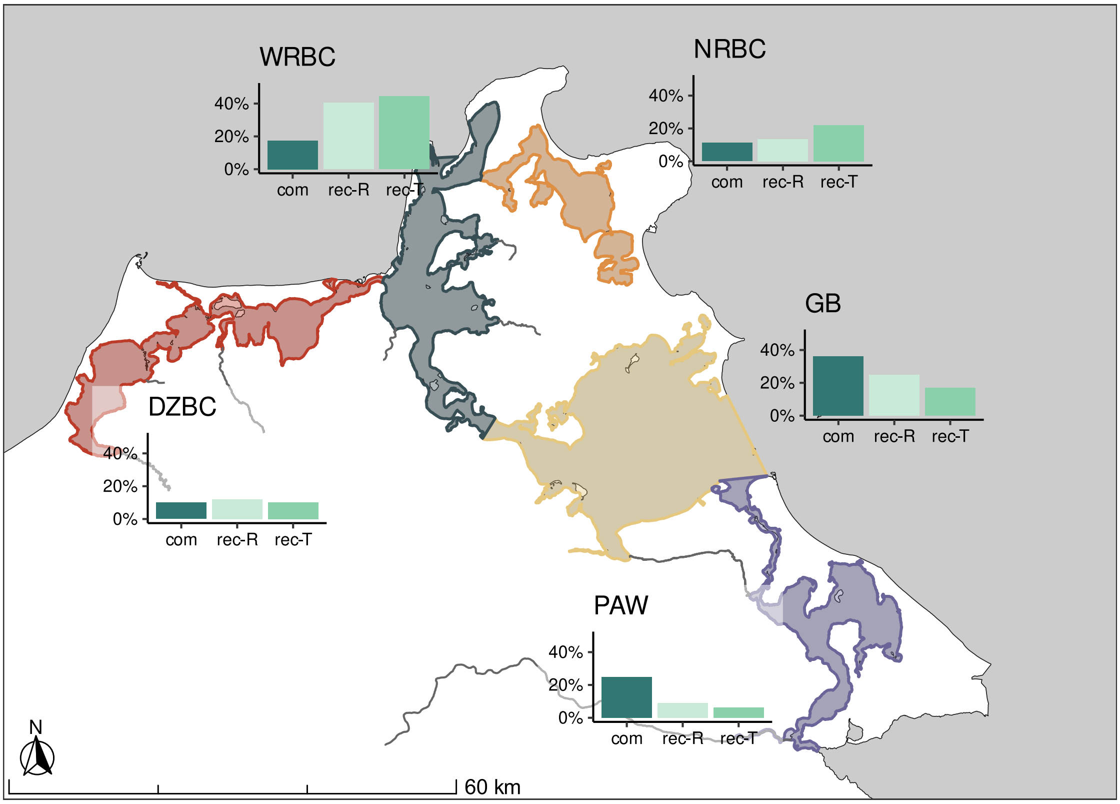

Figure 3 Spatial preferences for a specific Bodden area (Germany) by user groups, as obtained from survey data. Plots show relative frequencies of main fishing areas for commercial fishers (com) and relative frequencies of preferred angling areas for recreational anglers from Mecklenburg-Western Pomerania (resident anglers [rec-R]) and recreational anglers originating from other German states (tourist anglers [rec-T]). Abbreviations are as follows: DZBC = Darß-Zingst Bodden Chain, WRBC = Western Rügen Bodden Chain, NRBC = Northern Rügen Bodden Chain, GB = Greifswalder Bodden, and PAW = Peenestrom/Achterwasser.

high-reward tags, average potential F was estimated as 0.16 per year (95% CI = 0.11–0.24; Table 1). On average, across years and Bodden areas, the potential fishing pressure (based on captures) induced by anglers and that induced by fishers were estimated to be of a similar magnitude, with $F_{\text{rec-A}}$ equal to 0.10 per year (95% CI = 0.08–0.13) and F_{com} also equal to 0.10 per year (95% CI = 0.05–0.18; Table 1). Under otherwise identical model assumptions (e.g., 80% reporting of high-reward tags) but considering releases of pike as reported by the anglers (corrected for hooking mortality), the actual $F_{\text{rec-B}}$ was noticeably lower and was estimated as 0.04 per year (95% CI = 0.03–0.06) across all years and Bodden areas—half as large as F_{com} (Table 1).

Our spatially differentiated estimation of F revealed user-group-specific differences across Bodden areas (Figure 4; Supplementary Figure 5). Over the 3-year study period, the average potential $F_{\text{rec-A}}$ in the DZBC was estimated as 0.16 per year (95% CI = 0.11–0.24), while F_{com} in the same area was negligible and only 0.01 per year (95% CI = 0.00–0.04). By contrast, average F_{com} in the WRBC was estimated as 0.14 per year (95% CI = 0.06–0.24), while potential $F_{\text{rec-A}}$ was estimated to be half that value (0.07 per year; 95% CI = 0.05–0.09). In other Bodden areas, estimated F-values for both user groups were either roughly similar (e.g., the NRBC) or associated with larger uncertainties in assessing the differences between anglers and fishers due to small sample sizes of tagged and recaptured fish. Specifically, uncertainty in estimated F (quantified as the 95% CI of F) among years and user groups was highest for both F_{rec} and F_{com} in GB, whereas uncertainty was lowest in the WRBC for F_{rec} and lowest in the DZBC for F_{com} (Figure 5). Generally, uncertainties in F-estimates were rather stable across years (Figure 5; Supplementary Figure 6) except for the PAW, where the width of the 95% CI of F_{com} dropped from 0.30 in 2020 to 0.08 in 2021 (and was not estimable for 2022 due to no recapture by fishers in that year; Supplementary Table 2).

User-group-specific F-estimates and the corresponding spatial use preferences by a user group for a given Bodden area were not significantly related for either of the two user groups (Pearson's correlation: anglers, $r = -0.52$, $p = 0.37$; fishers, $r = 0.54$, $p = 0.34$; Supplementary Figure 7). Additionally, the proportion of F_{total} induced by anglers was unrelated to the preference for a given area by anglers ($r = -0.68$, $p = 0.21$).

Natural mortality rate

Estimated Bodden area-specific natural mortality (residual mortality; $M = Z - F$) ranged between 0.21 per year (95% CI = 0.00–0.48) in the PAW and 0.39 per year (95% CI = 0.31–0.53) in the WRBC (Figure 6; Supplementary Table 5). Relating the estimates of fishing mortality to the natural mortality within each Bodden area revealed that F was within the range of 52% of M (in the WRBC) to 132% of M (in GB). The F-to-M

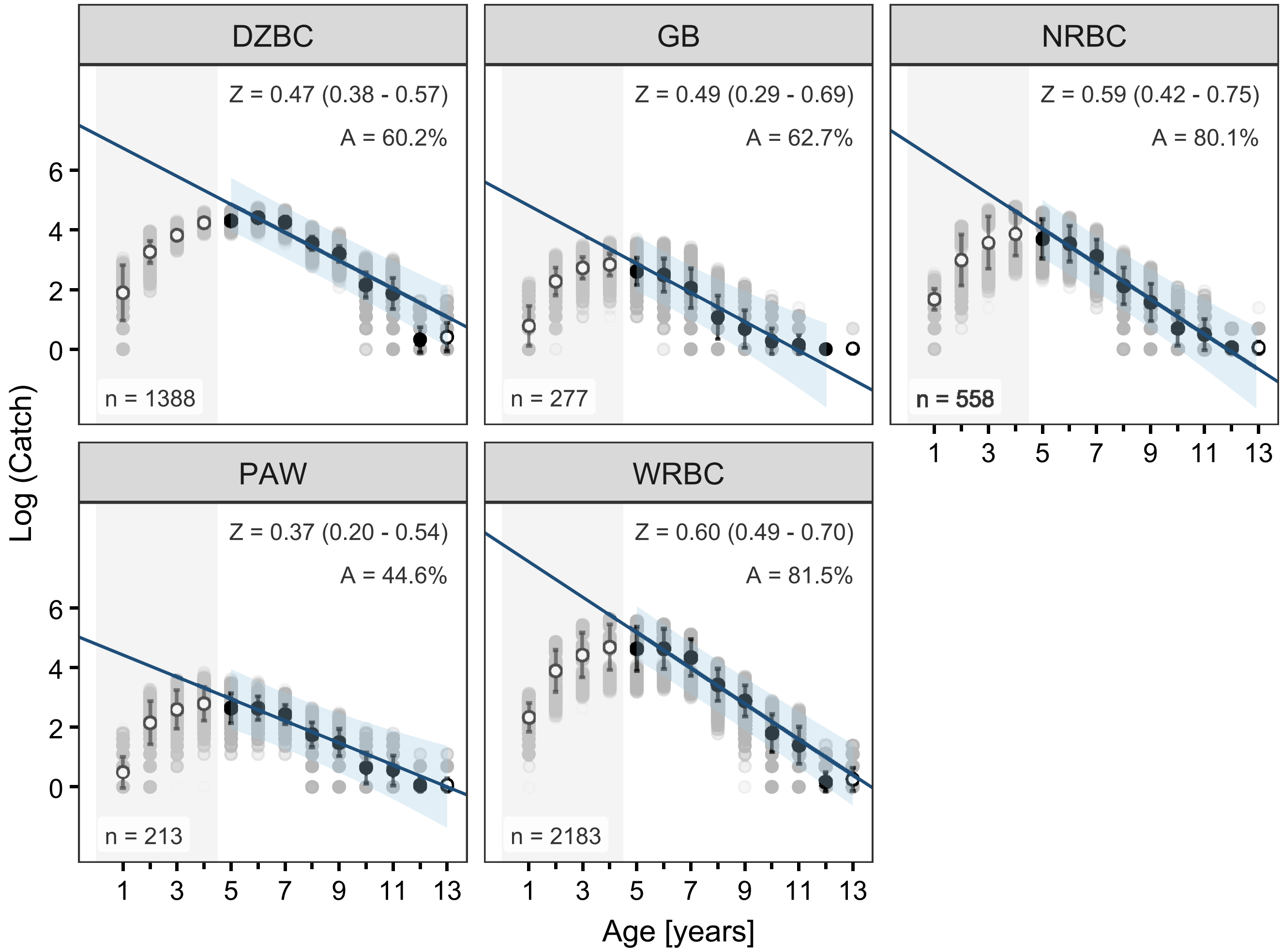

Figure 4 Instantaneous total mortality (*Z*; per year) and corresponding annual mortality rate (*A*; %) of Northern Pike estimated from catch curves across five Bodden areas (Germany). Catch-curve analyses considered only age-classes greater than 5 years (filled circles). Shaded bands (and values in parentheses) indicate the 95% CI of the fitted catch curve across repeated model runs. Abbreviations are as follows: DZBC = Darß-Zingst Bodden Chain, GB = Greifswalder Bodden, NRBC = Northern Rügen Bodden Chain, PAW = Peenestrom/Achterwasser, and WRBC = Western Rügen Bodden Chain.

indicator showed that an optimal reference point (target $F < 0.87M$; Zhou et al., 2012) was surpassed in GB but not in the other Boddens.

Landings status and trends

The time series analysis revealed a significant decrease in commercial pike landings ($p < 0.01$) for the DZBC (-0.014 kg·ha^{-1}·year^{-1}), GB (-0.033 kg·ha^{-1}·year^{-1}), and NWRBC (-0.028 kg·ha^{-1}·year^{-1}). Only the PAW pike landings showed a nonsignificant trend ($p > 0.10$; Supplementary Figure 8). The mean of pike landings between 2020 and 2022 ranged between 5% (GB) and 48% (PAW) of the long-term mean of a given area. Compared with their historic maximum landings, the mean pike landings between 2020 and 2022 in each Bodden area ranged between 2% (GB) and 26% (PAW). Based on Kleisner et al. (2013), the current pike landings status (2020–2022) was classified as overfished in all studied Bodden areas (current landings range between 10% and 50% of the long-term maximum landings) except for GB, where the status was classified as collapsed (<10% of the long-term maximum).

Spatial assessment

The integration of several social, economic, and ecological indicators across Bodden areas revealed pronounced spatial differences in the investigated status, trends, and socioeconomic importance of the pike stocks (Figure 7). The GB area stands out, as its current fishing mortality rates largely are beyond biological reference points and landings trends are negative, with indications of overfishing, while at the same time, GB is strongly preferred—particularly by fishers. Another problematic area seems to be the WRBC, which is an area of high importance to resident and tourist anglers, but landings status and trends are negative and environmental threats are high. Importantly, although the WRBC is not of high relevance to fishers, this user group is responsible for most of the pike fishing mortality, suggesting the potential for conflict between anglers and fishers. Developments in the NRBC are also negative in terms of decreasing landings status and rising environmental pressures, with their joint impact most severely affecting tourist anglers, for whom the area is particularly important. The DZBC and the PAW are somewhat less conflict prone, as anglers are the dominant source of pike mortality

Table 1 Instantaneous fishing mortality rates (F; per year) of Northern Pike across Bodden areas (Germany) and user groups (rec = recreational anglers; com = commercial fishers). Results are displayed for calculations with and without the correction of the high-reward tag reporting rate from 100% to 80%. Values in parentheses provide the 95% CI of the mean of repeated model calculations under considerations of uncertainties in input parameters (e.g., tagging mortality, tag loss, and reporting rates; see *Methods*). Subscripts A ($F_{rec\text{-}A}$, $F_{total\text{-}A}$) and B ($F_{rec\text{-}B}$, $F_{total\text{-}B}$) denote potential exploitation (scenario A: all recaptures were treated as removals) and actual exploitation (scenario B: released pike were excluded), respectively. Abbreviations are as follows: DZBC = Darß-Zingst Bodden Chain, GB = Greifswalder Bodden, WRBC = Western Rügen Bodden Chain, NRBC = Northern Rügen Bodden Chain, and PAW = Peenestrom/Achterwasser (Figure 1).

Bodden area	$F_{rec\text{-}A}$	$F_{rec\text{-}B}$	F_{com}	$F_{total\text{-}A}$	$F_{total\text{-}B}$
With corrected reporting rate of high-reward tags (80%)					
DZBC	0.16 (0.11–0.24)	0.04 (0.02–0.08)	0.01 (0.00–0.04)	0.17 (0.12–0.26)	0.05 (0.02–0.10)
GB	0.13 (0.00–0.26)	0.07 (0.00–0.15)	0.15 (0.00–0.34)	0.28 (0.05–0.51)	0.22 (0.05–0.42)
WRBC	0.07 (0.05–0.09)	0.03 (0.01–0.06)	0.14 (0.06–0.24)	0.20 (0.12–0.31)	0.17 (0.09–0.28)
NRBC	0.14 (0.06–0.21)	0.07 (0.02–0.13)	0.11 (0.01–0.26)	0.24 (0.12–0.44)	0.18 (0.08–0.33)
PAW	0.08 (0.01–0.24)	0.02 (0.00–0.08)	0.07 (0.00–0.29)	0.15 (0.01–0.48)	0.09 (0.00–0.34)
Total	0.10 (0.08–0.13)	0.04 (0.03–0.06)	0.10 (0.05–0.18)	0.20 (0.14–0.30)	0.14 (0.08–0.23)
With uncorrected reporting rate of high-reward tags (100%)					
DZBC	0.13 (0.08–0.19)	0.03 (0.01–0.06)	0.01 (0.00–0.03)	0.14 (0.10–0.21)	0.04 (0.02–0.08)
GB	0.10 (0.00–0.20)	0.06 (0.00–0.12)	0.12 (0.00–0.26)	0.22 (0.05–0.41)	0.17 (0.05–0.33)
WRBC	0.05 (0.04–0.07)	0.03 (0.01–0.05)	0.11 (0.05–0.19)	0.16 (0.10–0.25)	0.13 (0.07–0.22)
NRBC	0.11 (0.05–0.17)	0.05 (0.01–0.10)	0.09 (0.01–0.20)	0.19 (0.10–0.35)	0.14 (0.06–0.26)
PAW	0.07 (0.01–0.19)	0.02 (0.00–0.06)	0.05 (0.00–0.23)	0.12 (0.01–0.37)	0.07 (0.00–0.27)
Total	0.08 (0.07–0.10)	0.03 (0.02–0.05)	0.08 (0.04–0.14)	0.16 (0.11–0.24)	0.11 (0.06–0.18)

and the dominant user group in the DZBC, while the PAW is of particular relevance to fishers, with relatively little angler use.

Discussion

Our case study on the coastal pike stock in Bodden lagoons quantified spatially differentiated exploitation pressures by recreational anglers and commercial fishers and where the overall stock status has been declining in recent years (Olsson et al., 2023) while conflicts among user groups are rising (Arlinghaus et al., 2022). Given that the different lagoons vary in their social importance, use intensity, landings status and trends, and environmental pressures, fisheries managers would benefit from incorporating spatially explicit dynamics through lagoon-specific management strategies. Our study emphasizes that there is value in considering space in social–ecological assessments of fisheries, even at relatively small spatial scales within estuarine lagoon systems, by revealing one specific lagoon (GB) as a particularly problematic area and revealing others (e.g., DZBC) as carrying limited conflict potential.

Fishing mortality rates

The directly estimated F_{total} of 0.20 per year for the Bodden pike stock (combined for both commercial and recreational fisheries and all areas) is concordant with previous data-poor, indirect assessments of F by van Gemert et al. (2022; based on catch-only models) and Fitzgerald et al. (2023; using length-based population assessments). Both previous assessments suggested that the pike stock is fully exploited to slightly growth-overfished, with estimates of F exceeding 0.17 per

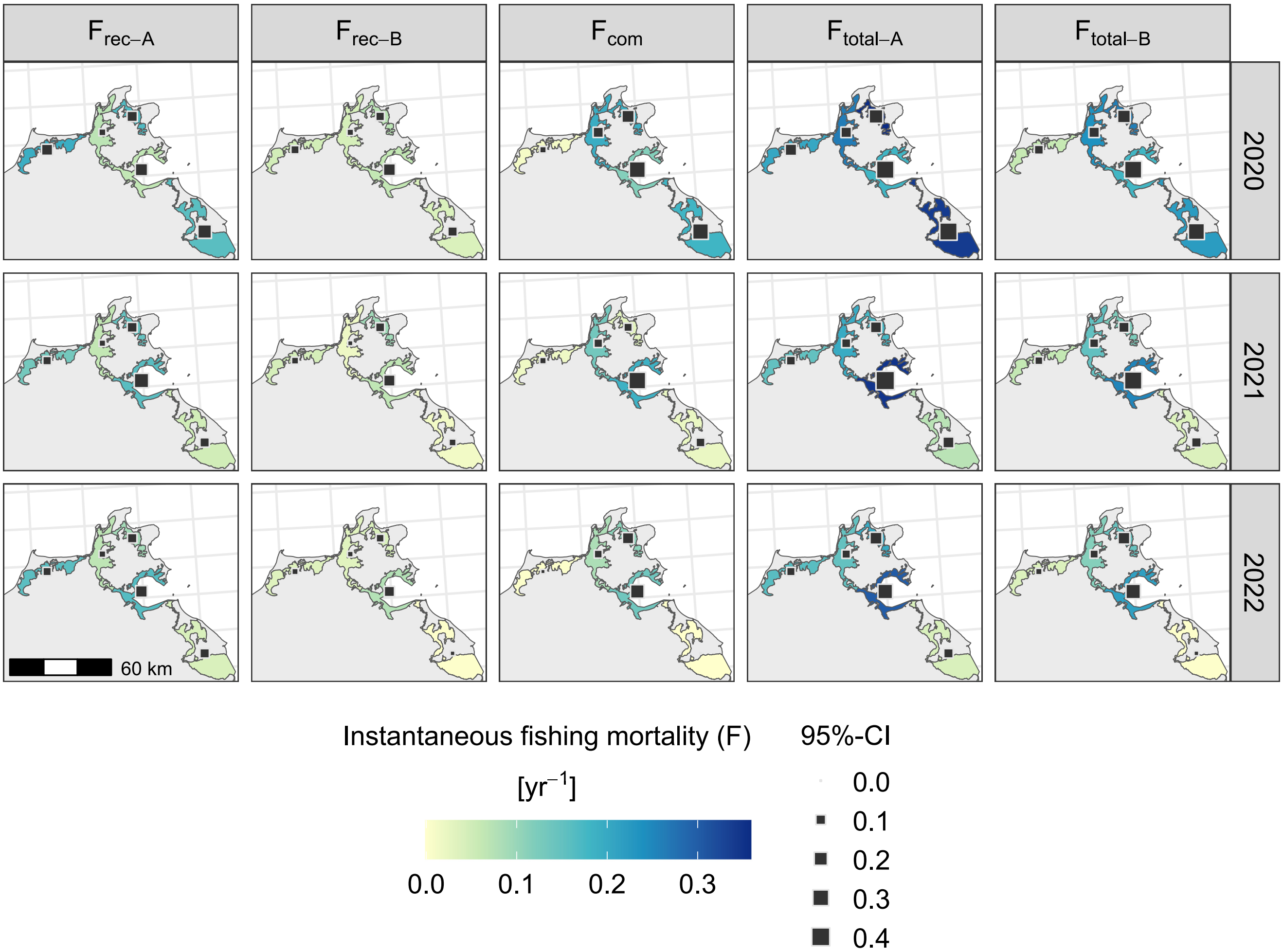

Figure 5 Instantaneous fishing mortality rates (*F*; per year) of Northern Pike across years, Bodden areas (Germany), and user groups (rec = recreational anglers; com = commercial fishers). Results displayed are corrected for the reporting rate of high-reward tags (80%). The 95% CIs (represented by box size) of the mean were calculated from repeated model runs under considerations of uncertainties in input parameters. Subscripts A ($F_{\text{rec-A}}$, $F_{\text{total-A}}$) and B ($F_{\text{rec-B}}$, $F_{\text{total-B}}$) denote potential exploitation (scenario A: all recaptures were treated as removals) and actual exploitation (scenario B: released pike were excluded), respectively.

year (2013–2018; van Gemert et al., 2022) and ranging between 0.1 and 0.3 per year (2019–2022; Fitzgerald et al., 2023). However, both data-poor assessments carried substantial process and model uncertainties emerging from underlying model assumptions, parameter uncertainty, and limitations in data inputs (Ovando et al., 2022). Despite its own limitations (discussed below), our novel mark–recapture-based assessment provides a complementary estimate of contemporary *F* that is of value to local fisheries management. The method relies directly on (re)capture rates of previously marked pike in specific Bodden lagoons—a robust approach that remains underutilized compared to indirect methods of estimating *F* in coastal and marine fisheries (Walters & Martell, 2004). Encouragingly, the mark–recapture estimate of *F* broadly agreed with previous stock assessment results. Previous studies have successfully used mark–recapture data to estimate *F* in pike populations within lakes (Arlinghaus et al., 2018; Dahiya et al., 2000; Pierce et al., 1995), and our work shows that the method can also work in more spatially extensive coastal ecosystems. Importantly, mark–recapture studies allow for separate estimation of *F* for different geographical subunits or user groups, such as fishers and anglers.

We found that fishers and anglers exerted approximately similar fishing pressure on pike ($F_{\text{com}} \approx F_{\text{rec}} = 0.10$ per year), suggesting that if anglers removed all captured pike, the resulting fishing mortality rates would be equivalent to that of the commercial fisheries but not higher. This finding is important because previous calculations from roughly 10 years ago, which extrapolated total landings from average per-capita removals by anglers from self-reports in diaries, suggested that the total removals of pike by anglers could far exceed the pike removals by commercial fisheries (Arlinghaus et al., 2021). The equality of F_{com} and F_{rec} estimated in our study suggests that the recreational exploitation component either has significantly decreased in recent years or was previously overestimated—for example, because of biased extrapolations of self-reports by anglers in diary studies (Weltersbach et al., 2021). It is also possible that catch-and-release rates by anglers have risen in recent years, which would lower fishing mortality. When we considered only fish that were retained, the estimated fishing mortality rates from

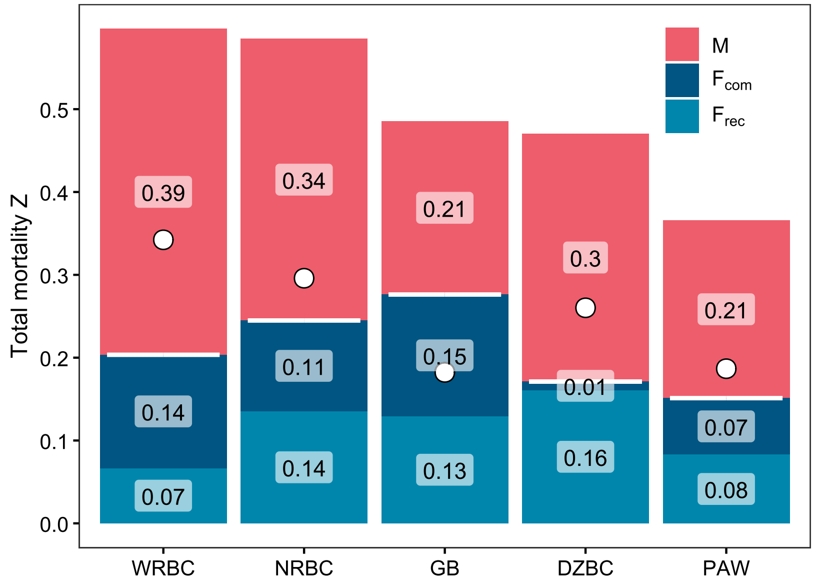

Figure 6 Area-specific total mortality (Z; per year) of Northern Pike estimated from catch-curve analyses encompassing natural mortality (M), fishing mortality caused by recreational anglers (F_{rec}), and fishing mortality caused by commercial fishers (F_{com}). The white dot marks the maximum sustainable yield reference point (87% of M) according to Zhou et al. (2012). White lines ($F_{total} = F_{rec} + F_{com}$) above white dots indicate areas with a total fishing mortality exceeding the reference point. Abbreviations are as follows: WRBC = Western Rügen Bodden Chain, NRBC = Northern Rügen Bodden Chain, GB = Greifswalder Bodden, DZBC = Darß-Zingst Bodden Chain, and PAW = Peenestrom/Achterwasser (Figure 1).

anglers dropped substantially to 0.04 per year, suggesting that contemporarily, fishers may be removing twice as many pike as are removed by anglers. However, the lower estimates of F that explicitly disregard released pike likely underestimate the true harvest rates, as our study design may have encouraged anglers to release more pike than they would have otherwise. Importantly, F_{com} and F_{rec} were estimated independently from user-group-specific tag returns, and the alternative release assumptions only affect the estimate of F_{rec}; they do not imply compensatory changes in F_{com}, as the analysis is based on observed tag-return data rather than a predictive model of interactions between fisheries.

Several other factors may have additionally influenced the fishing mortality rates reported in this study. For instance, recreational fishing pressure for the year 2020 could have been lower during the COVID-19 pandemic, as restricted travel during that period prevented the usual influx of tourist anglers (Britton et al., 2023). Moreover, our calculations did not account for potential movements and exchanges of pike between lagoons, which would affect the migration of tags available to be recaptured. Continuous tagging throughout the study period and study area was intended to minimize the influence of systematic migrations, yet some misestimation of F due to movement-related model misspecifications at the lagoon level cannot be fully excluded. We consider this risk to be low, as previous telemetry studies of coastal pike around Rügen Island indicated limited connectivity between lagoons (Lukyanova et al., 2024), and recaptures observed outside the marking areas were very rare in the present work. It is also important to note that F can be overestimated if disproportionately vulnerable pike are marked (Monk et al., 2021), as they might subsequently be selectively captured and reported. Alternatively, marked pike may have become less responsive to angling due to tagging or due to hook avoidance learning (Roser et al., 2025), which could have led to an underestimation of F, an effect that we cannot fully exclude.

In estimating exploitation rates, we did not have direct data on the reporting of high-reward tags. However, previous studies from both the United States (Henry, 2003) and Germany (Beck, 2015) that varied reward levels suggested that a €100 reward during 2020–2022 may have been insufficient to ensure full reporting. Indeed, we have anecdotal evidence of captures of high-reward tags appearing on social media and in the products of pike wholesalers that were not reported to the project team. Accordingly, we applied an adjustment based on relationships between reward level and return rates informed from studies in other species of fish and wildlife (Largemouth Bass *Micropterus nigricans*: Henry, 2003; mallards *Anas platyrhynchos*: Nichols et al., 1991). While this approach represents an informed estimate, reporting rates likely vary by species, region, and user group—factors that could not be addressed by our study design. Despite these limitations, our findings allowed for a meaningful estimation of the regional variation in recaptures, providing a measure of exploitation by different user groups in a mixed commercial–recreational fishery.

Area-specific differences in fishing mortality and use preferences

Pike fishing mortality attributable to the two user groups (F_{rec} and F_{com}) and the spatial preference by fishers and anglers varied among the Bodden areas. Thus, our study goes beyond previous assessments of the regional pike stock as a whole (Fitzgerald et al., 2023; van Gemert et al., 2022), which neither provided a spatially differentiated assessment of fishing mortalities within individual Bodden lagoons nor distinguished

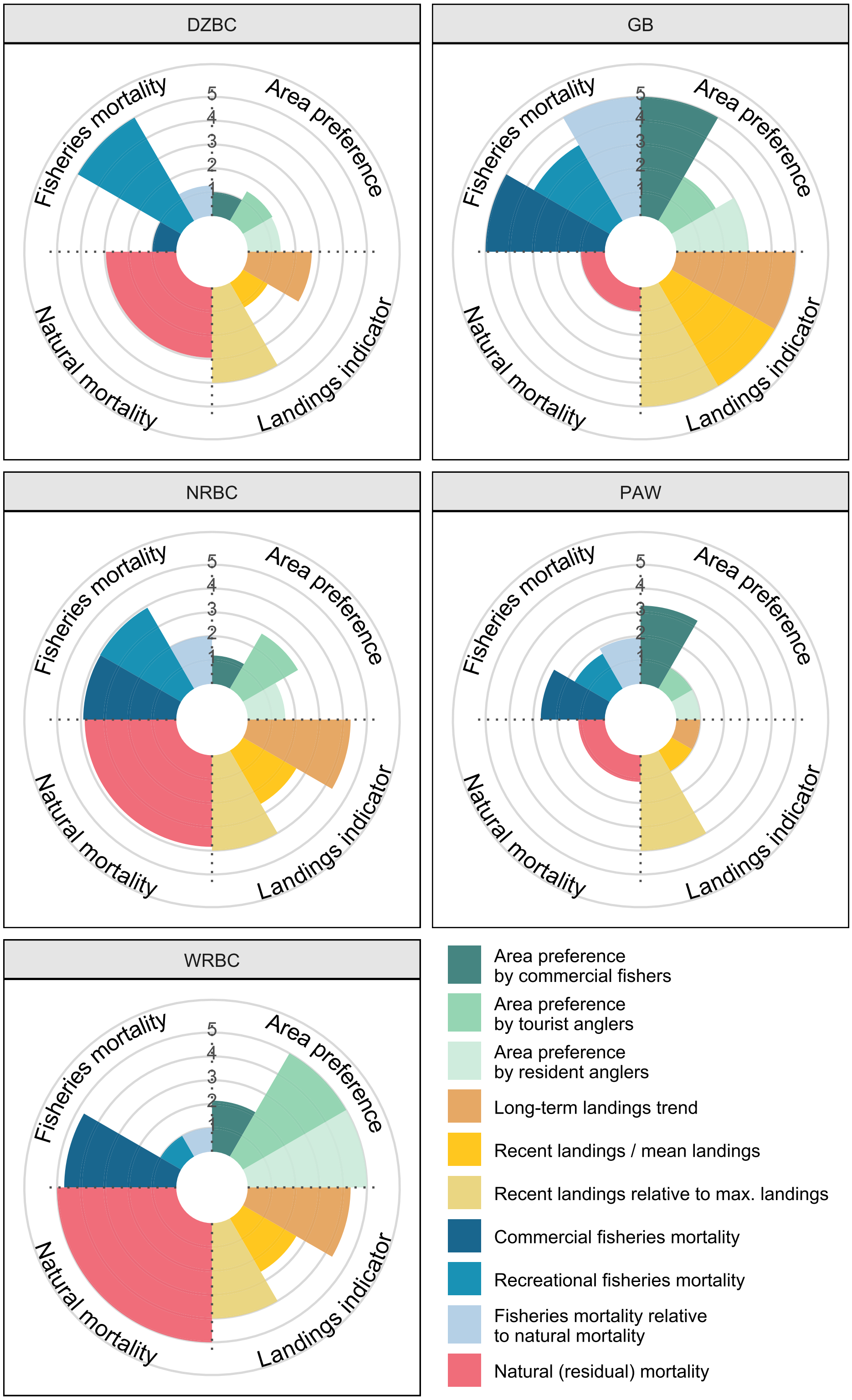

Figure 7 Composite index of Northern Pike use for each Bodden area (Germany) comprising fishing mortality (blue), natural mortality (red), spatial use preferences by recreational anglers and commercial fishers (green), and pike landings indicators (yellow). Larger index values indicate a more severe attribute (e.g., higher fishing mortality, steeper stock decline). Abbreviations are as follows: DZBC = Darß-Zingst Bodden Chain, GB = Greifswalder Bodden, NRBC = Northern Rügen Bodden Chain, PAW = Peenestrom/Achterwasser, and WRBC = Western Rügen Bodden Chain.

between the specific contributions of fishers and anglers to *F*. Previous tag-return research on pike stocks in North American inland lakes has uncovered substantial variation among water bodies, with exploitation rates ranging between 4% and 22% per year (Pierce et al., 1995). Different lagoons, although connected, share similarities with spatially structured lake fisheries in terms of attracting different angler types or fishers with different propensities to harvest pike. Except for the DZBC, where F_{rec} dominated over F_{com}, anglers and fishers contributed to potential F (based on catches) at roughly similar magnitudes in all other Bodden areas (Figure 6). However, within a given user group, the spatial preference for a given area was not correlated with the estimated fishing mortality. In fact, the WRBC, despite being the area most preferred by anglers, exhibited the lowest F_{rec} of all areas. Conversely, the DZBC, as the second most sought-after area by anglers, showed the highest F_{rec}. Several reasons might cause this counterintuitive relationship. First, our study focused on five larger Bodden areas and did not consider fine-scale spatial variability in area preferences, human behavior (e.g., propensity to release fish voluntarily), or fisheries exploitation rates within these areas. However, within each Bodden area, certain locations may be more extensively fished than others (e.g., specific bays by fishers; certain areas surrounding harbors by anglers). This is related to the fact that spatial preferences for a given area partly depend upon stock-related attributes, such as catch rates, but are also driven by site-specific characteristics, such as accessibility, local regulations, boating opportunities, guiding services, or accommodations (Hunt et al., 2019; Koemle et al., 2022). Furthermore, the estimated exploitation rates depend on the catchability of pike and subsequent reporting, which may both vary between the investigated areas, such as through hook avoidance learning (Beukema, 1970; Lucas et al., 2023; Roser et al., 2025), and with the presence or absence of protected areas where pike can recover their reactivity to the gear (Camp et al., 2015; Roser et al., 2025). Although we accounted for different reporting rates between anglers and fishers, the data did not allow the estimation of robust area-specific tag reporting rates for each user group. We acknowledge that differences in reporting rates among the Bodden areas may have contributed to the observed mismatch between spatial preference for a given area and corresponding F. We also believe that area preferences by particular anglers that exert exceptionally low or high voluntary release rates could have distorted our area-specific estimation of F.

Natural mortalities as a biological reference point for fishing mortalities

Estimated M obtained in this study, ranging from 0.2 to 0.4 per year, broadly agree with previous growth-based estimators of natural mortality in pike of this region (ranging between 0.23 and 0.50 per year; Fitzgerald et al., 2023) and estimation from other brackish regions (e.g., $M = 0.27$ per year for 2–8-year-old pike in the Caspian Sea; Moslemi-Aqdam et al., 2017). Previous analyses showed that changing habitats through loss of macrophytes, water infrastructure changes that block migration routes for anadromous pike, climate-induced warming, reduced forage bases, and increases in natural predation by great cormorants, gray seals, and Threespine Sticklebacks (Arlinghaus, Rittweg, et al., 2023; Olin et al., 2024) all potentially contribute to the overall decline of pike in the region and to the observed area-specific differences in natural mortality. Previous work has shown that fishers in the region avoid areas with large seal abundances, such as GB (Koemle et al., 2025), suggesting that direct (through predation of target species; Bergström et al., 2022) and indirect (through depredation in gill nets; Glemarec et al., 2024) impacts of natural predators could affect effort decisions by fishers. We note that analyses of the relationship of lagoon-specific natural mortality and its underlying sources (e.g., predation by great cormorants, gray seals, or Threespine Sticklebacks or salinity spikes during critical early life stages of pike; Möller et al., 2019; Sunde et al., 2018) remain challenging and require spatiotemporal data at a higher resolution than was available in our study.

True natural mortality of Bodden pike is not precisely known because the stock represents an exploitation situation. Catch-curve analyses used in combination with analyses of exploitation rates to estimate concurrently operating M and F in this study provide the best estimates of natural mortality so far. Because Z was estimated independently via the catch curve (Figure 4), natural mortality represents a residual component after accounting for the fishing mortality components (F_{rec} and F_{com}). This reflects the accounting structure of the modeling framework rather than implying that natural mortality would necessarily adjust if fishing mortality changed, as total mortality itself could vary over time. We used age–length keys based on scales and corroborated otolith readings (Rittweg, Trueman, Ehrlich, et al., 2024) to reduce aging errors, we combined sampling data from multiple gears (angling, gill nets, and fyke nets), and we focused on pike older than 5 years to reduce size-selectivity issues as a basis for our Z-estimates. However, we note that the scale-based age determination may have introduced structural aging bias, particularly through underestimation of age for older age-classes (Rittweg, Trueman, Ehrlich, et al., 2024). Such bias would in turn inflate estimates of total mortality through a systematic error but would have limited effect on comparisons among lagoons. Moreover, we cannot fully exclude that the reliance on passive fishing gears and the choice of sampling sites have resulted in selectivity of certain growth types of pike (e.g., selectivity of faster-growing pike in angling data; Crane et al., 2015), which may have biased our catch-curve analysis. We also acknowledge that the simultaneous estimation of M and F might introduce some bias, as overestimation of fishing mortality from recapture rates could lead to underestimation of natural mortality and vice versa—an issue that cannot be resolved with the data currently available.

In a previous meta-analysis of studies encompassing 245 fish species, Zhou et al. (2012) emphasized M as the most important factor affecting biological reference points for fishing mortality, with F_{MSY} equal to $0.87M$ to achieve MSYs. Analogous to previous studies (Fitzgerald et al., 2023), our results did not point to recruitment overfishing of the Baltic pike stock in Bodden lagoons, but current F-estimates were in part close to or even beyond this optimal MSY-based reference point (Zhou et al., 2012). Our results indicated that especially for GB, the estimated F was significantly above the F_{MSY} reference value (Zhou et al., 2012). In the DZBC and the WRBC, fishing mortality may be below this optimal threshold; however, we cannot rule out an area-specific effect of caught pike being underreported by individual user groups, which would lead to an underestimation of F and thus an incorrect assessment in relation to the reference value. Such a scenario is plausible considering the relatively high total mortality in the WRBC compared with the relatively low F (Figure 6). Moreover, we note that fishing mortality rates may become unsustainable even if the above-mentioned sustainability reference point is met, particularly when recruitment is impaired and stock productivity is pervasively declining—a development that is affecting a range of Baltic fish species, suggesting an ongoing productivity regime shift toward lower productivity levels (Möllmann et al., 2021).

Landings-based indicators

The long-term trend of commercial pike landings was negative in almost all studied areas over the past decades, with current landings largely below historic maxima. It is well known that landings-based stock assessments have a negative bias and suggest a poorer state of the fishery than may be the case (Ovando et al., 2022). Using landings as a fishery status indicator therefore has obvious limitations, as landings are jointly affected by effort, catchability, and abundance, which might not necessarily track underlying stock status (Olsson et al., 2023; Ovando et al., 2022). However, in our study focusing on a small-scale multispecies fishery of the Baltic Sea, landings and stock status are likely correlated to some degree given that fishers have fished pike together with other (predatory) fish for the entire time series, fishing effort has mainly declined offshore and less so in the lagoons over time (Arlinghaus, Braun, et al., 2023; Arlinghaus, Rittweg, et al., 2023), and reporting is legally mandatory. Spatially explicit long-term fishing effort data for the single Bodden areas are lacking to complement the landings series from 1970 such that our total landings indicator should not be interpreted to index stock sizes. We also note that the underreporting of landings by fishers may occur, but we have no reason to assume that underreporting varies by lagoon areas. However, spatially coarser previous analyses that corrected for effort using the number of commercial fishing vessels registered in the broader area still estimated a declining trend in commercial CPUE (landings per boat; Arlinghaus, Rittweg, et al., 2023; van Gemert et al., 2022), which agreed with our results. Moreover, a previous stock assessment using ensembles of multiple catch-only models also indicated a declining trend in the pike stock across the entire study region, particularly during the 5 years preceding 2018 (van Gemert et al., 2022). Despite their limitations, we consider the insights from the landings indicators to be relatively robust (especially as a comparative measure between the Bodden areas), which consistently pointed to an overfished or even collapsed status (Kleisner et al., 2013) throughout the entire study areas. Only PAW pike landings were not declining, but landings there have always been low, as this lagoon is polytrophic and is not the most suitable pike habitat.

Integrative spatially differentiated conflict assessment

The composite index of spatial pike use (Figure 7), which was interpreted here as an index of conflict potential over a limited resource, revealed marked differences among the five Bodden areas. Fisheries conflicts can be differentiated into intersectoral (e.g., between fisheries and conservation) and intrasectoral (e.g., between commercial and recreational fisheries; Arlinghaus, 2005). The underlying social–psychological process is goal interference, where one group's ability to achieve its objectives is perceived to be reduced by the actions of another group (Arlinghaus, 2005). Such conflicts may be symmetrical or asymmetrical (i.e., felt by both groups or by only one group) and typically involve either social conflicts or resource conflicts arising from reduced resource availability due to harvest, environmental change, increased natural predation, or management actions (Arlinghaus, 2005).

Against this background, GB constitutes a particularly intersectoral conflict-prone lagoon with regard to pike fisheries. The area is characterized by high pike fishing mortalities from commercial and recreational fisheries that collectively exceed the life-history-based reference value of optimal use (Zhou et al., 2012). The trajectory of GB pike landings also suggests a collapsed state (Kleisner et al., 2013). Despite this, GB remains a key pike fishing ground, particularly for fishers. Populations of gray seals have been increasing in this area, potentially increasing natural predation pressure on the pike stock (Bergström et al., 2022) while simultaneously reducing the attractiveness of commercial gill-net fisheries through gear depredation (Glemarec et al., 2024). In addition, as the lagoon most open to the Baltic Sea, GB may be especially vulnerable to increasing abundances of Threespine Sticklebacks, which negatively affect pike recruitment (Olin et al., 2024). Overexploitation of the GB pike stock generates resource conflicts, while increasing populations of fish-eating predators reduce fishability and may further intensify competition, creating both resource and social conflicts. Consequently, GB requires immediate management attention. The resulting conflict is likely felt most strongly by fishers and appears to arise less from competition between commercial and recreational fisheries than from the challenge of balancing fisheries objectives with conservation goals.

The WRBC and, to a smaller degree, the NRBC can be characterized primarily by intrasectoral conflicts among anglers and commercial fisheries (Arlinghaus, 2005), involving both social and resource conflicts that are felt asymmetrically by anglers. While the pike landings trend and the estimates of M and F showed a similar negative pattern in both lagoons, the spatial preferences of fishers and anglers (especially resident anglers) appeared to be lower for the NRBC compared with the WRBC. This may indicate a somewhat lower intrasectoral conflict potential in the NRBC despite broadly comparable stock status and mortality estimates. Based on landings data, both lagoons can be considered overfished for pike (Kleisner et al., 2013) and were characterized by estimates of high M and intermediate to high F. In the WRBC, F_{com} was estimated to be approximately twice the F_{rec}. At the same time, the WRBC was the most preferred area for both resident and tourist anglers, suggesting that in this lagoon, anglers may be differentially affected by commercial fishing pressure exerted by a small set of dedicated pike fishers. Previous research in lakes has shown that even individual fishers can negatively affect recreational fishing quality via reduction of local pike abundances (Jansen et al., 2013)—a prevalent issue in the WRBC, where certain bays are prime targets of specialized fishers in a gill-net-based prespawn fishery (Arlinghaus et al., 2022). Here, local depletion coupled with low movement rates of pike may negatively affect local abundance and the resulting catch benefits for anglers (Lukyanova et al., 2024). The comparatively high *M*-estimate for the WRBC was also a source of concern, as it would indicate additional (environmental) sources of mortality acting on the stock. However, we cannot exclude the possibility of WRBC-specific underestimation of capture rates, resulting in a misestimation of *M* versus *F*.

Anglers that are attracted to the WRBC and NRBC lagoons might ascribe reductions in personal satisfaction, following goal interference theory (Arlinghaus, 2005), to the higher fishing pressure exerted by fishers (Arlinghaus et al., 2022). Such goal interference is also suggested by a related study from the same region (Koemle et al., 2025), which documented spatial displacement—especially among the more involved and specialized anglers—away from lagoons that were heavily used by fishers. Indeed, there are anecdotal reports that angling guides who were historically active particularly in the WRBC are increasingly moving their fishing activities to the DZBC and the PAW, where commercial fishing pressure has been documented to be low. Overall, given that the WRBC was identified as a preferred area for pike anglers and given that commercial fishing pressure was particularly strong, appropriate reductions in commercial fishing mortality rates, such as through protecting spawning bays prior to spawning time in spring or regulation of mesh sizes in gill nets, may prevent or reduce the potential for conflict among user groups and may allow for local pike subpopulation recovery.

The DZBC and the PAW were among the least conflict-prone areas and are currently not characterized by strong intersectoral or intrasectoral conflicts. As in the other lagoons, recent landings in the DZBC and the PAW were also low compared with historical levels. However, these two areas were generally less preferred by fishers and anglers. In our study, estimated fishing mortalities in the DZBC and PAW were assessed as intermediate to low, with the exception of F_{rec} in the DZBC, which was notably high despite F_{total} remaining below reference limits following the criteria of Zhou et al. (2012). We suspect that these two areas may experience increased use in the future as anglers displace their effort from the more stressed neighboring lagoons. This assumption is supported by anecdotal observations indicating that anglers and guides are increasingly shifting their activities away from the WRBC and toward the DZBC (throughout the year) and the PAW (mainly during the winter pike fishery).

Management implications

Coastal pike that are characterized by localized population dynamics are prone to local overfishing (Lukyanova et al., 2024). Therefore, lagoon-specific harvest regulations of both input (including no-take areas, wintering areas in key spawning bays, and protected seasons) and output (e.g., lagoon- and commercial enterprise-specific annual quotas, size limits, and daily bag limits) might be needed to limit local overharvest in the Bodden areas. Anglers today release 75% of the pike that they catch (Arlinghaus, Braun, et al., 2023; Arlinghaus, Rittweg, et al., 2023), and postrelease mortalities are low in esocids (Hühn & Arlinghaus, 2011). Thus, future harvest controls may perhaps preferentially focus on regulating pike harvest by commercial fisheries while promoting best handling practices for released pike among anglers. Harvest regulations may benefit from being designed in a lagoon-specific fashion considering the relevance of fishing grounds for specific user groups and the current fishing mortality rates exerted by the different fisheries sectors. For example, it may be recommended to design harvest regulations specifically tailored for pike commercial fisheries in the WRBC (where their relative share of total removals of pike is particularly large), while harvest regulations specific to anglers may be more needed in the DZBC. Currently, annual quotas do not exist for coastal pike around Rügen Island. Previous surveys among anglers have shown that a majority of anglers would like to see reductions in the daily bag limits implemented (Arlinghaus, Koemle, et al., 2023); similarly, a majority of fishers would be willing to contribute to the stock's conservation through increased conservation of large-sized pike (Arlinghaus, Koemle, et al., 2023; Arlinghaus, Rittweg, et al., 2023; Ehrlich, Niessner, & Arlinghaus, 2023). However, the majority of fishers would reject proposals to introduce annual quotas for pike (Arlinghaus, Koemle, et al., 2023). Addressing intrasectoral fisheries conflicts might benefit from spatial or temporal zoning in areas of high overlap between user groups, such as GB or the WRBC, or in areas that are particularly relevant for one sector (e.g., anglers) while being intensively fished by another, as occurs in the WRBC. It is also conceivable to preferentially manage selected lagoons for the benefit of individual fishing sectors, such as managing GB or the PAW for commercial fisheries and managing the WRBC, NRBC, and DZBC preferentially for anglers. More generally, implementing harvest slots to replace minimum length limits for both anglers and fishers or introducing upper mesh-size limits for gill nets may help to preserve large pike (Ahrens et al., 2020)—a regulation that is preferred by the current angler population (Koemle et al., 2022, 2024). In addition, increased protection for pike aggregating in selected bays (Flink et al., 2023) during the commercial prespawn gill-net and fyke-net fishery might be advisable to reduce conflicts (Arlinghaus et al., 2022; Ehrlich, Niessner, & Arlinghaus, 2023). Indeed, the first specific winter closures in spawning bays have recently been implemented to protect pike from the prespawn fishery (Landesamt für Landwirtschaft, Lebensmittelsicherheit und Fischerei, 2024). Overall, fishers and anglers frequently agree on future harvest regulations except when they involve annual quotas or strong caps on allowed gear, both of which are rejected by a majority of fishers (Arlinghaus, Koemle, et al., 2023).

It is important to recognize that regulating the fishery alone would not be sufficient to recover the Rügen Island pike stock or resolve conflicts among the user groups. In all studied areas, the overall productivity potential of pike is co-driven by nonfishery environmental factors influencing natural mortality, growth, and recruitment. Thus, fishing mortality cannot be the sole culprit of the contemporarily steep decline of the pike population (Arlinghaus, Braun, et al., 2023). Fishery management strategies targeting pike would thus benefit from engaging in ecosystem-based management and restoration of natural processes (Lukyanova et al., 2024; Radinger et al., 2023). For example, many streams in the Bodden areas are blocked, so restoring natural flooding regimes could strengthen stock resilience independent of harvest constrains (Roser et al., 2023). Reducing nutrient inputs might improve macrophytes, which are key spawning and refuge habitats for pike, and management of fish-eating predators could reduce natural predation on pike and their prey fish (Arlinghaus, Braun, et al., 2023; Bergström et al., 2022) while also improving the fishability of lagoons with extensive gill-net depredation. Creating wetlands that serve as recruitment habitats could also help to restore coastal pike populations, as shown in other Baltic areas (Tibblin et al., 2023).

Thus, in addition to the local perspective, the wider Baltic Sea ecosystem also needs to be considered in future management of lagoon pike. Specifically, increasing predator populations, a warming climate, and disrupted food webs in many areas of the Baltic Sea may offset conservation measures in pike fisheries by increasing predation from cormorants and seals, despite reduced fisheries harvest, and by lowering prey availability and quality (Berggren et al., 2022; Bergström et al., 2022; Faithfull et al., 2026; Olin et al., 2024). Therefore, future pike management should be embedded in a wider management of the lagoon ecosystem and the Baltic Sea as a whole, as the strong interlinkages between processes spilling over from the open Baltic Sea (e.g., Atlantic Herring, seals, and Threespine Stickleback populations) and pike population dynamics in nearshore areas and lagoons are now well established (Olin et al., 2024). Policymakers will need to answer difficult questions, including how to allocate pike among natural predators and among fishers and anglers in light of a rapidly deteriorating Baltic Sea ecosystem that is substantially—and likely persistently—reducing pike productivity into the future.

Our work suggests that a combination of local lagoon-level management and ecosystem-based management of the lagoon network as part of the Baltic Sea might be needed to deal with the contemporary decline of the Bodden pike stock and to address the conflicts between commercial and recreational fisheries. However, changes in pike management are unlikely to show rapid improvements given pervasive ecosystem changes in the Baltic Sea (Faithfull et al., 2026; Olin et al., 2024) and given experience from Sweden, where coastal pike populations continued to decline despite commercial fishery closures (Olsson et al., 2023) and large-scale habitat restoration (Tibblin et al., 2023). Therefore, given the large degree of uncertainty with which natural and coupled social–ecological systems respond to changing management action, we recommend investment in continued monitoring of the German pike fishery, and the findings of this snapshot study should be revisited in the future. For example, changing user behavior and user group patterns could substantially change the sector-specific fishing mortality rates. The present study should thus be regarded as a baseline spatial assessment that is representative of the recent historical period and should therefore be regularly revisited if changes occur in regulations, fishing effort, recruitment and ecological dynamics, or fisher behavior. As part of continued monitoring, we recommend periodic tagging and tag-return studies as well as the establishment of regular assessments of the length and age structure of the pike stock at the lagoon level. We also recommend setting up regular monitoring to assess pike recruitment dynamics. These data would be useful for updating sector-specific fishing mortality estimates, while routine length/age sampling could provide updated estimates of total mortality through time and enhance our understanding of recruitment variability. Additionally, tracking user-group-specific landings and fishing activity across lagoons will help to identify changes in user preferences and shifts in stock status. These data would be crucial for establishing a long-term operational decision-support system for adaptive, lagoon-specific pike management, with potential application also to other predatory fish species of fisheries importance in the Bodden lagoons.

Supplementary material

Supplementary material is available at *Marine and Coastal Fisheries* online.

Data availability

The data and analysis scripts underlying this study are available via Figshare (https://doi.org/10.6084/m9.figshare.30555698).

Ethics statement

The field procedures for sampling, including the animal care protocol for tagging fish, were reviewed and approved by Landesamt für Landwirtschaft, Lebensmittelsicherheit und Fischerei Mecklenburg-Vorpommern (Aktenzeichen 7221.3-1-052/19).

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Conflicts of interest

None declared.

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