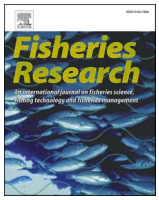
Fisheries Research 251 (2022) 106307

Contents lists available at ScienceDirect

Fisheries Research

journal homepage: www.elsevier.com/locate/fishres



Long-term decline in northern pike (*Esox lucius* L.) populations in the Baltic Sea revealed by recreational angling data

Ulf Bergström [*], Stefan Larsson, Mårten Erlandsson, Maria Ovegård, Henrik Ragnarsson Stabo [1], Örjan Östman, Göran Sundblad

Swedish University of Agricultural Sciences, Department of Aquatic Resources, Sweden

ARTICLE INFO

Handled by: B. Morales-Nin

Keywords:
Angling
Sport fishing
Logbook data
Large predatory fish
Marine mammals
Fish-eating birds

ABSTRACT

In the Baltic Sea, the large predatory fish northern pike (*Esox lucius L.*) is important for both recreational fisheries and ecosystem functioning. As existing fishery-independent surveys do not adequately monitor pike populations, a general lack of knowledge on population status and trends poses challenges for management. Here we use recreational angling data as an alternative method to describe pike population development along the Swedish Baltic Sea coast from 1938 onwards and assess the change over time in potential mortality factors by estimating harvest by fisheries and consumption by large predators. Data from a Swedish national register on trophy-sized pike (>12 kg) showed that numbers and maximum sizes peaked in 1990–1995, after which declines in both metrics are evident. In logbooks from a sport fishing club in the Stockholm archipelago, a simultaneous decrease in maximum sizes of pike was observed, together with a decrease in the total number of pike caught per fishing day. Jointly, these data indicate a decline in the abundance of large pike since around 1990. While commercial pike fisheries in the Baltic Sea have decreased continuously since the 1950s, recreational fishing increased after 1985, when Swedish coastal waters were made open access to anglers. The declines in large pike starting in the 1990s could, thus, have been driven by an increase in mortality from recreational fisheries, which at the time primarily practiced catch and kill. Since the 2000s, bag and slot length limits, spawning closures, and a general increase in catch-and-release fishing has reduced the landings of pike in recreational fisheries. Despite these fisheries regulations and higher release rates the decline in catches of large pike has continued, indicating an effect of other mortality factors. The strong growth of grey seal (*Halichoerus grypus*) and great cormorant (*Phalacrocorax carbo sinensis*) populations suggest that predation pressure on pike has increased over time. In the Stockholm archipelago these two predators were estimated to remove 5–18 times (range based on different diet composition estimates) more pike biomass than total fisheries landings in 2014–2017. To improve the situation for northern pike in the Baltic Sea managers need to consider both fisheries restrictions and measures to decrease predation pressure and increase recruitment. Catch data from recreational fisheries may be used to evaluate such management efforts by providing information on the population development of this keystone species.

1. Introduction

Globally, recreational fishing is of high social and economic importance (Arlinghaus et al., 2019; Arlinghaus and Cooke, 2009; Cooke and Cowx, 2004; Hyder et al., 2018). In many instances, recreational fisheries are targeting large, predatory fish species (Donaldson et al., 2011; Hyder et al., 2018), which are central to ecosystem functioning (Donadi et al., 2017; Frank et al., 2005; Lewin et al., 2006). Maintaining strong populations of these species is thus of importance both for the benefit of anglers and to maintain resilient ecosystems. At the same time, recreational fishing may impose fish mortality with negative effects on both population and ecosystem levels (Coleman et al., 2004; Cooke and Cowx, 2004; Post et al., 2002). Therefore, monitoring population status of predatory fish species is important both to assure the sustainability of fishing practices and the viability of aquatic ecosystems (Arlinghaus et al., 2021; Olsson, 2019).

* Correspondence to: Swedish University of Agricultural Sciences, Department of Aquatic Resources, Institute of Coastal Research, Skolgatan 6, 742 42 Öregrund, Sweden.
E-mail address: ulf.bergstrom@slu.se (U. Bergström).
[1] Deceased 29 February 2016

https://doi.org/10.1016/j.fishres.2022.106307
Received 9 July 2021; Received in revised form 21 March 2022; Accepted 22 March 2022
Available online 9 April 2022

For many stocks targeted mainly by recreational fisheries, management is hampered by a low availability of data on population status and catches (Ihde et al., 2011; Radford et al., 2018). This is especially true for species with highly localised population structure, such as many coastal and freshwater predatory fish species (Gunderson et al., 2008; Lewin et al., 2019; Olsson, 2019). To remedy this lack of information, systematic use of catch and effort data from recreational fisheries is highly warranted (Venturelli et al., 2017). While scientific on-site or questionnaire-based surveys are increasingly being implemented (Hyder et al., 2018; Radford et al., 2018), keeping record of catch and effort has a long tradition among recreational fishers. Data collection of catches may allow for reconstruction of multidecadal time series and descriptions of the population development of many otherwise data-poor species (Jansen et al., 2013; McClenachan, 2009; Richardson et al., 2006).

Northern pike (*Esox lucius* L.), hereafter pike, is a large-bodied keystone predatory fish (females growing up to over 20 kg) found in many estuarine and inland ecosystems of the northern hemisphere. It is one of the most popular target species in recreational angling in Northern Europe, where chances of catching trophy-sized fish make it particularly attractive (Arlinghaus et al., 2018). Pike is an ambush predator in shallow, vegetated habitats, where it feeds on a wide variety of prey, including its conspecifics (Casselman and Lewis, 1996; Craig, 2008). In the Baltic Sea, one of the world's largest brackish water basins, pike has a widespread distribution and is one of the most abundant piscivores in the coastal zone (Larsson et al., 2015). With migrations rarely exceeding 5 km and a strong homing behaviour, pike has a localised population structure with a limited gene flow potentially resulting in adaptations to local conditions (Laikre et al., 2005; Saulamo and Neuman, 2002; Sunde et al., 2018; Tibblin et al., 2015; Wennerström et al., 2017), making it vulnerable to local-scale pressures such as habitat loss (Hansen et al., 2019; Nilsson et al., 2019), fisheries and predation (Hansson et al., 2018; Nilsson et al., 2019).

While the catches of pike in coastal commercial fisheries in the Baltic Sea has declined by 80% over the last 50 years (Hentati-Sundberg, 2017), it has become one of the most popular species for angling, and today pike angling is associated with large socioeconomic values (Arlinghaus et al., 2018; Hansson et al., 2018; Swedish Agency for Marine and Water Management, 2019). The central importance of pike, not only for recreational fishing but also for maintaining the trophic structure of the coastal ecosystem (Donadi et al., 2017; Eklöf et al., 2020), emphasises the need for population status assessments for both fisheries and environmental management. Knowledge on past and current abundances is needed for management to take measures to sustain viable populations of pike and the ecosystem services they provide.

Due to poor catchability in the passive gears used in standardised monitoring programmes for coastal fish, data on the population development of pike in the Baltic Sea is scarce. Still, indications of declining pike populations have been observed in the Swedish national monitoring programme for coastal fish (Olsson, 2019), and a few earlier studies have indicated local long-term declines in pike populations (Lehtonen et al., 2009; Ljunggren et al., 2010). Concerns about dwindling catches of pike along the Swedish coast have been raised by both anglers and local fisheries managers, calling for a need to collate available information on the development of pike populations and potential pressures in order to advice management on what actions may be effective.

In this study, we use long-term recreational fisheries data from the Swedish Anglers Association and a local angler club to analyse population changes of pike in the Baltic Sea from 1938 to 2019. We use the data to assess changes in size distributions and abundances of this data-poor species along the Swedish coast. In addition we relate the observed changes in pike abundance estimated from recreational fisheries to changes in major mortality factors of pike. These include recreational and commercial fisheries as well as grey seal (*Halichoerus grypus*) and great cormorant (*Phalacrocorax carbo sinensis*), two top predators that have increased strongly in abundance from the 1990s and onwards (Hansson et al., 2018; HELCOM, 2018; Herrmann et al., 2019).

2. Material and methods

The data on pike recreational catches used in this study are based on rod-and-reel angling, obtained from two different sources: (i) the Swedish Anglers Association's national register of trophy-sized fish ("Storfiskregistret"), and (ii) fishing logbooks of the Stockholm Sport Fishing Club ("Stockholms sportfiskeklubb", hereafter SSFK). The national register of trophy fish was established in 1971 and relies on voluntary angling reports of the largest specimens of game fish species caught each year in Swedish waters. Each record in the database is validated based on photographs and additional information about the catch (Näslund and Lundgren, 2018). For pike, the minimum weight for eligible registration is 12 kg. The weight of a registered pike must be recorded on a scale verified by the SP Technical Research Institute of Sweden and at least one witness must attest the weighing. A photo of the fish is also required, while measurements of fork length and girth are optional. In total, 1 560 pike have been reported in 1971–2019. Due to the strong requirements on documentation, we judge the credibility of this register as high. To be included in this register is considered prestigious for many in the sport fishing community, so the propensity to report catches has likely been high. Reporting a detailed position of the catch is not required, but the name of the water body or coastal area is. Based on this information we classified all catches to either coastal (n = 620) or inland (n = 926) waters (catch location name could not be assigned to coastal or inland for 14 of the pike in the register), and for the coastal pike also into different regions (shown in Fig. 1) based on catch location.

SSFK was established in 1926, with members belonging to a well-educated upper class in Stockholm. Since 1938 members and guests of SSFK have reported their angling catches of pike, European perch (*Perca fluviatilis* L.), and pikeperch (*Sander lucioperca* L.) in the fishing waters leased by the club in the Stockholm archipelago. In logbooks, data on number of caught fish and total weight per species and day, as well as the weight of the largest individual, were recorded for each specified site. Summary data from these logbooks are available in the yearbooks of SSFK. From these yearbooks, information on numbers and weights of catch per site, species and year was collated for three sites with multidecadal time series available, Årsta, Häringe, and Rydboholm (Fig. 1). The sites are 2.1–2.4 km^2 in size, all including suitable reproduction areas for pike. Data availability varied between sites and variables (maximum weight, average weight, numbers per day), with 31–56 years of data, starting between 1938 and 1960 (Table 1, Figs. S1-S2). Fishing was only allowed for members of the SSFK until 1985 when all Swedish coastal waters and the five largest Swedish lakes were made open access to angling through a reform. Logbook reporting in the club slowly decreased and the time series were upheld until 2002–2015 depending on site.

To depict the development of major mortality factors of pike in the Stockholm archipelago (Fig. 1), data on landings in commercial and recreational fisheries and estimates of the removal of pike by predation from grey seal and great cormorant were collated. These calculations are detailed in the Supplementary information. Data on commercial landings of pike 1914–2013, available by county, were retrieved from Hentati-Sundberg (2017) and were extended to 2018 with official landings from the Swedish Agency for Marine and Water Management. Estimates of landings of pike in recreational fisheries were available for 1990 (Anon, 1991), 2006 (Thörnqvist, 2009), 2010 and 2014–2018 (Swedish Agency for Marine and Water Management, 2019), based on questionnaires commissioned by the Swedish Agency for Marine and Water Management (previously Swedish Board of Fisheries) to Statistics Sweden. In addition, we used data on pike landings for 2002 from a questionnaire-based survey of recreational fishing specifically in the Stockholm archipelago (Soutukorva and Söderqvist, 2005).

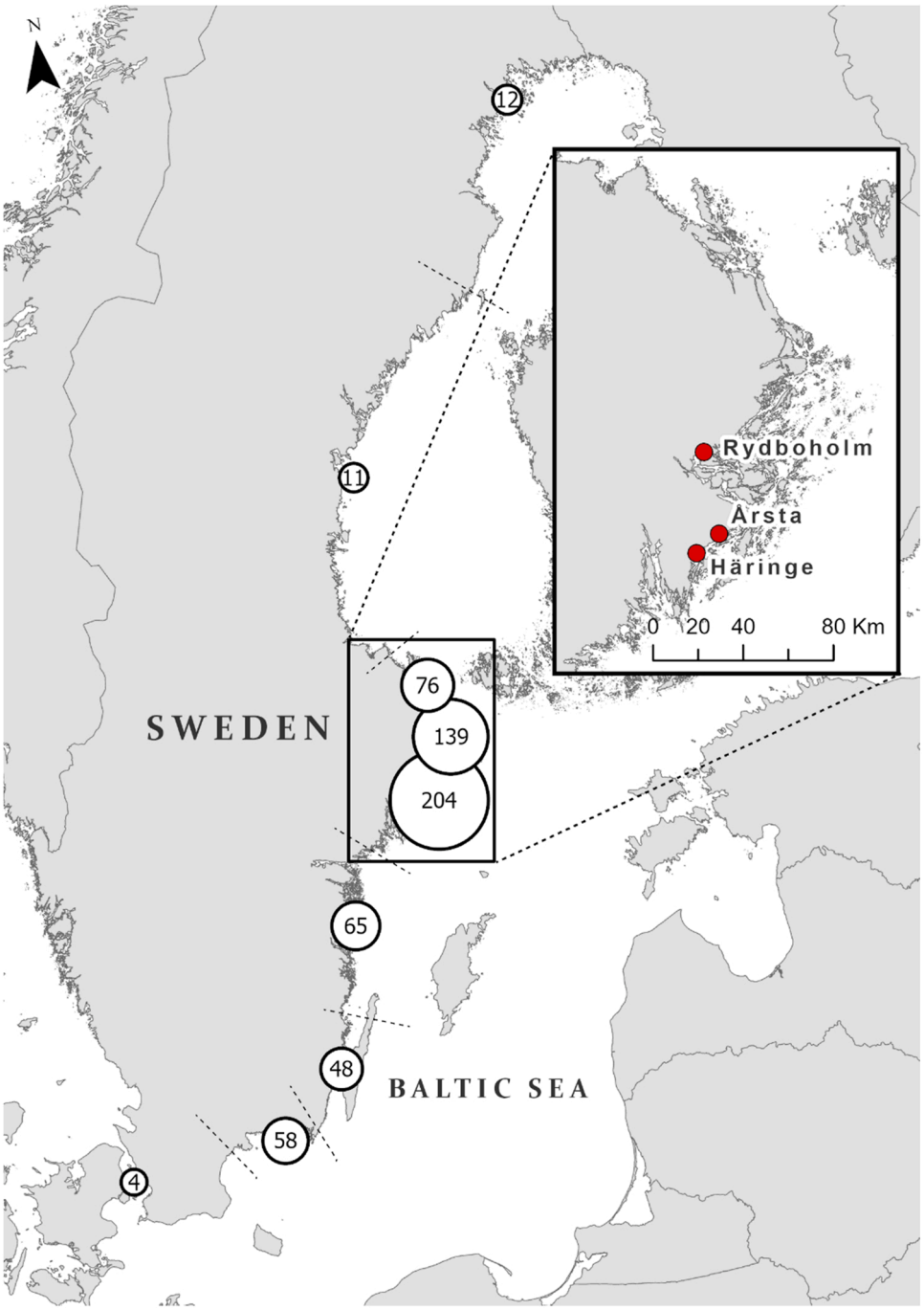


Fig. 1. Map showing the spatial distribution and number of trophy-sized pike registered in Swedish coastal waters in 1971–2019. The inserted map shows the Stockholm archipelago with the three fishing waters of the Stockholm Sport Fishing Club, where long-term catch data were available.

Removals of pike by grey seal and great cormorant were estimated by combining data on population abundances, diet compositions and bioenergetic needs of the two species. For grey seal, count data for haul-out sites in the Stockholm archipelago in 1989–2017 was retrieved from the Swedish database for environmental monitoring data (www.sharkweb.smhi.se, Swedish Hydrological and Meteorological Institute). For cormorant, count data of breeding pairs of cormorants in the county of Stockholm was available from inventories coordinated by the county administrative board and the Swedish Environmental Protection Agency, available for 1994–2017. To estimate the approximate consumption of pike by grey seal and cormorant in the Stockholm archipelago, the consumption estimates for 2012–2013 presented in Hansson et al. (2018) were applied, and scaled to the smaller region of the Stockholm archipelago based on annual counts. In that study, a total fish consumption rate for cormorant of 500 g/day (adults and subadults feeding 185 days/year and juveniles 140 days/year) and for grey seal of 4.8 kg/day and feeding 365 days per year were applied (see S1 and S2 in Hansson et al., 2018). While many studies use similar estimates for grey seal consumption (based on Hammond and Grellier, 2006), there is some discrepancy regarding estimates of cormorant consumption rates. Some studies use consumption estimates that are in the range of 15–30% lower than the one used here (e.g. Arlinghaus et al., 2021; Heikinheimo et al., 2021), while on the other hand the detailed calculations in Östman et al. (2013) give estimated total yearly consumptions (for the adult, subadult and juvenile birds associated with each nest) that are slightly higher than the ones from Hansson et al. (2018). For consistency, we stick to the

Table 1
Data from the Stockholm Sport Fishing Club (SSFK) on numbers and weights of pike caught in three sites of the Stockholm archipelago. The total number of registered pike was 14, 179 for Häringe, 3.844 for Rydboholm and 21, 824 for Årsta.

Sites and years	Years with data on fishing days /pike weight	No. of fishing days per year (mean ± SD)[a]	No. of pike per year (mean ± SD)	Max weight (kg, mean ± SD)	Individual weight (kg, mean ± SD)	Total catch weight (kg, mean ± SD)
Häringe: 1956–74, 1976–77, 1979–91, 1994, 2000–05, 2012–15	38 / 41	261 ± 122	315 ± 172	10,1 ± 2,9	2,1 ± 0,5	670 ± 316
Rydboholm: 1960–74, 1976–82, 1984–96, 1999, 2002	31 / 38	148 ± 168	113 ± 149	8,9 ± 2,8	2,6 ± 0,6	258 ± 335
Årsta: 1938–40, 1949–74, 1976–92, 2000–09	50 / 56	454 ± 197	390 ± 199	10,4 ± 2,3	1,8 ± 0,5	646 ± 343

[a] excluding years with less than 15 fishing days. Details on fishing days per year are shown in Fig. S1.

estimates from Hansson et al. in the current study.

There are many uncertain parameters in the estimations of grey seal and cormorant consumption of pike, but uncertainty estimates (e.g. confidence intervals) are not available for these data. However, the year-to-year variability seen in the estimates of removal rates (Fig. 4) reflects some of the uncertainty in the abundance data since grey seal and cormorant are both long-lived species not expected to display large year-to-year variation. The largest source of uncertainty is, however, the diet composition, especially since pike is a relatively rare prey item, constituting 9% of the cormorant diet and 3% of the grey seal diet according to Hansson et al. (2018). To illustrate the potential range of pike removal from grey seal, we also applied estimates of diet proportions specifically from the Stockholm archipelago (Bergström et al., 2016), where the proportion of pike in the diet of cormorant was 2.8% and in the diet of grey seal 11%. We therefore calculated two different point estimates that reflect uncertainty in diet composition. No uncertainty estimates were applied for the total fish consumption, although there is undoubtedly some variation between existing studies (as described above). However, as this variation is much lower than the uncertainty associated with population abundance and diet composition estimates it would only have a limited additional impact on calculations of fish removals.

2.1. Statistical analyses

The temporal development of pike catches from both the national register of trophy fish and SSFK were analysed with generalised additive models as implemented in the *mgcv* package in R (R Core Team, 2013; Wood, 2017, 2011). Gaussian distributions, restricted maximum likelihood and default settings were used. For the trophy fish records, a smooth function for year, by region (coastal or inland), was applied to describe the development of the response variables number of reported pike and maximum weight. Analyses of the SSFK data were conducted similarly to the trophy fish records, with a smooth function for year by site (Häringe, Rydbyholm and Årsta), and site also as a fixed parametric model term as needed, which was evaluated by AIC values (see Supplementary information). In the Häringe site in 2015, ten years after the previous observation, an exceptionally high number of pike caught per day was reported (nearly three times higher than the average for the five previous years (2001–2005) in the site and the highest in the whole dataset). As this record was deemed erroneous, and including it did not affect the qualitative results or the conclusions, it was removed from the final analyses. The *visreg* and *ggplot2* packages were used to illustrate the predicted population dynamics over year conditional on region and sites (Breheny and Burchett, 2017; Wickham, 2016). Raw data plots are provided in the Supporting information (Fig. S2). For the estimates of pike removals from fisheries and seal and cormorant predation, no statistical analyses of temporal relationships could be made as data were not available for the same time periods. Instead, these estimates were used to compare the temporal trends of the removals from fisheries and predators.

3. Results

The total number of reported pike in the register of trophy-sized fish has increased since the start in 1971, but the development differs between coastal and inland waters. For coastal waters, both the number of trophy-sized pike and the largest pike recorded increased from the early 1970 s and peaked around 1990, with maximum weights over 18 kg in 1989, 1990 and 1993 (Fig. 2, Table 2). Since then both the number and maximum weight has decreased and in 2018, there was no trophy-sized pike registered at all from coastal waters, and only one pike in 2019. For inland waters, there was a slow increase in registrations until 1995, after which there was a substantial increase up to 40–50 pike reported per year around 2010, an increase that occurs simultaneously with the decline in coastal reports. Although the number of reported pike from inland waters has somewhat declined since 2010, the maximum reported weight remains high (Fig. 2, Table 2).

The spatial distribution of the registered trophy-sized pike in coastal waters shows that the majority (68%) has been caught in the Stockholm archipelago, the largest archipelago area along the Swedish coast (Fig. 1). While 28% of the large pike have been caught on the southeast coast of Sweden, only a few trophy-sized fish were registered in the Gulf of Bothnia in the north and in the southernmost parts of the Swedish coast.

The SSFK data showed a similar development in coastal pike populations as the register of trophy fish. After an initial increase in the maximum size of pike caught per year after 1938, there was a rapid decline from 12 kg in the maximum weight of pike caught in the early 1990s to 4 kg in 2015 (Fig. 3a, Table 2, Fig. S2). Simultaneously there was an increase in the average weight of pike (Fig. 3b, Table 2) and an overall continuous decline in the number of pike caught per angler and fishing day (Fig. 3c, Table 2).

The compilation of data on the major external mortality factors of pike for the Stockholm archipelago showed that the yearly commercial landings have been reduced from around 150 tons prior to 1960, to an average of 8 tons in the 2000 s. For recreational fishing, estimated landings of pike in the area decreased from 1100 tons in 1990 to an average of 100 tons in 2014–18 (Fig. 4). For grey seal, the consumption of pike in 2013 in the Stockholm archipelago was estimated to 430–1570 tons, based on data from Hansson et al. (2018) and additional diet composition data (Bergström et al., 2016). The consumption by grey seal for the years 1989–2017 was then calculated based on the counts of seals relative to 2013, resulting in estimated removals of pike increasing from 40–140 to 520–1900 tons over the period. For cormorant, the consumption of pike in 1994–2017 was also calculated from Hansson et al. (2018) with additional diet composition data from Bergström et al. (2016), where the estimate of 90–300 tons in 2012 was scaled to the other years based on cormorant counts. Pike consumption by cormorant increased from 0.6–2 to 100–340 tons over the period. At the end of the period, in 2014–2017, grey seal and great cormorant together were estimated to remove 5–18 times more pike by weight than the commercial and recreational fisheries combined (Fig. 4).

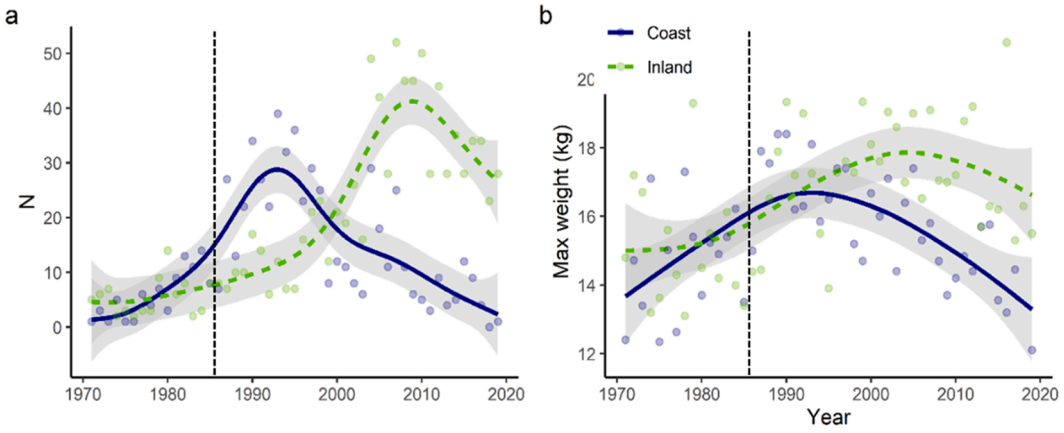


Fig. 2. (a) Number of reported pike over 12 kg and (b) maximum weight of individual pike caught by angling in coastal (solid) and inland waters (dashed) reported to the Swedish national register of trophy fish between 1971 and 2019. Curves show fitted GAMs with 95% CI (grey bands) and points are partial residuals. The dashed vertical lines indicate when Swedish coastal waters and the five largest Swedish lakes were made open access to angling.

Table 2
Summary of generalised additive models describing the catches of pike over time and by region/site on data from the a-b) Swedish national register of trophy sized fish, separated into coastal and inland waters, and c-e) logbooks from the three fishing sites of the Stockholm Sport Fishing Club (SSFK).

Dataset	Parameter	Deviance explained (%)	Estimate or estimated df	se	t or F-value	P
Trophy fish	**a) Maximum weight**	44	**Estimate**		**t**	
	Intercept		15.4	0.2	72.2	< 0.001
	Inland		1.2	0.3	4.0	< 0.001
			edf		**F**	
	s(Year):Coast		3.1		6.2	< 0.001
	s(Year):Inland		3.1		6.7	< 0.001
	b) Number of records	81	**Estimate**		**t**	
	Intercept		12.7	0.9	14.3	< 0.001
	Inland		6.2	1.2	5.0	< 0.001
			edf		**F**	
	s(Year):Coast		6.0		13.5	< 0.001
	s(Year):Inland		5.9		32.5	< 0.001
SSFK	**c) Maximum weight**	52	**Estimate**		**t**	
	Intercept		10.5	0.36	29.5	< 0.001
	Rydboholm		-1.6	0.57	-2.8	< 0.01
	Årsta		0.1	0.44	0.2	0.88
			edf		**F**	
	s(Year):Häringe		4.3		5.1	< 0.001
	s(Year):Rydboholm		1.6		1.9	< 0.001
	s(Year):Årsta		4.0		4.9	< 0.001
	d) Number per day	76	**Estimate**		**t**	
	Intercept		1.3	0.04	34.1	< 0.001
	Rydboholm		-0.6	0.05	-11.7	< 0.001
	Årsta		-0.5	0.05	-10.8	< 0.001
			edf		**F**	
	s(Year):Häringe		4.7		5.7	< 0.001
	s(Year):Rydboholm		1.0		39.8	< 0.001
	s(Year):Årsta		1.4		40.5	< 0.001
	e) Average weight	63	**Estimate**		**t**	
	Intercept		2.1	0.09	23.3	< 0.001
	Rydboholm		0.3	0.14	2.3	0.0207
	Årsta		-0.3	0.10	-2.7	0.0088
			edf		**F**	
	s(Year):Häringe		4.5		9.2	< 0.001
	s(Year):Rydboholm		2.4		4.4	0.0092
	s(Year):Årsta		2.7		11.3	< 0.001

4. Discussion

This study demonstrates how catch data from anglers can provide information on the population development of northern pike, which is one of the most popular species of recreational fisheries in many temperate coastal and inland waters. Both a Swedish register of trophy-sized pike and logbook data from a sport fishing club in the Stockholm archipelago show decreases in catches of large pike at the Baltic Sea coast since the early 1990s. The data from the Stockholm archipelago indicates a decline also in numbers of pike caught per angler and fishing day. At the same time, average weight of pike in the catch has increased, indicating a higher dominance of mid-sized individuals in the area. Together, these data indicate a general decline in abundance of large pike at the Baltic Sea coast since around 1990, while the increase in average weight may indicate a higher growth rate, consistent with a recent study on pike at the Swedish Baltic coast (Berggren et al., 2021).

The decline in large pike appears a few years after angling at the coast was made open access in 1985. Thereby, previously private fishing

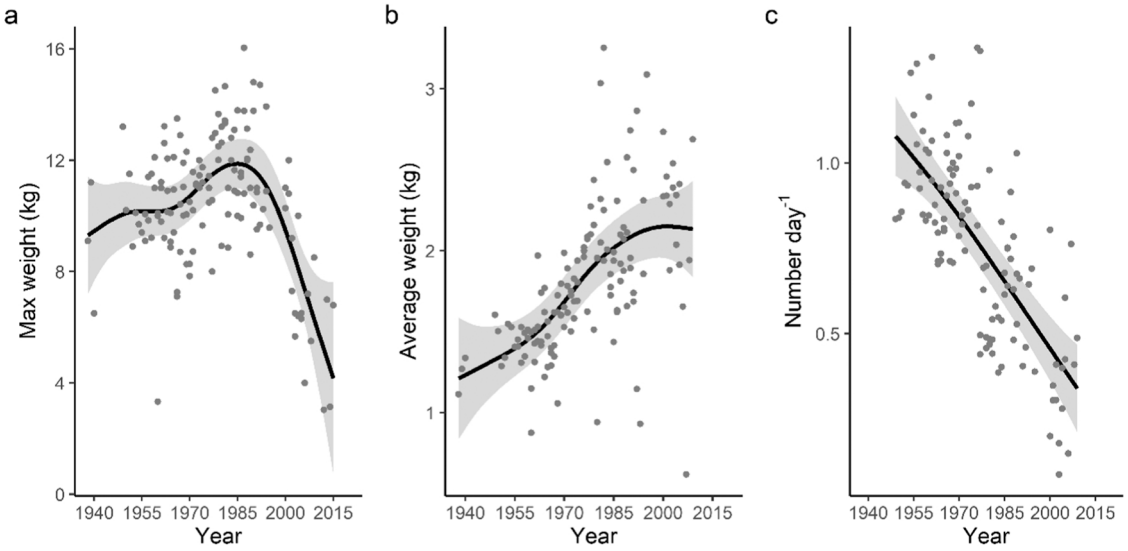


Fig. 3. Angling catches of pike reported by the Stockholm Sport Fishing Club in the Stockholm archipelago in 1938–2015, described by (a) yearly maximum individual weight, (b) average weight and (c) mean number of pike per fisher and day. Black lines show the GAMs predicted effect of year conditional on site, dots are partial residuals and grey bands are 95% CI.

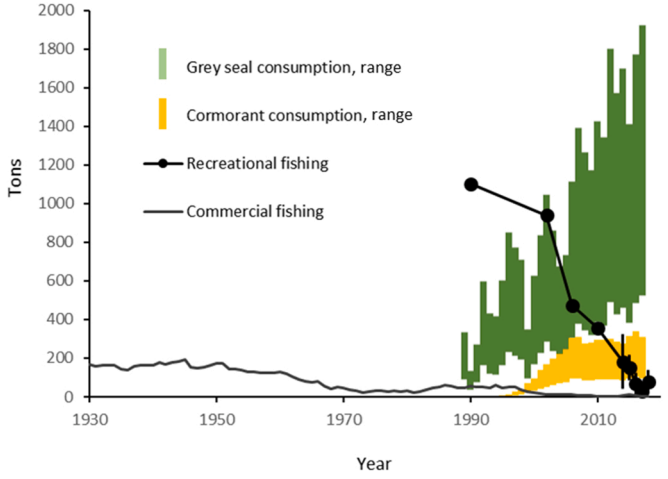


Fig. 4. Estimates of pike removals by recreational and commercial fisheries and by consumption by top predators in the Stockholm archipelago. Records of commercial landings of pike in 1914–2018 are based on official fisheries statistics, and landings in recreational fisheries in 1990, 2002, 2006, 2010 and 2014–2018 (mean ± 95% CI) are estimated from questionnaires.
Grey seal and cormorant consumption were calculated from population counts of grey seal in 1989–2017 and of cormorant in 1994–2017 combined with two separate point estimates of proportions of pike in the diet of seal and cormorant that provide a range to illustrate a major source of uncertainty (Bergström et al., 2016; Hansson et al., 2018).

waters were made accessible to a large community of recreational fishers, which in many areas likely led to a substantial increase in fishing pressure. We can see an initial increase in reports of trophy pike directly after 1985, likely as a response to a higher fishing effort for pike in coastal areas. At that time, the commercial fishery had declined since the 1950s, possibly due to a loss in popularity of pike for human consumption, as shown by a decrease in relative market price (Hentati-Sundberg, 2017), while grey seal and cormorant populations were still small. It is thus plausible that the decline in trophy-sized pike was primarily a consequence of the increase in mortality from recreational fisheries. Traditionally, most pike in recreational fisheries were killed at catch, and it is only in the last two decades that a clear shift towards a catch-and-release fishery has taken place. In 2006, when catch-and-release fishing had already gained popularity for some time, it was estimated that 63% of the pike in Swedish waters were landed (Thörnqvist, 2009). In 2020, only 15% of the pike caught was landed (Statistics Sweden, 2021). While catch-and-release may have pronounced effects on pike behaviour and growth, survival of pike is high (Arlinghaus et al., 2018; Hühn and Arlinghaus, 2011) and effects on reproductive traits are minor (Flink et al., 2021). Although some negative population-level effects from extensive catch-and-release fisheries can still be expected, this shift in practices has likely led to lower fishing-related mortality. To further reduce recreational fishing mortality of pike, a slot length limit of 40–75 cm and a bag limit of three pike per day was implemented in Swedish coastal waters in 2010. Judging from national survey data, these restrictions together with the shift towards catch-and-release practices seem to have reduced recreational landings of pike in the last decade. Despite the decrease in pike landings from commercial and recreational fisheries, our analyses suggest that the loss of large pike continues. In addition to the long-term trends found in this study, dwindling catches during the last years are also evident from some areas in the Swedish national coastal fish monitoring programme (Olsson, 2019).

Several factors may contribute to the continued losses. Size distributions of stocks tend to lag five years or more behind changes in fishing pressure for larger fish species (Modica et al., 2014), which is consistent with the decline of large pike that appeared 5–10 years after making coastal waters open access to angling in 1985. At the same time, this also means that the time series in this study may not be long enough to record a potential recovery of pike following the decrease in fishing pressure since around 2010. However, several other pressures on pike populations have increased during the last decades, which may prevent or delay a recovery.

Habitat deterioration and food-web changes have affected both recruitment success and adult survival of pike in the Baltic Sea. Pike has suffered long-term losses of suitable spawning and nursery areas owing to drainage of wetlands and to coastal construction, boating and eutrophication (Bergström et al., 2013; Hansen et al., 2019; Nilsson et al., 2014; Sundblad and Bergström, 2014). From the 1990s onwards, a decline in recruitment success stemming from ecosystem changes in the open sea has also been reported (Eriksson et al., 2011; Ljunggren et al., 2010). Recent studies have demonstrated that the lower pike recruitment is related to strong increases in three-spined stickleback

(*Gasterosteus aculeatus*), a species that may have a negative impact on recruitment of pike especially at open coasts through predation on pike eggs and larvae (Bergström et al., 2015; Eklöf et al., 2020; Nilsson et al., 2019). The overall reduction in recruitment success due to habitat loss and stickleback predation are not likely causes of the pronounced decline of trophy-sized pike, but these may still have contributed to the lower catches through a general decline in the population sizes of pike in the Baltic, despite a potential positive effect on individual growth rate through a reduced density dependence (see below).

Simultaneously with the decrease of large pike along the Swedish coast since the early 1990s, a pronounced population recovery of the top predators grey seal and great cormorant has taken place in the Baltic Sea. After a rapid population increase, the cormorant population has remained fairly constant in the Baltic Proper from around 2005, while there is an ongoing increase in the Gulf of Bothnia (Herrmann et al., 2019). For grey seal, the population is continuously increasing by about 5% per year in the Baltic Sea, with the strongest rate of increase currently taking place in the southern areas (HELCOM, 2018). Hansson et al. (2018) estimated that in the early 2010 s these two predators together removed more pike biomass than the commercial and recreational fisheries combined at a Baltic Sea scale, but there can be considerable variation at the local scale. In contrast, a recent study in the German Baltic coast showed that the extraction of pike from fisheries is substantially higher than that from cormorants (Arlinghaus et al., 2021). Grey seal was not included in that study, but as seal densities are still low in the southern Baltic their removal of pike can be expected to be low (Hansson et al., 2018; HELCOM, 2018). Focusing specifically at the Stockholm archipelago, the estimates presented here (Fig. 4) are highly uncertain, but suggest that the removals from grey seal and cormorant have exceeded that of commercial and recreational fisheries during the 2010 s. For 2014–2017, predator removals are estimated to be 5–18 times higher (lower and higher range of estimated removals) than total landings of recreational and commercial fisheries combined. Of the two predators, grey seal is estimated to remove around 5 times more pike than cormorants. These results suggest that management would gain from broadening the narrow focus on the impacts of fisheries when planning measures for coastal fish stocks, as rebounding top predator populations in combination with decreasing landings in fisheries may cause extensive changes in the relative importance of mortality factors.

Cormorants mainly eat smaller pike (<50 cm length; Östman et al., 2013), which could reduce the impact on adult populations if there are compensatory effects. Grey seal can be expected to selectively target larger individuals. Information on size distributions of pike in grey seal diet is scarce, but a recent study of grey seal predation on cod in the southern Baltic Sea shows that 75% of the cod eaten (by weight) was above 55 cm length (Eero et al., 2019), even though a very low proportion of cod in the area is currently above that size (Svedäng and Hornborg, 2017). A similar size-selectivity is indicated by frequent observations of large pike carcasses eaten by seals, with the head left intact (usually fish larger than 2 kg; Niklas Sjöberg and Henrik C Andersson, County Administrative Board of Stockholm, pers. comm.). Partial ingestion of larger prey seems to be common among grey seals (Benoît et al., 2011; O'Boyle and Sinclair, 2012), why the proportion of large pike may be underestimated in studies relying on hard parts found in stomachs and scats. Despite this, the higher removal rates compared to fisheries and cormorants found in this study suggest that predation from grey seal is currently the largest source of mortality for large pike along the Swedish Baltic Sea coast.

Besides external drivers there can also be behavioural, phenotypic and demographic changes contributing to the decline in pike catches in angling. Pike may learn or angling select for pike to become more timid and avoid lures, hence resulting in lower catchability and slower growth (Carlson et al., 2007; Edeline et al., 2007; Monk et al., 2021). While the maximum size and the number of fish caught per day in the Stockholm archipelago have decreased, the mean weight increased up to around 1990. Presumably, the establishment of the sport fishing club in the three study sites increased the mortality on pike long before the introduction of open access recreational fishing in 1985, leading to a decrease in pike abundance as reflected in the numbers caught per fishing day. Reduced density dependence in combination with increasing temperatures and elevated levels of eutrophication may have increased the growth rate of pike (Berggren et al., 2021; Pierce and Tomcko, 2003). Since the 1960 s, a similar increase in mean size over time has been observed also in other areas of the Baltic Sea coast (Berggren et al., 2021; Lehtonen et al., 2009) and has been shown to be connected to a substantial increase in early-life growth rates (Berggren et al., 2021). Thus, we find it unlikely that behaviour or body growth per se could explain the reduction in catches of large pike. Technological creep, i.e. the development of more efficient fishing gear and techniques over time, is another factor that may have contributed to the increase in mean size of pike caught during this period. There is, however, little information available on how technological creep affects recreational fishing (Kleiven et al., 2019).

In inland waters, there was an increase in registrations of trophy-sized pike in 2000–2010 coincident with the decrease in coastal areas, which suggests that the decrease in coastal waters was not an effect of regional climate change or a reduced will to report trophy-sized pike. This shift may to some extent reflect a general trend of pike fishers turning to inland waters as a consequence of dwindling catches at the coast, a pattern that has been repeatedly reported by devoted pike fishers. Since around 2010 there is also a decrease in the number, but not maximum weight, of reported trophy-sized pike from inland waters. This pattern is potentially an early sign of overexploitation, and warrants further research as well as caution in management.

This study was made possible through the digitization of long-term recreational fisheries data, which can strengthen status assessments of data-poor species like pike (Jansen et al., 2013). Although recreational fishing data could constitute valuable support to fish monitoring programmes for species otherwise difficult to survey, recreational catch data has rarely been collected over long periods of time. Common deficits in recreational fishing data include a lack of effort information and of information on days with zero catches. Furthermore, assumptions must often be made regarding consistent catchability, willingness to report, development of fishing gear and practices, fishermen demographics, reporting bias etc. (concept reviewed in Lewandowski and Specht, 2015). In this context, data used in this study overcomes some of the caveats of recreational fisheries data. Data originate from fishing associations/clubs which have had high ambitions when it comes to recording catches. While the national register of trophy-sized fish follows a strict protocol for reporting, the Stockholm sport fishing club kept detailed logbooks, where summaries were published in year books. The data included days of zero catch, which implies that reporting has been mandatory.

There was a pronounced decline in fishing effort by the members of SSFK in the three study sites in the Stockholm archipelago from the 1990s onwards (Fig. S1). This was probably an effect of the open access fishing introduced in 1985, opening up vast new fishing waters to the members of the club (and the club waters to other fishers). The observed decline in maximum weight in the three sites may to some extent have been affected by the lower effort, as chances of catching a large pike depend on total effort. However, concurrent with the decrease in maximum weight of pike caught by the sport fishing club, the number (and weight) of reported fish in the national register of trophy-sized pike also declined from the early 1990s onwards, following an increase up to the reform in 1985 (Fig. S3). The sharp rise likely reflects an increased effort as a consequence of the newly introduced open access fishing along the coast. Although there is no data available on the development of angling effort in the Stockholm archipelago, there is good reason to believe that the decline in catches mainly reflects a decrease in the abundance of large pike rather than a decrease in fishing effort or willingness to report catches. Reports from inland waters continued to increase until around 2010, which probably better reflects the general

interest for pike fishing in Sweden. Even though there may have been some shift in total fishing effort towards inland waters during this period, popularity of pike fishing at the coast has remained high. Thus, the consistent pattern between the two datasets coming from different sources and representing different spatial scales, with a peak in catches of large pike a few years after all coastal waters were opened to angling, jointly support the main conclusion - that the abundance of large pike has seen a continuous decline along the Swedish coast since the 1990s.

Although we can show a continuous decline in abundance of large pike, this study highlights the need for a better understanding of the causes for this decline in the Baltic Sea. While comparisons of fish removals, such as in the present study and in Hansson et al. (2018) can provide indications of major mortality factors, other methods are necessary for estimating population level effects. One approach is to utilise natural experiments, where the development or status of fish populations are related to changes or differences in pressures in spatiotemporal comparisons (see e.g. Ovegård et al., 2021). Here regression-based approaches or BACI (Before-After-Control-Impact) analyses may be applied to estimate the impact of predators or fisheries. In a similar way, large-scale manipulations where either fisheries or predators are excluded from specific areas may be useful, such as no-take zones where the effects of fishing can be estimated (Bergström et al., 2016; Berkström et al., 2021). Another option is to apply quantitative modelling approaches (Östman et al., 2013), where the impact of natural predation and fisheries on population parameters are estimated. These models, however, require detailed and high-resolution data on diet compositions and abundance estimates of predators and catches in fisheries, why parameterisation is a challenge. Ultimately, a combination of approaches may be needed for an in-depth understanding of how different mortality factors affect fish populations.

In summary, our analyses suggest that the abundance of large-sized pike in coastal areas of the northern Baltic Sea has decreased substantially during the last three decades. The open access to the angling fishery at the Swedish Baltic Sea coast was likely a major contributing factor to the initial decline. Fisheries restrictions introduced at the Swedish coast in 2010, including maximum size and bag limits, and an increase in catch-and-release practices, have not resulted in any signs of recovery of the pike populations. This study cannot establish any causal relationship, but multiple factors in addition to fisheries, like predation from increasing populations of grey seal and cormorant inducing mortality, and habitat changes and stickleback predation affecting recruitment, have all probably contributed to the enduring decline. Our results in combination with the negative trends observed in coastal fish monitoring data (Olsson, 2019) indicate a poor status of pike populations, calling for further management actions. To enable a recovery, it may not be enough to introduce further restrictions on fisheries alone. Instead, management would gain from a broader focus on decreasing total mortality, including the effects of natural predation. There is also a need to establish targeted monitoring of pike populations to improve precision and spatial resolution of status assessments, and hence, the need for management actions. Here we believe that the use of citizen science may offer an additional way of collecting data for monitoring, while simultaneously raising awareness and fostering collaboration among stakeholder groups.

CRediT authorship contribution statement

Ulf Bergström: Conceptualization, Methodology, Data curation, Formal analysis, Writing – original draft. **Stefan Larsson**: Methodology, Formal analysis, Writing – original draft. **Mårten Erlandsson**: Data curation, Visualization. **Maria Ovegård**: Data curation, Writing – review & editing. **Henrik Ragnarsson Stabo**: Conceptualization, Data curation. **Örjan Östman**: Methodology, Writing – review & editing. **Göran Sundblad**: Conceptualization, Methodology, Data curation, Formal analysis, Visualization, Writing – original draft.

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.

Acknowledgements

We thank the Stockholm Sport Fishing Club and the Swedish Anglers Association for kindly providing catch data for this study, Sofie Westerberg and Axel Bergström for assistance in digitization of data, and two anonymous reviewers for helpful comments on the manuscript. This work was supported by the Swedish Agency for Marine and Water Management (HaV dnr 4637–18).

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fishres.2022.106307.

References

Anon, 1991, Fritidsfiske -90., Fiskeristyrelsen, Statistiska centralbyrån.
Arlinghaus, R., Abbott, J.K., Fenichel, E.P., Carpenter, S.R., Hunt, L.M., Alós, J., Klefoth, T., Cooke, S.J., Hilborn, R., Jensen, O.P., Wilberg, M.J., Post, J.R., Manfredo, M.J., 2019. Opinion: Governing the recreational dimension of global fisheries. Proc. Natl. Acad. Sci. 116, 5209–5213. https://doi.org/10.1073/pnas.1902796116.
Arlinghaus, R., Alós, J., Beardmore, B., Díaz, Á.M., Hühn, D., Johnston, F., Klefoth, T., Kuparinen, A., Matsumura, S., Pagel, T., Pieterek, T., Riepe, C., 2018. Recreational piking – sustainably managing pike in recreational fisheries. In: Biology and Ecology of Pike. CRC Press.
Arlinghaus, R., Cooke, S.J., 2009. Recreational fisheries: socioeconomic importance, conservation issues and management challenges. In: Recreational Hunting, Conservation and Rural Livelihoods. John Wiley & Sons, Ltd, pp. 39–58. https://doi.org/10.1002/9781444303179.ch3.
Arlinghaus, R., Lucas, J., Weltersbach, M.S., Kömle, D., Winkler, H.M., Riepe, C., Kühn, C., Strehlow, H.V., 2021. Niche overlap among anglers, fishers and cormorants and their removals of fish biomass: A case from brackish lagoon ecosystems in the southern Baltic Sea. Fish. Res. 238, 105894 https://doi.org/10.1016/j.fishres.2021.105894.
Benoît, H.P., Swain, D.P., Bowen, W.D., Breed, G.A., Hammill, M.O., Harvey, V., 2011. Evaluating the potential for grey seal predation to explain elevated natural mortality in three fish species in the southern Gulf of St. Lawrence. Mar. Ecol. Prog. Ser. 442, 149–167. https://doi.org/10.3354/meps09454.
Berggren, T., Bergström, U., Sundblad, G., Östman, Ö., 2021. Warmer water increases early body growth of northern pike *(Esox lucius)* but mortality has larger impact on decreasing body sizes. Can. J. Fish. Aquat. Sci. https://doi.org/10.1139/cjfas-2020-0386.
Bergström, U., Olsson, J., Casini, M., Eriksson, B.K., Fredriksson, R., Wennhage, H., Appelberg, M., 2015. Stickleback increase in the Baltic Sea – A thorny issue for coastal predatory fish. Estuar. Coast. Shelf Sci. 163, 134–142. https://doi.org/10.1016/j.ecss.2015.06.017.
Bergström, U., Sköld, M., Wennhage, H., Wikström, A., 2016, Ekologiska effekter av fiskefria områden i Sveriges kust- och havsområden (Rapport No. 2016:20). Öregrund.
Bergström, U., Sundblad, G., Downie, A.-L., Snickars, M., Boström, C., Lindegarth, M., 2013. Evaluating eutrophication management scenarios in the Baltic Sea using species distribution modelling. J. Appl. Ecol. 50, 680–690. https://doi.org/10.1111/1365-2664.12083.
Berkström, C., Florin, A.-B., Fredriksson, R., Lundström, K., Bergström, U., 2021. Rapid effects of a fishing closure on whitefish (*Coregonus maraena*) in the northern Baltic Sea. Boreal environment research 26, 89–104.
Breheny, P., Burchett, W., 2017. Visualization of regression models using visreg. R. J. 9, 56.
Carlson, S.M., Edeline, E., Asbjørn Vøllestad, L., Haugen, T.O., Winfield, I.J., Fletcher, J. M., Ben James, J., Stenseth, N.C., 2007. Four decades of opposing natural and human-induced artificial selection acting on Windermere pike (Esox lucius). Ecol. Lett. 10, 512–521. https://doi.org/10.1111/j.1461-0248.2007.01046.x.
Casselman, J.M., Lewis, C.A., 1996. Habitat requirements of northern pike (*Esox lucius*). Can. J. Fish. Aquat. Sci. 53, 161–174.
Coleman, F.C., Figueira, W.F., Ueland, J.S., Crowder, L.B., 2004. The Impact of United States Recreational Fisheries on Marine Fish Populations. Science 305, 1958–1960.
Cooke, S.J., Cowx, I.G., 2004. The role of recreational fishing in global fish crises. BioScience 54, 857. https://doi.org/10.1641/0006-3568(2004)054[0857:TRORFI]2.0.CO;2.
Craig, J.F., 2008. A short review of pike ecology. Hydrobiologia 601, 5–16.
Donadi, S., Austin, Å.N., Bergström, U., Eriksson, B.K., Hansen, J.P., Jacobson, P., Sundblad, G., van Regteren, M., Eklöf, J.S., 2017. A cross-scale trophic cascade from

large predatory fish to algae in coastal ecosystems. Proc. R. Soc. B Biol. Sci. 284, 20170045 https://doi.org/10.1098/rspb.2017.0045.
Donaldson, M.R., O'Connor, C.M., Thompson, L.A., Gingerich, A.J., Danylchuk, S.E., Duplain, R.R., Cooke, S.J., 2011. Contrasting Global Game Fish and Non-Game Fish Species. Fisheries 36, 385–397. https://doi.org/10.1080/03632415.2011.597672.
Edeline, E., Carlson, S.M., Stige, L.C., Winfield, I.J., Fletcher, J.M., James, J.B., Haugen, T.O., Vøllestad, L.A., Stenseth, N.C., 2007. Trait changes in a harvested population are driven by a dynamic tug-of-war between natural and harvest selection. Proc. Natl. Acad. Sci. 104, 15799–15804. https://doi.org/10.1073/pnas.0705908104.
Eero, M., Andersen, N.G., Berg, C.W., Christensen, A., Hansen, J.H., Hansen, K.K., Hüssy, K., Kristensen, K., Kroner, A.-M., Kindt-Larsen, L., Lund, H., Lundström, K., Mortensen, L.O., Neuenfeldt, S., Olsen, M.T., Ravn, P., Tomkiewicz, J., 2019, Eastern Baltic cod—New knowledge on growth and mortality. Institut for Akvatiske Ressourcer, Danmarks Tekniske Universitet.
Eklöf, J.S., Sundblad, G., Erlandsson, M., Donadi, S., Hansen, J.P., Eriksson, B.K., Bergström, U., 2020. A spatial regime shift from predator to prey dominance in a large coastal ecosystem. Commun. Biol. 3, 1–9. https://doi.org/10.1038/s42003-020-01180-0.
Eriksson, B., Sieben, K., Eklöf, J., Ljunggren, L., Olsson, J., Casini, M., Bergström, U., 2011. Effects of altered offshore food webs on coastal ecosystems emphasize the need for cross-ecosystem management. AMBIO 40, 786–797. https://doi.org/10.1007/s13280-011-0158-0.
Flink, H., Nordahl, O., Hall, M., Rarysson, A., Bergström, K., Larsson, P., Petersson, E., Merilä, J., Tibblin, P., 2021. Examining the effects of authentic C&R on the reproductive potential of Northern pike. Fish. Res. 243, 106068 https://doi.org/10.1016/j.fishres.2021.106068.
Frank, K.T., Petrie, B., Choi, J.S., Legget, W., 2005. Trophic cascades in a formerly cod-dominated ecosystem. science 308, 1621–1623.
Gunderson, D.R., Parma, A.M., Hilborn, R., Cope, J.M., Fluharty, D.L., Miller, M.L., Vetter, R.D., Heppell, S.S., Greene, H.G., 2008. The Challenge of Managing Nearshore Rocky Reef Resources. Fisheries 33, 172–179. https://doi.org/10.1577/1548-8446-33.4.172.
Hammond, P.S., Grellier, K., 2006. Grey seal diet composition and prey consumption in the North Sea. Final Rep. Dep. Environ. Food Rural Aff. Proj. MF0319.
Hansen, J.P., Sundblad, G., Bergström, U., Austin, Å.N., Donadi, S., Eriksson, B.K., Eklöf, J.S., 2019. Recreational boating degrades vegetation important for fish recruitment. Ambio 48, 539–551. https://doi.org/10.1007/s13280-018-1088-x.
Hansson, S., Bergström, U., Bonsdorff, E., Härkönen, T., Jepsen, N., Kautsky, L., Lundström, K., Lunneryd, S.-G., Ovegård, M., Salmi, J., Sendek, D., Vetemaa, M., 2018. Competition for the fish – fish extraction from the Baltic Sea by humans, aquatic mammals, and birds. ICES J. Mar. Sci. 75, 999–1008. https://doi.org/10.1093/icesjms/fsx207.
Heikinheimo, O., Marjomäki, T.J., Olin, M., Rusanen, P., 2021. Cormorant predation mortality of perch *(Perca fluviatilis)* in coastal and archipelago areas, northern Baltic Sea. ICES J. Mar. Sci. fsab258. https://doi.org/10.1093/icesjms/fsab258.
HELCOM, 2018. Population trends and abundance of seals. HELCOM Core Indic. Rep.
Hentati-Sundberg, J., 2017. Svenskt fiske i historiens ljus - en historisk fiskeriatlas. Swed. Univ. Agric. Sci., Dep. Aquat. Resour., Lysekil.
Herrmann, C., Bregnballe, T., Larsson, K., Leivits, M., Rusanen, P., 2019. Population development of Baltic bird species: Great cormorant *(Phalacrocorax carbo sinensis)*. HELCOM Balt. Sea Environ. Fact. Sheets HELCOM.
Hühn, D., Arlinghaus, R., 2011. Determinants of hooking mortality in freshwater recreational fisheries: a quantitative meta-analysis. In: Determinants of Hooking Mortality in Freshwater Recreational Fisheries: A Quantitative Meta-analysis. American Fisheries Society Symposium, pp. 141–170.
Hyder, K., Weltersbach, M.S., Armstrong, M., Ferter, K., Townhill, B., Ahvonen, A., Arlinghaus, R., Baikov, A., Bellanger, M., Birzaks, J., Borch, T., Cambie, G., de Graaf, M., Diogo, H.M.C., Dziemian, Ł., Gordoa, A., Grzebielec, R., Hartill, B., Kagervall, A., Kapiris, K., Karlsson, M., Kleiven, A.R., Lejk, A.M., Levrel, H., Lovell, S., Lyle, J., Moilanen, P., Monkman, G., Morales-Nin, B., Mugerza, E., Martinez, R., O'Reilly, P., Olesen, H.J., Papadopoulos, A., Pita, P., Radford, Z., Radtke, K., Roche, W., Rocklin, D., Ruiz, J., Scougal, C., Silvestri, R., Skov, C., Steinback, S., Sundelöf, A., Svagzdys, A., Turnbull, D., van der Hammen, T., van Voorhees, D., van Winsen, F., Verleye, T., Veiga, P., Vølstad, J.-H., Zarauz, L., Zolubas, T., Strehlow, H.V., 2018. Recreational sea fishing in Europe in a global context-Participation rates, fishing effort, expenditure, and implications for monitoring and assessment. In: Fish Fish., 19, pp. 225–243. https://doi.org/10.1111/faf.12251.
Ihde, T.F., Wilberg, M.J., Loewensteiner, D.A., Secor, D.H., Miller, T.J., 2011. The increasing importance of marine recreational fishing in the US: Challenges for management. Fish. Res. 108, 268–276. https://doi.org/10.1016/j.fishres.2010.12.016.
Jansen, T., Arlinghaus, R., Als, T.D., Skov, C., 2013. Voluntary angler logbooks reveal long-term changes in a lentic pike, *Esox lucius*, population. Fish. Manag. Ecol. 20, 125–136. https://doi.org/10.1111/j.1365-2400.2012.00866.x.
Kleiven, A.R., Moland, E., Sumaila, U.R., 2019. No fear of bankruptcy: the innate self-subsidizing forces in recreational fishing. ICES J. Mar. Sci. fsz128. https://doi.org/10.1093/icesjms/fsz128.
Laikre, L., Miller, L.M., Palmé, A., Palm, S., Kapuscinski, A.R., Thoresson, G., Ryman, N., 2005. Spatial genetic structure of northern pike (*Esox lucius*) in the Baltic Sea. Mol. Ecol. 14, 1955–1964.
Larsson, P., Tibblin, P., Koch-Schmidt, P., Engstedt, O., Nilsson, J., Nordahl, O., Forsman, A., 2015. Ecology, evolution, and management strategies of northern pike populations in the Baltic Sea. AMBIO 44, 451–461. https://doi.org/10.1007/s13280-015-0664-6.
Lehtonen, H., Leskinen, E., Selén, R., Reinikainen, M., 2009. Potential reasons for the changes in the abundance of pike, *Esox lucius*, in the western Gulf of Finland, 1939–2007. Fish. Manag. Ecol. 16, 484–491. https://doi.org/10.1111/j.1365-2400.2009.00701.x.
Lewandowski, E., Specht, H., 2015. Influence of volunteer and project characteristics on data quality of biological surveys. Conserv. Biol. 29, 713–723. https://doi.org/10.1111/cobi.12481.
Lewin, W.-C., Arlinghaus, R., Mehner, T., 2006. Documented and potential biological impacts of recreational fishing: insights for management and conservation. Rev. Fish. Sci. 14, 305–367. https://doi.org/10.1080/10641260600886455.
Lewin, W.-C., Weltersbach, M.S., Ferter, K., Hyder, K., Mugerza, E., Prellezo, R., Radford, Z., Zarauz, L., Strehlow, H.V., 2019. Potential environmental impacts of recreational fishing on marine fish stocks and ecosystems. Rev. Fish. Sci. Aquac. 27, 287–330. https://doi.org/10.1080/23308249.2019.1586829.
Ljunggren, L., Sandström, A., Bergström, U., Mattila, J., Lappalainen, A., Johansson, G., Sundblad, G., Casini, M., Kaljuste, O., Eriksson, B.K., 2010. Recruitment failure of coastal predatory fish in the Baltic Sea coincident with an offshore ecosystem regime shift. ICES J. Mar. Sci. 67, 1587–1595. https://doi.org/10.1093/icesjms/fsq109.
McClenachan, L., 2009. Documenting loss of large trophy fish from the florida keys with historical photographs. Conserv. Biol. 23, 636–643. https://doi.org/10.1111/j.1523-1739.2008.01152.x.
Modica, L., Velasco, F., Preciado, I., Soto, M., Greenstreet, S.P.R., 2014. Development of the large fish indicator and associated target for a Northeast Atlantic fish community. ICES J. Mar. Sci. 71, 2403–2415. https://doi.org/10.1093/icesjms/fsu101.
Monk, C.T., Bekkevold, D., Klefoth, T., Pagel, T., Palmer, M., Arlinghaus, R., 2021. The battle between harvest and natural selection creates small and shy fish. Proc. Natl. Acad. Sci. 118. https://doi.org/10.1073/pnas.2009451118.
Näslund, J., Lundgren, M., 2018. Mapping the distribution of scale-rayed wrasse Acantholabrus palloni in Swedish Skagerrak using angling records. PeerJ 6, e5900. https://doi.org/10.7717/peerj.5900.
Nilsson, J., Engstedt, O., Larsson, P., 2014. Wetlands for northern pike (Esox lucius L.) recruitment in the Baltic Sea. Hydrobiologia 721, 145–154. https://doi.org/10.1007/s10750-013-1656-9.
Nilsson, J., Flink, H., Tibblin, P., 2019. Predator–prey role reversal may impair the recovery of declining pike populations. J. Anim. Ecol. 88, 927–939. https://doi.org/10.1111/1365-2656.12981.
O'Boyle, R., Sinclair, M., 2012. Seal–cod interactions on the Eastern Scotian Shelf: Reconsideration of modelling assumptions. Fish. Res. 115–116, 1–13. https://doi.org/10.1016/j.fishres.2011.10.006.
Olsson, J., 2019. Past and current trends of coastal predatory fish in the baltic sea with a focus on perch, pike, and pikeperch. Fishes 4, 7. https://doi.org/10.3390/fishes4010007.
Östman, Ö., Boström, M.K., Bergström, U., Andersson, J., Lunneryd, S.-G., 2013. Estimating competition between wildlife and humans–a case of cormorants and coastal fisheries in the Baltic Sea. PLoS ONE 8, e83763. https://doi.org/10.1371/journal.pone.0083763.
Ovegård, M.K., Jepsen, N., Bergenius Nord, M., Petersson, E., 2021. Cormorant predation effects on fish populations: A global meta-analysis. Fish Fish 22, 605–622. https://doi.org/10.1111/faf.12540.
Pierce, R.B., Tomcko, C.M., 2003. Interrelationships among production, density, growth, and mortality of Northern Pike in Seven North-Central Minnesota Lakes. Trans. Am. Fish. Soc. 132, 143–153. https://doi.org/10.1577/1548-8659(2003)132<0143:IAPDGA>2.0.CO;2.
Post, J.R., Sullivan, M., Cox, S., Lester, N.P., Walters, C.J., Parkinson, E.A., Paul, A.J., Jackson, L., Shuter, B.J., 2002. Canada's Recreational Fisheries: The Invisible Collapse? Fisheries 27, 6–17. https://doi.org/10.1577/1548-8446(2002)027<0006:CRF>2.0.CO;2.
R. Core Team, 2013, R: A language and environment for statistical computing [WWW Document]. Vienna. URL ⟨https://www.R-project.org/⟩.
Radford, Z., Hyder, K., Zarauz, L., Mugerza, E., Ferter, K., Prellezo, R., Strehlow, H.V., Townhill, B., Lewin, W.-C., Weltersbach, M.S., 2018. The impact of marine recreational fishing on key fish stocks in European waters. PLOS ONE 13, e0201666. https://doi.org/10.1371/journal.pone.0201666.
Richardson, E.A., Kaiser, M.J., Edward-Jones, G., Ramsay, K., 2006. Trends in sea anglers' catches of trophy fish in relation to stock size. Fish. Res. 82, 253–262.
Saulamo, K., Neuman, E., 2002. Local management of Baltic fish stocks-the significance of migrations. FINFO 2002, 9.
Soutukorva, Å., Söderqvist, T., 2005, Gone fishing to the Stockholm-Roslagen archipelago – results from surveys on anglers' travels, catches and habits 126.
Statistics Sweden, 2021. Recreational fishing 2020 (In Swedish). Stat. Medd. JO 57.
Sundblad, G., Bergström, U., 2014. Shoreline development and degradation of coastal fish reproduction habitats. AMBIO 43, 1020–1028. https://doi.org/10.1007/s13280-014-0522-y.
Sunde, J., Tamario, C., Tibblin, P., Larsson, P., Forsman, A., 2018. Variation in salinity tolerance between and within anadromous subpopulations of pike (Esox lucius). Sci. Rep. 8, 22. https://doi.org/10.1038/s41598-017-18413-8.
Svedäng, H., Hornborg, S., 2017. Historic changes in length distributions of three Baltic cod (*Gadus morhua*) stocks: Evidence of growth retardation. Ecol. Evol. 7, 6089–6102. https://doi.org/10.1002/ece3.3173.
Swedish Agency for Marine and Water Management, 2019. Recreational fishing in Sweden. Insight into recreational fishing extent 2013-2017 (Swed.) (Swed. Agency Mar. Water Manag. (No. 2019), 5 (Report).
Thörnqvist, S., 2009. Fritidsfiskets utövare, 2006. Fiskeriverket informerar. Swedish Board of Fisheries,, Gothenburg, p. 1.

Tibblin, P., Forsman, A., Koch-Schmidt, P., Nordahl, O., Johannessen, P., Nilsson, J., Larsson, P., 2015. Evolutionary Divergence of Adult Body Size and Juvenile Growth in Sympatric Subpopulations of a Top Predator in Aquatic Ecosystems. Am. Nat. 186, 98–110. https://doi.org/10.1086/681597.

Venturelli, P.A., Hyder, K., Skov, C., 2017. Angler apps as a source of recreational fisheries data: opportunities, challenges and proposed standards. Fish Fish 18, 578–595. https://doi.org/10.1111/faf.12189.

Wennerström, L., Olsson, J., Ryman, N., Laikre, L., 2017. Temporally stable, weak genetic structuring in brackish water northern pike (*Esox lucius*) in the Baltic Sea indicates a contrasting divergence pattern relative to freshwater populations. Can. J. Fish. Aquat. Sci. 74, 562–571. https://doi.org/10.1139/cjfas-2016-0039.

Wickham, H., 2016, Elegant graphics for data analysis. Media 35, 10.1007.

Wood, S.N., 2017. Generalized Additive Models: An Introduction with R. CRC Press.

Wood, S.N., 2011. Fast stable restricted maximum likelihood and marginal likelihood estimation of semiparametric generalized linear models. J. R. Stat. Soc. Ser. B Stat. Method. 73, 3–36. https://doi.org/10.1111/j.1467-9868.2010.00749.x.