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A pan-Baltic assessment of temporal trends in coastal pike populations

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A R T I C L E   I N F O

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A B S T R A C T

The northern pike (*Esox lucius*) is an iconic predatory fish species of significant recreational value and ecological role in the Baltic Sea. Some earlier studies indicate local declines of pike in the region, but a thorough spatial evaluation of regional population trends of pike in the Baltic Sea is lacking. In this study, we collate data from 59 unique time-series from fisheries landings and fishery-independent monitoring programs to address temporal trends in pike populations since the mid-2000′s in eight countries surrounding the Baltic Sea. In a common analysis considering all time-series in concert, we found indications of an overall regional temporal decline of pike in the Baltic Sea, but trends differed among countries. Individual negative trends in time-series were moreover found in several regions of the Baltic Sea, but predominantly so in the central and southern parts, while positive trends were only found in Estonia and northern Finland. The mix of data used in this study is inherently noisy and to some extent of uncertain quality, but as a result of the overall negative trends, together with the socioeconomic and ecological importance of pike in coastal areas of the Baltic Sea, we suggest that actions should be taken to protect and restore pike populations. Management measures should be performed in combination with improved fishery-independent monitoring programs to provide data of better quality and development of citizen-science approaches as a data source for population estimates. Possible measures that could strengthen pike populations include harvest regulations (including size limits, no-take areas and spawning closures), habitat protection and restoration, and an ecosystem-based approach to management considering also the impact of natural predators.

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1. Introduction

The global decline of populations of predatory fish (Christensen et al., 2014; Estes et al., 2011; Myers and Worm, 2003; Pauly et al., 1998) is commonly caused by overexploitation, changes in food web structure and function, as well as unfavorable environmental conditions (Christensen et al., 2014; Hammerschlag et al., 2019; Möllmann et al., 2021; Valdivia et al., 2017). In coastal areas, predatory fish are often caught for food and recreation, and are of high socioeconomic value (Hyder et al., 2018; Koemle et al., 2021). Besides providing direct benefits to humans, predatory fish also play important regulatory and structuring roles in aquatic food webs (Lotze et al., 2006; Norderhaug et al., 2021; Pauly et al., 1998). A decline in predatory fish populations may lead to knock-on effects in the food web resulting in trophic cascades and changes in food web functioning (Casini et al., 2008; Daskalov, 2002; Daskalov et al., 2007; Eriksson et al., 2011; Frank et al., 2005; Worm et al., 2006). Recent studies in coastal areas have, for example, shown that strong predatory fish populations might be as important for reducing the negative symptoms of eutrophication in coastal vegetated habitats as reduction of nutrient loading (Baden et al., 2012; Donadi et al., 2017; Östman et al., 2016; Sieben et al., 2011). Overall, knowledge of the temporal and spatial variation in trends of predatory fish populations is thus essential for aquatic ecosystem management related to sustainable natural resource use, human welfare, recreation, as well as ecosystem functioning.

Predatory fish species exhibit a range of natural behaviors and life histories, including species that are primarily sedentary with an ambush foraging mode, active hunters, and others that undertake extensive migrations, while many of them also change habitat use over ontogeny (Daly et al., 2021; Richardson et al., 2016; Wearmouth et al., 2014). The combination of often low relative abundances of predators compared to lower trophic level fish (Auster and Link, 2009; Guidetti et al., 2010) and sometimes generally low catchability in standardized monitoring gears, makes it challenging to assess population trends in predatory fish (Pierce and Tomcko, 2003). To overcome these challenges, different indirect methods of abundance assessment can be applied, including environmental DNA (Karlsson et al., 2022), mark-recapture methods (Kuparinen et al., 2012), or records from recreational fishers' associations or fishing clubs (Bergström et al., 2022; Jansen et al., Lehtonen et al., 2009). In order to achieve a perspective in a larger geographical context, often a combination of different data sources and monitoring techniques, including fisheries independent and fisheries dependent data might be required (Olsson, 2019).

The northern pike (*Esox lucius*), hereafter referred to as pike, is an iconic predatory fish species in the Baltic Sea, with a high value for recreational fisheries (Arlinghaus et al., 2021; Blenckner et al., 2021; Hansson et al., 2018; Koemle et al., 2021), and an important ecological role as a predator in coastal ecosystems (Donadi et al., 2017; Eklöf et al., 2020). Pike is of freshwater origin (Craig, 1996), and is therefore confined to shallow coastal areas in the less saline central and northern parts of the Baltic Sea, and in the southern and western parts of the region to estuaries and sheltered lagoons and bays with sufficiently low (or no) salinity due to freshwater inflow or lower water exchange with the Baltic Sea (HELCOM, 2012; Jacobsen et al., 2007; Raat, 1988; van Gemert et al., 2022). As a large-bodied obligate piscivore, pike has relatively low population densities in the Baltic Sea (HELCOM, 2012). Similar to many other coastal fish species of freshwater origin found in the Baltic Sea, pike has a local population structure with limited movements and migrations, often between 10 and 70 km depending on the region (Laikre et al., 2005; Östman et al., 2017a; Saulamo and Neuman, 2002; Wennerström et al., 2017).

The limited migration and large body size, combined with a sit-and-wait behavior typical for ambush predators (Craig, 1996), results in low catchability and poor representation of pike in coastal fish monitoring programs and other fishery-independent surveys with sedentary gear of small mesh sizes (HELCOM, 2012, 2018). Therefore, it has been challenging to perform thorough regional assessments of the status of the species in the Baltic Sea. Earlier attempts have therefore been rather limited in their spatial and temporal coverage (Bergström et al., 2022; Olsson, 2019), and regional assessments at a Baltic Sea scale are lacking.

At present, pike is of relatively low commercial importance for fisheries in the Baltic Sea region (Zanzi and Holmes, 2017), making up 0.3% and 0.05% of the total value and landings, respectively, of fish caught in the Baltic Sea during 2015–2019 (https://stecf.jrc.ec.europa.eu/dd/fdi). There is a widespread perception among fishers and managers that pike in the Baltic Sea is in decline. Earlier studies do provide support for this perception by showing local declines in pike population status (Bergström et al., 2022; Eriksson et al., 2011; Lehtonen et al., 2009; Ljunggren et al., 2010; Nilsson et al., 2004; Olsson, 2019; van Gemert et al., 2022; Greszkiewicz et al., 2022). As a result of the limitations in data and the lack of earlier regional assessments, pike is not listed on the HELCOM red list of species as being in decline (HELCOM, 2022).

In this study, we aim to update and extend the available information provided in earlier studies to assess pike population trends in the Baltic Sea on both a regional and pan-Baltic scale. We compiled time-series since the mid-2000′s to address the state of pike populations in the Baltic, using combined data from coastal fish monitoring programs, recreational fisheries surveys, and commercial fisheries landings in all countries bordering the Baltic Sea except Russia. The data are used to analyze common trends in population development across time-series, data sources, countries, and regions. We further provide suggestions for future and developed monitoring and assessments of pike in the Baltic Sea to improve fisheries management plans, and aid implementation of the Baltic Sea Action Plan (HELCOM, 2007) and regional legislative acts as the Marine Strategy Framework Directive (EU, 2008).

2. Materials and methods

2.1. Data

Data from different sources were screened for further analyses, excluding time-series with a high occurrence of zero-observations (typically with a frequency of occurrence > 50%) distributed over the years considered. These time-series were excluded because a high frequency of zero-observations would reduce the possibility to detect significant trends in data, and that pike have naturally low occurrences in some Baltic regions. Excluding time-series with a high occurrence of zero-observations should hence represent a rather conservative approach with respect to the presence of any potential negative trends. For a comprehensive list of the 99 official monitoring programs in 2018 targeting coastal fish in the Baltic Sea region, please see HELCOM (2019). After exclusion, 59 time-series from eight countries with data on pike catch to support trend analysis, including 15 time-series from fisheries-independent coastal fish monitoring programs (multimesh gillnets) from four countries, seven time-series from recreational fisheries surveys (angling, gillnets and trapnets) only from Finland, and 37 time-series from commercial fisheries landings (gillnets, fykenets, pound nets, angling and trolling, line fishing and trap nets) from all eight countries considered remained (Fig. 1, Table 1). The length of the time-series differed with some dating back to the 1920′s (Denmark) and the shortest to the mid-2000′s (Table 2). As pike has a local population structure (see Östman et al., 2017a; Wennerström et al., 2017), we find it highly likely that the individual time-series represents spatially independent pike populations. The different methods to some extent catch pike of different size, where monitoring programs using gillnets mainly catch juveniles to 60–70 cm pike, commercial fisheries larger individuals as a result of larger mesh sizes used, and recreational fisheries, including anglers, from juveniles to mega-sized pike. To compare trends over time among sites, regions, and countries, in a comprehensive way, we restricted the data used to years 2005 – 2020 (2005–2021 in Lithuania). Data from the Finnish recreational fisheries surveys only

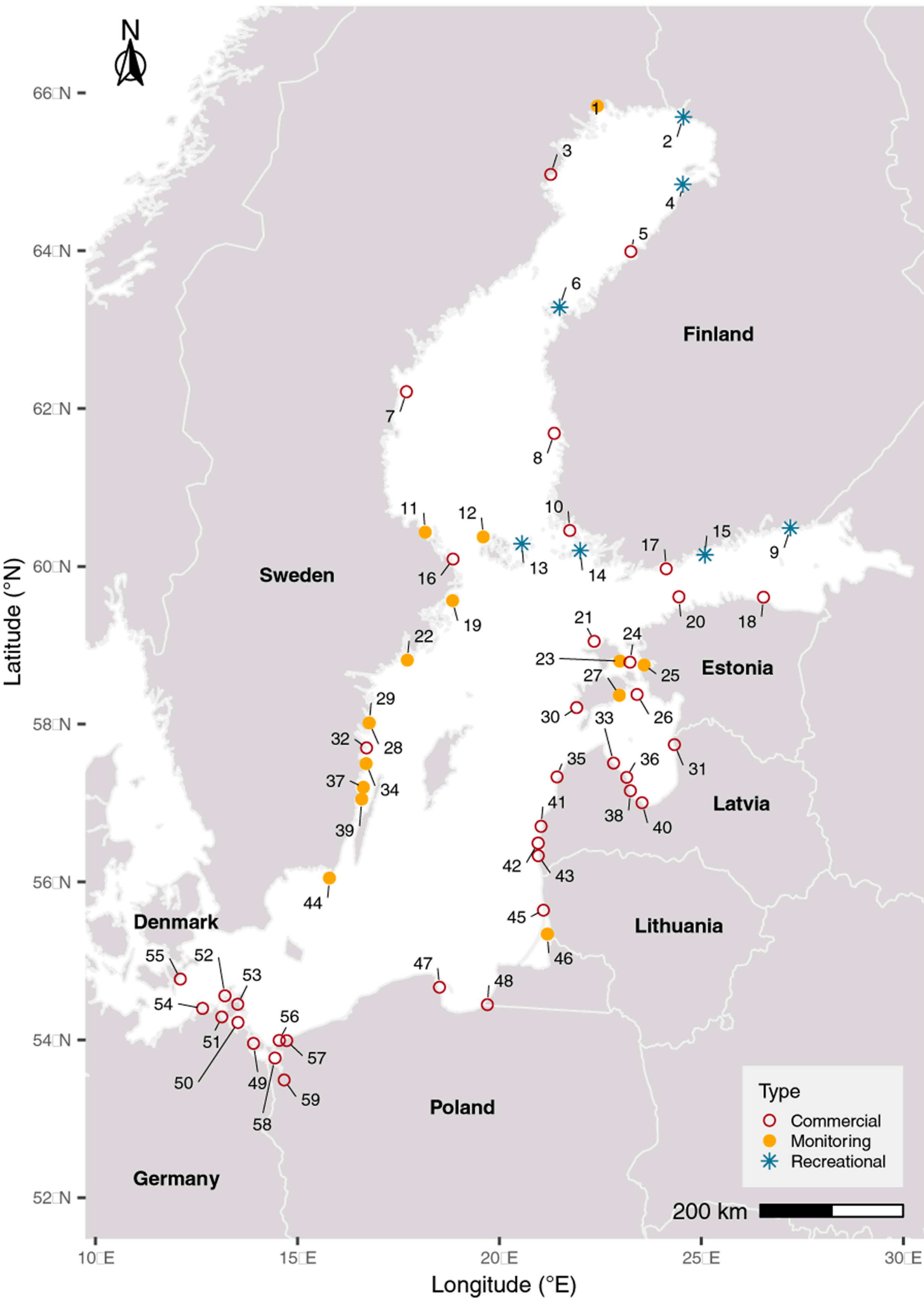

Fig. 1. Map of the Baltic Sea and all sampling sites included in the analyses. Each number on the map denotes a sampling site (monitoring) or region (recreational and commercial data), and details on each location are shown in Table 2. Points representing recreational or commercial catch data are placed in the center of the waterbody/area in the cases of lagoons and tidal lakes (Poland and Germany), or at the midpoint of the coastline bordering the fishing region (Finland).

Table 1
Overview of the data from each country that was used in the analyses.

Country	Data type	Gear	# of sites
Denmark	commercial	gillnets, fykenets, pound nets	1
Estonia	commercial	gillnets, trapnets, angling	6
	monitoring	gillnets	3
Germany	commercial	gillnets, fykenets, long lines	6
Finland	commercial	gillnets, fykenets, angling-trolling, line fishing	4
	monitoring	gillnets	1
	recreational	gillnets, trapnets, angling	7
Latvia	commercial	gillnets	9
Lithuania	commercial	traps, gillnets	1
	monitoring	gillnets	1 *
Poland	commercial	gillnets, fykenets	6
Sweden	commercial	gillnets, fykenets, pound nets	4
	monitoring	gillnets	10

*Collation of data from 28 different smaller and nearby sites.

covered the even years between 2006 and 2018. Below we describe the three types of data sets in more detail.

2.1.1. Fisheries-independent coastal fish monitoring data

Monitoring time-series with low occurrence of zero catches to support trend analyses of pike were available for Estonia, Sweden, Finland, and Lithuania. In the other Baltic countries, the occurrence of pike in monitoring catches is too low and/or includes too many zero observations to allow for statistical analyses. A complete list of monitoring sites, including information on the gear used, time period, number of stations fished, fishing season and effort is shown in Table 3. For additional detailed information see HELCOM (2019).

2.1.2. Recreational fisheries survey data

Data on recreational pike catches was only available for Finland. The data was collected biennially through postal surveys distributed to a random sample of the whole Finnish population. The random sample was taken from the population information system maintained by the Population Register Centre (see https://stat.luke.fi/en/description-recreational-fishing_en for additional information). The recreational data survey is reported for coastal areas bordering the regions Uusimaa, Varsinais-Suomi, Pohjanmaa, Lappi, Ahvenanmaa, Kaakkois-Suomi and Kainuu (Fig. 1, Table 2). Between 4000 and 11000 questionaries were distributed every survey year with an overall average response rate of between 23% and 65% making the number of responses per survey year vary between 2470 and 4088 (https://stat.luke.fi/en/description-recreational-fishing_en). The average response rates (response $n \pm SD$) across regions were only available for the years 2012–2018 and were 75.25 ± 26.21 for the region Uusimaa, 125.25 ± 21.33 for Varsinais-Suomi, 19.25 ± 4.79 for Kaakkois-Suomi, 41.75 ± 11.35 for Pohjanmaa, 42.00 ± 8.49 for Kainuu, 13.00 ± 2.94 for Lappi, and 52.75 ± 18.87 for Ahvenanmaa. In the Finnish recreational fishery, most pike are caught via angling, but to a lesser extent also by gillnets and trapnets, and the data from the survey spans all seasons. In this study, the different gears were pooled for the analysis. In this data, fishing effort is calculated as the total number of fishers in a region, and biomass-per-unit-effort (BPUE) was calculated by dividing the total annual catch in a region by the estimated summed annual effort (total number of fishers) in the specific region. The total number of fishers in a region is a very rough estimate of the fishing effort, but the best available at the time of this study.

2.1.3. Commercial fisheries landings

In countries bordering the Baltic Sea, data on effort in commercial fisheries is at best coarse and often unreliable due to changes in fishing behavior and effort, fishing location and gear type use over time (Lappalainen et al., 2020; Olsson et al., 2015). In addition, the effort data is subject to intentional and unintentional misreporting, or missing altogether. Many of these shortcomings also apply to landings data, but in order not to make the abundance estimates even more unreliable, we only included data on the commercial landings instead of biomass per unit effort (BPUE) of pike in this study, being aware that landings alone do not necessarily track population abundance (Ovando et al., 2022). There are commercial landings data for trend analyses of pike in Sweden, Finland, Estonia, Latvia, Lithuania, Poland, Germany, and Denmark. In Russia, the ninth country boarding the Baltic Sea, commercial landings data was only available for the Russian parts of the Gulf of Finland and the years 2005–2013 (Shurukhin et al., 2016). As such, Russian data was excluded from the trend analysis in this study. Commercial gears not targeting pike and with a high frequency (more than 50% of the years) of annual zero landings were excluded from analyses and landings data were pooled across all remaining gear types within the reporting region/site (Table 2).

2.2. Analysis

2.2.1. Calculating CPUE for fisheries independent monitoring data

In Finland, Sweden, and Estonia, catch-per-unit-effort (CPUE) in monitoring was calculated as the total number (individuals) of pike caught divided by total effort (number of fished stations and nights). Because of an overall positive correlation between water temperature during monitoring and pike CPUE in these countries ($R = 0.33$, $p < 0.001$) (Fig. A1), the pike CPUE was controlled for temperature. We used a linear mixed-effects model with $\log_{10}$(Pike CPUE+0.001) as the dependent variable, temperature as a fixed effect, and sampling station as a random effect. Pike CPUE was adjusted for temperature using the following equation: adjustedPikeCPUE $= \mathrm{Log}_{10}(\mathrm{observedPikeCPUE}+0.001) + \beta 1 \times (\text{mean temp} - \text{observed temp})$. This correction neither changed the direction of any trends, nor changed trends from insignificant to significant or vice versa; nevertheless, adjusted CPUE values were used in subsequent analyses.

In Lithuania, the gear material, gear length, soak time, mesh size, and effort have to some extent varied over the 30-year sampling period. Therefore, the CPUE was standardized using a generalized linear model (GLM), as implemented in the R package 'statmod' (v. 1.4.33; Giner & Smyth, 2016). For the standardization, year, season, gear material (nylon, capron), gear length, soak time and mesh size were treated as fixed effects, and the year parameter was used as standardized CPUE values:

CPUEsc ~ year + season + gear_material + gear_length + soak_time + mesh_size + error

To account for the statistical properties of the fishery-independent monitoring data, where many fishing events yield zero catches for a given species, we used the Tweedie distribution (Shono, 2008), as implemented in the R package 'tweedie' (v. 2.3.3; Dunn, 2017). The parameter *year* was treated as an unordered factor, which means that the model estimated separate coefficients for each *year*. This series of *year* deviations was then extracted as GLM model coefficients and used in further analyses as standardised annual CPUE. Exact net lengths, mesh sizes or soak times were not available for all monitoring survey data in 1992–2000. Therefore, in the GLM analyses net lengths were assigned into five groups (short to very long), mesh sizes into three groups (small, large, and full), and soak times into three values (short to long) and treated as ordered factors. Our sensitivity analyses showed that these categories were sufficient to capture CPUE trends.

2.2.2. Common trends

We used a linear mixed effects model, as implemented in the R package "lme4″ (Bates et al., 2012) to examine differences in pike catch over time and between countries for each of the two major data types (monitoring and commercial landings). Recreational data were not used

Table 2
Overview of trends in commercial landings and monitoring CPUE of pike per each country and site. Years (all) indicate the span of the full time-series within each site. For each of the sites and time-series, statistics of the linear trend from 2005 (2006 Finnish recreational BPUE) is given by R and p-values (column "Trend 2005–2020″). In the column "Change %" the magnitude of change (in %) between the mean catch of the three first and last years in each times-series since 2005 is presented. The column "Trend all years" denote the linear trend of the full time-series in each site (note that some time-series start in 2005 whereby the R and p-values of this column and the "Trend 2005–2020″ are identical). Bold figures denote significant positive and negative trends at p = 0.00085 (Bonferroni adjusted p-value). Abbreviations: Gillnets – GNS, Fykenets – FYK, Poundnets – FPN, Trapnets – TN, ngling-trolling – AT, Line fishing – LF, Angling – A, Nordic multimesh gillnets – Nordic, Net series 'summer' – NSS, Net series 'Autumn' – NSA, Traps – T.

#	Country	Data type	Site	Gear	Years (all)	Trend 2005–2020	Change (%)	Trend all years
55	Denmark	Commercial	Denmark (all)	GNS,FYK,FPN	1929–2020	- 0.31, 0.24	-63	-0.82, **2.2E-16**
18	Estonia	Commercial	Area 32–2	GNS + FYK	1993–2020	- 0.45, 0.089	-50	- 0.13, 0.59
20	Estonia	Commercial	Area 32–1	GNS + FYK	1993–2020	0.26, 0.34	16	- 0.31, 0.16
21	Estonia	Commercial	Area 29–2	GNS + FYK	1993–2020	0.54, 0.04	77	0.17, 0.38
24	Estonia	Commercial	Area 29–4	GNS + FYK	1993–2020	0.89, **0.0000096**	448	0.52, 0.0045
26	Estonia	Commercial	Area 28–1	GNS + FYK	1993–2020	0.88, **0.000012**	372	0.36, 0.06
30	Estonia	Commercial	Area 28–2	GNS + FYK	1993–2020	0.73, 0.002	44	-0.0088, 0.96
23	Estonia	Monitoring	Hiiumaa	NSS	1998–2020	0.47, 0.074	362	0.41, 0.06
25	Estonia	Monitoring	Matsalu	NSS	1993–2020	-0.25, 0.37	-56	0.036, 0.87
27	Estonia	Monitoring	Kõiguste	NSS	2005–2020	0.44, 0.14	45	0.44, 0.14
5	Finland	Commercial	Area31	GNS, FYS, AT, LF	1998–2019	0.79, **0,00051**	65	0.78, **0.000021**
8	Finland	Commercial	Area30	GNS, FYS, AT, LF	1998–2019	0.11, 0.69	4	-0.58, 0.005
10	Finland	Commercial	Area29	GNS, FYS, AT, LF	1998–2019	-0.9, **0.0000061**	-58	-0.92, **7.6E-10**
17	Finland	Commercial	Area32	GNS, FYS, AT, LF	1998–2019	-0.67, 0.006	-39	-0.74, **0.000075**
12	Finland	Monitoring	Finbo	Nordic	2002–2020	0.10, 0.71	157	-0.053, 0.83
2	Finland	Recreational	Lappi	A, GNS, TN	2006–2018	0.093, 0.84	101	0.093, 0.84
4	Finland	Recreational	Kainuu	A, GNS, TN	2006–2018	-0.50, 0.25	-27	-0.50, 0.25
6	Finland	Recreational	Pohjanmaa	A, GNS, TN	2006–2018	-0.64, 0.12	-31	-0.64, 0.12
9	Finland	Recreational	Kaakkois-Suomi	A, GNS, TN	2006–2018	-0.71, 0.074	-80	-0.71, 0.074
13	Finland	Recreational	Ahvenanmaa	A, GNS, TN	2006–2018	-0.76, 0.047	-50	-0.76, 0.047
14	Finland	Recreational	Varsinais-Suomi	A, GNS, TN	2006–2018	-0.53, 0.22	-34	-0.53, 0.22
15	Finland	Recreational	Uusimaa	A, GNS, TN	2006–2018	-0.28, 0.54	-12	-0.28, 0.54
52	Germany	Commercial	West&GJ Bodden	GNS + FYK	1992–2018	-0.25, 0.35	-32	-0.25, 0.35
53	Germany	Commercial	Kleiner Jasmunder Bodden	GNS + FYK	1992–2018	-0.42, 0.10	-26	-0.42, 0.1
54	Germany	Commercial	Darß-Zingster-Bodden-chain	GNS + FYK	1992–2018	-0.20, 0.46	13	-0.2, 0.46
51	Germany	Commercial	Strelasund/Kubitzer Bodden	GNS + FYK	1992–2018	-0.27, 0.31	-32	-0.27, 0.31
50	Germany	Commercial	Greifswalder Bodden	GNS + FYK	1992–2018	-0.73, 0.0014	-68	-0.73, 0.0014
49	Germany	Commercial	Peenstrom & Stettiner Haff	GNS + FYK	1992–2018	0.26, 0.33	24	0.26, 0.33
31	Latvia	Commercial	Salacgriva	GNS	1995–2020	-0.54, 0.039	-43	-0.14, 0.5
33	Latvia	Commercial	Roja	GNS	1995–2019	0.20, 0.49	136	0.14, 0.49
35	Latvia	Commercial	Targale	GNS	1995–2019	-0.31, 0.26	-87	0.22, 0.34
36	Latvia	Commercial	Mersrags	GNS	1995–2020	-0.61, 0.017	-53	-0.73, **0.000032**
38	Latvia	Commercial	Engure	GNS	1996–2020	-0.079, 0.77	-40	0.04, 0.85
40	Latvia	Commercial	Lapmezciems	GNS	1995–2019	-0.66, 0.0072	-94	0.15, 0.48
41	Latvia	Commercial	Vergale	GNS	1996–2020	-0.098, 0.73	-74	0.11, 0.62
42	Latvia	Commercial	Liepaja	GNS	1996–2020	-0.50, 0.048	-70	0.16, 0.43
43	Latvia	Commercial	Nica	GNS	1996–2019	-0.43, 0.11	-77	-0.11, 0.62
45	Lithuania	Commercial	Lithuania (all)	GNS + T	2005–2020	-0.87, **0.00021**	-67	-0.87, **0.00021**
46	Lithuania	Monitoring	Curonian Lagoon	GNS	1992–2021	-0.55, 0.028	-43	-0.43, 0.02
47	Poland	Commercial	Puck Bay	GNS + FYK	2004–2020	0.18, 0.50	103	0.33, 0.2
48	Poland	Commercial	Vistula Lagoon	GNS + FYK	2004–2020	-0.47, 0.064	-73	-0.55, 0.02
56	Poland	Commercial	Pomeranian Bay	GNS + FYK	2004–2020	-0.48, 0.059	-77	-0.45, 0.07
57	Poland	Commercial	Kamieński Lagoon	GNS + FYK	2004–2020	-0.48, 0.063	-63	-0.44, 0.08
58	Poland	Commercial	Szczecin Lagoon	GNS + FYK	2004–2020	0.26, 0.33	26	0.28, 0.27
59	Poland	Commercial	Dąbie Lake	GNS + FYK	2004–2020	0.25, 0.34	-40	-0.23, 0.38
3	Sweden	Commercial	Bothnian Bay	GNS,FYK,FPN	1994–2020	-0.91, **0.0000012**	-91	-0.92, **6.4E-12**
7	Sweden	Commercial	Bothnian Sea	GNS,FYK,FPN	1994–2020	-0.97, **4,8E-10**	-85	-0.85, **0.000000022**
16	Sweden	Commercial	Ålands Sea	GNS,FYK,FPN	1994–2020	-0.81, **0.00016**	-89	-0.88, **1.2E-09**
32	Sweden	Commercial	Baltic Proper	GNS,FYK,FPN	1994–2020	0.36, 0.17	-1	-0.41, 0.035
1	Sweden	Monitoring	Råneå	Nordic	2002–2020	0.072, 0.79	-1	-0.11, 0.65
11	Sweden	Monitoring	Forsmark	Nordic	1987–2020	-0.61, 0.016	-75	-0.63, **0.0001**
19	Sweden	Monitoring	Lagnö	Nordic	2002–2020	-0.92, **0.0000016**	-100	-0.91, **0.00000015**
22	Sweden	Monitoring	Asköfjärden	Nordic	2005–2020	-0.86, **0.000019**	-100	-0.86, **0.000019**
28	Sweden	Monitoring	Kvädöfjärden	Nordic	2002–2020	-0.77, **0.00052**	-95	-0.79, **0.000056**
29	Sweden	Monitoring	Kvädöfjärden	NSS, NSA	1987–2020	-0.60, 0.014	-96	-0.45, 0.008
34	Sweden	Monitoring	Vinö	NSS	1995–2020	-0.78, 0.001	-99	-0.78, 0.001
37	Sweden	Monitoring	Mönsterås (Svartö)	NSS	1995–2020	0.19, 0.52	38	-0.19, 0.52
39	Sweden	Monitoring	Mönsterås (Ödängla)	NSS	1995–2020	-0.063, 0.83	40	-0.063, 0.83
44	Sweden	Monitoring	Torhamn	Nordic	2002–2020	-0.60, 0.015	-62	-0.58, 0.009

in this analysis as it differed in time-period and frequency (data available for every second year). As input in the models, we used temperature adjusted monitoring data as described above, and a log10(x) transformation for the commercial landings data to meet the assumption of normality. Year, Country and the interactions between Country and Year were used as fixed factors in the linear mixed effect model. Site was used as a random intercept to account for the non-independence of catch within sites across years. Thus, the model was:

Catch ~ Country*Year + (1| Site)

Table 3
Overview of the gears used per site for the fisheries independent data in Estonia, Sweden, Finland and Lithuanina. Abbreviations: Gillnets – GNS, Nordic multimesh gillnets – Nordic, Net series 'summer' – NSS, Net series 'Autumn' – NSA.

Country	Site	Years	Type of gear	Mesh sizes	Stations	Season	Effort
Estonia	Hiiumaa	1998–2020	NSS, 1.8 m deep and 30 m long	14, 17, 22, 25, 30, 33, and 38 mm, knot-to-knot	12 fixed stations	July-August	number of stations × nights fished
	Matsalu	1993–2020	NSS, 1.8 m deep and 30 m long	14, 17, 22, 25, 30, 33, and 38 mm, knot-to-knot	36–40 semi-randomly distributed stations fished for one night	July-August	number of stations × nights fished
	Kõiguste	2005–2020	NSS, 1.8 m deep and 30 m long	14, 17, 22, 25, 30, 33, 38, 42, 45, 50, 55, and 60 mm, knot-to-knot	22 fixed stations	July-August	number of stations × nights fished
Sweden	Råneå	2002–2020	Nordic, 1.8 m deep and 45 m long	10, 12, 15, 19, 24, 30, 38, 48, and 60 mm, knot-to-knot	45 fixed stations	August	number of stations fished
	Forsmark	1987–2020	Nordic, 1.8 m deep and 45 m long	10, 12, 15, 19, 24, 30, 38, 48, and 60 mm, knot-to-knot	45 fixed stations	August	number of stations fished
	Lagnö	2002–2020	Nordic, 1.8 m deep and 45 m long	10, 12, 15, 19, 24, 30, 38, 48, and 60 mm, knot-to-knot	45 fixed stations	August	number of stations fished
	Asköfjärden	2005–2020	Nordic, 1.8 m deep and 45 m long	10, 12, 15, 19, 24, 30, 38, 48, and 60 mm, knot-to-knot	48 fixed stations	August	number of stations fished
	Kvädöfjärden	2002–2020	Nordic, 1.8 m deep and 45 m long	10, 12, 15, 19, 24, 30, 38, 48, and 60 mm, knot-to-knot	44 fixed stations	August	number of stations fished
	Kvädöfjärden	1987–2020	NSS, NSA	17, 21.5, 25 and 30 mm, knot-to-knot, 21.5, 30, 38, 50 and 60 mm, knot-to-knot	12 fixed stations, 12 fixed stations	August, October	number of stations fished
	Vinö	1995–2020	NSS	17, 21.5, 25 and 30 mm, knot-to-knot	6 fixed stations	August	number of stations × nights fished
	Mönsterås (Svartö)	1995–2020	NSS	17, 21.5, 25 and 30 mm, knot-to-knot	6 fixed stations	August	number of stations × nights fished
	Mönsterås (Ödängla)	1995–2020	NSS	17, 21.5, 25 and 30 mm, knot-to-knot	6 fixed stations	August	number of stations × nights fished
	Torhamn	2002–2020	Nordic, 1.8 m deep and 45 m long	10, 12, 15, 19, 24, 30, 38, 48, and 60 mm, knot-to-knot	40 fixed stations	August	number of stations fished
Finland	Finbo	2002–2020	Nordic, 1.8 m deep and 45 m long	10, 12, 15, 19, 24, 30, 38, 48, and 60 mm, knot-to-knot	45 fixed stations	August	number of stations fished
Lithuanina	Curonian Lagoon	1992–2021	GNS	14, 17, 21.5, 25, 30, 33, 38, 45, 50, 60, and 70 mm, knot-to-knot	28 fixed stations	August	number of stations × nights fished

2.2.3. *Site-specific trends*

Besides addressing common trends in the two most comprehensive types of data used (fisheries independent monitoring data and commercial landings data), we also looked at site-specific trends in all three data types. To meet the assumption of normality in data, we $\log_{10}(x)$ transformed all commercial landings and recreational fisheries data, and used a $\log_{10}(x + 0.001)$ transformation for monitoring data due to the presence of some years with zero catches. We used linear regressions to examine changes in pike time-series since 2005 (2006 for Finnish recreational data) and the full time-series within each sampling site or region. To control for elevated risks for Type-I errors associated with multiple testing we applied Bonferroni corrections with the adjusted p-value set to 0.00085 ($n = 59$). All r- and p-values are reported along with individual regression plots for each data set in Table 2 and in the supplemental materials (Figs. A2-A4). A second set of analysis shows data from all available years in each site, and are fit with second degree polynomial regressions to illustrate how recent trends fit within the longer time perspective (Figs. A5-A6).

All analyses were performed in R version 4.0.2 using RStudio (RStudio Team, 2016). Linear mixed models were performed using the lme4 package (Bates et al., 2015) and all figures were created using ggplot2 (Wickham, 2016).

3. Results

3.1. *Common trends*

There was a difference in pike catch over time across countries as revealed by the significant country-year interaction for both data types (Table 4). For both data types, however, there was a significant overall effect of year indicating change in catches over time (Table 4). The country-specific differences in trends were related to strong negative

Table 4
Results from the Linear Mixed Model examining the development of pike catch in monitoring and commercial landings testing whether there are significant trends over time and differences between countries.

Fixed effects	df	F-value	p-value
Monitoring			
Country	(3, 212)	12.091	< 0.001
Year	(1, 212)	5.588	0.0164
Country:Year	(3, 212)	12.217	< 0.001
Commercial landings			
Country	(7, 534)	7.177	< 0.001
Year	(1, 534)	20.788	< 0.001
Country:Year	(7, 534)	7.254	< 0.001

trends in monitoring data from Sweden, but no trend in the other countries (Fig. 2). For commercial landings there was a positive trend in Estonia but no or negative trends in the other countries (Fig. 2). For estimates of the fixed effects from the Linear Mixed Model, see Table A1.

3.2. Site-specific trends

3.2.1. Commercial landings

The northernmost commercial landings (Swedish and Finnish data) showed declining trends in one of the Finnish sites (SD 29) and all three Swedish sites (Bothnian Sea, Bothnian Bay and Åland Sea), but an increasing trend in the northernmost Finnish site (SD 31) during the period 2005–2020 (Fig. 3, Table 2, Fig. A2). In the more central parts of the Baltic Sea (along the southern Swedish, Estonian, Latvian and Lithuanian coasts), the majority of time-series showed no change over time, with the exception of an increase in two of the six Estonian sites, and a decrease in the Lithuanian site (Fig. 3, Table 2, Fig. A2). There was a similar pattern with no significant trends over time in the individual time-series in the southernmost region of the Baltic Sea including sites from Poland, Germany and Denmark (Fig. 3, Table 2, Fig. A2). One

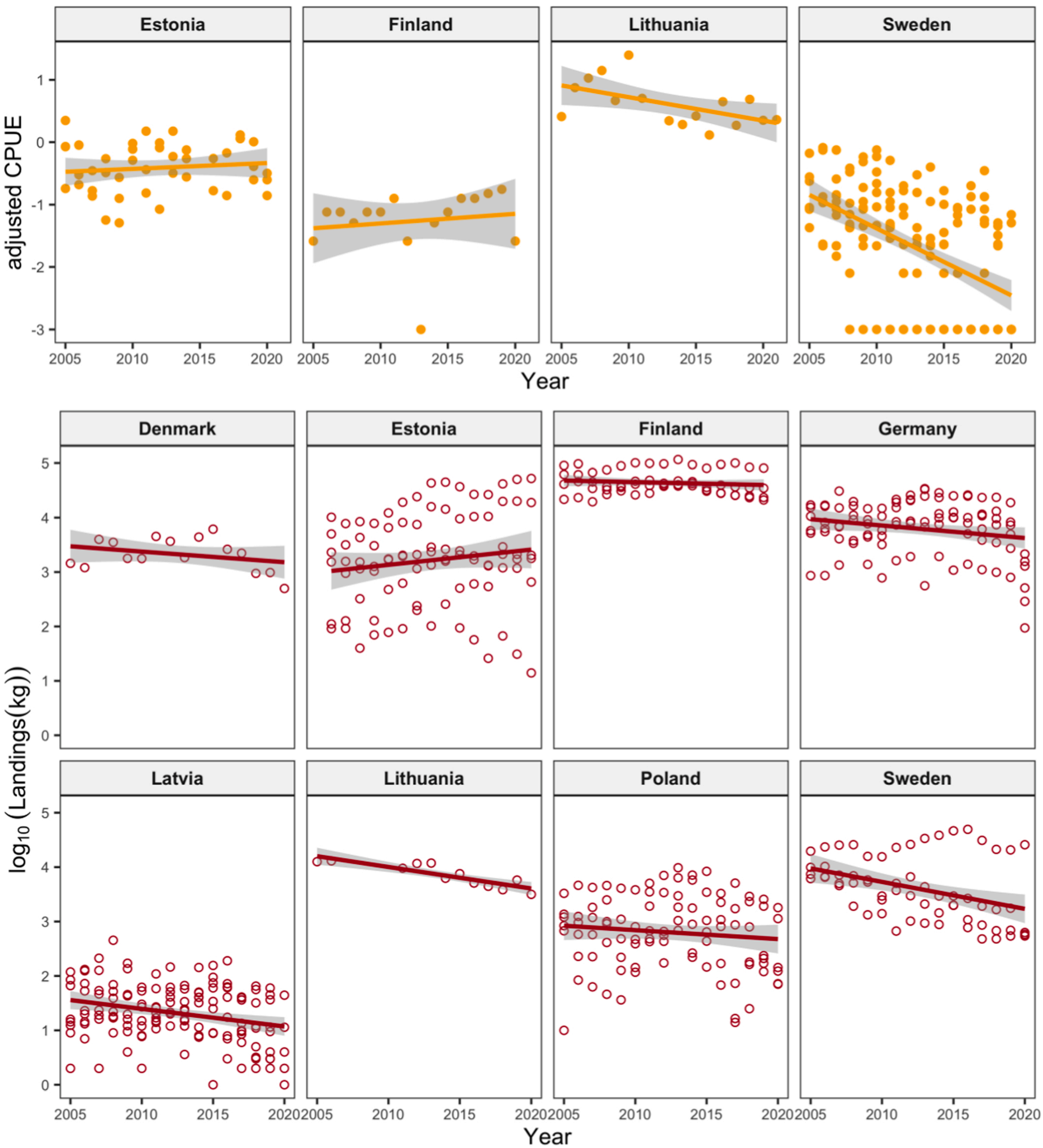

Fig. 2. Linear trends in pike monitoring CPUE (top panel) and commercial landings (lower panel) split by country from the linear mixed effects model.

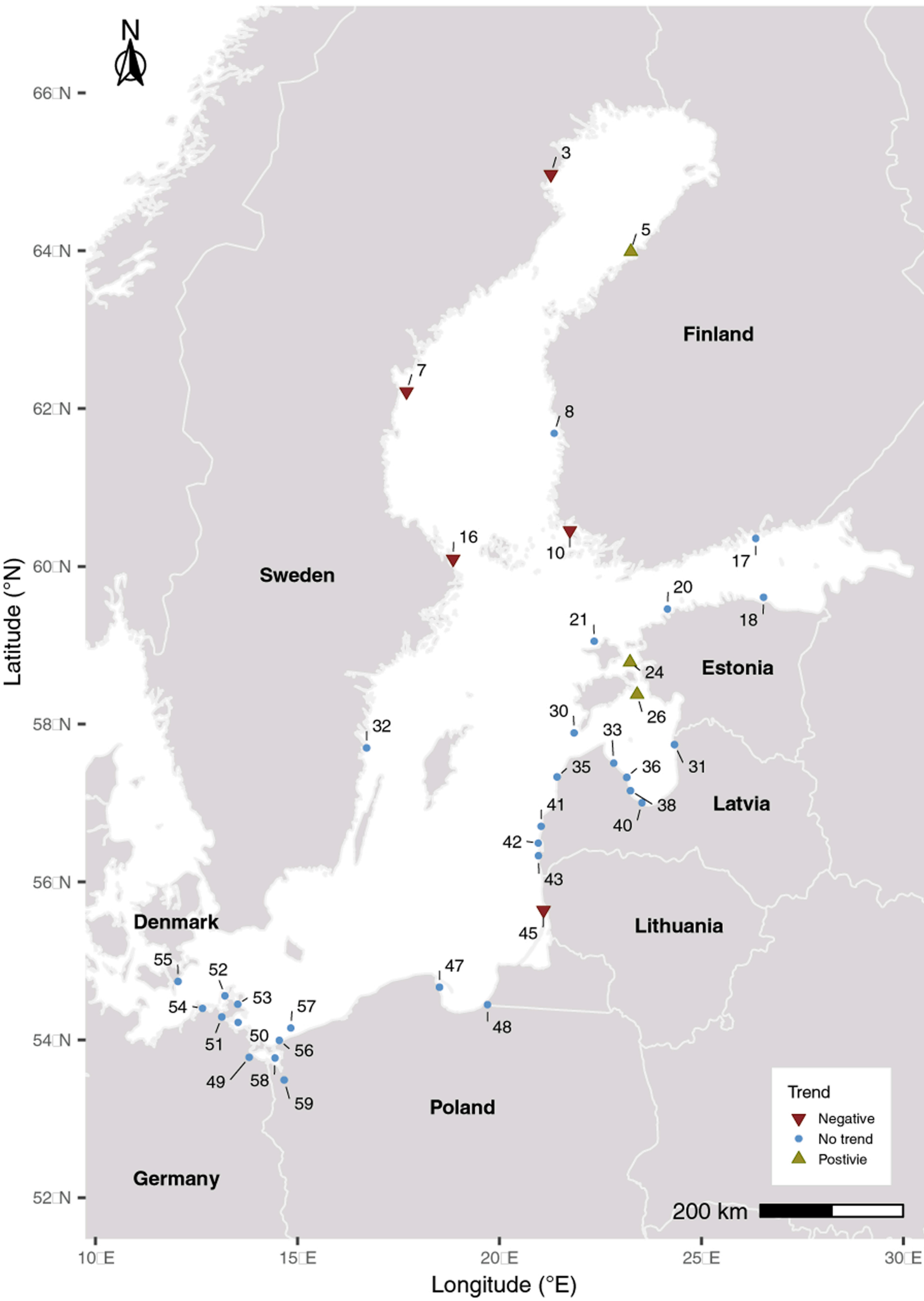

Fig. 3. Trends in commercial fisheries landings of pike in Baltic Sea coastal waters for the sites included in the study. Significant trends at p < 0.002 are shown in green (positive) or red (negative). Points representing sites with commercial fisheries landings are placed in the center of the waterbody in the cases of lagoons and tidal lakes, or at the midpoint of the coastline bordering a fishing region for in which the data is collected.

additional observation is that in those sites where there was a negative or no trend over time, the landings have been exceptionally low during the last few years in many of the time-series. In sites with decreasing landings over time the magnitude of change, calculated as the difference in mean landings of the first and last three years of each time-series, ranged between 39% and 94% lower landings over time (Table 2).

When considering full available time-series on commercial landings, the aggregated German data from the mid-1950′s showed a significant negative trend over time (Fig. A5). For the Finnish, Swedish and Lithuanian sites the pattern in trends before 2005 is similar to that for the more recent trends during 2005–2020 (Table 2, Fig. A5). In the extended time-series from Estonia, starting 1993, there is a U-shaped development of the commercial landings over time with the lowest landings around 2005 followed by an increase until 2020 (Fig. A5). A similar pattern was also evident for the Swedish coast of the Baltic Proper, with data starting in 1994 (Fig. A5). Several sites in Latvia with data extending back to 1995 showed the opposite pattern, with an initial increase in landings peaking around 2005, followed by a subsequent decline (Fig. A5). The differences in the patterns in landings across regions, countries and sites, could reflect true changes in pike abundance, but also changes in fishing effort over time. The reliability and quality of data on fishing effort in the commercial fisheries were low, as previously mentioned, but there were indications of substantial declines in the commercial fishing effort over time in many sites, for example, in Finland, Lithuania, and Germany (Fig. A7).

3.2.2. Fisheries-independent coastal fish monitoring data

When considering most recent data (from 2005 and onwards) there was a negative trend after Bonferroni correction in the in three of the ten Swedish time-series, with no trend in the other Swedish sites and the only Lithuanian and Finnish monitoring site (Fig. 4a, Table 2, Fig. A3). Among the three Estonian sites, there were no trend in any of the three sites (Fig. 4a, Table 2, Fig. A3. The magnitude of the decrease ranged between 53% and 100% lower catches during the last three compared to the first three years of the time-series exhibiting a negative development over time (Table 2).

When extending the data to also cover years before 2005, the trends in CPUE in the sites in Estonia, Lithuania, and Finland, were overall similar as the pattern found when using only more recent data (from 2005 and onwards) as presented above (Table 2, Fig. A6). Though the longer time-series' from the Swedish monitoring sites were similar to the data sets starting in 2005, the extended time-series shows a period of consistent stable pike CPUE until 2010 when there was a drop in the sites Kvädöfjärden, Forsmark, Lagnö, and Torhamn (Fig. A6).

3.2.3. Recreational fisheries survey data

The BPUE from recreational fisheries data in Finland starting in 2006 showed no trends in any of the sites after Bonferroni correction (Fig. 4b, Table 2, Fig. A4). The magnitude of the decrease in BPUE was between 12% and 80% across time-series.

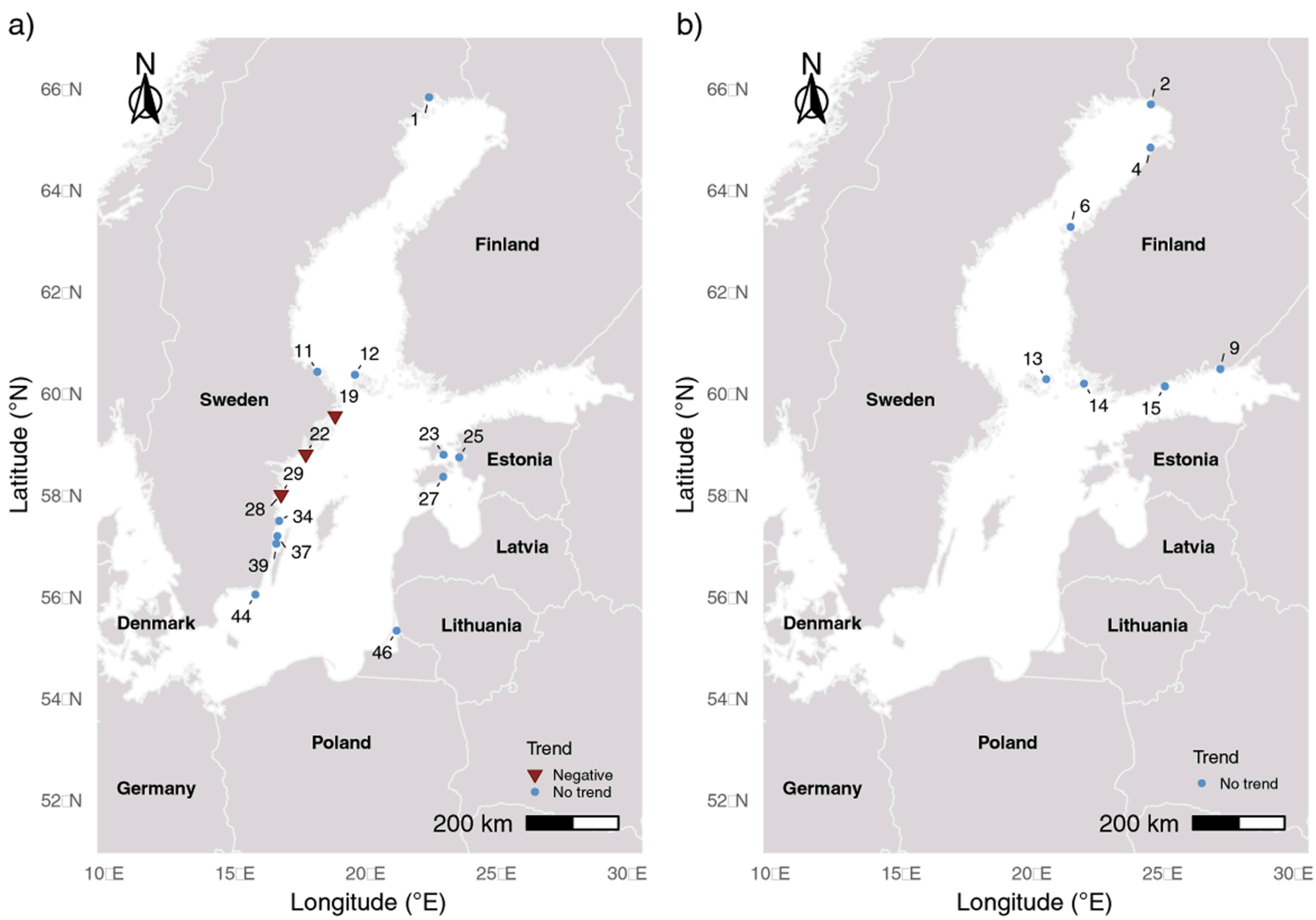

Fig. 4. Trends in a) fisheries-independent monitoring CPUE and b) recreational fisheries BPUE of pike in Baltic Sea coastal waters for the sites included in the study. Significant trends at $p < 0.002$ are shown in green (positive) or red (negative). Points representing sites with commercial fisheries landings are placed in the center of the waterbody in the cases of lagoons and tidal lakes, or at the midpoint of the coastline bordering a fishing region for in which the data is collected.

4. Discussion

The results of this study suggest overall temporal trends in available proxies for the population status of pike since the mid 2000′s, but with local differences across sites and countries in the direction and magnitude. In several regions of the Baltic Sea individual time-series exhibited negative temporal trends, and the reduction in catches over time in these sites ranged from 12% to 100%. These findings do, to a large extent, corroborate the negative trends shown in previous more local studies along the Swedish, Finnish, Polish and German coasts in the central and more southern parts of the Baltic Sea (Bergström et al., 2022; Eriksson et al., 2011; Lehtonen et al., 2009; Ljunggren et al., 2010; Nilsson et al., 2004; Olsson, 2019; van Gemert et al., 2022; Greszkiewicz et al., 2022). The results presented in this study thus expand the spatial coverage of earlier work, showing indications of population declines in other parts of the Baltic Sea including the coasts of Latvia, Lithuania, Poland and Northern Sweden.

The local occurrence and population structure of pike in the Baltic Sea (Laikre et al., 2005; Östman et al., 2017a; Saulamo and Neuman, 2002), make it challenging to provide a general description of the factors driving the change in population size of pike in different coastal areas and regions of the Baltic Sea. Indications of declines over larger regions suggest that the causes may have occurred on a regional level but with local differences. Among the potential influencing factors are habitat degradation both along the coast and in freshwater tributaries, fishing (foremost recreational), eutrophication, and changes in the coastal food web including increased interactions with three-spined stickleback (*Gasterosteus aculeatus*) and increased levels of natural predation from mammals and birds (Bergström et al., 2022; Olsson, 2019). An overall decline in pike population numbers in the Baltic Sea, as suggested by our common trends analysis, could also indicate the influence of some general Baltic-wide factors influence population trends, such increasing water temperatures, elevated levels of eutrophication and growing populations of bird and mammal apex predators. Being a species of freshwater origin occupying shallow coastal waters, pike should rather be favored by warmer and less saline waters (Berggren et al., 2022). In Sweden there are indications that recreational fishing impacted pike negatively during the 1990′s (Bergström et al., 2022), after which the direct fishing mortality has likely decreased as a result of an increased propensity for catch-and-release fishing, lowered demand, and implementation of fisheries regulations (Bergström et al., 2022). As is made evident from this study and several others, however, the negative population development of pike has continued in Sweden. Other factors besides fishing, such as increased natural predation at a regional scale on both eggs and larvae (Eklöf et al., 2020; Nilsson, 2006; Nilsson et al., 2019) and juveniles and adults (Hansson et al., 2018; Bergström et al., 2022), as well as local ecosystem changes and habitat exploitation are perhaps currently of higher importance than fishing impacts (Bergström et al., 2022; Eklöf et al., 2020; Sundblad and Bergström, 2014). In Poland, anadromous pike populations decreased to a level close to extinction because of migration barriers, river regulation, and land drainage that removed wetland areas that used to serve as spawning habitats (Greszkiewicz et al., 2022). Also in southern Sweden, there are indications of recruitment problems due to destruction and degradation of freshwater spawning habitats (Nilsson et al., 2014). The low commercial catches, as observed for example in Germany, could to some extent be caused by reduced fishing effort. However, recreational anglers also clearly state that catches and pike size have declined strongly in Germany (van Gemert et al., 2022). Drivers for the potential population decline in Germany are not yet fully understood, but we can only speculate that it could be the result of a combination of environmental changes including rises in natural predators, climate change-induced effects on recruitment and mortality, loss of access to freshwater tributaries and wetlands, reduced forage base through reductions in prey populations and overfishing. In Estonia the contrasting pattern of increases in commercial catches and strong indications of a positive trend in one of the monitoring areas could be linked to several strong year classes during the 2010′s and increased number of fishers during recent years that potentially could have contributed to increasing commercial landings of pike (Armulik and Sirp, 2020).

The poor coverage and representation of pike in fisheries-independent coastal fish monitoring programs (HELCOM, 2019), low natural population densities (HELCOM, 2012, this study), and low commercial value of the species (Zanzi and Holmes, 2017), makes it a typically "data poor" species, for which status assessments are challenging. In this study, we combined different data sources, each with its limitations, but when analyzed in concert they provide the best currently available data and likely a robust assessment of general population trends. In our perspective, the most reliable data source is fisheries independent coastal fish monitoring data. However, the catch of the larger-bodied pike will be underrepresented in standard gill nets with upper limits on mesh sizes of 55 – 60 mm. To potentially increase the catchability of pike, using larger mesh sizes could be considered. Despite the current limitations of this gear for catching pike, clear advantages of using fishery-independent data is standardization of data collection where the fishing gear and method used is consistent over time, as is the effort and the geographical location of the sampling sites (HELCOM, 2019; Olsson et al., 2012). Derived estimates of trends in fish abundance from coastal fish monitoring should, in contrast to the other data sources utilized in this study, therefore not be influenced by changes in these potentially confounding factors. Because monitoring is performed using passive gear though, the catch might be influenced by changes in the surrounding environment that affect the behavior and catchability of different species (L. Bergström et al., 2016; U. Bergström et al., 2016; Lehikoinen et al., 2019; Östman et al., 2017b). One such confounding variable potentially influencing the catchability of the fish is water temperature (L. Bergström et al., 2016; U. Bergström et al., 2016; Olsson et al., 2012; Östman et al., 2017b). In this study, we attempted to control for the influence of differences in water temperature between monitoring events by regressing the catch of pike on water temperature during fish monitoring. As expected, we found a positive correlation between pike catch and temperature, but using the temperature-adjusted estimates of CPUE did not change the trends for the different monitoring sites.

Coastal fish monitoring data also includes several potential sources of uncertainties (e.g. L. Bergström et al., 2016; U. Bergström et al., 2016; Östman et al., 2020), especially for pike, where the catches are typically low and include a lot of zero observations (HELCOM, 2012, 2018). The presence of multiple zero observations limit the possibility of detecting statistically significant trends, which suggests that the results presented in this study are conservative in that they might miss some potential negative trends and that the status of pike in the Baltic Sea might hence be even worse than what is shown in existing monitoring data.

Statistics on landings in commercial fisheries are mandatory and available for all EU member states (reviewed in Lappalainen et al., 2020), and might therefore provide a comprehensive source of data for status assessments of commercially important fish species. The current economic value of pike in the Baltic Sea is relatively low, meaning that the commercial effort is hence typically low as well (Zanzi and Holmes, 2017; Greszkiewicz et al., 2022). In combination with potentially a wide array of potential errors, the credibility of the trends in commercial landings data as a source for extracting population trends of pike might hence be questionable. Sources of errors include for example fishers intentionally and unintentionally misreporting their catch (Hentati-Sundberg et al., 2014), and changes in fishing behavior, effort and gears over time to maximize catch (Lappalainen et al., 2020). Trends in total landings in a fishery might thus reflect other changes than population trends, such as changing market demand, fishing effort, and fisheries regulations (allowable catches, bag limits, and regulations of catch and release) and other management incentives as fisheries regulations (i.e. no-take zones, temporal fishing closures). Another factor that can distort the relationship between landings and population trends are hyperstable catch rates. These can occur in commercial fisheries as fishers selectively exploit aggregations during spawning time or otherwise strategically shift locations, fishing method, and gear over time to sustain their catch levels. Hyperstable catch rates will mask local population declines or result in false positive trends in a region (Lappalainen et al., 2020; Olsson et al., 2015). A consistent increase in landings over a consecutive number of years does, however, likely not indicate a severe population decline, such that declines in total landings may be considered conservative assuming that fishing effort is maintained. To that end, if there are no changes in demand, fishing effort, fishing regulations, and management actions of the species in focus, a negative trend in the fisheries landings more likely reflects the temporal development of the species in an area. In this study, due to limitations in data, we have not been able to control for potential sources of errors and changes in effort over time when analyzing trends over time in the catch from commercial fisheries.

In Sweden, there has been no substantial change in the regulation of the coastal commercial fishery during the past two decades, but a general decrease in the demand and fishing effort for pike due to a decreasing number of active fishers. In Denmark, historically declining catches (i.e. long before the mid 2000′s) in 2015 resulted in a ban on landing pike issued in four of the most popular fishing areas (Præstø Fjord, Jungshoved Nor, Stege Nor, and Fanefjord; Danish AgriFish Agency, 2015). In addition, in 2014 a seasonal closure for pike fishing was issued for all marine waters in Denmark. The sharply lower landings of pike in the most recent years in Denmark might hence have been at least partially a result of these regulations. There are also strong indications of decreases in the estimated fishing effort over time in Finland, Lithuania, and in some of the Latvian and German sites that could be linked to decreasing catches (Fig. A7). In one German site, there was, in contrast, an increase in effort over time, but overall pike fishing effort has likely been declining in Germany with no obvious changes in regulations since 2005. The negative trends in landings in German data is also in agreement with recent stock assessment results as based on catch-only stock assessments (van Gemert et al., 2022). In Estonia, there have been no major changes in fisheries regulations for pike over the time-period considered, and there has been a slight increase in the number of commercial fishers.

In spite of the clear limitations and weaknesses in using trends in commercial landings as a proxy for pike population trends, we found in general a good coherence between the commercial and fisheries-independent monitoring data in sites where both data sources were available, and an overall negative trend over time across all data sources.

The common trend-analyses as presented in this study dating back to only the mid 2000′s might miss any potential long-term negative trend of pike in the Baltic Sea, ignoring also the documented regime shift in the Baltic Sea ecosystem in the late 1980s (Möllmann et al., 2009). Our results are, however, consistent with earlier studies using a longer time-series (reviewed in Olsson, 2019) and the results as presented here from the longer time-series from monitoring and commercial landings data, suggest that the direction of the trends was in most cases similar also before 2005. Furthermore, the longest time-series from Denmark (since 1920′s) and Germany (since 1950′s) show strong decreasing trends over time. Exceptions in consistency of the patterns since 2005 include commercial landings in Estonia and the Swedish Baltic Proper, where there was a declining trend in landings until the mid-2000s, after which they have increased. In the commercial landings from the Danish, some of the Latvian, Polish and German sites, the opposite pattern is observed with a tendency for positive trends until the 2000′s, followed by a sharp decline during recent years. It cannot be excluded that already in 2020, the Covid-related marketing constraints affected the commercial landings negatively. Current data from Russia was unavailable when compiling data for this study, but an earlier paper including data until 2013 suggests an increase in Russian landings of pike in the Gulf of Finland (Shurukhin et al., 2016).

5. Conclusions and implications

As this study suggests negative trends in indicators of pike population status in several regions of the Baltic Sea, and overall trends when considering all data in common trend analyses, we recommend that measures should be taken to strengthen the status of this large predatory fish in those regions where needed. These should be based on scientifically supported measures with high likelihood of positive effects such as fisheries restrictions and regulations (Berggren et al., 2022; L. Bergström et al., 2016; U. Bergström et al., 2016; Edgren, 2005), protection and restoration of spawning and recruitment habitats (Kraufvelin et al., 2018; Larsson et al., 2015; Nilsson et al., 2014; Sundblad and Bergström, 2014), while also ensuring the connectivity between those areas (Berkström et al., 2022). Because factors impacting coastal pike in the Baltic Sea are related to direct human impact, large-scale environmental change, and food web interactions including cross-ecosystem effects (reviewed in Olsson, 2019), we do not believe there is a single "silver-bullet" to strengthen pike populations in the Baltic Sea. Instead, we advocate a holistic, transdisciplinary, and ecosystem-based approach in future management plans aimed at protecting habitats and restoration of food webs rather than biomanipulation.

Our study represents the most comprehensive attempt so far to address the regional changes in the state of pike in the Baltic Sea. As is evident from the results presented, the currently-available data sources to address pike population trends include many uncertainties, and the different data sources used do, to some extent, represent differently-sized pike: commercial fisheries mainly target adult pike, fisheries independent monitoring juveniles to mid-size individuals, and recreational fisheries juvenile to trophy-sized fish. There is hence a scope for improved monitoring of pike in the Baltic Sea, both of juveniles and adults, and we suggest that such efforts should consider the use of additional passive gears such as large fyke nets, which show higher catch rates for pike compared to gill nets (Eriksson et al., 2011), and are non-invasive. Standardized gill nets with larger mesh sizes and in general an improved quality of the data collected from commercial and recreational fisheries with, for example, designated fishers (or anglers) that provide detailed log-book reporting of their catch and effort are additional means to improve data collection (Olsson et al., 2015). An additional, even more promising method, for collecting information and data on pike population trends might be dedicated citizen science approaches focused on recreational fishers as is done for coastal fish in Denmark (Gundelund et al., 2021; Støttrup et al., 2018). When using citizen science as a data source for populations trends, a randomization of catching sites is important to avoid biased estimates related to differences in quality and fishers' skills between fishing grounds. Because pike is a popular game fish for recreational fishers, detailed information on catches and effort may be utilized, as demonstrated by examples from Finland and Sweden (Bergström et al., 2022; Jansen et al., 2013; Lehtonen et al., 2009). Monitoring of juvenile fish and larvae has been carried out in Sweden and Finland using small under water detonations, scooping, white plate and other methods (see for example Eklöf et al., 2020; Lappalainen et al., 2008; Kallasvuo et al., 2011), that are suited to follow the recruitment success of pike. To that end, besides improved monitoring and data collection via for example sampling of eDNA (Karlsson et al., 2022), there is also a need for developing additional and complementary assessment methodologies using for example novel approaches to address changes over time in time-series (Östman et al., 2020) and stock assessment models suited for typically "data-poor" species like pike (van Gemert et al., 2022). Overall, a more harmonized effort based on both fishery-independent standardized surveys and fishery-dependent data is needed to monitor the development of this iconic species across the Baltic.

CRediT authorship contribution statement

Jens Olsson: Conceptualization, Data curation; Funding acquisition, Investigation, Methodology, Project administration, Writing – original draft. **Matilda L. Andersson**: Data curation, Formal analysis, Investigation, Methodology, Writing – original draft. **Ulf Bergström**: Methodology, Writing – review & editing. **Robert Arlinghaus**: Data contribution, Writing – review & editing. **Asta Audzijonyte**: Data contribution, Writing – review & editing. **Soren Berg**: Data contribution, Writing – review & editing. **Laura Briekmane**: Data contribution. **Justas Dainys**: Data contribution, Writing – review & editing. **Henrik Dalby Ravn**: Data contribution. **Jan Droll**: Data contribution, Writing – review & editing. **Łukasz Dziemian**: Data contribution. **Darius P. Fey**: Data contribution, Writing – review & editing. **Rob van Gemert**: Data contribution. **Martyna Greszkiewicz**: Data contribution. **Adam Grochowski**: Data contribution. **Egle Jakubavičiūtė**: Data contribution. **Linas Lozys**: Data contribution. **Adam M. Lejk**: Data contribution, Writing – review & editing. **Noora Mustamäki**: Data contribution; Writing – review & editing. **Rahmat Naddafi**: Data contribution, Writing – review & editing. **Mikko Olin**: Data contribution, Writing – review & editing. **Lauri Saks**: Data contribution, Writing – review & editing. **Christian Skov**: Data contribution. **Szymon Smoliński**: Data contribution, Writing – review & editing. **Roland Svirgsden**: Data contribution, Writing – review & editing. **Joni Tiainen**: Data contribution, Writing – review & editing. **Örjan Östman**: Methodology, Writing – review & editing.

Declaration of Competing Interest

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

Data Availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fishres.2022.106594.

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