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Original Article

Size-based indicators for assessments of ecological status of coastal fish communities

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Human impact does not only affect the abundances of fish, but also the age- and size-distributions. Indicators of fish age and size-structures can hence be useful tools for fisheries- and environmental management. Size-based indicators have been tested and proposed for large, homogenous marine ecosystems with high fishing mortality, but rarely for fine-scaled heterogeneous ecosystems in coastal zones. Here we analyse a suite of size indicators for coastal fish communities in the Baltic Sea, including mean and median length, 10th and 90th-percentile of the length distribution (L10, L90), mean length of the 10% largest fish (L_{max}), large fish indices, size-spectra, and size-diversity. Results show good precision and accuracy of most indicators at realistic sample sizes, except for size-spectra and size-diversity, making them less suitable. Different indicators showed correlations among sites, indicating similar responses to environmental variation. Most size indicators responded positively to lower fishing pressure, especially indicators emphasizing the largest individuals in the population (e.g. L90 and L_{max}), whereas eutrophication and physical disturbances had less impact. We conclude that size-based indicators aiming at describing the occurrence of larger fish, like L90 and L_{max}, are useful for establishing management targets and assessing the status of coastal fish.

Keywords: Baltic Sea, body size, ecosystem-based management, indicators, length, mortality, somatic growth.

Introduction

Anthropogenic pressures like climate change, habitat degradation, harvesting, and pollutants affect the abundances and distribution of a large fraction of the globe's marine and freshwater species (Adams *et al.*, 2014; Visconti *et al.*, 2016; Nieto *et al.*, 2017). Assessments of population status often require surveys of high statistical quality and spatial coverage, that are expensive and mainly available for species of the highest human interest, such as the most exploited or endangered species. However, several anthropogenic pressures affect the size-, age- or demographic structure of populations, which can be used as indicators of the ecological state of species and communities that lack high-quality survey data (Froese, 2004; Niemi and McDonald, 2004; Servanty *et al.*, 2011; Blanchard *et al.*, 2014, 2017; Fitzgerald *et al.*, 2018).

For several fish species in marine systems where (trawl) fisheries are the dominating human impact, size-based indicators exhibit responses to variation in fishing pressure (Blanchard *et al.*, 2005, 2014, 2017; Greenstreet *et al.*, 2011; Mindel *et al.*, 2018). In nearshore coastal and transitional waters, size-based indicators are rarely applied (but see Smoliński and Całkiewicz, 2015; Lappalainen *et al.*, 2016; Fitzgerald *et al.*, 2018 for other ecosystems) for several reasons. Here, fisheries and fish surveys use a diverse array of gears (e.g. gill nets, pots, and traps) that may have different size selectivity, and catches tend to be in the order of 100–1000 individuals, compared to 10 000 s in trawl catches and surveys. Coastal fish species generally also show finer-scale spatial population structures relative to species occurring in open marine systems (Östman *et al.*, 2017). Whereas fisheries often are the main human impact on marine fish communities, coastal areas face an array of human activities and development, like habitat exploitation, dredging, maritime traffic, pollution, eutrophication, and both commercial and recreational fishing (Hal,pern et al., 2008; Bleckner *et al.*, 2021). Consequently, the degree of a given human impact can vary over small geographic distances (Bergström *et al.*, 2016; Östman *et al.*, 2017). It is therefore important for management and status assessments of coastal fish communities that indicators reflect the spatial variation in human pressures.

Here we calculated eight size-based indicators, previously suggested for offshore fish communities (e.g. Blanchard *et al.*, 2005, 2014, 2017; Greenstreet *et al.*, 2011; Mindel *et al.*, 2018; Queirós *et al.*, 2018), to four organizational levels of coastal fish communities [community, key species, cyprinids, large (predatory) fish] to study the accuracy, precision, and spatial variation of indicators across sites. Specifically, we analyse (i) the relationship between sample size and precision or accuracy of the indicators; (ii) correlation between different size-based indicators across sites; (iii) differences in indicator values between gears and commercial and monitoring

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fisheries, and finally; (iv) the study indicator values across sites and broad categories of human impacts on coastal waters.

Material and methods

Fish data and organizational groups

We compiled data on body length distributions of coastal fish from fisheries independent monitoring surveys and commercial catch data available in the national databases in Estonia, Finland, Sweden, and Poland from 2000–2019 (HELCOM, 2019; Figure 1; Table S1). Fish lengths were recorded as centimetre classes, rounded downwards. The fish monitoring data mainly come from gill nets with multiple mesh sizes, i.e. multi-mesh or net-series, but also from coastal trawls (Pärnu in Estonia) (HELCOM, 2019). Commercial data with gill nets and fyke nets were available from randomly chosen fish from landings in Estonia (Pärnu Bay) and catch (including bycatch) in Finland (SD29: ICES rectangles 49H0-H2, and SD30: 50H1).

We apply a minimum threshold size in order to exclude ≤ 1-year old fish that mainly reflect variation in reproduction and not somatic growth and mortality. This minimum size differs between 12 and 25 cm depending on fish species and group (Table S1) and was based on known approximate length at age 1 or limitations of gears, as fish <12 cm are poorly sampled in monitoring gill nets.

The Baltic Sea has strong gradients in temperature and salinity in a north-south direction, and from the inner to the outer coastal zone (HELCOM, 2018a), that result in fish communities composed of different species. Therefore, HELCOM (2018b) use generic organizational groups of indicators in the Baltic Sea:

1) Community includes all fish species in monitoring data. The smallest mesh size is around 10 mm and therefore we applied a minimum threshold body size of 12 cm as smaller fish are not representatively sampled (HELCOM, 2018b). This excludes most fish ≤ 1-year old but for many small-bodied species also older individuals. Not possible to use for commercial landings as bycatches are not reported.
2) Key species include perch (*Perca fluviatilis*) and flounder (*Platichthys flesus/solemdali*). Perch is common in archipelagos, sheltered, and vegetated areas, whereas flounder occurs in exposed, sandy/rocky, and southern areas (HELCOM, 2018b). Flounder occurs in two ecological species (Momigliano *et al.*, 2018); European flounder (*P. flesus*) and Baltic flounder (*P. solemdali*), but are here treated as one species. The minimum threshold size is 15 cm.
3) Cyprinids is a functional group indicator for coastal fish in the Baltic Sea (HELCOM, 2018b). Roach (*Rutilus rutilus)* is usually the most common cyprinid in coastal fish communities, but most cyprinids have a similar ecological function as benthic feeders, except bleak (*Alburnus alburnus*), which is mainly a plankton feeder. The minimum threshold size is 12 cm.
4) Large (predatory) fish includes pikeperch (*Sander lucioperca*), pike (*Esox lucius*), and whitefish (*Coregonus maraena*). Despite not being a strict piscivore, whitefish can become large (>50 cm) and occurs in exposed parts of the coastal zone where other larger coastal fish species are absent. The minimum threshold size is 25 cm.

We calculate indicators for all species in a group combined. However, due to environmental variation, key species and large fish in many sites only include a single species (perch, flounder, pikeperch, pike, or whitefish). It was further not possible to calculate size indicators for all organizational groups at all sites due to limitations in sample size and species composition. For community, cyprinids, and key species—perch we have used data, unless other stated, during the latest HELCOM assessment period 2011–2016 (HELCOM, 2018a), but for key species—flounder and Large fish we have used data from 2010–2019 due to generally lower sample sizes (Table S1).

Indicators

We evaluate a set of indicators previously suggested for data-limited fish stocks (Froese, 2004; Greenstreet *et al.*, 2011; Blanchard *et al.*, 2017; Fitzgerald *et al.*, 2018). Mean (mL) and Median length are the arithmetic average length and length of the 50-percentile, respectively. To put more emphasis on larger fish we also use the 90th percentile of the length distribution (*L90*). ICES (2011) suggests using *L95* but this is more applicable to data with large numbers of fish (Probst *et al.*, 2012). In static gears, typical in coastal zones, <100 individuals of a species are usually captured, resulting in a large sampling variation in the *L95*. We also calculate the mean length of the 10th largest percentile, L_{max} (Fitzgerald *et al.*, 2018). As an indicator of the recruitment of smaller fish, we use the 10th percentile of the fish length distribution (*L10*).

The Large Fish Index (LFI) is the proportion of fish biomass in a population or community above a threshold size, S_L. In many offshore ecosystems $S_L = 40$ cm (Greenstreet *et al.*, 2011; Mindel *et al.*, 2018; Queirós *et al.*, 2018). In coastal fish monitoring, however, individual weights are not measured, and we, therefore, apply *LFI* as the proportion of the number of fish above S_L. Fish >40 cm are rare in coastal fish monitoring and as there is a trade-off between sampling errors and the threshold size for "large" fish. We use two different S_L to study how the threshold affects sampling variation. For community, key species, and cyprinids, we use $S_L = 25$ cm (LFI_{25}) and $S_L = 30$ cm (LFI_{30}), and for *Large fish* $S_L = 35$ cm (LFI_{35}) and $S_L = 40$ cm (LFI_{40}).

The Size-spectrum (SS) is the regression slope between $\log_e(Abundance_i)$ vs. L_i (Blanchard *et al.*, 2017). A highly negative slope (few large fish) indicates high mortality, net emigration of larger fish, or slow growth. Size diversity (SD) is the Shannon diversity index of length classes, $SD = \Sigma(-P_L * \ln(P_L))$, where P_L is the proportion of fish in length class L. A higher value means a larger number of size classes and a more even size distribution.

Statistical diagnostics

To analyse how sample size influences the precision and accuracy of size-based indicators, we here apply an in-house developed resampling technique in R4.0.4 (Supplementary Material). From the observed length distributions during the study period (Table S1), we resampled *N* individuals, with replacement, and recalculated indicator values 100 times for each sample size *N*. We assess precision from the interquartile distance between samples of the same sample size, whereas we assess accuracy as the difference in the median of sampling distributions with different sample sizes (assuming a high sample size better reflects true indicator value).

Figure 1. Map over the sampling sites in the Baltic Sea divided per human impact category. "MPA" is marine protected areas, "NOF" is No-fishing areas. "Other" is a non-categorised monitoring area. Finnish commercial catches are from SD29 (Ices rectangles 49H0-H2) and SD30 (50H1).

To study correlation of different size-based indicators among sampling sites we run a PCA of the matrix with one value for each indicator at each monitoring site. For each site, we aggregated length distributions from the study period into one length distribution (Table S1). Indicators with similar loadings on a PC-axis are covariant (redundant), whereas indicators with different loadings explain unique variation.

Gear, spatial, and temporal variation in indicator values

To study how gear types (gill- or fyke nets, or trawls) and sampling schemes (monitoring or commercial catch data) influence indicator values, we use data on large fish—pikeperch and key species—perch. Pikeperch have been sampled in fisheries-independent gill net monitoring in all countries and with monitoring trawls in Estonia and in commercial fisheries in Estonia and Finland. Here we used data from 2000 to 2014 but because annual sample sizes were too small for an annual basis we combined data into two periods, 2000–2006 and 2007–2014. Finland is the only country where we have data on commercial catches of perch, with both gill- and fyke nets.

To study the influence of different human impacts, we used data from 35 coastal sites in Sweden using standardised "Nordic coastal multimesh gill nets" 2011–2016. Sites were divided into five categories of human influence along the Swedish Baltic Sea coast (Bergström *et al.*, 2016): NOF, MPA where fishing is allowed, reference areas (REF) where fishing is allowed but otherwise not directly impacted by human activities, urban areas (URB) affected by physical disturbances and effluents, and eutrophic areas (EUT). For the organizational groups community, key species—perch, and cyprinids we had enough data to categorise sites into all five levels of human impact. For large fish and key species—flounder the number of sites with fish above the minimum sample size in the different categories were too low (1–2 observations for some categories) for analyses to be meaningful. We did linear mixed models (LMM) to assess significant differences among categories of human influence with the size indicator as the response variable and human impact category and year as explanatory variables using the lmer-function in R (Bates *et al.*, 2015) and Satterthwaite's method for adjusting the denominator's degrees-of freedom using "lmerTest"-package (Kuznetsova *et al.*, 2017). To study which categories significantly differed from each other we did Tukey's HSD post-hoc test using the "emmeans" package for R (Lenth, 2022).

Although data was unbalanced, we studied which factors explained most spatial and temporal variation in indicator values using general linear models (ANCOVA). For key species and large fish indicators, we included factor country (Estonia, Finland, Sweden, and Åland), while for community and cyprinids indicators, we included the factor sampling site (within Sweden) in the model. Additional explanatory variables included in all models were gear (trawl, fyke net, gill net, or multimesh), human impact category (see above), season (spring: May–June, summer: July–August, and autumn: September–October), and sample size.

Results

Precision and accuracy

Two of the indicators, size-spectra and size-diversity, showed evident structural deviation with sample sizes for all fish groups in almost all analysed sites, indicating poor accuracy at sample sizes below at least 1000 individuals, whereas for other indicators there was no obvious deviation with sample size (Figure 2, Figure S1). The precision as expected increased with sample size (interquartile range of indicator values decreased), for all indicators but stabilized around sample sizes of 500 individuals or less for mL, Median, *L10,* and *L90* (Figure 2, Figure S1). For the indicators with length as a unit (*mL*, *Median*, *L10*, *L90*, and L_{max}) the precision measured as interquartile intervals were <±1 cm at sample sizes down to 300 individuals (Figure 2, Figure S1). The *L10* indicator was for some fish groups, especially community and cyprinids, identical to the applied minimum threshold size.

Correlations between indicators

The PCA of size-based indicators at different coastal sites showed that most indicators tend to cluster along the first PC-axes (explaining 65–85% of variation), whereas indicators separated more along the second axes (explaining 5–25% of variation; Figure 3). Thus, there is clear redundancy of indicators within each organizational group. For most groups, the separation of indicators was related to the indicators' dependency on larger individuals. *L10* and Median cluster at one end, whereas size-spectra, L_{max}, and LFI more influenced by the variation among larger individuals separated on the other end for all organizational groups (Figure 3).

Spatial, temporal, and sampling variation

For large fish—pikeperch size indicators derived from commercial pikeperch fisheries data differed from fisheries-independent data ($F_{4,20} > 4.8$, $p < 0.01$, $n = 20$) for all indicators (Figure 4a). This is an effect of larger mesh sizes in commercial fisheries, which shifts the size-distribution towards larger individuals, e.g. *L10* was 10–15 cm larger than in fisheries-independent data (Figure 4a). In contrast, size-spectra were lower in commercial fisheries data than in fisheries-independent data due to a narrower range of mesh sizes used in commercial fisheries ($F_{1,4} = 18$, $p = 0.01$, $n = 6$; Figure 4a). Size indicators from Estonian fisheries-independent data did not differ between trawl monitoring and gill net monitoring data ($F_{1,4} < 1.2$, $p > 0.3$, $n = 6$; Figure 4a).

For key species—perch the size indicator obtained from the commercial gill net fisheries was also higher than in fisheries-independent data and commercial fyke nets ($F_{2,9} > 10$, $p < 0.01$, $n = 13$; Figure 4b), except for size-diversity and size-spectra that were lower. It should be noted that data from commercial fisheries was based on the whole catch, including discard, so the fyke nets catch a broader array of size classes, similar to the multimesh gill nets used in fisheries-independent monitoring (Figure 4b).

In the *standardised* gillnet monitoring from 35 Swedish sites, most indicator values for the group community and key species—perch were significantly higher in NOF compared to REF, but not for cyprinids (Table 1, Figure 5). The values of size indicators were also often higher in MPA's and EUT, whereas urban and REF showed similar values (Table 1, Figure 5).

When combining data from all countries, sites and gears into one ANCOVA (for each indicator and group), space related to country or sampling site explained significant part of total variation for almost all indicators and organizational groups (Table 2). Gear explained variation in indicator values for both key species and large fish. Different categories of human impact still explained variation in size-indicators of the community and key species—perch, but less for the functional groups cyprinids and *large fish*, with notably significant exceptions for *L90* and L_{max} (Table 2). In our data, time (year or period) only explained variation in few indicators, whereas there were some seasonal variations in key species

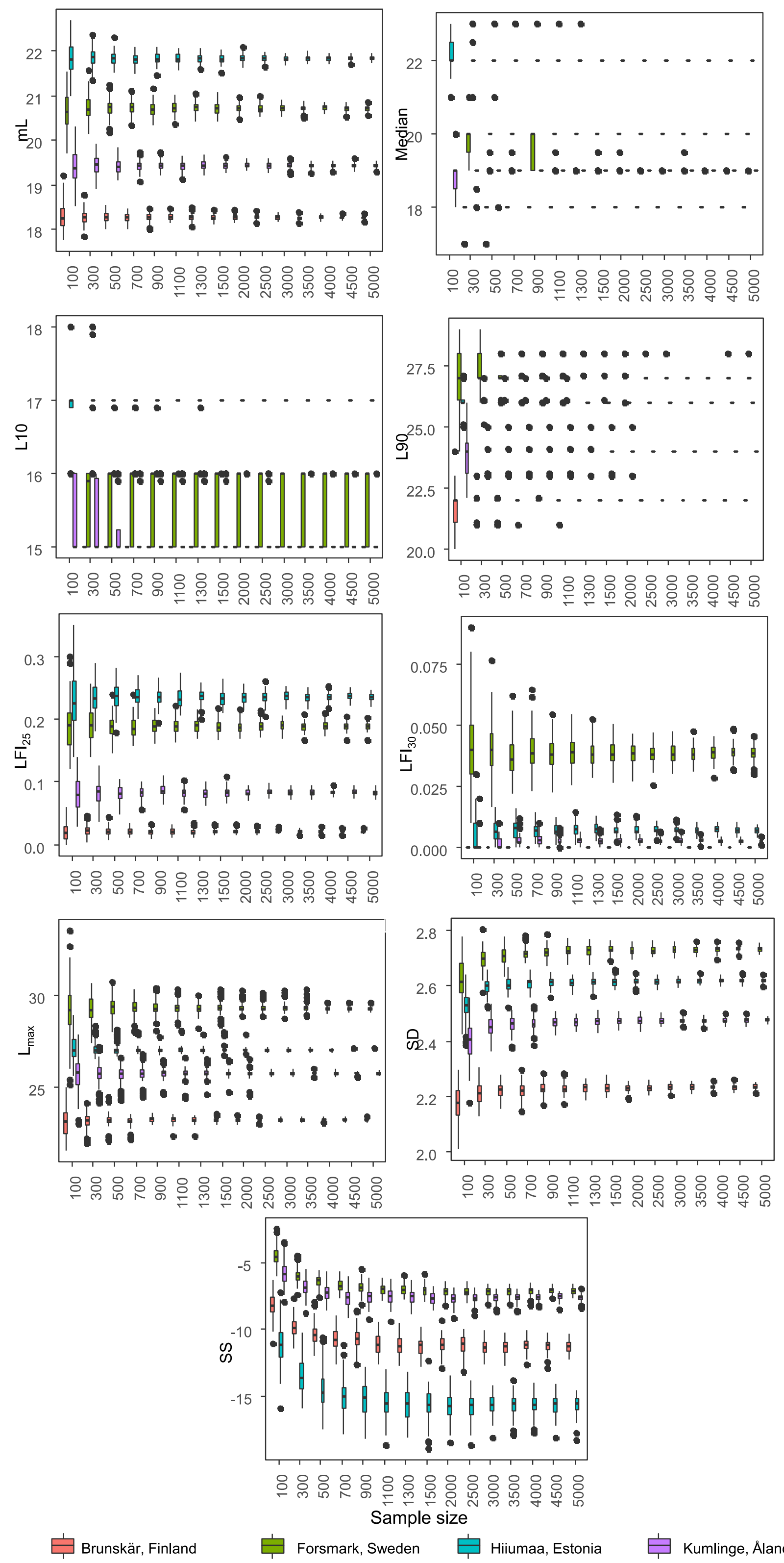

Figure 2. Boxplot of resampled size-based indicator values (y-axes) of key species—perch from four monitoring sites with >5000 perch 2011–2016. For each sample size (x-axes), indicator values are resampled 100 times. The bars indicate the median, the box the 25th–75th percentile interval (IQR) and whiskers 1.5∗IQR. Dots (•)indicate outlier values, whereas hyphens (–) indicates no variation among sub-samples. Note that x-axis is not to scale and the scale of y-axes differ between indicators. See Figure S1 for the other fish groups.

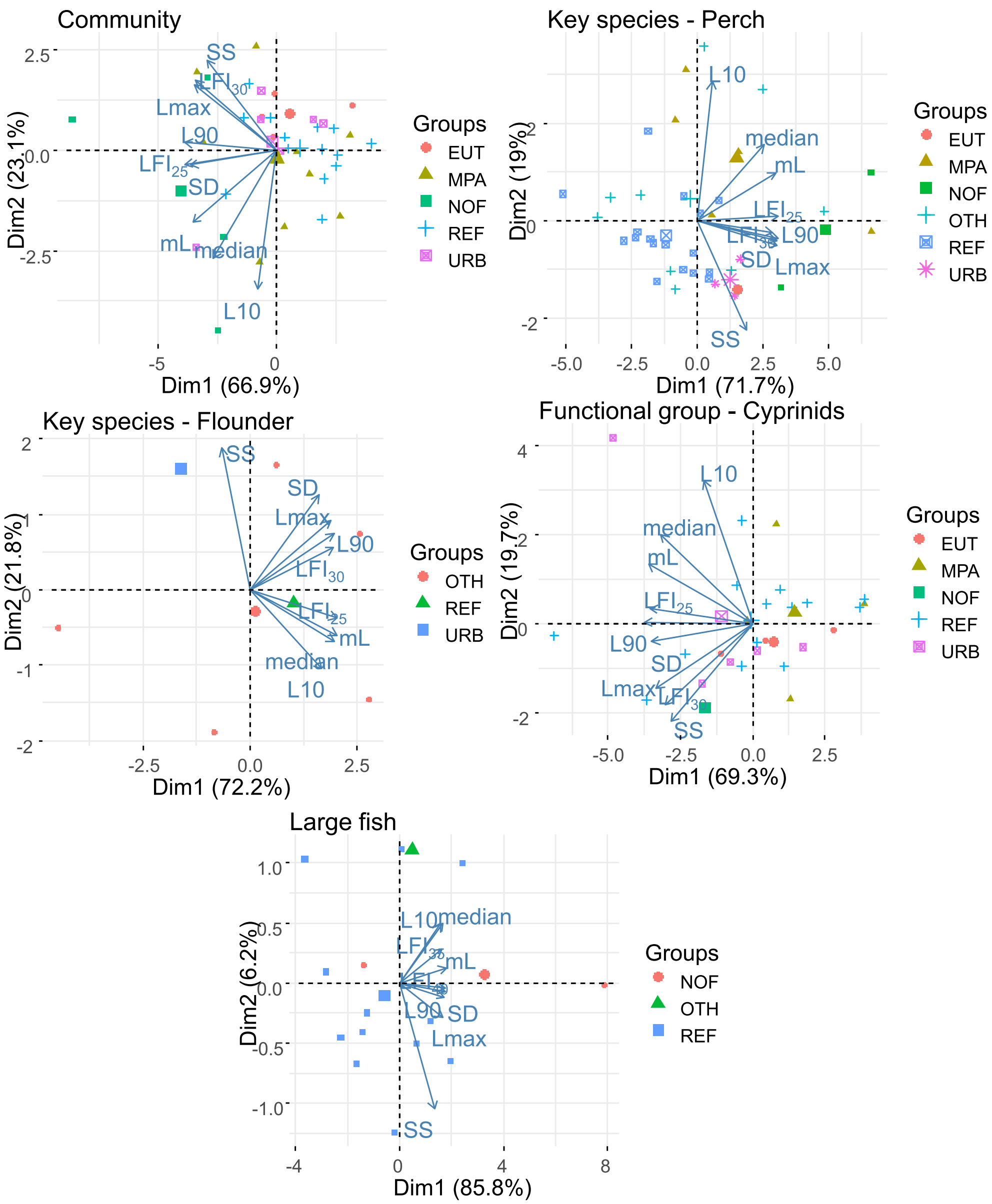

Figure 3. Biplots from PCA of size-based indicators from different sites. Arrows indicate different size-based indicators and indicators close to each other show high correlation across sites, redundancy. Dots are the different sites divided on different categories of human impact (EUT, MPA, NOF, OTH—Other, REF, and URB).

indicators (Table 2). Sample sizes (above the minimum sample size, see Table S1) generally explained little variation in indicator values with some exceptions of community and key species—flounder (Table 2).

Discussion

All size-based indicators investigated here have their merits and demerits but we conclude that size-based indicators are suitable for coastal fish assessments. Several indicators responded to spatial variation in the level of human impact in the coastal zone, which supports the use of these indicators for assessing the ecological status of coastal fish communities. Hence, we propose to use size-based metrics as a complement to abundance-based indicators for stock and ecosystem assessments in coastal waters. However, LFI, size-spectra, and size-diversity showed lower precision or accuracy at lower sample sizes (<1000) suggesting they are not preferable as coastal fish indicators, unless sample sizes are large to overcome the stochastic process of including larger individuals that influences their indicator values. Our results suggest that the different size-based indicators capture similar (spatial) variation, and hence, redundant and are partly supplementary to each other. We cannot identify a single superior indicator and below we discuss which indicator to use depending on which part of the fish community is of interest and available sample sizes.

The indicators median (median size) and *L10* (10th percentile of the size-distribution) best represent the smaller-sized fish in the sample, and hence, recruitment of younger fish. Both indicators show high precision and accuracy at sample sizes above 100 individuals and show spatial variation for most groups, but *L10* become identical to the minimum size for several organizational groups. Hence, *L10* may be most rele-

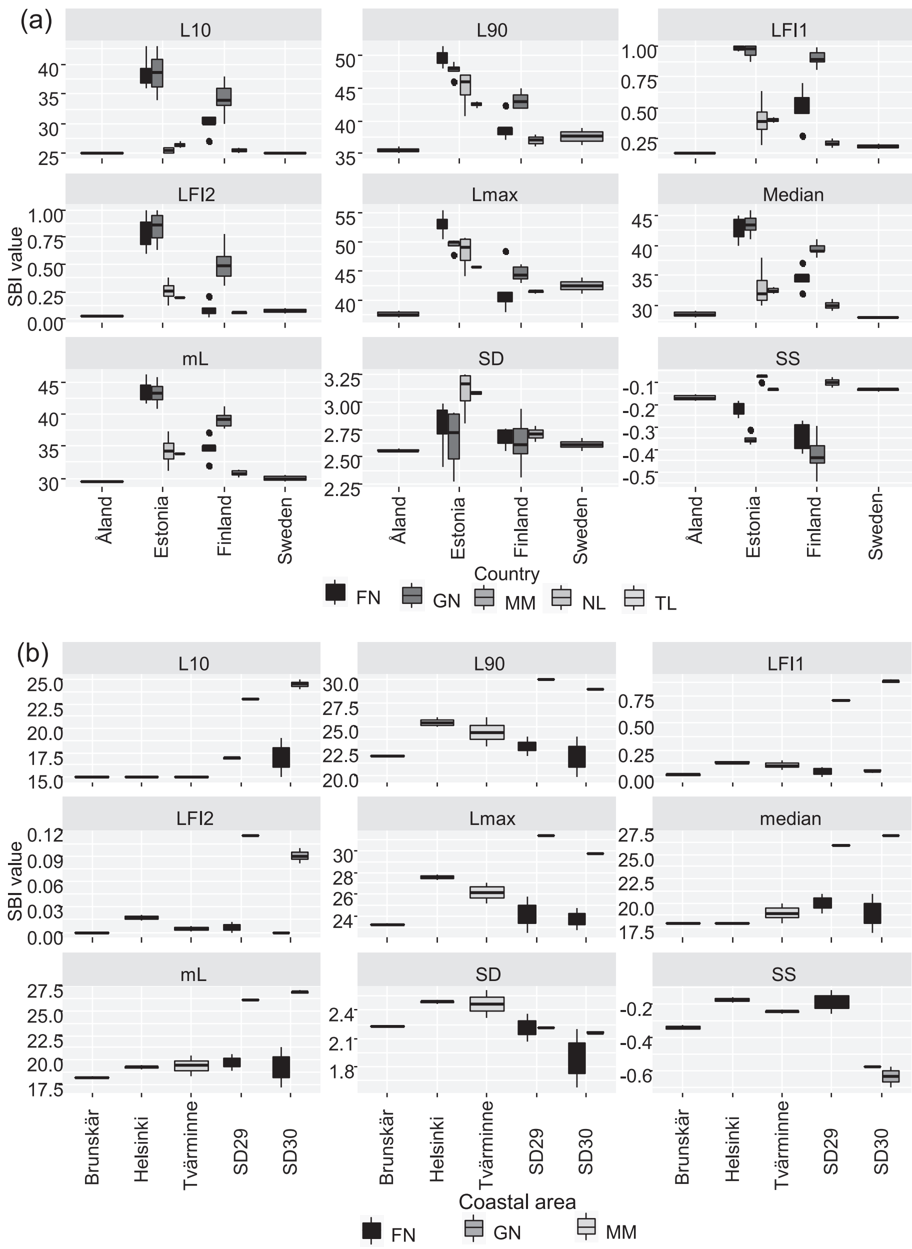

Figure 4. (a) Box-plots of size based indicators values of large fish—pikeperch between different countries and sampling gears. Fyke net and Gill net are from commercial catches whereas Multimesh (gill net), Netlink (gill net), and Trawl are from fishery independent monitoring data. (b) Box-plots of size based indicators values of key species—perch between commercial and monitoring in Finland. Gear FN—Fykenet, GN—Gillnet, MM—Multimesh net, NL—Netlink, TL—Trawl.

vant to use for large fish, and not from multimesh monitoring data that tend to catch a lot of smaller fish (Table 3). Because both *L10* and median capture variation in the lower end of the size-distribution, higher values are not necessarily better, as this could indicate low recruitment, an under-representation of small individuals.

Mean length (mL) has a higher dependency on larger fish and showed good precision and accuracy with at least 500 individuals sampled. At lower sample sizes, *mL* showed larger sampling errors compared to *L10*, *L90*, and median, because the stochastic process of including a large fish has a higher impact on the indicator value at lower sample sizes. While mL is easy to calculate and understand, it is ambiguous what mL actually indicates as it represents the central tendency of the size distribution that is influenced by many ecological processes (mortality, growth, and recruitment). The indicator nevertheless seems to respond to fishing pressure, except for cyprinids, with larger mL in NOF.

We find *L90* (90th percentile of the length distribution) to be informative for all fish groups as it aims at describing variation among larger fish. The precision and accuracy of *L90* were high, within one centimetre, also at sample sizes of 200–300 individuals. It also differed between human impact categories for community and key species—perch (key species—flounder and large fish not tested), responding positively to MPAs and NOF, but also to eutrophication. Thus, *L90* seems to reflect anticipated differences in fishing pressure and body growth (eutrophication). The L_{max} indicator (mean length of

Table 1. F-values and ranks from Tukey's HSD comparisons of size-based indicators between different categories of human influence. Categories are sorted from highest to lowest value and categories separated with a "," are significant different at $p < 0.05$, whereas "/" indicates non-significant differences. Tests are divided for different organizational groups of fish (community—all fish, key species—perch, cyprinids—all cyprinid fish species). The different categories are EUT, MPA (but some fishing allowed), NOF, REF where fishing is allowed but otherwise not directly impacted by human activities, and URB affected by physical disturbances and effluents.

Indicator	Community	Key species—perch	Cyprinids
mL	$F_{4,54.2} = 9.5^{***}$ NOF, URB/REF/MPA/EUT	$F_{4,95.9} = 9.1^{***}$ NOF/MPA/EUT, REF/URB	$F_{4,42.1} = 0.6$
Median	$F_{4,55.5} = 5.4^{***}$ NOF, URB/REF/MPA/EUT	$F_{4,103.6} = 6.4^{***}$ NOF/MPA/EUT, REF/URB	$F_{4,40.7} = 0.8$
L10	$F_{4,61.1} = 1.5$	$F_{4,61.2} = 4.5^{**}$ MPA/NOF, REF/URB/EUT	$F_{4,40.2} = 0.6$
L90	$F_{4,65.7} = 7.4^{***}$ NOF, MPA/EUT/URB/REF	$F_{4,85.5} = 7.3^{***}$ NOF/MPA/EUT, URB/URB	$F_{4,39.5} = 0.9$
$LFI_{25/35}$	$F_{4,50.8} = 8.4^{***}$ NOF, MPA/EUT/URB/REF	$F_{4,76.9} = 6.8^{***}$ NOF/EUT/MPA/REF,URB	$F_{4,42.8} = 1.1$
$LFI_{30/40}$	$F_{4,81.2} = 17^{***}$ NOF, MPA/EUT/URB/REF	$F_{4,73.7} = 22^{***}$ NOF, EUT/MPA/URB/REF	$F_{4,38.7} = 1.4$
Lmax	$F_{4,81.6} = 7.0^{***}$ NOF, MPA/EUT/URB/REF	$F_{4,74.5} = 17^{***}$ NOF, EUT/MPA, URB/REF	$F_{4,37.4} = 1.4$
SD	$F_{4,61.1} = 4.2^{**}$ NOF, MPA/EUT/URB/REF	$F_{4,84.1} = 5.3^{***}$ NOF/EUT/MPA/URB, REF	$F_{4,40.4} = 1.0$
SS	$F_{4,55.5} = 2.7^{*}$ NOF/MPA/EUT/URB, REF	$F_{4,89.1} = 2.2$	$F_{4,34.1} = 0.6$

$^{*}p < 0.05$, $^{**}p < 0.01$, and $^{***}p < 0.001$.

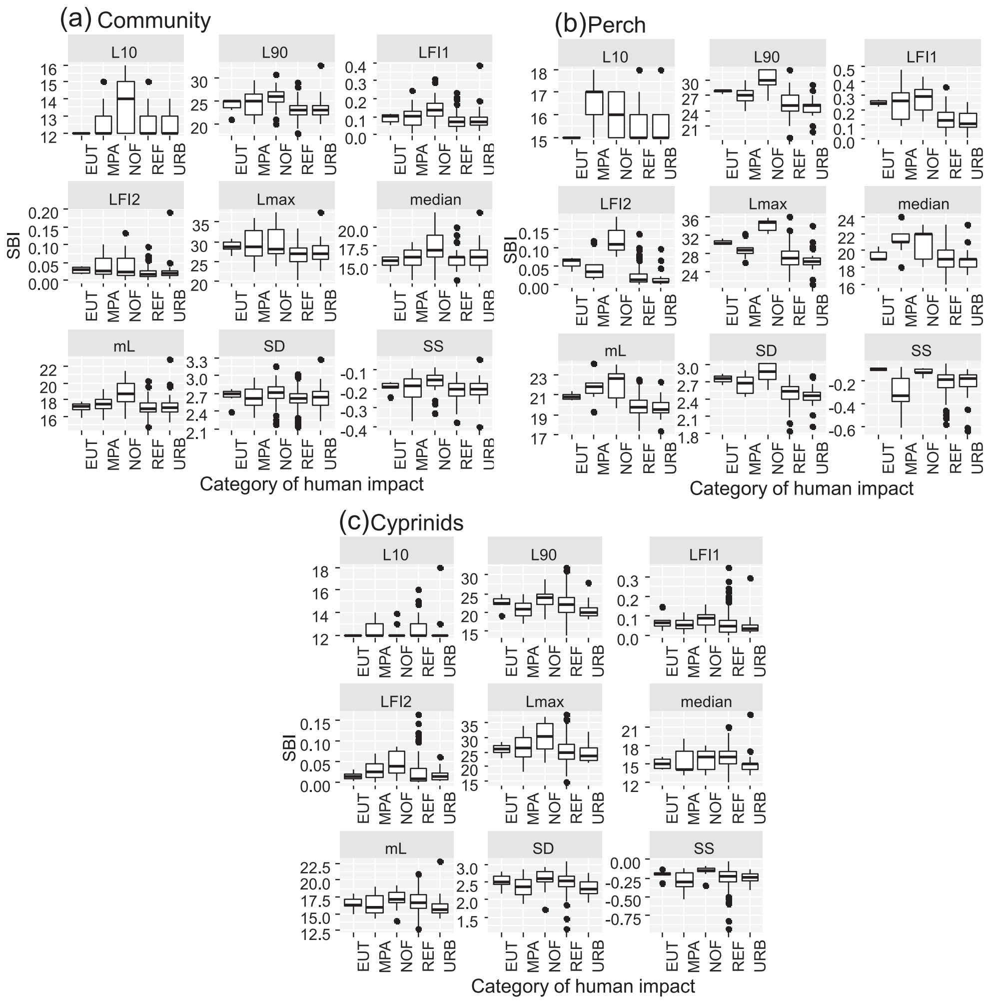

Figure 5. Boxplots of size-based indicators divided on five different categories of human impact for three different fish groups. The different categories are NOF, MPA (but fishing allowed), REF where fishing is allowed but otherwise not directly impacted by human activities, EUT, and URB affected by physical disturbances and effluents.

the largest 10th percentile), showed a similar pattern to human impacts as *L90*. L_{max} also captures the variation in the actual size of the largest individuals if the focus is on the largest individuals alone. At smaller sample sizes L_{max} will be calculated from a few individuals with a risk of stochastic variation. We, therefore, think the L_{max} indicator works best for samples >500 individuals.

The large fish index (LFI; the proportion number of fish above a threshold size) has been applied to marine fish communities where trawl fishing dominates (Greenstreet *et al.*,

Table 2. F-values from ANCOVAs of different size-based indicators between different countries or sites (within Sweden), categories of human influence (Impact), gear types, seasons, years, and sampling size (N). Results are divided for different organizational groups of fish. df is degrees of freedom for the nominator (explanatory factor) and denominator (organizational group).

F-values	*mL*	*Median*	*L10*	*L90*	L_{max}	$LFI_{25/35}$	$LFI_{30/40}$	*SD*	*SS*
Community—all species (df = 97)									
Site (df = 34)	5.9***	5.5***	8.6***	10***	16***	6.2***	14***	7.2***	5.3***
Impact (df = 4)	9.0***	5.3***	0.2	9.6***	8.8***	9.9***	19***	5.6***	2.7*
Year (df = 5)	2.3*	1.9	2.8*	1.8	1.0	1.7	0.6	2.3*	1.9
N (df = 1)	4.3*	2.6	0.8	9.5**	11**	1.7	3.6	5.2*	3.1
Key species—perch (df = 110)									
Country (df = 3)	7.5***	5.0**	9.3***	6.5***	5.1**	4.1**	0.3	7.1***	2.3
Impact (df = 5)	8.1***	5.7***	4.2**	8.6***	11***	8.1***	19***	6.8***	3.2**
Gear (df = 2)	8.2***	6.7**	26***	1.3	1.0	37***	7.6***	5.2**	20***
Season (df = 2)	5.1**	2.9	2.6	4.0*	3.4*	0.9	0.4	8.8**	6.3**
Year (df = 5)	1.5	0.8	1.3	2.2	2.2	1.3	1.8	1.5	1.0
N (df = 1)	1.9	2.1	0.1	0.8	0.1	3.1	0.7	0.5	24***
Key species—flounder (df = 11)									
Country (df = 2)	20***	21***	4.1*	11**	5.9*	15***	7.6**	0.2	8.3**
Gear (df = 1)	3.6	3.4	3.3	0.3	0.4	0.3	0.1	2.5	10**
Season (df = 2)	5.9*	5.5*	0.2	5.5*	2.7	4.3	0.1	0.1	0.1
N (df = 1)	3.1	3.7	0.1	14**	14**	0.7	3.1	9.8**	11**
Cyprinids (df = 59)									
Site (df = 28)	10***	10***	11***	7.2***	6.3***	11***	6.6***	7.6***	2.7***
Impact (df = 3)	1.2	2.0	2.4	3.0*	4.6**	4.0*	3.8*	1.0	0.5
Year (df = 5)	2.5	1.5	3.1*	0.7	1.3	0.9	1.6	0.7	1.3
N (df = 1)	0.1	0.3	0.2	1.1	1.8	0.9	3.6	0.1	0.8
Large fish (df = 11)									
Country (df = 2)	22***	17***	30***	14***	17***	6.4*	63***	3.3	7.2*
Impact (df = 3)	0.5	1.5	0	5.5*	72***	0.4	0.4	0.1	0.2
Gear (df = 2)	12**	13***	8.0**	14***	4.8*	7.9**	14***	2.9	2.8
Season (df = 2)	0.5	0.4	2.1	0.7	0.8	0.5	5.0*	4.1*	0.2
Period (df = 1)	0.1	0.1	2.1	0.2	0.2	0.1	0.6	1.8	2.2
N (df = 1)	0.1	0.2	0.3	0.1	0.1	0.1	0.4	0.2	0.6

*$p < 0.05$, **$p < 0.01$, and ***$p < 0.001$.

2011; Mindel *et al.*, 2018; Queirós *et al.*, 2018). In coastal areas, LFI does not work as well where static gears are mainly used. The precision is poorer than other indicators up to a sample size of 500 individuals, as the proportion of fish above a specific threshold size tends to be low (<10% in some cases). One solution to this caveat is to lower the threshold size defining a large fish, but then it becomes questionable whether LFI actually represents "large fish." This also highlights the second problem, how to decide on a relevant threshold size. Size-at-maturity or at first-catch, or size where natural mortality equals somatic growth (L_{opt}) have been suggested as threshold sizes (Fitzgerald *et al.*, 2018), but are rarely known for coastal fish and likely to vary between areas. Threshold size may therefore be set arbitrarily for coastal fish populations and communities. Still, LFI responded to differences in human impacts, but we think it is more suitable for larger catches and when it is possible to apply an ecologically relevant threshold size.

The indicators size-spectra and size-diversity exhibited the most deviant pattern in the PCA and seem to capture variation in the largest fish. This was expected as the addition of a fish in larger, but less frequent size classes will have a disproportional effect on indicator values. This also makes them sensitive to sample size and in the cases studied here, there is a high risk of biased sampling errors underestimating real indicator values for sample sizes below 2000 individuals. For coastal fish communities, we think they are most suitable as size indicators for community or cyprinids that tend to have larger sample sizes.

An issue with assessments of coastal fish communities in the Baltic is coastal fish monitoring is undertaken using a suite of methods and gears reflecting a combination of spatial variation in environmental conditions and historic practises (HELCOM, 2019). We have mainly used fishery-independent gill net monitoring data, but especially for the large fish group differences between gears were evident. For pikeperch, we could compare gill net and trawl monitoring data from Estonia, and as long as we applied a minimum size (here 25 cm), size indicators were similar between the two gears. In contrast, commercial catches of pikeperch in gill nets from Finland and Estonia differed considerably from monitoring data by a lack of smaller individuals and more truncated size distribution due to a larger but narrow range of mesh sizes used in commercial pikeperch fisheries, mainly 43 mm. We observed a similar pattern for commercial catches of perch in gill nets in Finland, whereas indicators from Finnish commercial catches in fyke nets (where size indicators are calculated on the whole catch) had similar values as monitoring data. Thus, we find it relevant to use commercial catches from fyke nets (or pound- or trap nets) that sample a wider range of size classes for assessing size indicators.

There are many size-based indicators suggested that are not considered here (Froese, 2004; Fitzgerald *et al.*, 2018), because these require additional information about maturity, length-at-age or size-at-catch in commercial fisheries (L_c). We have here focused on those that are possible to use and calculate without any prior knowledge of life-history. In a few cases in the Baltic Sea, there is prior information for the targeted

Table 3. Summarizing results and recommendations for applying size-based indicators on coastal fish communities. Min N is our recommended minimum sample size for calculating the respective size indicator, recommended group is which organizational groups we find most suitable (com-community, KS-key species, Cyp-cyprinids, LF-large fish), and unsuitable gear is if samples from any gear type are less suitable for calculating indicator values (MM-Multimesh). Target level is an indicative range of a target level based on our data, inferred from differences between reference sites and no-fishing sites (Figure 5). Aim indicates to which part of the size distribution the indicator mainly responds. Key species only refer to perch as we had too few sites with differences in human impact for flounder.

Indicator	mL	Median	L10	L90	Lmax	LFI_{25}	Size-diversity	Size-spectra
Min N	500	300	300	300	500	500–1000	2000	2000
Recommended Group	KS, LF	KS, LF	LF	All	All	Com, KS	Com, Cypr.	Com, Cypr.
Unsuitable gear	–	–	MM	–	–	Gill net	Gill net	Gill net
Potential target level (multimesh)	KS: 20-22 cm LF: 32–34 cm	KS: 18-22 cm LF: 29–31 cm	–	Com: 22-25 cm KS: 23-28 cm Cypr: 20-24 cm LF: 40–45 cm	Com: 25-30 cm KS: 26-34 cm Cypr: 26-30 cm LF: 45–55 cm	Com: 5–10% KS: 10–20%	Com: 2.5–2.7 Cypr: 2.3–2.5	Com: -(0.15–0.2) Cypr: -(0.3–0.1)
Aim	–	Recruits	Recruits	Larger fish	Larger fish	Relevant threshold size	Rare length classes	Largest individuals

populations of coastal fish (e.g. pikeperch, Lappalainen *et al.*, 2016), but the general lack of such information hinders the establishment of reference levels and management targets for coastal fish when applying these indicators. A possible alternative solution to overcome this shortcoming is to adopt a "Robin Hood"-approach (Punt *et al.*, 2011; Hordyk *et al.*, 2015), where missing life-history information is used from related stocks or life-history invariants. This type of knowledge transfer could be used for further development on current fisheries management, basing the decisions on data-rich fisheries of similar species, for example walleye in North America for pikeperch.

All studied indicators show variation between countries or sampling sites, although it can partly be due to unbalanced data reflecting differences in gear selectivity, season, or sample size. Using data from an identical gear and season, however, does show size indicators of at least community and key species—perch differ in relation to variation in anthropogenic influence. There is probably other environmental variation influencing size distributions, like temperature, depth, and habitat, which can change on a relatively fine scale in the coastal zone. It would be desirable to analyse such influence and make necessary adjustments when assessing the ecological status of coastal fish, but adjustments likely have to be indicator and group-specific.

In our analyses, time generally explained less variation than space. For key species (perch and flounder), there was some significant difference, lower values in spring, which could reflect the body growth during the season, but data was unbalanced and covariation with other factors cannot be excluded. The year effect (interannual variation) is more interesting as the purpose of size indicators is to follow changes over a longer time periods—in the HELCOM framework six years assessment cycles. In our analysis, year effect rarely explained any indicator variation but we have to stress that analyses here focused on spatial variation as we combined data from many sites in the analysis, and changes within sites over time may have counteracted each other. However, over the time periods studied here (Table S1) we could not find any major synchronous changes in size indicators across the Baltic Sea.

Size-based indicators have so far not been widely used in coastal fish management. The results presented here suggest that size-based indicators can be useful also for coastal management, despite smaller sample sizes, and fine-structured populations than marine fish communities. It is not straightforward to propose which indicators to use, but will depend on the specific case and question posed. In Table 3, we list some conclusions for using size-based indicators on coastal fish communities. Most notably, the sample size and gear selectivity but also additional information about basic biological parameters (length-at-age, size-at-maturation) and what aspect of community (group) and size (recruitment, occurrence of large fish, body growth, mortality), to consider are influential. A higher sample size is required for precise and accurate estimation of the indicators aiming at describing the fraction of the largest individuals in the population. In our study, LFI, size-diversity, and size-spectra, were sensitive to sampling errors and required larger sample sizes. We conclude that $L90$ and L_{max} show acceptable compromises of statistical precision and accuracy at realistic sample sizes but still respond to differences at the larger end of the size distributions.

Assessing the ecological status of coastal fish from size indicators requires some reference levels or management targets, which we have not addressed here. For the size indicators we suggest that reference levels and management targets could be set using data from relatively low-impacted coastal areas (Samhouri *et al.*, 2012; Borja *et al.*, 2013). More precise target levels may be set by linking size-based indicators to other parameters such as fishing intensity and stock biomass (Modica *et al.*, 2014; Östman *et al.*, 2020), but require additional data that may be missing for most coastal fish species. Another option is to use time-series analyses to set management targets that correspond to a sustainable (stationary) state over time, i.e. a target that would prevent a deterioration of indicator values (Greenstreet *et al.*, 2011; Modica *et al.*, 2014; Probst and Stelzenmüller, 2015; Shepard *et al.*, 2015; Östman *et al.*, 2020).

Conclusions

We have applied different size-based indicators to empirical data from coastal fish communities to investigate their statistical properties and spatial variation across coastal sites, in particular with different levels of human impact. Several of the investigated indicators have desirable statistical properties at sample sizes relevant for the monitoring of coastal fish communities, except for the indicators that give the highest weights to the largest individuals. We show that there is significant spatial variation in indicator values, and most seem to respond to variation in fishing pressure and other types of human pressures. Several indicators were correlated among sites, hence indicators are partly redundant. Which one or ones to use is largely up to the aim and available sample sizes (Table 3). We have shown that size indicators of coastal fish communities are scientifically sound to use and respond to variations in human pressures. A challenge for these indicators to be relevant and incorporated in coastal zone management is to understand how these indicators respond to other types of environmental variability, and set relevant reference levels or management targets.

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Supplementary data

Supplementary material is available at the *ICESJMS* online version of the manuscript.

Conflict of interest

The authors declare no conflicts of interest.

Data availability

Data from Sweden and Åland is publically available in the open access coastal fish monitoring database 'KUL' hosted by the Swedish university of Agricultural Sciences:
https://www.slu.se/en/departments/aquatic-resources1/databases/database-for-coastal-fish-kul/
Finnish monitoring data is available by request from the Hertta database, Finnish Environment Institute (SYKE). Finnish commercial fishery data were collected under EU Data Collection Framework within the Common Fisheries Policies, and transfer of data is regulated by Council Regulation (EC) No:2017/1004, article 17.7.
Estonian monitoring data are available through contact with Estonian Marine Institute, University of Tartu.
Polish monitoring data are administered by the Polish Chief Inspectorate of Environmental Protection and available through contact.
A R-script for calculations and resampling of indicator values is available as Supplementary Information.

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Authors' contributions

Ö.Ö. and J.O. conceived the ideas and designed methodology; Ö.Ö., K.H., A.M.L., O.H., M.O., A.M.L., R.S., S.S., and L.S. and E.F. collected and compiled the data; Ö.Ö. and S.S. developed the R-script for analyses and Ö.Ö., K.H. and E.B. analysed the data; Ö.Ö., K.H., E.B. and J.O. led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

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