



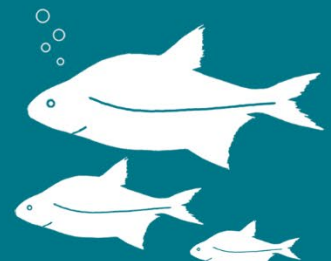
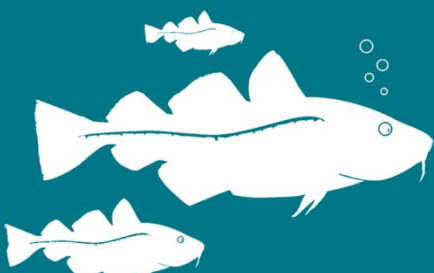
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Using the size distribution and length at maturity to develop threshold values for nationally managed fish stocks

Tröskelvärden baserade på storleksstrukturen och längden vid könsmognad för nationellt förvaltade fiskarter

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Sammanfattning

Storleksfördelningen hos fiskpopulationer är av avgörande betydelse både för populationernas överlevnad och för näringsvävens funktion. Trots detta har få fullt fungerande indikatorer för storleksstruktur utvecklats. Vidare har det visat sig vara utmanande att utveckla tröskelvärden för indikatorer för storleksfördelningen hos fiskarter, och den här bristen på kvantitativa referenspunkter begränsar användbarheten av storleksbaserade indikatorer i förvaltningen. Vi fokuserar på längden av den 90:e percentilen av storleksfördelningen (L90) hos fisk för stickprovet av populationen. L90 reagerar på mänskliga påverkansfaktorer och kan beräknas med hög precision och noggrannhet även när relativt få individer kan provtas. Vi bygger vidare på en metod som utvecklats för att beräkna ett operativt tröskelvärde för L90 för abborre i Östersjön. Vi tillämpar metoden på två nationellt förvaltade fiskbestånd längs Sveriges Östkust och i svenska sjöar; gös (längs kusten och i sjöar) och sik (längs kusten). Vi utökar också de tidigare analyserna av abborre genom att lägga till data för abborrens storleksstruktur i svenska sjöar. Med hjälp av standardiserade övervakningsdata från både kust och sjö, använder vi linjära mixade modeller för att beräkna årliga värden på L90 som tar metodologisk variation som beror på skillnader mellan provtagningsredskap, säsong och habitat (kust vs sjö) i beaktande. För att placera L90 inom en biologiskt relevant kontext, kombinerar vi dessa analyser av storleksstruktur med uppskattningar av längd vid könsmognad (L_{mat}) hos honor, som beräknas med hjälp av logistisk regression. Därmed kan vi utvärdera vilken proportion av populationen som nått reproduktiv ålder vid föreslagna tröskelvärden för L90.

Vi föreslår artspecifika, och när relevant även redskaps- och säsongsspecifika tröskelvärden för L90 som kan indikera en god miljömässig status. För abborre, varierar de föreslagna tröskelvärdena från 23 till 25 cm, beroende på redskapstyp och säsong, och ligger mycket nära uppskattningar av längden vid 90% könsmognad. Hos gösen framträder tydliga skillnader mellan populationer från kust och sjö och en minskande trend i L90 över tid längs kusten samtidigt som längden vid könsmognad är relativt hög. Sammantaget stöder det ett tröskelvärde på 39 cm längs kusten enligt försiktighetsprincipen. För sik föreslås ett tröskelvärde på 37 cm, vilket överstiger längden vid 90% könsmognad som därmed tillåter majoriteten av honorna i populationen att reproducera sig innan de utsätts för fisketryck. Våra resultat visar att L90, när det utvärderas tillsammans med livshistorieinformation såsom längd vid könsmognad, bör kunna tillhandahålla en robust, ekologiskt relevant och praktisk indikator av populationsstatus.

Det föreslagna ramverket gör det möjligt att sätta tröskelvärden som tar kontexten i beaktande samtidigt som vikten av att undvika skiftande baslinjer understryks. Metoden erbjuder ett transparent och användbart verktyg för att integrera storleksbaserade indikatorer i nationell och regional övervakning och utvärdering av fiskpopulationer.

Summary

The size distribution of fish populations is of key importance both for population viability and food web function. Yet few fully operational indicators of size structure have been developed. Further, developing thresholds for indicators of the size distribution of fish species has proven challenging, and this lack of quantitative reference points limits the usefulness of size-based indicators in management. Here, we focus on the length at the 90th percentile of the size distribution (L90), an indicator that responds to anthropogenic pressures, requires no prior life-history information, and can be estimated with high precision and accuracy even from relatively small sample sizes. Building on a previous method that developed an operational threshold for L90 in perch in the Baltic Sea, we apply this method to two additional nationally managed fish stocks along the East coast of Sweden and in Swedish lakes: pikeperch (from coastal areas and lakes) and whitefish (along the coast). We also extend the analyses of perch by incorporating monitoring data on perch size structure in Swedish lakes. Using standardized monitoring data from coastal and lake ecosystems, we estimated annual L90 values while accounting for methodological sources of variation related to sampling gear, season, and habitat (coast versus lake) through linear mixed-effects models. To place L90 in a biologically meaningful context, we combined size-structure analyses with estimates of female length at sexual maturity (Lmat), derived from logistic regression models of maturity status. This allowed us to evaluate which proportion of individuals have reached reproductive size at a proposed L90 threshold.

We propose species-specific and, where relevant, gear- and season-specific threshold values for L90 that are indicative of good environmental status. For perch, the proposed thresholds range from 23 to 25 cm depending on gear type and season, which closely match estimates of length at 90% maturity. For pikeperch, clear differences between coastal and lake populations, together with a declining temporal trend in coastal L90 and relatively high maturity lengths, support the use of a precautionary coastal threshold of 39 cm. For whitefish, a threshold of 37 cm was identified, exceeding the estimated length at 90% maturity and thereby allowing most females to reproduce before being subject to fishing mortality. Our results show that L90, when evaluated jointly with life-history information such as length at maturity, may provide a robust, ecologically relevant, and practical indicator of population status. The proposed framework allows for context-dependent threshold setting while emphasizing the importance of avoiding shifting baselines. As such, this approach offers a transparent and useful tool for integrating size-based indicators into national and regional monitoring and assessment frameworks for fish populations.

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1. Introduction

The size distribution of fish populations is of key importance both for population viability and food web function. In the Marine Strategy Framework Directive (MSFD; 2008/56/EC) there are several descriptors which aim to evaluate the age- and size distribution of fish. Specifically, for commercial fish criterion 3 within descriptor 3 (D3C3) states that “Populations of all commercially exploited fish and shellfish are within safe biological limits, exhibiting a population age and size distribution that is indicative of a healthy stock.” Further, criterion 3 within descriptor 1 (D1C3) pertaining to biodiversity, states that “The population demographic characteristics (e.g. body size or age class structure, sex ratio, fecundity, and survival rates) of the species are indicative of a healthy population which is not adversely affected due to anthropogenic pressures” (EU 2008). To evaluate these descriptors, improved monitoring and evaluation of size structure are required for fish species that are not targeted by commercial fisheries or that are caught alongside commercially caught species, given the ecological importance of large individuals (Estes Jr *et al.* 2021). Yet few fully operational indicators of size structure have been developed (Birk et Birk *et al.* 2012, Fitzgerald *et al.* 2018, Froese *et al.* 2018, Kell and Sharma 2025). For an indicator to be useful, it must be quantitatively defined, its response to anthropogenic pressures must be clearly understood, and methods must be available to assess it in relation to a threshold for good environmental status (Rice and Rochet 2005, Birk *et al.* 2012). Developing thresholds for indicators of fish size distribution has proven challenging, partly because it is difficult to identify the drivers behind observed changes in population size structure. (Alonso-Fernández *et al.* 2021, Probst *et al.* 2021, Griffiths *et al.* 2024, Kell and Sharma 2025). This lack of quantitative reference points limits the usefulness of size-based indicators in management (Samhuri *et al.* 2012, Miethe *et al.* 2019). Therefore, there is an urgent need to develop and implement indicators of size structure with associated threshold values that can be integrated into existing monitoring and assessment frameworks.

We focus on the length at the 90th percentile of the size distribution (L_{90}), which can be estimated without any prior life-history knowledge, responds to anthropogenic pressures, and can be estimated with high precision and accuracy even from relatively small sample sizes (200-300 individuals) (Östman *et al.* 2023). Bolund et al developed an operational threshold for L_{90} for perch in the Baltic Sea (Bolund et al in prep.), and this indicator has been implemented both in the assessments of coastal fish status in the Baltic Sea (HELCOM 2023) feeding into the fourth holistic assessment of the Baltic Sea (HELCOM 2024) and in national assessments in Sweden (Bolund and Olsson 2024).

Here, we build on this work to develop thresholds for L90 for two additional nationally managed fish stocks: pikeperch (from coastal areas and lakes) and whitefish (along the coast). We also extend the analyses of perch by adding monitoring data on size structure from Swedish lakes. To calculate a suitable threshold, we consider the possible variation in L90 arising from confounding effects such as differences in fishing gear and seasonal sampling over multiple years.

We combine the information on size structure with a crucial biological parameter, the length at sexual maturity (L_{mat}), for each species. L_{mat} is the total length at which 50% of individuals (often just females) are mature, and it is widely used in fisheries management to assess the reproductive potential of a population (Beverton and Holt 2012). It has been applied as an indicator of fishing pressure for pikeperch in the Northern Baltic Sea, because sustained removal of large individuals can drive an evolutionary response toward earlier maturation at a smaller size, allowing reproduction before individuals are caught (Lappalainen *et al.* 2016). Thus, L_{mat} provides a biologically relevant context for interpreting variation in L90.

2. Methods

Monitoring of fish along the Swedish coast of the Baltic Sea is conducted annually using standardised methods in a number of monitoring locations. Briefly a number of stations are sampled within each location in a standardised manner, producing comparable time series data of the abundance and size of different fish species (Appelberg *et al.* 2020, Karlsson 2020). Monitoring in the great lakes in Sweden follows a protocol similar to the coastal monitoring programme, as does monitoring in smaller lakes (for small lake monitoring, see Kerstin and Petersson 2023). Along both the coast and in lakes, time series data are collected at different time points during the year and in this study, we use data collected under cold water conditions in autumn and warm water conditions in summer. Several types of sampling gears are used, which we classify into three main categories: multimesh, netlink, and lake gears. The lake gears are very similar to the multimesh gears but have additional mesh sizes, resulting in different catch selectivity.

2.1 Data selection

We used time series data from 63 coastal monitoring locations along the Swedish and Åland coasts, and from 198 monitoring locations in Swedish lakes.

We included all available data from each monitoring area from the beginning of its respective time series, with the following restrictions: First, we excluded all individuals with a body length below 15 cm for all species to reduce the influence of interannual variability in recruitment, thereby excluding the majority of individuals that had not yet reached one year of age. Second, we applied minimum requirements for the number of individuals and the number of years available in each time series. A balance between precision and accuracy of the L90 estimates and data availability resulted in the following data selection criteria: a minimum of 50 individuals per year and at least 6 years of data per time series for perch, a minimum of 200 individuals in total, and with at least 10 individuals in any given year; and at least 2 years of data per time series for pikeperch and whitefish. Applying these criteria resulted in L90 time series for perch from 25 coastal monitoring areas and 48 lakes monitoring locations, for pikeperch from 8 coastal monitoring areas and 5 lakes monitoring locations, and for whitefish from 7 coastal monitoring areas.

After applying the data selection criteria, we calculated the 90th percentile of the size distribution for each species and monitoring area, with one value calculated per year, gear, and season combination. Because some monitoring areas include more than one time series, collected during different seasons and/or with different gears, this resulted in 63 time series for perch, 14 for pikeperch, and 9 for whitefish (supplementary table 1).

2.2 L90 reference values accounting for methodological differences

Estimates of L90 may differ among monitoring areas due to either real differences in the population size structure between areas, or methodological effects, such as the sampling gear used or the sampling season. To account for these potential biases, we used a linear mixed-effects modelling framework in R (Bates *et al.* 2015) with gear, season and lake versus coast as fixed effects. To account for repeated measures, we included the year of sampling a random effect. Specifically, the random effects capture random differences between monitoring areas in the mean (random intercept) and allow for different slopes of change over time within each monitoring area (random slope). To support meaningful interpretation of model estimates, year was centered to a mean of zero, and contrast coding was applied to the fixed effects. Contrast coding enables model estimates to be interpreted relative to an ‘imaginary mean category’ of the fixed effects (Schielezeth 2010). The model formula for perch was implemented in R as follows (Team 2024):

```
lmer(L90 ~ Gear * Season + Year +(Year|Monitoring Area), contrasts=list(Gear=contr.sum, Season=contr.sum))
```

For pikeperch, we used a random slope model without a random intercept, because a high correlation between intercept and slope caused convergence problems in the full random-effect models. This simplification implies that differences in means L90 among time series are attributed solely to the fixed effects of gear and season. We did not include an interaction between gear and season because only one gear type was used during the autumn season. This resulted in the following model formula representation (a shared intercept, random slope model):

```
lmer(L90 ~ Gear + Season + Year + (0+Year|Monitoring Area), contrasts=list(Gear=contr.sum, Region=contr.sum, Season=contr.sum))
```

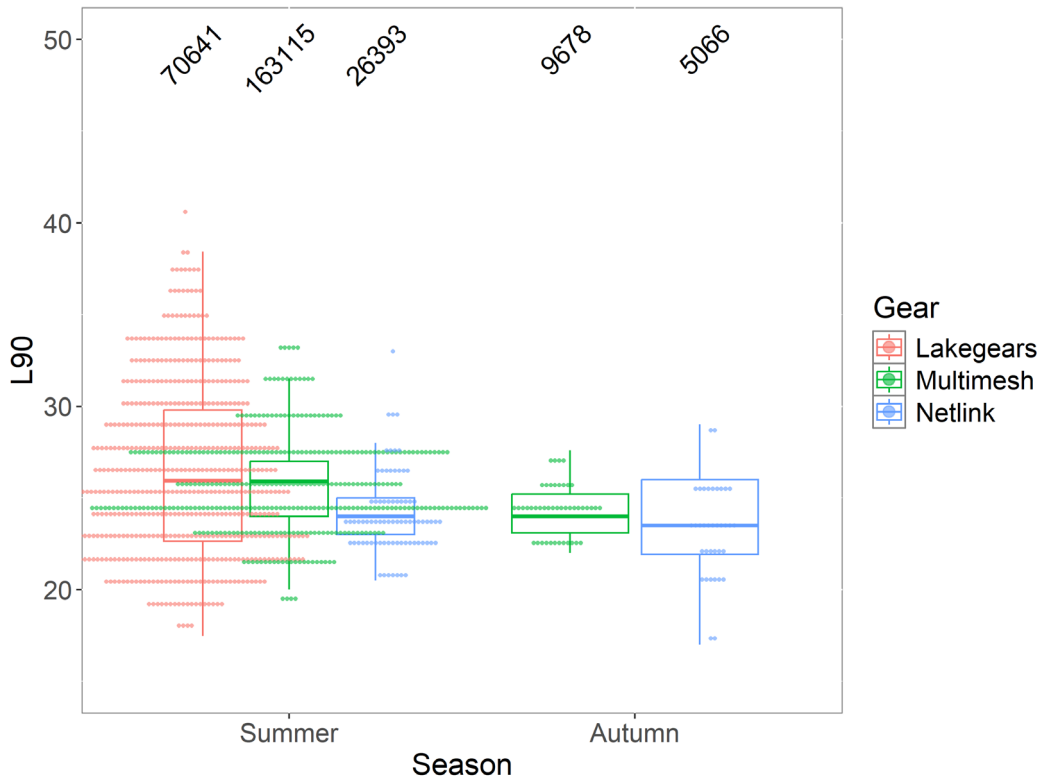
For whitefish, we also used a random slope model without random intercept. Because the netlink is used only in autumn and the multimesh gear only in summer (Figure 1c), the model could not disentangle the confounded effects of gear and season. We therefore included only gear as a fixed effect in the model, while acknowledging that any effect ascribed by the model to gear may reflect differences between gears, seasons, or both. This resulted in the following model formula representation (a shared intercept, random slope model):

```
lmer(L90 ~ Gear + Year + (0+Year|Monitoring Area), contrasts=list(Gear=contr.sum, Region=contr.sum, Season=contr.sum))
```

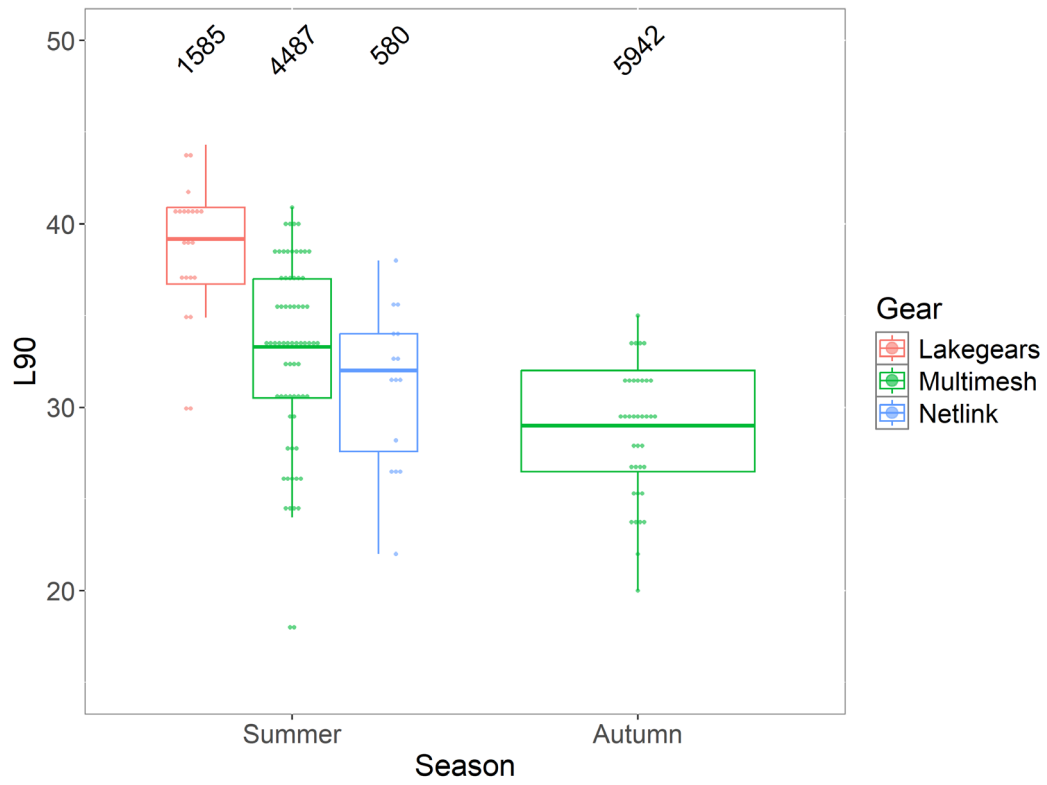
Significant predictors indicate factors that need to be considered when setting a threshold value(s). In cases where predictors were significant, we used the package *effects* to obtain model predicted values for each combination of fixed effect. Model performance was evaluated by plotting residuals versus fitted values, and by ensuring that a histogram of residuals conformed to a Gaussian distribution.

Figure 1. Mean L90-values for different gear-season combinations for perch (a), pikeperch (b), and whitefish (c). Dots represent annual L90 estimates for each time series. The boxes illustrate the first quartile, median, and third quartile, while the whiskers indicate the minimum and maximum values. Total number of individuals in each gear-season category is also indicated.

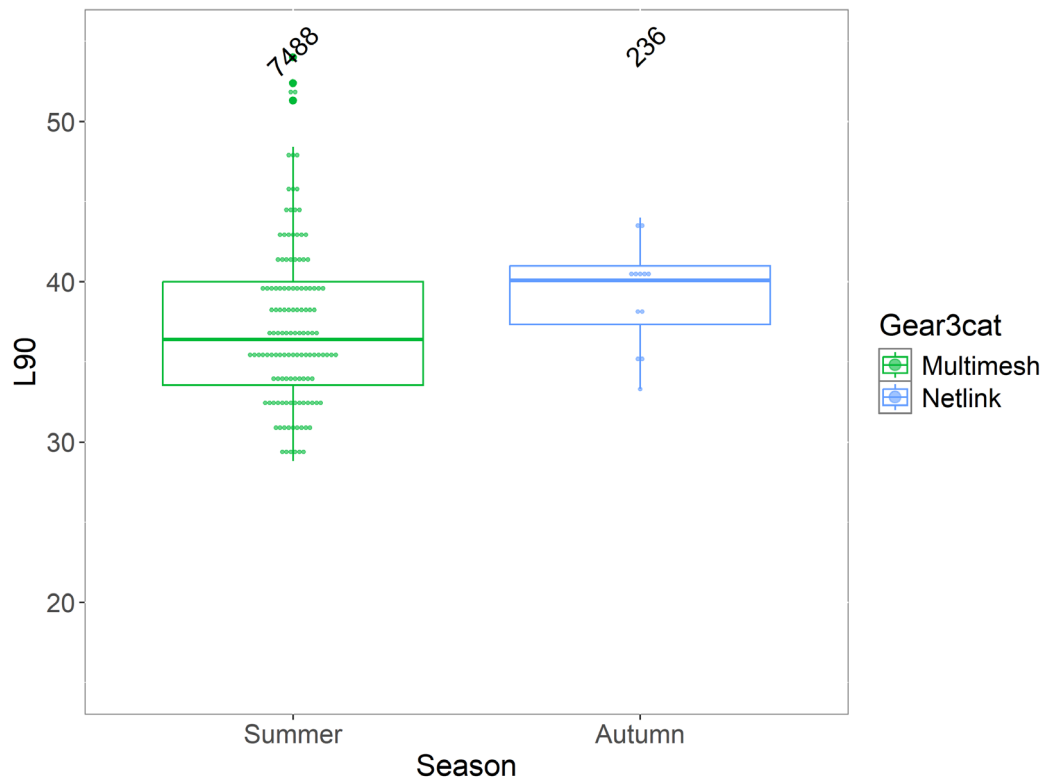
1a. Perch



1b. Pikeperch



1c. Whitefish



2.3 Length at maturity

We used a subset of data for each species with information on length and maturity, according to the SMSF-scale (see ICES 2018). For perch and pikeperch, we required at least 500 sampled females per monitoring location. For whitefish, sample sizes were considerably smaller; therefore, all sampled females were included to maximise sample size (Table 2). This resulted in maturity data from seven monitoring locations in perch, two monitoring locations in pikeperch and 11 monitoring locations in whitefish (Table 2). To estimate female length at maturity, we used logistic regression with a logit link, with maturity as a binomial response variable and the length (in one cm bins) as the predictor. To validate the use of a logit link, we also explored the following families: probit, cauchit and cloglog, and compared model performance by comparing AIC values and estimated parameters. In all cases, the models with a logic link showed superior performance. We used the R package *MASS* to estimate the lengths at 50% and 90 % maturity and applied bootstrapping to estimate confidence interval for these estimates, using the package *car*. All statistical analyses were conducted in R (R Core Team 2024).

Table 2. Number of sampled females per monitoring location for maturity determination in the three focal species.

Monitoring location	Perch	Pikeperch	Whitefish
Agöfjärden			15
Askrikefjärden	913	Excluded	
Biotestsjön, Forsmark	2091		
Forsmark	2789		10
Galtfjärden		1224	22
Gävlebukten			108
Kinnbäcksfjärden	Excluded		13
Kvädöfjärden	2684		
Lagnö	Excluded		32
Långvindsfjärden	1466		
Muskö	Excluded	937	43
Norrbyn			40
Råneå	614		
Simpevarp	3087		153
Vallviksfjärden			91
Västerbottens län			68

2.4 Threshold value logic

The point of departure for threshold setting is the statement in the MSFD-guidance (MSFD; 2008/56/EC); that the size structure of populations should be “healthy” and not “adversely” effected by human activities. In perch, the data used to assess L90 likely reflect a situation where the populations are not overfished, as there was an overall increase in L90 over time during the study period, and trends in catch per unit effort (CPUE) do not indicate population crashes (Bolund and Olsson 2024, HELCOM 2024). Although perch abundance have declined in some areas, recent assessments suggest that in many coastal regions they have been stable or even increasing over the past 20 years (HELCOM 2024). At the same time, most populations were likely still subject to fishing and other anthropogenic disturbances that may affect size structure, as indicated by comparatively high L90 values observed in four no-take areas in Sweden (range 27-31 cm; Östman et al 2023). In contrast, pikeperch showed an overall decrease in L90 over time, and CPUE trends indicate population declines in nearly half of the surveyed populations along the Swedish coast and in the Baltic Sea (Bolund and Olsson 2024, HELCOM 2024). Furthermore, CPUE of large individuals increased rapidly in a no-fishing area compared to a reference area along the Swedish coast, suggesting that fishing pressure impacts size structure (Bolund 2025). In whitefish, there was no overall negative temporal trend in L90; however, CPUE indicates population declines in more than half of the surveyed populations along the Swedish coast and in the Baltic Sea. In summary, perch, pikeperch, and whitefish populations along the Swedish coast are likely in a moderately healthy state but remain moderately adversely affected by human activities. To determine a threshold value, we therefore combined results from the two approaches described above. For each species, we used the intercept of the final linear mixed-effect model as a reference value. The contrast coding allows us to interpret the intercept as the grand mean after controlling for both fixed and random effects. This reference value reflects the average L90 over the study period for each species. We then related this reference value to the estimated length at maturity for each species, which reflects the reproductive potential of the population, to determine a threshold value for each species.

3. Results

3.1 L90 reference values

For perch, the linear mixed-effects model based on data from monitoring locations along both the coast and in lakes indicated significant effects of gear type, season, and year, with an overall increase in L90 over time (Table 3). The intercept (i.e. the model estimated grand mean) for L90, predicted by gear, season, and year was 24.95 cm (95% CI: 23.93-25.99). Note that sample sizes differed substantially among gear-season combinations (Figure 1a), and not all gear types were used in both seasons. Within the coastal dataset, a model including the interaction between gear and season showed significant main effects of both factors (Table 3), with a model grand mean of 24.3 cm. The predicted mean L90 values were 24.5 cm for multimesh in autumn, 25.6 cm for multimesh in summer, 22.9 cm for netlink in autumn, and 24.1 cm for netlink in summer (Figure 1a). A model based on the lake dataset showed a significant effect of year (Table 3), and the model grand mean was 26.5 cm.

For pikeperch, the (full) linear mixed-effects model combining coastal and lake monitoring data indicated a significant effect of gear type, season, and year, with an overall decrease in L90 over time (Table 3). The intercept (i.e. model estimated grand mean) for L90 predicted by gear, season, and year was 32.56 cm (95% CI: 31.39-33.80). Within the coastal dataset, season and year had significant effects (Table 3), with predicted mean L90 values of 28.7 cm in autumn and 32.5 cm in summer (Figure 1b). Within the lake dataset, year had no significant effect (Table 3), and the model grand mean was 38.8 cm. Sample sizes varied markedly among gear-season combinations (Figure 1b), and not all gear types were used in both seasons.

For whitefish, the linear mixed-effects model based on coastal monitoring data indicated no significant effects of gear or year, and the model estimated grand mean for L90 was 37.0 cm (95% CI: 35.08-39.07).

Table 3. Analysis of deviance table (Type III Wald chi-square tests) from linear mixed-effects models including gear and season as fixed effects and year as a random effect. For perch, the full model includes 1028 yearly L90 values grouped into 60 monitoring locations. The coastal model includes 493 yearly L90 values from 24 monitoring locations, while the lake model includes 535 yearly L90 values from 36 monitoring locations. For pikeperch, the full model includes 142

yearly L90 values from 13 monitoring locations. The model within the coastal data includes 121 yearly L90 values from 8 monitoring locations, and the model within the lake data includes 21 yearly L90 values from 5 monitoring locations. For whitefish, the model along the coast includes 138 yearly L90 values from 9 monitoring locations.

Model	Chisq	df	P
Perch full			
Gear	21.74	2	<0.0001
Season	5.06	1	<0.024
Year	16.65	1	<0.0001
Perch coast			
Gear	19.12	1	<0.0001
Season	11.75	1	0.0006
Year	1.47	1	0.23
Gear:Season	0.029	1	0.87
Perch lake			
Year	28.9	1	<0.0001
Pikeperch full			
Gear	33.8	2	<0.0001
Season	18.2	1	<0.0001
Year	11.9	1	0.0006
Pikeperch coast			
Gear	0.0007	1	0.98
Season	17.4	1	<0.0001
Year	11.55	1	0.0007
Pikeperch lake			
Year	0.02	1	0.89
Whitefish coast			
Gear	0.04	1	0.84
Year	0.11	1	0.74

3.2 Length at maturity

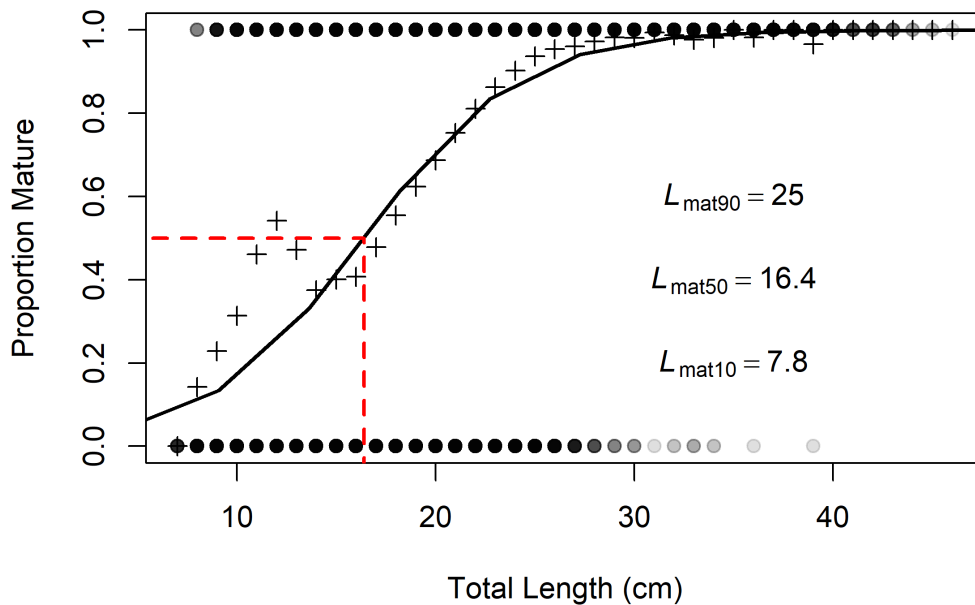
For perch, the predicted length at which 50% of the sampled females had reached sexual maturity (L_{mat50}), based on the logistic regression, was 16.4 cm (95% CI: 16.2-16.6), while the length at which 90% of the females were mature (L_{mat90}) was 25 cm (95% CI: 24.7-25.3) (Figure 2a). Estimates varied among the seven monitoring locations (details not shown), with L_{mat50} ranging from 10.8 to 20.9 cm and L_{mat90} ranging from 14.7 to 26.3 cm.

For pikeperch, L_{mat50} was 38.1 cm (95% CI: 36.6-40.0) and L_{mat90} was 47.3 cm (95% CI: 44.5-51.0) (Figure 2b).

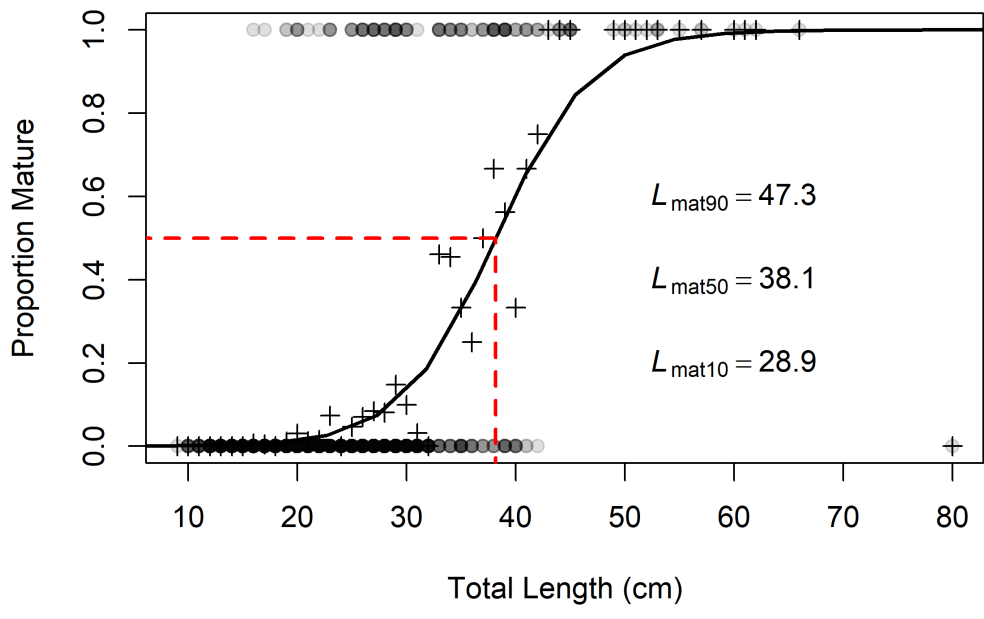
For whitefish, L_{mat50} was 16.2 cm (95% CI: 10.6-19.8), while L_{mat90} was 32.4 cm (95% CI: 29.8-34.7) (Figure 2c).

Figure 2. Raw data on maturity (transparent points) reflecting sample size per each length class, proportion of mature individuals per each length class (plus signs), the fitted line from the logistic regression (solid line), red dashed lines that intersect at L_{mat50} , and estimated maturity lengths at 10, 50, and 90 % for a) perch, b) pikeperch, c) whitefish.

2a. Perch



2b. Pikeperch



2c. Whitefish

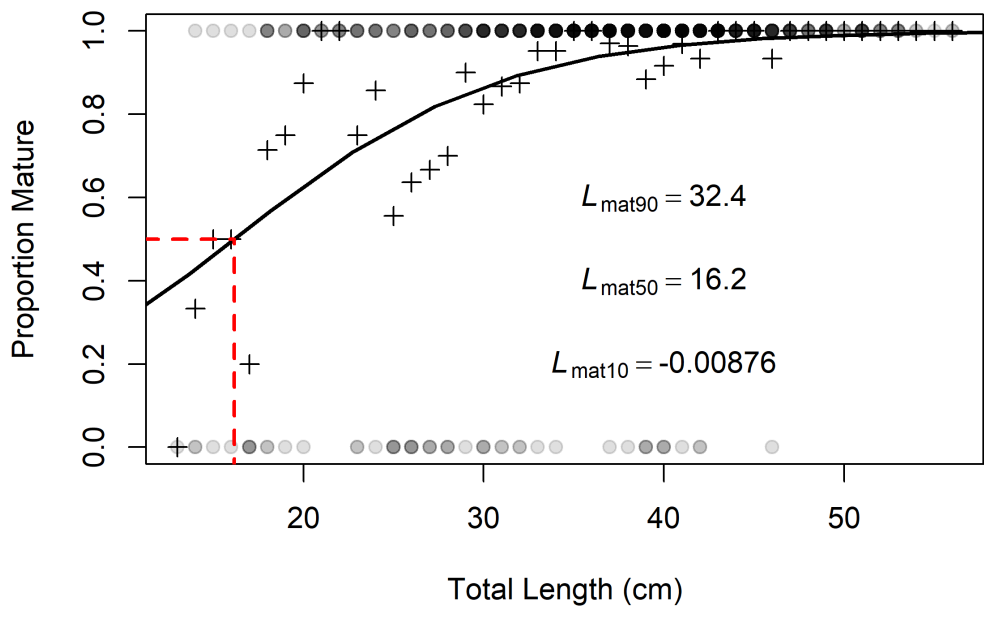


Table 4. Model parameters from logistic regression models with proportion of mature individuals as a (binomial) response variable and body length as predictor for female perch, pikeperch and whitefish.

Perch				
Coefficient	Estimate	Standard error	z value	Probability (> z)
Intercept	-4.19	0.11	-38.68	<2e-16
Length	0.26	0.0055	46.11	<2e-16
Null deviance: 15860 on 13332 degrees of freedom				
Pikeperch				
Coefficient	Estimate	Standard error	z value	Probability (> z)
Intercept	-9.12	0.5	-18.34	<2e-16
Length	0.24	0.016	14.72	<2e-16
Null deviance: 971.8 on 2160 degrees of freedom				
Whitefish				
Coefficient	Estimate	Standard error	z value	Probability (> z)
Intercept	-2.2	0.58	-3.8	0.00015
Length	0.14	0.019	7.24	<2e-13
Null deviance: 346.39 on 560 degrees of freedom				

3.3 Suggested threshold values

For perch, threshold values were derived from the linear mixed-effect model, accounting for significant effects of gears and seasons. We suggest thresholds of 24 cm for multimesh in autumn, 25 cm for multimesh in summer, 23 cm for netlink in autumn, and 24 cm for netlink in summer. Given the variability in length at maturity along the coast, with an overall mean L_{mat90} of 25 cm, the suggested thresholds should ensure that the majority of females in most populations reach maturity size and are able to contribute to reproduction.

For pikeperch, the observed negative trend over time in L_{90} , combined with the relatively low coastal reference value (29-32 cm, depending on season), contrasts with the lake reference value of 38 cm and the coastal maturity length of 38 cm (L_{mat50}) and 48 cm (L_{mat90}). Thus, we suggest a threshold of 39 cm along the coast, which would indicate that a sufficient proportion of females reach reproductive size in coastal populations.

For whitefish, we suggest a threshold of 37 cm based on the reference value from the linear mixed effect model. Given an L_{mat90} of 32 cm, this threshold is precautionary and indicates that the vast majority of females are able to reach maturity size within the population.

4. Discussion

This study reveals that the L90, when evaluated jointly with information on length at sexual maturity, provides a strong, ecologically meaningful, and operational indicator for assessing the status of nationally managed fish stocks. By explicitly accounting for differences in gear, season, and habitat using linear mixed-effects models, we developed context-dependent threshold values for perch, pikeperch, and whitefish. This approach responds to long-standing calls for size-based indicators that are quantitatively defined, pressure-responsive, and are linked to reference points that can be used for management and policy evaluation (Rice & Rochet 2005; Birk et al. 2012; Samhuri et al. 2012).

Thresholds developed within this framework are not static and are subject to revision at regular intervals. They are based on all the available data, so as new data are added, the models can be updated and thresholds re-evaluated. This reassessment may occur every six years, to align with status assessment cycles implemented at national and international levels (e.g. MSFD and Helcom assessments). Using all available data allows for the development of context-dependent thresholds on a relevant spatiotemporal scale. This context-dependence can be illustrated by comparing the analyses in the current report with those performed to establish a Baltic-wide threshold for assessment of good environmental status of perch within the context of the third Holistic assessment of the Baltic Sea (see HELCOM 2023, Bolund et al in prep.). Spatial and temporal differences between the two datasets resulted in slightly different recommended threshold values for good environmental status. This dependence on available data carries the risk of thresholds being adjusted due to a shifting baseline, for example if L90 slowly decreases on average over time. Such a trend could lead to a lowered threshold for good status in response to prolonged overfishing, potentially reducing both L90 and the length at maturity (Heino *et al.* 2015, Hutchings and Kuparinen 2020). Thus, a negative average trend in L90 over time, as observed in pikeperch in this study, should be interpreted as a warning sign of potentially decreasing overall status rather than as justification for downward revision of thresholds. Given this risk of a shifting baseline, we included information on a biological life history parameter, the length at sexual maturity, to establish a threshold value for good environmental status for L90 in pikeperch. Incorporating this life history information provides a biologically anchored safeguard against such baseline shifts, because it ensures that a stable proportion of individuals reaches sexual maturity before being subjected to fishing. A reduction in length at maturity in response to prolonged fishing pressure is an evolutionary adaptation that allows individuals to reproduce before being harvested. This makes the issue of a shifting baseline somewhat ambiguous, because the evolutionary response can partially circumvent the adverse effects of anthropogenic pressures. Ideally, L_{mat} should be estimated from populations that are minimally affected by fishing and other human impacts, although such populations are rarely available.

Integrating L90 with female length at maturity places size-based thresholds in a clear biological context by linking indicator performance directly to reproductive capacity. Ensuring that a large proportion of individuals reach maturity before becoming vulnerable to fishing mortality is a fundamental principle of sustainable fisheries management (Beverton & Holt 2012). In data-rich species, analytical stock assessment models often relate the spawning stock biomass (SSB, the biomass of mature individuals) of an exploited population to that of an unexploited population, with thresholds (e.g. 35-40% of the unfished SSB) set to ensure the stock can replenish itself over the long-term (Clark 2002, Deroba and Bence 2008, Horbowy and Hommik 2020). Such calculations indicate the proportion of a population that must reach maturity to sustain it under fishing pressure. In data-limited species, simpler decision rules such as ensuring fish can spawn at least once before being caught, can be applied. For example, setting a fisheries threshold above $L_{\text{mat}50}$ ensures that, on average, at least 50% of the population reaches maturity and has the opportunity to reproduce. Thus, status thresholds that assess population status in relation to reproductive capacity can potentially be used to guide biologically anchored fishing regulations in populations subjected to fishing pressure.

For pikeperch, available evidence indicates that selective fishing pressure can reduce length at maturity, especially in coastal stocks subject to high exploitation rates (Lappalainen *et al.* 2016; Olin *et al.* 2018). Estimates of pikeperch L_{mat} range from 33 to 46 cm along the Baltic coasts and in Nordic lakes (Lappalainen *et al.* 2003, Lappalainen *et al.* 2016, Olin *et al.* 2018, Jyrki *et al.* 2020). Our suggested coastal threshold of 39 cm is larger than $L_{\text{mat}50}$ and is close to maturity estimates reported for Baltic populations (Lappalainen *et al.* 2016), which can support a precautionary management approach that helps protect fish reproduction. Similarly, for whitefish, the suggested threshold of 37 cm substantially exceeds the estimated length at 90% maturity in our study. Only one L_{mat} estimate for Baltic whitefish is available in the literature: 30 cm in the Northern Baltic Sea, where fishing closures rapidly increased the abundance of large, mature individuals (Berkström *et al.* 2021). Given the limited data, a precautionary approach suggests that the reference value from the linear mixed-effects model provides a suitable threshold value. Establishing a threshold that prioritises the presence of large-bodied individuals is especially important in systems where predation pressure from seals and cormorants can be substantial and may rival or exceed fisheries removals (Berkström *et al.* 2021).

Analysing temporal trends in perch size structure across 2121 Swedish lakes over a 26-year period (1996–2021), Holmgren & Petersson (2023) found that while mean length decreased in southern lakes, it increased in the northern region, showing regionally divergent size trends in perch populations. The variability in length at maturity for perch, in our study aligns well with published data. Heibo *et al.* 2005 reviewed $L_{\text{mat}50}$ values for perch in 75 populations along the coasts and lakes of Sweden and Finland, and found L_{mat} values ranging from 8.5 to 27.5 cm. The single available value along the Swedish coast, 21.5 cm (in Norrbyn), corresponds reasonably well with our findings. Such variability highlights the

need for thresholds that are species-specific and, where necessary, gear and season-specific.

From an ecological perspective, large predatory fish such as perch, pikeperch, and whitefish may play important roles in structuring food webs through both consumptive and non-consumptive effects. Ontogenetic diet shifts during their life cycles imply that individuals typically begin exerting strong top-down control around or after sexual maturity. Thus, ensuring that the majority of individuals in a population reach sexual maturity contributes to stock productivity as well as food web stability and resilience. Using the lengths at which 50 and 90% of individuals reach sexual maturity provides a biologically grounded basis for defining thresholds for predatory fish species, ensuring ecological relevance in terms of their functional role within the food web.

Finally, evaluating the robustness of length-based stock assessment approaches for sustainable management in data- and capacity-limited situations, Kell & Sharma (2025) revealed that simpler empirical indicators often matched or outperformed complex quantitative models, which were frequently the least reliable. A key strength of L90 is that it can be estimated with high precision from relatively small sample sizes and without detailed life-history inputs, making it well suited for data-limited contexts (Östman et al. 2023). Compared with indicators like Lmax5% (a length-based indicator representing the mean length of the largest 5% of individuals in a catch) (Miethe et al. 2019), which is highly sensitive to errors in asymptotic length, L90 is less sensitive to rare large individuals and to recruitment variability, while still responding strongly to fishing pressure (Östman et al. 2023). In the present study, average sample sizes were lower for pikeperch and whitefish than for perch. This is reflected in the wider confidence intervals around the intercepts of the linear mixed-effects models. The uncertainty observed in the results, particularly in whitefish, further supports the precautionary threshold we propose.

In conclusion, using L90 together with the length at sexual maturity provides a practical and scientifically sound way to set thresholds in data-limited fisheries. This approach helps avoid shifting baselines, keeps the results ecologically meaningful, and supports precautionary management of fish populations under different fishing pressures and environmental conditions. The proposed framework supports the use of MSFD indicators related to population size structure and fits well with current HELCOM work on indicators for coastal fish communities (HELCOM 2023). By combining solid statistics with ecological relevance, this approach provides a clear and transparent way to include size-based indicators in national and regional assessments. More broadly, better biological monitoring of key traits such as size structure is increasingly recognized as important for effective conservation and the sustainable use of marine resources.

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Appendix 1

Appendix 1. Overview of time-series data.

Table A1. Overview of time-series data used for perch, pikeperch, and whitefish. The table shows whether each time series comes from a coastal area or a lake, along with the location, species, gear used, and season. It also presents the mean and range of annual L90 values (in cm), as well as the mean and range of the annual number of individuals (N) above the lower size cut-off of 15 cm that were caught. A given monitoring area may include multiple time series derived from surveys conducted using different gears and/or during different seasons.

Coast/ lake	Location	Species	Gear	Season	mean L90	range L90	mean N	range N	First year	Last year	No yrs
C	Galtfjärden	Perch	Multim	A	24.0	22-26.2	199.6	116-320	2002	2023	22
C	Gävlebukten	Perch	Multim	A	26.3	25-27.6	107.1	68-145	2011	2020	8
C	Lumparn										
C	Åland	Perch	Multim	A	24.2	23-26	295.3	193-441	2010	2024	15
C	Galtfjärden	Pikeperch	Multim	A	26.7	20-35	88.6	21-202	2002	2023	22
C	Lumparn										
C	Åland	Pikeperch	Multim	A	31.5	29-34	266.2	123-550	2010	2024	15
C	Kvädöfjärden	Perch	Netl	A	23.3	17-29	164.8	54-306	1989	2022	26
C	Muskö	Perch	Netl	A	23.6	21.1-28.4	78.1	53-161	1992	2013	10
C	Kvädöfjärden	Whitefish	Netl	A	39.2	33.3-44	19.7	11-38	1994	2013	12
L	Krageholmssjön	Perch	Lakeg	S	25.6	19.3-36.8	141.9	73-355	1994	2022	9
L	Blanksjön	Perch	Lakeg	S	22.9	19.5-27.4	74.0	53-104	2005	2012	6
L	Harasjön	Perch	Lakeg	S	28.1	20.4-36.8	96.7	62-160	1996	2024	7
L	Hjärtsjön	Perch	Lakeg	S	32.9	27.2-40.6	219.0	141-294	1996	2021	8
L	Fiolen	Perch	Lakeg	S	27.5	21.0-35.1	151.5	62-295	1994	2024	31
L	Stengårdshultasjön	Perch	Lakeg	S	30.5	25.1-37.6	98.8	55-173	1994	2023	25
L	Stora Härsjön	Perch	Lakeg	S	27.4	21.7-36.4	111.0	60-231	1994	2024	25
L	Allgiutten	Perch	Lakeg	S	26.7	21.2-36.1	67.1	50-94	1994	2023	17

L	Vänern Byviken	Perch	Lakeg	S	27.9	27.2- 28.7	199.1	72-339	2009	2024	8
L	Vänern Fågelö	Perch	Lakeg	S	27.6	26.0- 29.6	160.4	67-223	2009	2024	7
L	Vänern Spårön	Perch	Lakeg	S	25.8	23.2- 30.3	152.2	92-213	2010	2024	6
L	Vänern Ölmeviken	Perch	Lakeg	S	26.9	22.64- 31.7	113.3	74-141	2010	2024	6
L	Långsjön	Perch	Lakeg	S	27.7	22.8- 30.4	73.4	61-104	1994	2003	9
L	Björken	Perch	Lakeg	S	30.3	24.5- 33.2	132.1	103-162	1996	2019	7
L	Rotehogstjärne n	Perch	Lakeg	S	23.2	20.8- 27.2	63.9	50-108	1994	2019	13
L	Ejgdesjön	Perch	Lakeg	S	30.1	23.6- 34.9	184.2	67-407	1994	2024	20
L	Stora Envättern	Perch	Lakeg	S	27.4	21.7- 33.9	68.3	51-127	1994	2024	19
L	Västra Solsjön	Perch	Lakeg	S	34.1	30.5- 38.4	75.6	60-107	1996	2021	7
L	Stensjön	Perch	Lakeg	S	24.9	19.9- 37.1	102.7	51-263	1994	2024	44
L	Årsjön	Perch	Lakeg	S	22.0	21-22.8	55.8	51-65	1998	2010	6
L	Mälaren Prästfjärden	Perch	Lakeg	S	23.5	21.0- 25.4	695.6	300-1147	2009	2022	7
L	Örvattnet	Perch	Lakeg	S	21.2	18.6- 30.9	132.4	53-234	2005	2024	14
L	Lien	Perch	Lakeg	S	32.0	24.6- 36.3	97.3	55-128	1994	2009	16
L	Övre Skärsjön	Perch	Lakeg	S	22.6	20.2- 26.7	176.4	62-366	1994	2024	31
L	Dagarn	Perch	Lakeg	S	31.7	24.5- 38.4	69.2	52-110	1996	2024	22
L	Västra Skälsjön	Perch	Lakeg	S	23.6	19.0- 27.4	137.2	70-227	1997	2023	14
L	Skifsen	Perch	Lakeg	S	25.5	19.6- 28.9	75.6	52-101	2007	2019	7
L	Tryssjön	Perch	Lakeg	S	20.9	17.5- 23.5	125.8	63-227	1998	2024	21
L	Gipsjön	Perch	Lakeg	S	23.6	22.6- 25.5	105.7	55-176	1996	2022	7
L	Rädsjön	Perch	Lakeg	S	24.8	21.2- 31.9	206.6	138-416	2007	2024	17
L	Källsjön	Perch	Lakeg	S	22.1	19.7- 24.8	65.7	51-87	1994	2018	15
L	Degervattnet	Perch	Lakeg	S	31.2	28.1- 34.7	147.3	99-189	1996	2024	23
L	Remmarsjön	Perch	Lakeg	S	26.4	23.9- 32.3	133.6	64-224	1994	2024	30
L	Bjännsjön	Perch	Lakeg	S	27.0	22.8- 36.4	117.0	63-194	1996	2022	7
L	Vuolgamjaure	Perch	Lakeg	S	27.1	18.3- 34.2	224.8	71-338	1996	2023	6
L	Jutsajaure	Perch	Lakeg	S	23.7	18.2- 31.3	175.1	53-365	1997	2024	18
L	Vänern Byviken	Pikeperch	Lakeg	S	34.6	29.9- 41.1	38.0	13-67	2010	2024	6
L	Storhjälmaren	Pikeperch	Lakeg	S	37.9	37.4- 38.8	71.7	38-118	2009	2011	3
L	Mälaren Blacken	Pikeperch	Lakeg	S	39.9	39.2- 40.3	82.0	70-91	2009	2011	3
L	Mälaren Granfj.	Pikeperch	Lakeg	S	41.2	36.5- 44.3	70.3	53-101	2013	2022	4

L	Mälaren Västeråsfj.	Pikeperch	Lakeg	S	40.5	38.9- 41.7	123.0	100-163	2010	2016	5
C	Askrikefjärden	Perch	Multim	S	27.9	24-33.4	359.7	232-532	2016	2024	9
C	Asköfjärden	Perch	Multim	S	22.7	19-26	469.5	111-1061	2005	2024	20
C	Björnöfjärden	Perch	Multim	S	31.5	30-33.2	170.6	89-341	2011	2020	10
C	Finbo Åland	Perch	Multim	S	26.7	25-28	776.7	583-942	2002	2024	23
C	Forsmark	Perch	Multim	S	26.7	22-29	656.1	399-1021	2002	2024	23
C	Gaviksfjärden	Perch	Multim	S	25.3	21.4-27	314.6	108-827	2004	2024	21
C	Holmön Kinnbäcksfjärd en	Perch	Multim	S	26.3	24-29	518.0	169-1111	2002	2024	23
C	Kumlinge Åland	Perch	Multim	S	23.8	22-26	310.1	110-485	2004	2024	21
C	Åland	Perch	Multim	S	24.1	21-27	919.3	605-1442	2003	2024	22
C	Kvädöfjärden	Perch	Multim	S	26.6	23-31.5	287.8	136-555	2002	2024	23
C	Lagnö Långvindsfjärd en	Perch	Multim	S	24.1	22-27	495.0	198-856	2002	2024	23
C	Muskö	Perch	Multim	S	25.4	23-28	575.0	272-1360	2002	2024	23
C	Muskö	Perch	Multim	S	30.3	29-32	624.0	462-795	2009	2016	8
C	Norrbyn	Perch	Multim	S	23.7	21.2-26	312.3	81-719	2002	2024	23
C	Råneå	Perch	Multim	S	26.7	21-29	512.8	260-1010	2002	2024	23
C	Torhamn	Perch	Multim	S	24.0	20-29	486.0	165-1017	2002	2024	23
C	Älgöfjärden	Perch	Multim	S	30.6	30-32	277.9	169-337	2011	2020	10
C	Herrvik	Perch	Multim	S	26.7	23-30	236.0	56-483	2018	2024	6
C	Asköfjärden	Pikeperch	Multim	S	30.0	24-40	44.3	10-138	2005	2018	6
C	Finbo Åland	Pikeperch	Multim	S	35.2	26-40.4	31.8	11-102	2002	2024	22
C	Forsmark Kumlinge Åland	Pikeperch	Multim	S	32.0	18-39	31.2	11-99	2002	2021	10
C	Åland	Pikeperch	Multim	S	32.1	25.9-36	33.0	10-83	2003	2013	5
C	Kvädöfjärden	Pikeperch	Multim	S	32.1	18-40.9	38.2	11-86	2003	2024	18
C	Muskö	Pikeperch	Multim	S	31.8	26-35.1	294.8	214-386	2009	2016	8
C	Gaviksfjärden	Whitefish	Multim	S	35.5	31-39	40.2	15-72	2004	2024	21
C	Holmön Kinnbäcksfjärd en	Whitefish	Multim	S	42.5	31-51.3	34.8	10-71	2002	2024	17
C	Klingerfjärden Kumlinge Åland	Whitefish	Multim	S	32.8	30-36.9	114.1	47-218	2004	2024	21
C	Klingerfjärden Kumlinge Åland	Whitefish	Multim	S	34.7	33-36	185.7	145-246	2022	2024	3
C	Åland	Whitefish	Multim	S	46.8	41.6-54 32.6-	15.7	10-22	2005	2023	10
C	Lagnö Långvindsfjärd en	Whitefish	Multim	S	38.3	43.1	24.3	10-44	2002	2023	20
C	Lagnö Långvindsfjärd en	Whitefish	Multim	S	35.6	31-40	19.3	10-33	2003	2024	11
C	Norrbyn	Whitefish	Multim	S	35.4	28.8-42	97.6	46-147	2002	2024	23
C	Kvädöfjärden	Perch	Netl	S	24.2	21-29	405.9	50-854	1988	2024	37
C	Mönsterås	Perch	Netl	S	27.0	21-33 20.5-	183.9	66-429	2007	2024	8
C	Simpevarp	Perch	Netl	S	24.0	26.5	333.6	62-1027	2007	2024	18
C	Vinö	Perch	Netl	S	23.1	22-25	259.9	82-579	2007	2024	15
C	Kvädöfjärden	Pikeperch	Netl	S	31.1	22-38	38.7	10-107	2009	2024	15

Appendix 2

Appendix 2. Time series of yearly L90-values

Figure A1a-c

Annual L90 values are shown with a linear trend line for each time series, arranged from south to north. Two monitoring locations include more than one time series: in these cases, the respective gear and season are indicated as follows: Nn = Nordic net, Nl = Netlink, S = summer, A = autumn. For perch, graph a) shows time series fished with multimesh, graph b) shows netlink, and graph c) shows lake gears. For pikeperch (d) and whitefish (e), data from all gears are pooled within each respective graph.

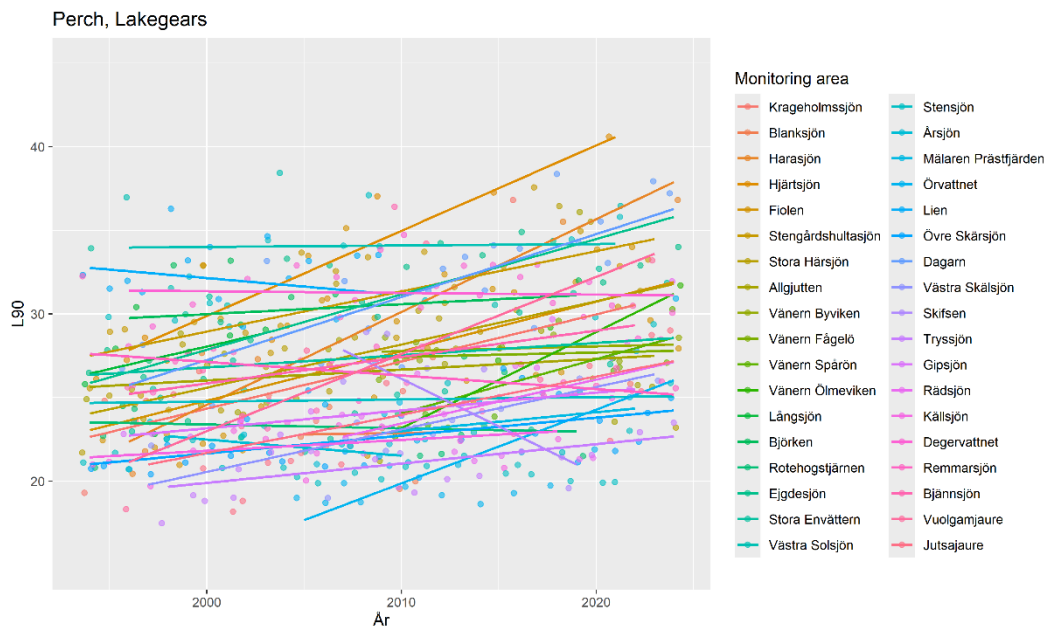
1a. Perch, multimesh



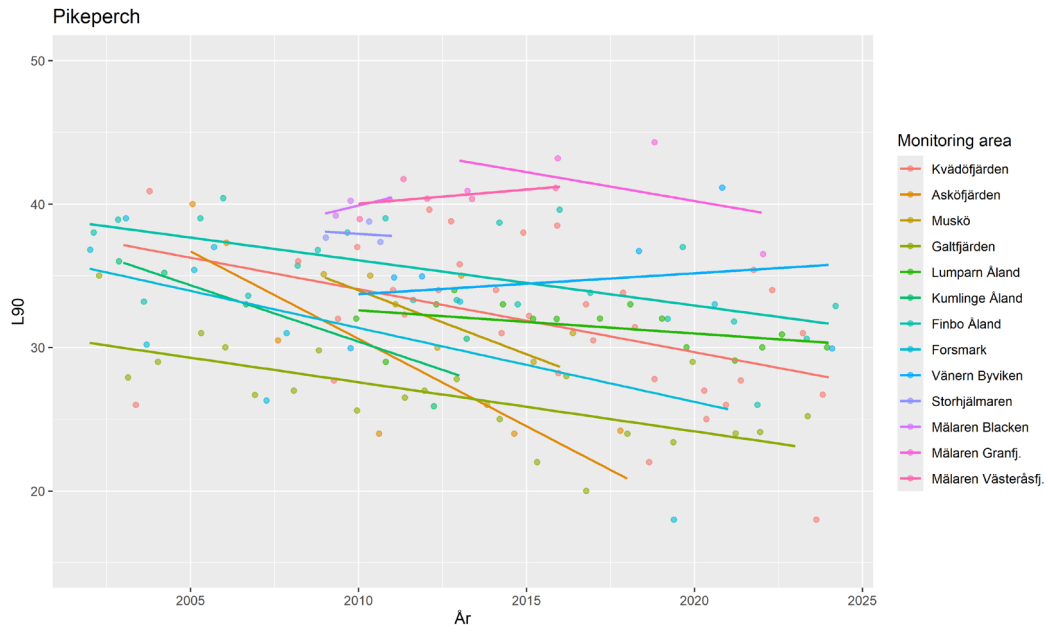
1b. Perch, netlink



1c. Perch, lake gears



1d. Pikeperch



I.e. Whitefish

