

Assessing Yellow Perch populations with experimental sampling gears

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Abstract

Yellow Perch *Perca flavescens* are an important forage species in Minnesota fish communities and a popular target for anglers. Data from the Minnesota Department of Natural Resources (MN DNR) state-wide fisheries surveys showed declining catch rates of Yellow Perch in standard survey gill nets and trap nets from 1970 to 2013. However, both gear types only sample Yellow Perch > 140 mm, so it was unclear whether the decline reflected a lower overall abundance, increased mortality among certain size classes resulting in fewer fish reaching larger sizes, or a shift in size structure affecting mean catchability. To fill the gap in information about Yellow Perch < 140 mm, researchers used additional gears, including boat electrofishing and fine-mesh gill nets, alongside standard survey gear to target all size classes of Yellow Perch. The goal of the study was to document life history metrics and characteristics of Yellow Perch populations across various lakes in Minnesota. Working with MN DNR fisheries management staff and partners, we sampled 28 lakes during 37 separate events between 2019-21. We compared total length, weight, sex, maturity, age, and growth of Yellow Perch among different gears and lakes. Our findings showed that life history traits varied widely across lakes, but most populations matured in the fall before spawning at lengths less than 140 mm and at ages less than 2 years. We also identified useful correlations among life history metrics that could provide insights into populations, including from data collected using standard sampling methods. For example, the mean maximum length of the largest 10% of individuals sampled (MML10) was positively correlated with modeled population maximum length and modeled female length at maturity. Since MML10 can be calculated using standard gill-net data, we recommend it as an initial tool to assess Yellow Perch populations and their catchability in standard survey gears. For more detailed evaluation, the methods developed here can be used to analyze life history traits such as growth and maturity. Data and analyses from this project suggest that Yellow Perch populations have shifted toward a smaller size structure over time, likely decreasing their catchability in standard survey gears.

Introduction

Throughout the Midwestern United States, Yellow Perch *Perca flavescens* are an important part of lentic fish communities. During early life stages, Yellow Perch are primary consumers relying on lower trophic levels such as zooplankton and macroinvertebrates. In later stages, they may become secondary consumers, mainly preying on fish (Knight et al. 1984; Munter et al. 2019; Fullhart et al. 2002). In Minnesota, Yellow Perch serve as the main forage for sport fish including Walleye *Sander vitreus* and Northern Pike *Esox lucius*, and recreational anglers also target them in certain lakes. As a result, Yellow Perch can be sensitive to changes in both lower and higher trophic levels, and their response can lead to cascading ecological effects impacting predator species. Furthermore, factors influencing the abundance and size structure of Yellow Perch populations also affect anglers who fish for them.

An analysis of Minnesota Department of Natural Resources (MN DNR) statewide standard survey data collected from 1970 to 2013 found that average Yellow Perch catch rates have declined in both gill nets and trap nets (Bethke and Staples 2015). This decline in catch was consistent across different lake types and ecoregions in Minnesota. Subsequent efforts to determine the cause using environmental and fish community data were inconclusive (B. Bethke, unpublished data). Yellow Perch become susceptible to MN DNR standard sampling gears at a length of approximately 140 mm, but data from several Minnesota lakes indicated that maturity may occur well below this length. The lack of information on smaller Yellow Perch also makes it difficult to determine whether declining catch rates in standard gears were reflective of declines in overall population abundance, increases in mortality on certain size classes causing fewer fish to reach larger lengths, or decreases in size structure causing changes in mean catchability.

Identifying effective sampling methods and key population metrics for Yellow Perch is crucial for managing fisheries that rely on this species. However, because *Perca* spp. exhibit diurnal shoaling behavior, resulting in patchy distributions (Nursall 1973; Probst et al. 2009), obtaining accurate estimates of a population's relative abundance requires extensive sampling in most lakes (Jackson and Harvey 1997; Dembkowski et al. 2012; Wagner et al. 2016). It can be especially difficult to accurately sample Yellow Perch populations in large or morpho-

logically complex lakes, although these lakes generally support higher predator populations, making them especially important for managers seeking to better understand predator-prey dynamics.

Indirect metrics such as growth and maturity provide useful information about Yellow Perch populations without the need for intensive sampling to estimate abundance. Yellow Perch display life history plasticity, allowing them to adapt to various environmental conditions (Jansen 1996). This plasticity manifests in populations with different size structures (Ridgway and Chapleau 1994; Heath and Roff 1996). Research on Yellow Perch and the closely related Eurasian Perch, *Perca fluviatilis*, indicates that resource limitation and density dependence can reduce growth and alter size distributions (Headley and Lauer 2008; Arranz et al. 2015; Munter et al. 2019). For example, higher abundance correlates negatively with the mean length of Yellow Perch and Eurasian Perch (Rose et al. 1999; Arranz et al. 2015). Additionally, prey availability influences Yellow Perch growth rates (Heath and Roff 1996). When abundant year classes of Yellow Perch occur, they can suppress subsequent year classes through competition and cannibalism, leading to cyclical population dynamics and shifts in size structures over time (Post and Evans 1989; Sanderson et al. 1999).

Timing of sexual maturity also influences the size distribution of Yellow Perch because tradeoffs in growth and mortality modify how energy is allocated between somatic and gonadal growth (Stearns and Koella 1986). Growth and maturity could theoretically interact in several ways to affect the size structure of Yellow Perch populations. For instance, in a high-growth scenario, a population might seem to mature at a certain age because small changes in the timing of individual maturity result in larger differences in size at maturity (Stearns and Koella 1986). Additionally, rapid growth early in life may encourage earlier maturation (Hutchings 1993; Henderson and Morgan 2002; Heibo and Magnhagen 2005). Conversely, in a low-growth scenario, a population may appear to mature at a specific length because substantial delays in the age at which individuals mature are required to produce noticeable changes in the length at maturity (Stearns and Koella 1986).

Mortality rates also influence tradeoffs between somatic and gonadal growth and affect the timing of maturation (Shuter et al. 2005; Marty et al. 2011). High mortality rates may cause earlier maturation because individuals that mature sooner have a better chance of reproductive success compared

to those that delay maturity and might not survive to reproduce (Stearns 1989; Roff et al. 2006). In cases where mortality is positively linked to increased growth (i.e., higher mortality reduces competition for resources), Yellow Perch may mature at younger ages but reach larger sizes (Feiner et al. 2017).

Evaluating Yellow Perch population demographics requires examining multiple factors, including sexual dimorphism. Growth, size, and age at maturity vary between sexes (Headley and Lauer 2008; Uphoff and Schoenebeck 2012), leading to different life history tradeoffs. For instance, in stratified lakes, differential growth rates may result from males and females occupying different thermal habitats, with males preferring deeper, cooler waters (Sandheinrich and Hubert 1984). Additionally, males might allocate more energy to anaerobic activities like spawning, foraging, and predator avoidance, potentially resulting in slower growth compared to females (Schoenebeck and Brown 2012). Sex-specific differences in mortality also exist; for example, female Yellow Perch experience higher angling mortality than males (Schoenebeck and Brown 2011), and females tend to mature earlier in response to increased mortality (Feiner et al. 2017).

The objectives of this research project were to 1) develop sampling and analysis tools for evaluating indirect metrics of Yellow Perch populations, such as maturity, size structure, and growth, and 2) to understand the range of population characteristics in Minnesota lakes. To meet these objectives, experimental sampling gears including fine-mesh gill nets and boat electrofishing were used along with standard gill nets to sample a wider size range of Yellow Perch and to gather information on juveniles and adults of both sexes. We developed standardized protocols for evaluating growth, sex, and maturity and developed statistical methods to estimate life history metrics. The results from this project offer guidance for managers aiming to more effectively evaluate Yellow Perch populations and include a range of assessment tools, from simple metrics calculated using standard gill-net data to more complex metrics obtained using multiple sampling methods.

Methods

Lake Selection

Multiple MN DNR programs conducted Yellow Perch sampling in collaboration, including Area Offices, Large Lakes, Sentinel Lakes, and the Fisheries Research Unit. External partners also participated,

including Bemidji State University and the Fond Du Lac Band of Ojibwe. The resulting final study design included 28 individual lakes. We selected lakes based on prior knowledge of the Yellow Perch populations from standard surveys, anecdotal observations, and the objectives of the programs responsible for conducting field sampling. The number of lakes sampled with experimental sampling each year of the study included 17 in 2019, 8 in 2020, and 12 in 2021 (Table 1). Experimental sampling was repeated in six lakes across multiple years, so the final study design included 28 individual lakes that were surveyed during 37 sampling events. Lakes were located geographically across the state of Minnesota (Figure 1) and varied widely in physical traits such as surface area, maximum depth, and water clarity (Table 1).

Fish collection—Fisheries staff conducted standard surveys during the months of June–September, depending on the standardized protocol for each lake (MN DNR 2017). Experimental sampling occurred during the last week of August through the first week of October, with exact timing dependent on geographic location, weather, water temperature, and staff schedules. Based on the pros and cons related to size selectivity, capture efficacy, cost, and ease of deployment (Lyons 1986; Jackson and Harvey 1997), sampling crews used a combination of boat electrofishing and fine-mesh gill nets. These gears were complementary in that boat electrofishing sampled fish in shallow waters (< 2 m depth) and fine-mesh gill nets sampled fish in deeper waters (> 3 m depth). Targeting different habitats accounted for potential spatial segregation of Yellow Perch by sex or life history strategy.

Fine-mesh gill nets—We selected the dimensions of experimental fine-mesh gill nets comparable to standardized gear currently used to sample small forage fish in Ontario (Sandstrom et al. 2013) and in Europe (European Committee for Standardization 2005; Table 2). Fine-mesh gill nets were 14.6-m in length and 1.8-m in height, divided into six 2.4-m-long panes of monofilament bar mesh in following order: 7.9, 15.9, 9.5, 19.1, 6.4, and 12.7 mm. Gear deployment protocols for fine-mesh gill nets were developed, including setting nets on the bottom for approximately 24 h at a minimum of three sites to account for spatial variability. These sites were selected by management staff to maximize catch rates based on previous observational knowledge. The target sample size was 250 Yellow Perch because bootstrap models indicated

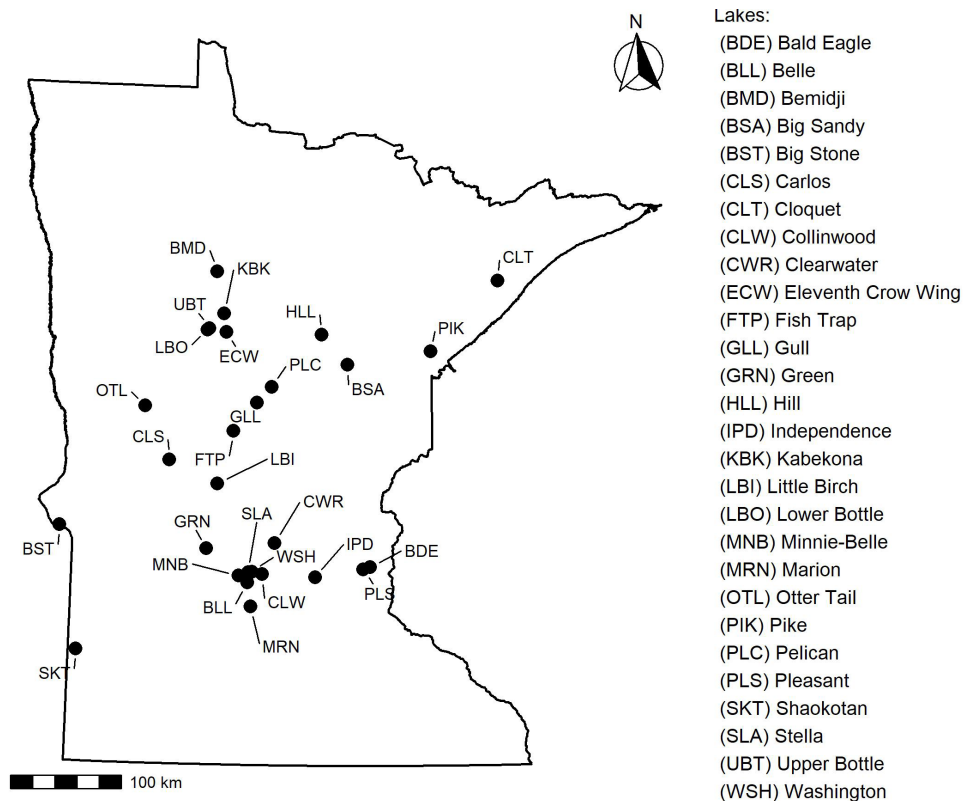


Figure 1. Lakes sampled for Yellow Perch with experimental gears including boat electrofishing and fine-mesh gill nets from 2019 to 2021 that were included in the final data analysis.

that this sample size would efficiently fill the most 10-mm length bins with the least amount of effort when using length data from multiple Yellow Perch populations. Project protocol directed initially setting nets at depths between 3.0 to 7.5 m, but included flexibility to adjust set depths based on catch rates and experience to maximize catch rates and minimize bycatch. Nets were set overnight and placed on ice when retrieved so fish could be processed at a MN DNR office location.

Boat electrofishing—Protocols for boat electrofishing allowed electrofishing either day or night, depending on staff schedules and workload, with one or two dip-netters. Protocol required netters to use a dip net with a maximum bar mesh size of 6 mm. Sampling crews adjusted electrofishing control box settings based on fish response due to differences in individual boats (e.g., generator and control box combinations) and in individual lakes (e.g., conductivity values). Survey crews selected a minimum of two sites to electrofish, based on prior knowledge, to maximize catch rates and to incorporate spatial variability. Sampling crews conducted electrofishing for a minimum total

time of 60 minutes of pedal on time or until 250 Yellow Perch were caught, whichever occurred first. Sampling crews froze Yellow Perch captured during electrofishing until they could be processed.

Standard gill nets—Sampling crews set multifilament gill nets at fixed stations as part of standard MN DNR lake surveys (MN DNR 2017). Nets were constructed of five 15.2 m wide x 1.8 m high panels of multifilament-nylon mesh with graduated bar mesh sizes in the following order: 19.05, 24.50, 31.75, 38.10, and 50.80 mm. Standard gill-net surveys took place within three years of when experimental sampling using fine-mesh gillnetting and/or boat electrofishing occurred.

Fish processing—We developed subsampling criteria based on statistical analyses conducted on pilot data. We determined the appropriate samples per length bin that would provide accurate estimates of growth and maturity while accounting for sexual dimorphism by bootstrapping length-based subsampling methods using different Yellow Perch population types. We developed data collection protocols including sex- and length-based subsampling to collect otoliths and information on maturity

Table 1. Summary of lake characteristics of the 28 lakes sampled with boat electrofishing and fine-mesh gill nets from 2019 to 2021. Division of Waters (DOW) number is used by the MN DNR as a unique identifier for each lake and the lake classification (lake class) system was based on Schupp (1992). Littoral % was the percentage of the lake by area that was ≤ 4.6 m deep. The year when experimental gears were used is listed under fine-mesh gill net/boat electrofishing (GFM/SEF) year and the year when standard gill nets were used is listed under gill-net (GN) year.

Lake name	DOW	Lake class	Latitude (UTM)	Longitude (UTM)	Area (ha)	Littoral %	Max depth (m)	Mean depth (m)	Mean Secchi (m)	GFM/SEF year	GN year
Bald Eagle	62000200	24	498754	4995658	424	56	11.3	4.1	1.6	2019	2020
Belle	47004901	24	387490	4981830	346	44	6.6	4.3	1.3	2020	2020
Bemidji	4013002	22	360615	5263066	2,663	28	23.2	10.1	2.4	2019	2017
Big Sandy	1006200	22	478162	5178527	2,472	52	24.4	4.9	1.6	2019 2021	2020 2021
Big Stone	6015200	41	217927	5034767	4,850	75	4.9	3	1.7	2019	2019
Carlos	21005700	22	317215	5092901	1,055	35	48.5	14.3	5.2	2021	2020
Clearwater	86025200	22	412242	5017385	1,278	48	21.3	6	3.1	2019	2019
Cloquet	38053900	17	613955	5254711	71	99	2.1	0.7	1.1	2019	2019
Collinwood	86029300	24	401157	4989473	258	60	7.8	3.6	1.1	2020	2020
Eleventh Crow Wing	29003600	23	368956	5208357	305	23	24.4	9.4	5.6	2021	2021
Fish Trap	49013700	25	375254	5118866	471	30	12.8	6.2	2	2021	2021
Green	34007900	22	350495	5012746	2,250	38	33.5	8.2	4	2019 2021	2019 2021
Gull	11030500	22	396225	5144520	4,034	34	24.4	9.8	4.5	2019 2020 2021	2019 2020 2021
Hill	1014200	25	454894	5205668	327	45	14.2	7.1	2.3	2019 2021	2020
Independence	27017600	24	448815	4986499	330	51	18.2	4.8	1.1	2019	2019
Kabekona	29007500	22	366687	5224842	985	25	40.5	15.3	3.3	2020	2020
Little Birch	77008900	22	360670	5071322	339	32	24.4	8.8	4	2019	2019
Lower Bottle	29018000	22	351901	5210256	259	48	35.1	8.2	5.4	2019	2018
Marion	43008400	42	390413	4960132	213	100	4.6	2	0.6	2020	2019
Minnie-Belle	47011900	27	379681	4988075	234	30	13.7	8	3.7	2020	2020
Otter Tail	56024200	26	295396	5141838	5,696	48	34	7.6	3.7	2019 2021	2021
Pelican	18030800	22	409892	5158722	3,386	46	31.7	6.7	4.5	2019 2020 2021	2019 2020 2021
Pike	69049000	5	553347	5190549	198	30	18.3	7.8	7.5	2019	2019
Pleasant	62004600	24	492243	4993757	246	47	17.6	5.1	1.4	2019	2020

Table 1 *continued*. Summary of lake characteristics of the 28 lakes sampled with boat electrofishing and fine-mesh gill nets from 2019 to 2021. Division of Waters (DOW) number is used by the MN DNR as a unique identifier for each lake and the lake classification (lake class) system was based on Schupp (1992). Littoral % was the percentage of the lake by area that was ≤ 4.6 m deep. The year when experimental gears were used is listed under fine-mesh gill net/boat electrofishing (GFM/SEF) year and the year when standard gill nets were used is listed under gill-net (GN) year.

Lake name	DOW	Lake class	Latitude (UTM)	Longitude (UTM)	Area (ha)	Littoral %	Max depth (m)	Mean depth (m)	Mean Secchi (m)	GFM/SEF year	GN year
Shaokotan	41008900	41	232570	4922309	403	100	3.4	2.4	1.7	2021	2021
Stella	47006800	24	388273	4991350	245	50	21.6	5.3	2.6	2021	2021
Upper Bottle	29014800	27	353576	5211697	186	38	20.2	6.2	4.5	2019	2018
Washington	47004600	41	391693	4991590	987	95	5.5	2.6	1.5	2019 2021	2019

Table 2. MN DNR experimental fine-mesh gill net compared with Ontario and European standardized nets for sampling small forage fish. The European CEN Nordic (small meshes) is part of a net with a larger series of meshes extending to 55 mm square measure.

Net Metric	MN DNR Fine-Mesh						Ontario Small Mesh					European CEN Nordic (small meshes)						
Square measure (mm)	6.5	8	9.5	12.5	16	19	6.5	9.5	12.5	16	19	5	6.3	8	10	12.5	15.5	19.5
Square measure (in)	0.3	0.3	0.4	0.5	0.6	0.8	0.3	0.4	0.5	0.6	0.8	0.2	0.3	0.3	0.4	0.5	0.6	0.8
Mono diameter (mm)	0.1	0.1	0.1	0.2	0.2	0.2	0.1	0.1	0.1	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.2	0.2
Order of panels	5	1	3	6	2	4	4	2	5	1	3	10	3	6	4	7	9	2
Panel length (m)				2.4					2.5						2.5			
Panel height (m)				1.8					1.8						1.5			
Panel area (m2)				14.6					14.8						12.5			

and weight. Total length was measured to the nearest 1-mm and weight was measured to the nearest 0.1-g. For fine-mesh gill-net samples, all Yellow Perch in each mesh were counted, and a random subsample of 25 fish per mesh were measured and evaluated for sex and maturity. For electrofishing samples, all fish were measured and evaluated for sex and maturity. For both experimental gears, otoliths and weights were collected from five females and five males per 10-mm length bin or until 20 individuals were evaluated per length bin. In the standard gill nets, all Yellow Perch were measured unless catch rates were so high that fish could not be processed in a timely manner in which case a representative subset was measured. Additionally, ten randomly selected fish per 10-mm length bin were dissected to evaluate sex and collect otoliths. Maturity was not evaluated for these fish because standard gill nets were set earlier in the summer prior to the development of gonads, except for Big Stone 2019, Green 2021, Pleasant 2020, and Otter Tail 2021 where standard gill nets were set in September and maturity data were collected.

Sex and maturity determination—To ensure consistency across participating Area Offices, we developed pictorial guides and a short video for determining sex and maturity status that were emailed to sampling partners and posted to an internal MN DNR website. We also conducted in-person training sessions. Instruction directed sex determination based on the presence of a single ovary for females or paired testes for males (Craig 2000). For female Yellow Perch, maturity determination was based on the color of the ovaries, vascularization, and the presence of eggs. Immature females had small thread-like pear-shaped ovaries which were clear and non-vascularized, without the presence of oocytes while mature females had vascularized, enlarged opaque ovaries with either small granular or large eggs present (Craig 2000). For male Yellow Perch, maturity determination was based on the size and color of testes. Immature males had small transparent thread-like paired testes while mature males had opaque or white testes with possibly some reddish coloration that occupied a greater proportion of the ventral cavity (Craig 2000).

Age estimation—We evaluated ages of Yellow Perch using sagittal otoliths, which have the highest level of agreement between independent readers and the lowest levels of variability (Niewinski and Ferreri 1999; Vandergoot et al. 2008).

We captured high-quality microscope images of 8,131 otoliths and compiled them in an image library for future reference. Two independent readers evaluated all Yellow Perch otolith images. If there was disagreement between age estimates, the readers re-evaluated otoliths including cracking, burning, and re-imaging until they mutually agreed upon an age estimate. Initial agreement in age estimates between readers was > 90%.

Data Analysis

Imputation—To account for subsampling methods and to generate a complete dataset, we used a tiered approach to assign length, sex, maturity, and age. We assigned length to Yellow Perch sampled with fine-mesh gill nets that were counted but not measured using random sampling with replacement based on mesh-specific data from each lake. We assigned sex and maturity to unexamined fish using a multinomial log linear model based on individual sex, maturity, and length data from each lake (Flores et al. 2019). Finally, we assigned ages to unaged Yellow Perch using lake-specific age-length keys based on sex-specific and lake-specific data. Age-length keys provide estimates of growth parameters and mean-length-at-age comparable to estimates from more complex statistical methods (Lusk et al. 2021).

Gear comparisons—We compared lengths of Yellow Perch captured in the 19.05-mm mesh common to both fine-mesh gill nets and standard gill nets. We also compared Yellow Perch length frequencies, sex ratios, and maturity ratios between experimental gears. We evaluated the effects of fish length and experimental sampling gear (boat electrofishing and fine-mesh gill nets) on the proportion of sampled females using a mixed effects linear regression model (mixed model) with lake as a random effect. We also evaluated the effects of fish length and experimental sampling gear on the proportion of mature fish using sex-specific mixed models with lake as a random effect. We evaluated potential effects of experimental gear type on age estimates using a sex-specific mixed model analysis with length and gear type as fixed effects and lake as a random effect and compared it to a null model with length as the fixed effect and lake a random effect. We compared mixed models and used the Bayesian Information Criterion (BIC) to select the most supported model.

Maturity—We analyzed the estimated age at 50% maturity (A_{50}) and length at 50% maturity (L_{50}) for each sex and compared these estimates between

gears and among lakes. We calculated the maturity estimates of L_{50} and A_{50} at the time of sampling, in autumn prior to first spawn. Therefore, A_{50} at the time of first spawn would be approximately 0.6 years later than the calculated estimate. We used logistic regression to calculate the probability of maturity based on length (L_{50}) or age (A_{50}). We generated confidence intervals around the estimates by bootstrapping the data 2,000 times and calculating the middle 85% confidence intervals, which can be used to visually infer significance similar to a two-sample t -test (Goldstein and Michael 1995, Austin and Hux 2002). We only included maturity metrics in subsequent analyses if the estimate was greater than zero and confidence intervals did not exceed 75% of the mean. With these criteria, we excluded lakes where small sample sizes or early maturity resulted in high variability around the estimate. We evaluated the effect of experimental gears on the maturity of both sexes using a mixed model analysis approach, accounting for lake-year as a random effect and using BIC as model selection criteria. We also combined Yellow Perch maturity data across gears to estimate female L_{50} and A_{50} for all lake-years using the same statistical methods described above.

Mortality—We estimated female survival using Chapman-Robson catch-curve estimates of mortality by modeling all year-classes one year older than the peak abundance and using a variance estimator corrected for overdispersion (Chapman and Robson 1960; Smith et al. 2012). For fine-mesh gill nets, lake-year events were included in the analysis if there was an age-0 year-class present and at least three age-classes after the peak value, all with a mean size ≤ 200 mm, which is the approximate maximum length of Yellow Perch captured in 19.05-mm bar mesh (the largest mesh size in fine-mesh gill nets). For standard gill nets, lake-year events were included in the analysis if there were at least three age-classes present after the peak value, all with a mean size ≥ 140 mm, the approximate minimum length of Yellow Perch captured in the 19.05-mm bar mesh (the smallest mesh size in standard gill nets). Gears were not combined because they were set at different depths, locations, and times of the year, and had different-sized mesh panels (Table 2). Male survival was not estimated because there were fewer age-classes and greater uncertainty around the estimates.

Growth—We were unable to model growth using frequentist growth models because many Yel-

low Perch populations were short-lived and length did not plateau with age. Therefore, we applied Bayesian length-at-age models to model growth for each sex and lake separately, using priors to constrain the values of length at age 0 (L_0) and asymptotic average length (L_{inf}) by using information from all the populations sampled as part of this study. We fit three different growth models (von Bertalanffy, Gompertz, and Logistic) for each individual sex-lake combination using Markov Chain Monte Carlo (Smart and Grammer 2021) and the model with the best fit was selected using leave-one-out-cross validation. Because the best-fit model varied by lake, we were unable to compare growth rate coefficients (k) between populations (Smart et al. 2016), but L_0 and L_{inf} were comparable (Smart and Grammer 2021). Because we were unable to compare k between populations, growth rates were estimated for females age 0 to age 2 in each lake using linear regression models. We compared dimorphic differences in mean length at age between males and females using a mixed model approach, where length and sex were fixed effects and lake-year was a random effect and compared against a null model without sex as a fixed effect.

Size structure – To characterize the maximum average length of populations more easily than using L_{inf} from Bayesian growth models, we explored the use of a length-based metric, mean maximum length (MML) of the largest individuals, similar to length-based metrics used in other studies to compare size structure between lakes or over time (Worm et al. 2009; Rypel et al. 2016; VanderBloemen et al. 2020; Holbrook et al. 2021). We calculated MML2.5, MML5, and MML10 as the mean length of the largest 2.5%, 5%, and 10%, respectively, of all individuals sampled from all gears using the complete imputed dataset and compared these estimates with L_{inf} . We also calculated sex-specific estimates of MML2.5, MML5, and MML10 and compared with sex-specific estimates of L_{inf} from Bayesian growth models. Similar to MML, we characterized longevity of populations using mean maximum age (MMA) of the oldest 2.5% of individuals (MMA2.5), using data from all gears and the complete imputed dataset and used this metric to compare longevity between sexes.

Data analyses indicated that MML was correlated to L_{inf} from growth models for the 28 lakes in this study, so we applied this metric to the more comprehensive statewide standard gill-net dataset collected during the years 1994 to 2021 to evaluate

whether there were changes in size structure over time. To evaluate the minimum sample size needed for the MML2.5, MML5, and MML10 metrics, we conducted a bootstrap analysis on a subset of study lakes ($n = 5$) where ≥ 300 Yellow Perch were captured in standard gill nets. Using sample sizes ranging from 50 to 300, we bootstrapped with replacement 1,000 times, calculating MML for each subsample. We plotted the results using boxplots and prediction intervals and visually identified the minimum sample size where variance stabilized. Using the statewide standard gill-net dataset, we then calculated MML10 for each survey, including lakes in the analysis if there were at least three standard gill-net surveys with 100 or more Yellow Perch captured in each survey. We normalized MML10 residuals with log-transformation and accounted for repeated measures of lakes with a mixed model approach with the linear model including a random intercept for each year, and random intercepts and random slopes for each lake. The estimated fixed-effect slope represented the average change in MML10 in Minnesota lakes from 1994 to 2021. The year 2020 was omitted from the data because fewer lakes were sampled due to the Covid-19 pandemic.

We used statewide standard gill-net data to evaluate trends in the number of lakes surveyed overall. Lakes were included in the analysis if there were at least three standard gill net surveys conducted between 1994–2021 with at least one individual of any fish species captured in the survey to eliminate lakes that were not routinely monitored. We then evaluated the number of individual lakes surveyed per year with standard gill nets using linear regression analysis. We evaluated changes over time in the number of lakes with the minimum sample size needed to calculate MML10 ($n = 100$) by filtering lakes where Yellow Perch were captured based on the preceding analysis to retain lakes where at least three standard gill-net surveys were conducted from 1994–2021. Individual surveys were then retained if Yellow Perch catch rates were ≥ 100 . Linear regression analysis was used to determine if the number of individual lakes with Yellow Perch catch rates ≥ 100 changed over time. The year 2020 was omitted from both trend analyses because fewer lakes were sampled due to the Covid-19 pandemic.

Statistical analysis—We analyzed and graphed all data in the statistical program R version 2024.12.0 (R Core Team 2024) using the packages FSA for assigning ages and calculating survival (Ogle et al. 2023), tidyverse (Wickham et al. 2019)

for summarizing data, lubridate (Grolemund and Wickham 2011) for manipulating dates, nnet (Venables and Ripley 2002) for conducting multinomial regression, DescTools (Signorell 2024) for comparing distributions and medians, lme4 (Bates et al. 2015) for evaluating mixed models, optimx (Nash and Varadhan 2011, Nash 2014) for optimizing mixed models, BayesGrowth for fitting Bayesian growth models (Smart and Grammer 2021), ggplot2 (Wickham 2016) for graphing data, and ggrepel (Slowikowski 2024) for placing labels on plots.

Results

Nearly 37,000 Yellow Perch were sampled in fine-mesh gill nets and boat electrofishing as part of this project, making it the most extensive Yellow Perch dataset ever collected by the MN DNR. Additionally, a total of 8,131 otoliths were collected from Yellow Perch captured in multiple gears, including standard gill nets ($n = 2,029$), fine-mesh gill nets ($n = 3,431$), and boat electrofishing ($n = 2,671$). The median number of Yellow Perch otoliths collected per lake-year was 57 from standard gill nets, 96 from fine-mesh gill nets, and 82 from boat electrofishing.

Gear Comparisons

Length distributions of Yellow Perch differed between fish captured in fine-mesh gill nets compared to boat electrofishing. Of the 37 lake-year sampling events, four lakes did not have paired experimental gears and an additional eight lakes had low boat electrofishing sample sizes ($n < 100$), so we included 25 lake-year events in the statistical comparisons. Of these lakes, Yellow Perch in 23 lake-years were likely sampled from a different length distribution when captured with boat electrofishing compared to fine-mesh gill nets ($p < 0.05$, Kolmogorov-Smirnov test). The median lengths of Yellow Perch were also significantly different between gears in 22 lake-years ($p < 0.05$, Wilcoxon rank sum test). However, we detected no uniformity in the differences in median lengths between experimental gears, with 10 lake-years having a larger median total length associated with boat electrofishing and 12 lakes having a larger median total length associated with fine-mesh gill nets (Figure 2).

We compared length distributions of Yellow Perch captured in the 19.05-mm bar mesh between standard gill nets and fine-mesh gill nets. Of the 37 lake-year combinations, 14 lake-years included deployment of both types of gill nets

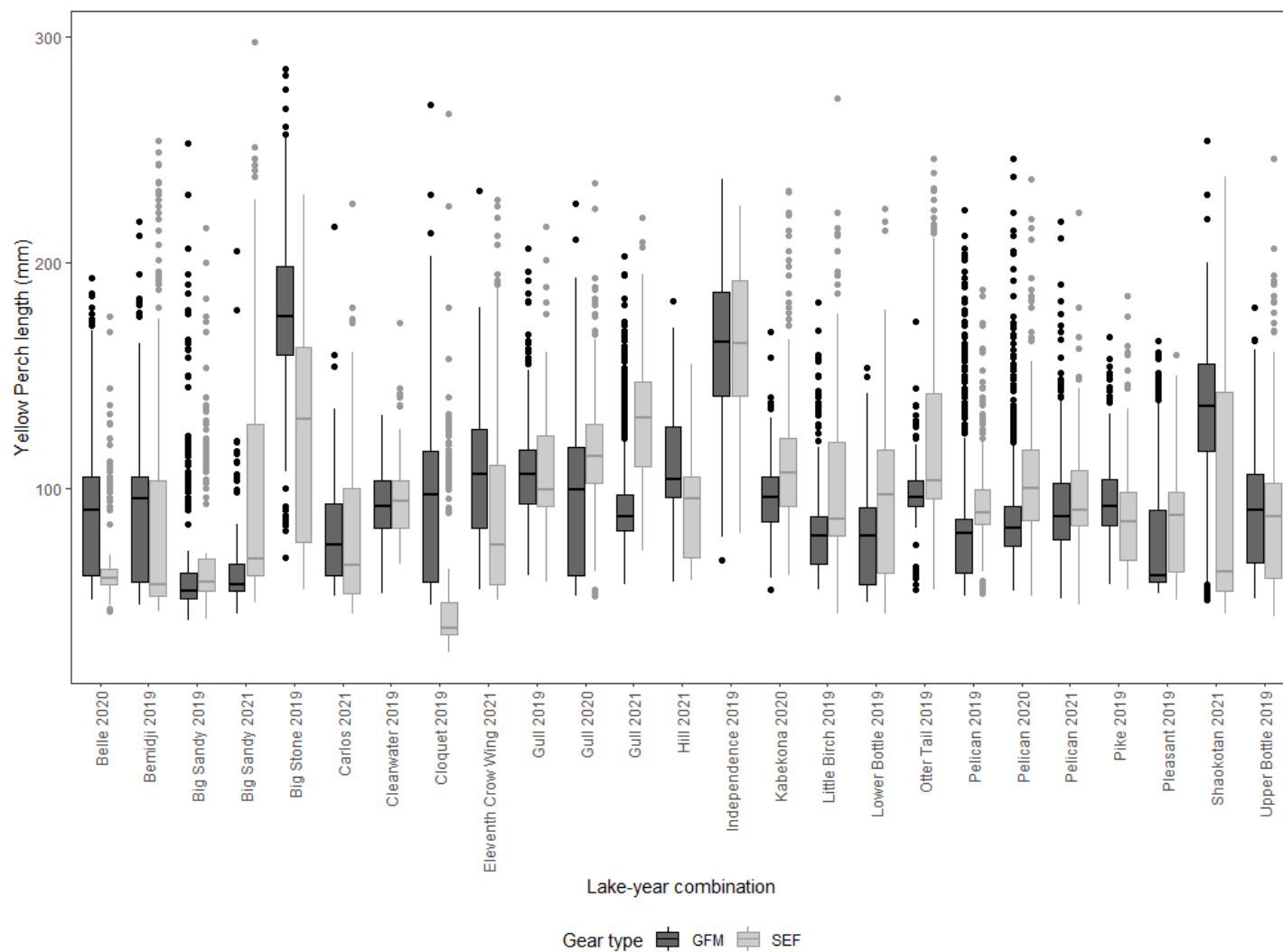


Figure 2. Box plot comparison of the length distribution and median total length (mm) of Yellow Perch sampled in different lake-years with experimental sampling gears including fine-mesh gill nets (GFM) and boat electrofishing (SEF). Lake-years with no significant differences in the length distribution or median between gears are indicated by “NS” and the lake-year with no significant differences in the median total length is indicated by “NS-W”.

during the same sampling year and with sample sizes greater than 15 Yellow Perch in each gear. Yellow Perch captured in the 19.05-mm mesh were likely sampled from different length distributions when captured with standard gill nets compared to fine-mesh gill nets in 12 of 14 lake-years ($p < 0.05$, Kolmogorov-Smirnov test). The median total length of Yellow Perch captured in the 19.05-mm mesh were significantly different in 10 of the 14 lakes ($p < 0.05$, Wilcoxon rank sum test), with 9 of these lakes having significantly larger fish captured in fine-mesh gill nets compared to standard gill nets (average length difference was 11 mm; Figure 3).

Overall comparisons of Yellow Perch lengths captured in all gears across all lake-years indicated that the peak density for each individual mesh size was associated with different lengths of Yellow Perch due to net selectivity (Figure 4). However, the combination of 11 mesh sizes in both fine-mesh gill nets and standard gill nets captured Yellow Perch ranging in length from 50 to 275 mm, which repre-

sented the full range of Yellow Perch lengths captured with boat electrofishing, except that boat electrofishing also captured fish less than 50 mm (Figure 4). The boat electrofishing data also indicated a bimodal distribution in length data, likely due to a peak of age 0 Yellow Perch around 58 mm.

When data from experimental gears were evaluated, length was a significant predictor of the proportion of females in 10-mm length bins ($p < 0.0001$), with significantly higher proportions of females occurring in length bins from 90 mm to 190 mm. The proportion of females sampled was also greater in boat electrofishing samples than in fine-mesh gill nets, although the difference diminished with increasing fish length (Figure 5). This gear effect was largest for length bins less than 110 mm, with an average proportion of 0.22 more females in boat electrofishing samples than in fine-mesh gill nets (Figure 5). Length was also a significant predictor of the proportion of mature females ($p < 0.0001$), with a greater proportion of mature fe-

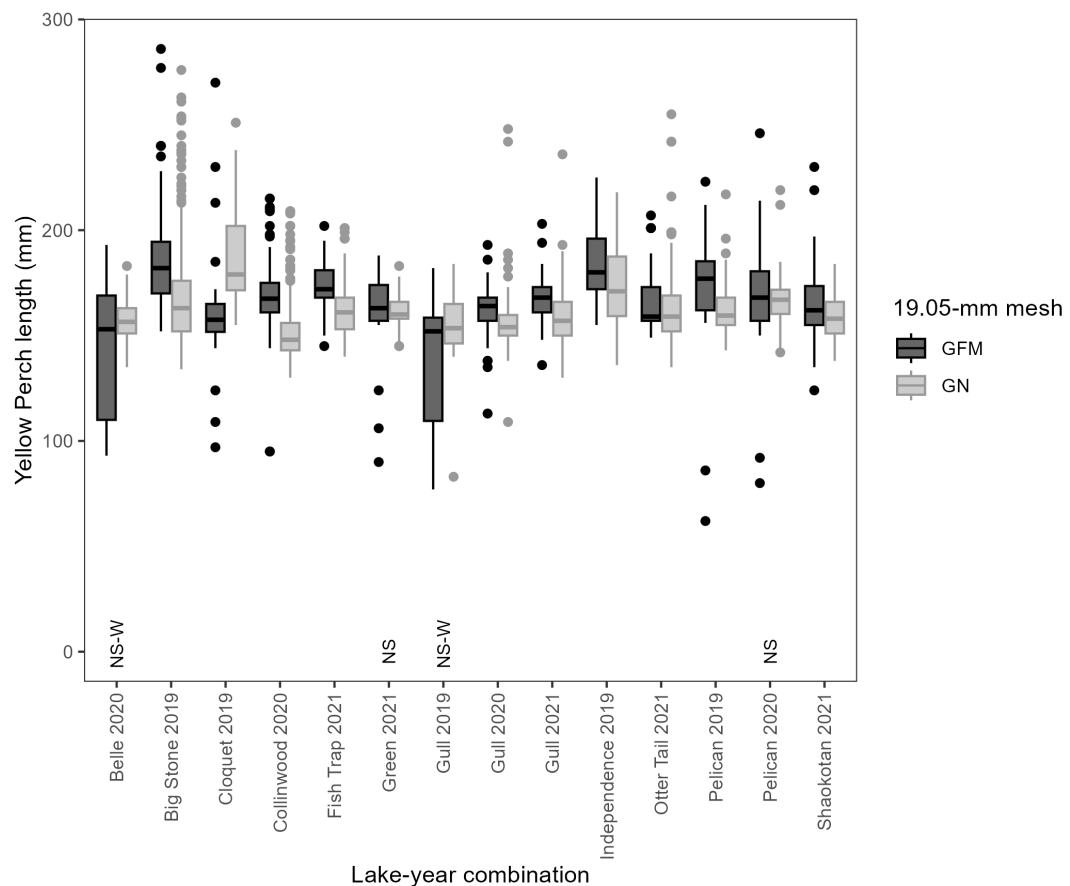


Figure 3. Box plot comparison of the length distribution and median total length (mm) of Yellow Perch sampled in different lake-years in the 19.05-mm mesh common to both fine-mesh gill nets (GFM) and standard gill nets (GN). Lake-years with no significant differences in the length distribution or median are indicated by “NS” and the lake-year with no significant differences in the median but significant differences in the distribution is indicated by “NS-W”

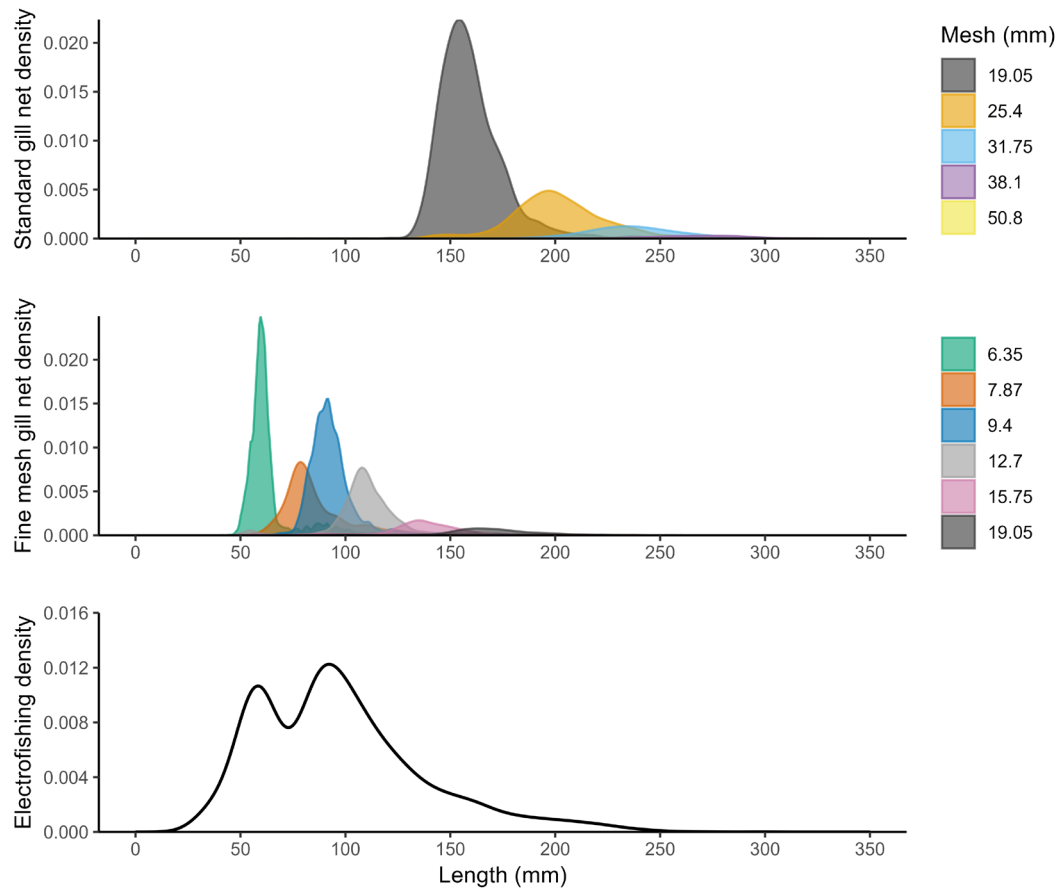


Figure 4. Density plots of lengths of Yellow Perch caught in each gill net scaled by the total net catch for standard gill nets (top panel) and fine-mesh gill nets (middle panel). The density plot for lengths of Yellow Perch captured with boat electrofishing is also shown (bottom panel).

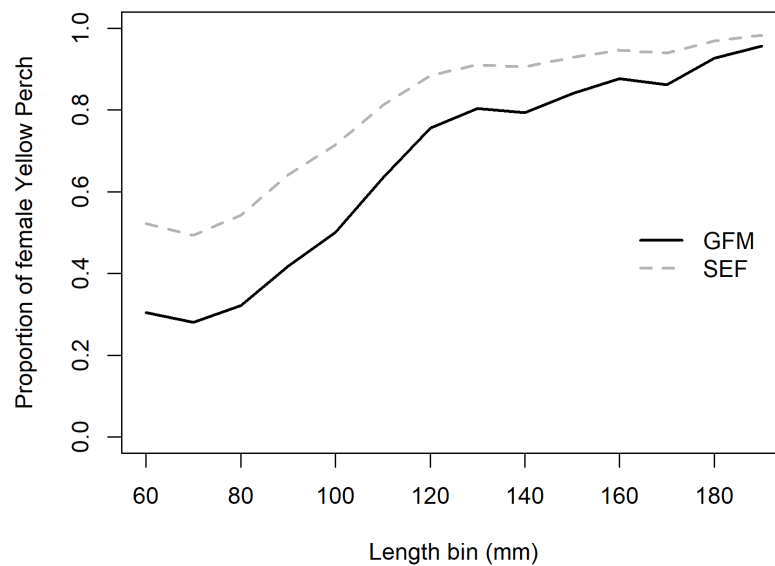


Figure 5. Effects of experimental gear including fine-mesh gill nets (GFM) and boat electrofishing (SEF) and length bin on the proportion of female Yellow Perch using a mixed model approach with lake as a random effect. Proportions of female Yellow Perch increased by length bin and were consistently higher when captured by boat electrofishing than by fine-mesh gill nets.

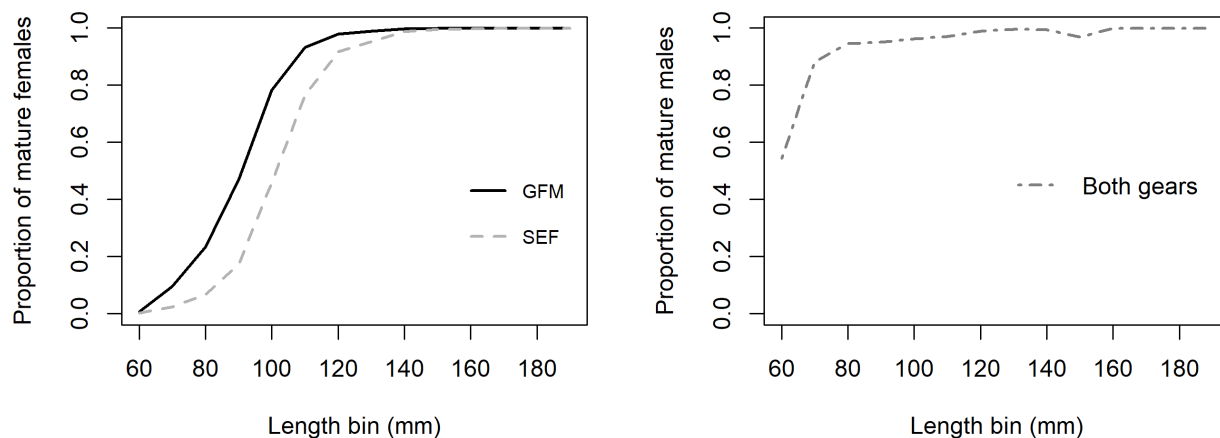


Figure 6. The proportion of mature Yellow Perch by length bin for females (left panel) and males (right panel). Mixed effects linear regression models indicated a significant effect of experimental gear type on the proportion of mature females by length bin, with a greater proportion of mature females sampled in fine-mesh gill nets (GFM) compared to boat electrofishing (SEF). There was no effect of gear type on the proportion of mature males by length bin (right panel), so gears were combined.

males occurring in all length bins from 60 mm to 190 mm. The proportion of mature females was greater in fine-mesh gill nets than boat electrofishing samples (Figure 6), with the largest gear effect occurring at length bins less than 100 mm where an average proportion of 0.26 more mature females were captured with fine-mesh gill nets than with boat electrofishing. This gear effect diminished with length to less than a 0.05 difference in proportion of mature females by 130 mm. Length was also a significant predictor of the proportion of mature males ($p < 0.0001$), with a greater proportion of mature males occurring in all length bins less than 160 mm (Figure 6). There were no differences in the proportion of mature males between boat electrofishing and fine-mesh gill nets (Figure 6).

Model results indicated a significant effect of experimental gear type on A_{50} and L_{50} for both females and males. On average, females captured with electrofishing matured at sizes 10.1 mm longer and ages 0.18 years older than females captured with fine-mesh gill nets. Similarly, males captured with electrofishing matured 1.9 mm longer and 0.09 years older than males captured with fine-mesh gill nets. Although these differences in maturity metrics were statistically significant, they were relatively minor biologically and yielded similar information about populations, particularly compared to differences in A_{50} and L_{50} between lakes. Therefore, we concluded that maturity data could be combined across gears to increase sample sizes for subsequent analyses.

Lake-Year and Population Comparisons

Female L_{50} varied from 58 to 204 mm across lake-year sampling events, with a median of 98 mm (Figure 7). Lakes that had a female L_{50} greater than 115 mm tended to have populations that supported targeted sport fisheries for Yellow Perch (personal communication with Aitkin, Bemidji, Ortonville, and Fergus Falls Area Managers). This breakpoint could be an important benchmark for future comparisons as more lakes are sampled for lake management. The proportion of females in standard gill nets was negatively correlated with female L_{50} (linear regression, $p < 0.0001$, $R^2 = 0.52$, $F_{1,29} = 31.8$), indicating that this relatively simple metric may provide an indicator of overall size structure. Small-maturing populations with female $L_{50} \leq 100$ mm were associated with standard gill-net proportions of females ≥ 0.90 and may indicate Figure 8. Female estimated length at 50% maturity (L_{50}) compared to the proportion of females in standard gill nets. The line represents a linear regression model. Populations with a female $L_{50} \leq 100$ mm were associated with a higher proportion of females ≥ 0.9 in standard gill-net surveys. populations less susceptible to being captured in standard gill nets (Figure 8). Male L_{50} could not be calculated for some populations because males were maturing at the end of their first summer and had surpassed the inflection point of the logistic regression. Of the populations ($n = 26$) where male L_{50} could be calculated, values varied from 44 to 102 mm (median = 65 mm).

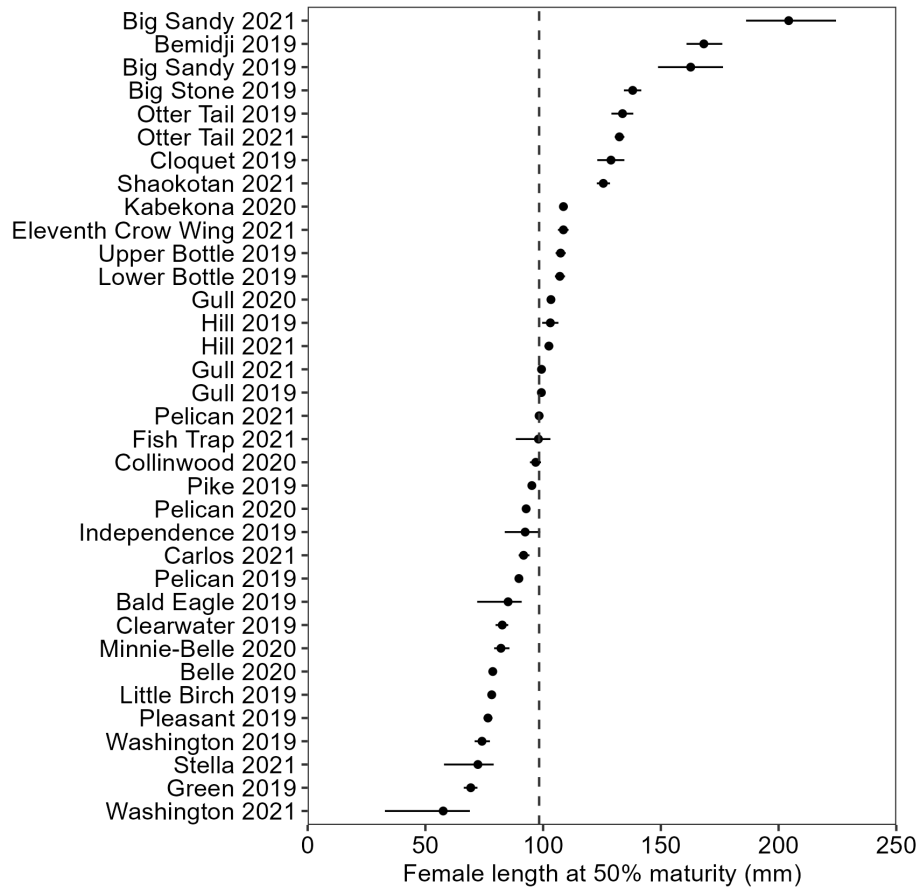


Figure 7. Female Yellow Perch estimated length at 50% (L50) maturity in lakes sampled with experimental gears, including shoreline boat electrofishing and fine-mesh gill nets. Error bars are bootstrapped 85% confidence intervals that allow for significant differences to be visualized (Goldstein and Michael 1995). The median value of 98 mm (dashed line) across all lake-years is also shown.

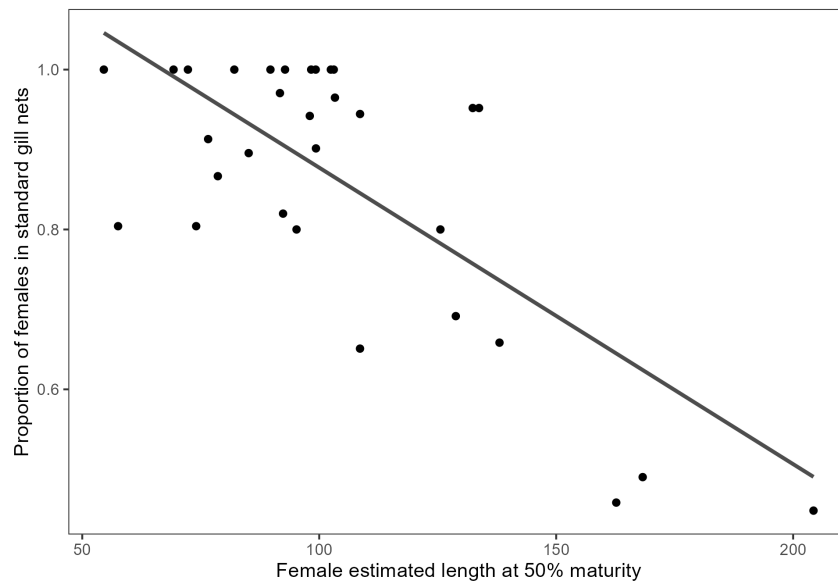


Figure 8. Female estimated length at 50% maturity (L50) compared to the proportion of females in standard gill nets. The line represents a linear regression model. Populations with a female L50 $\leq$ 100 mm were associated with a higher proportion of females $\geq$ 0.9 in standard gill-net surveys.

Female A_{50} varied from 0.4 to 2.8 years across lake-year sampling events (median = 1.3 years; Figure 9). We found that female L_{50} and A_{50} were correlated among populations ($p < 0.0001$, $R^2 = 0.58$, $F_{1,27} = 37.05$, Figure 10). Lakes where females matured later than expected based on length (lakes above the regression line) tended to support Yellow Perch sport fisheries. Lakes where females matured earlier than expected based on length (lakes below the regression line) tended to have stunted populations with indications of higher mortality (e.g., females maturing after their first summer of growth, limited number of year classes). Male A_{50} could not be calculated for most populations because males were maturing at the end of their first summer and had surpassed the inflection point of the logistic regression. Of the populations ($n = 11$) where male A_{50} could be calculated, values varied from 0.15 to 1.1 years, with a median age of 0.5 years.

There was no effect of experimental gear type on length-at-age estimates for Yellow Perch (mixed model analysis, null model without gear type as a fixed effect had the lowest BIC) despite previously discussed differences in length distributions, median lengths, sex ratios, and maturity estimates of Yellow Perch captured in the two experimental gears. Therefore, we combined age data across experimental gears to increase statistical power and sample sizes. Dimorphic differences in male and female length at age increased with age. The model with the most support (i.e., lowest BIC) included sex as a fixed effect for all ages tested, from age 0 to age 3. Sex-based differences in length at age 0 were statistically supported but were biological minimal, with females on average only 0.7 mm larger than males. Differences in length increased with each subsequent age-class with females larger than males by an average of 6, 16, and 28 mm at age

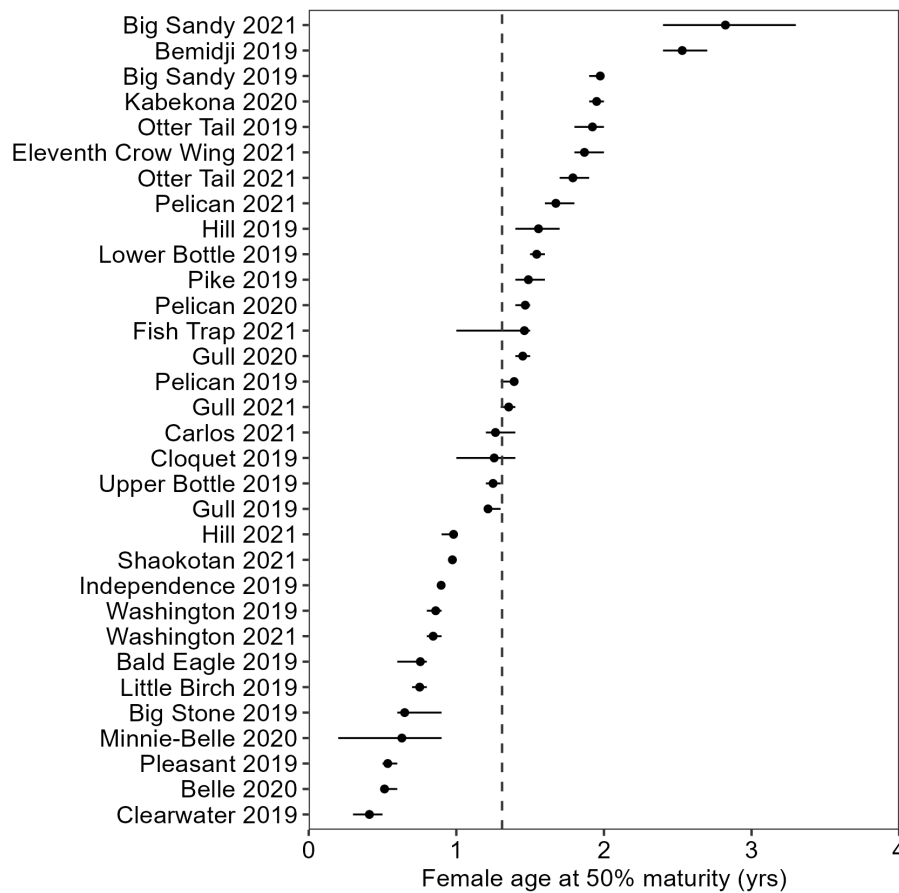


Figure 9. Female Yellow Perch estimated age at 50% maturity in the fall before spawning (A_{50}) in lakes sampled with experimental gears, including shoreline boat electrofishing and fine-mesh gill nets. Error bars are bootstrapped 85% confidence intervals that allow for significant differences to be visualized (Goldstein and Michael 1995). The median value of 1.3 years (dashed line) across all lake-years is also shown.

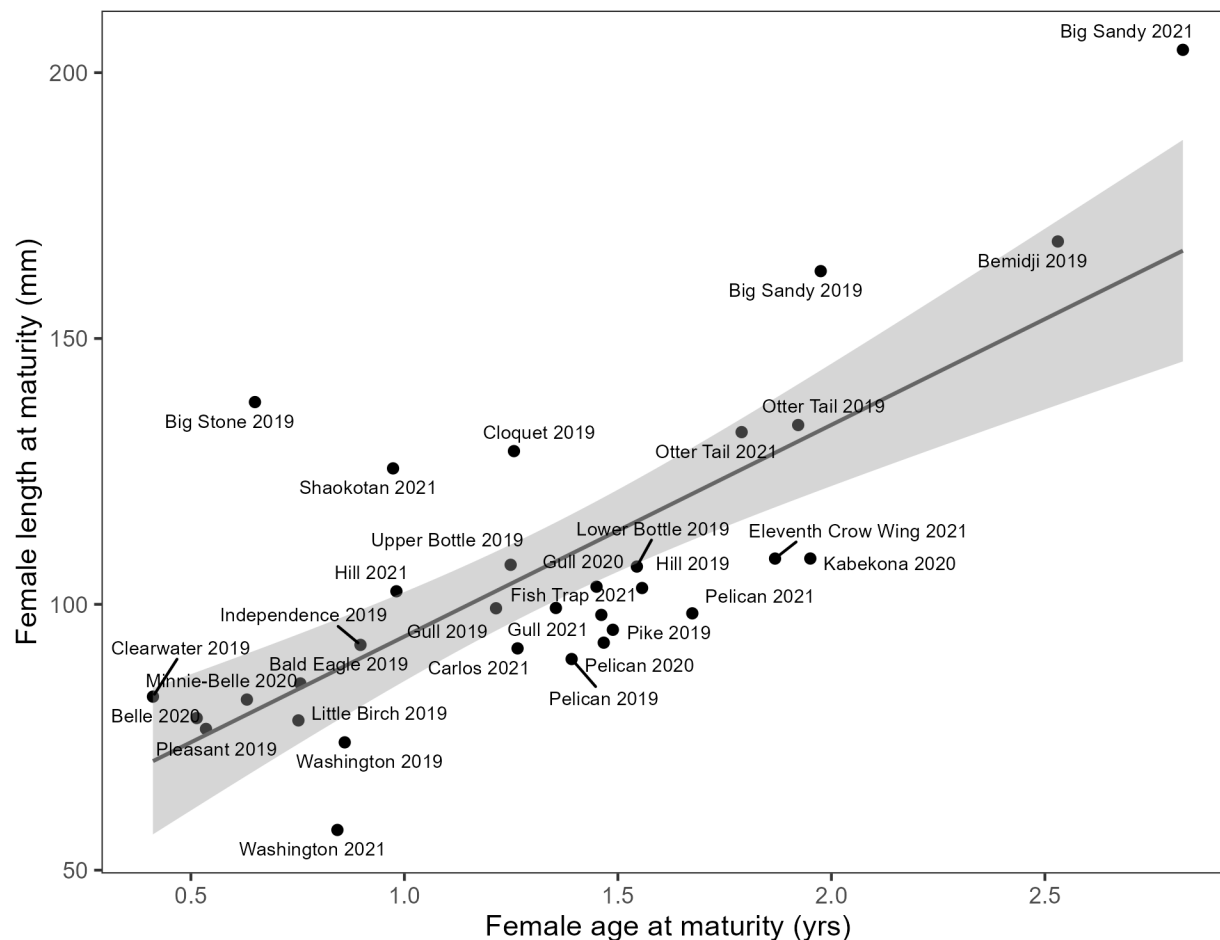


Figure 10. Yellow perch female age and length at maturity estimated in lakes sampled with experimental gears from 2019 to 2021 in Minnesota. Dark gray line indicates linear regression fit and lighter gray shading represents the 95% confidence interval of the linear regression. Labels denote lake-year sampling events.

1, age 2, and age 3 respectively (Figure 11). Length at age varied between sexes, among lakes, and within lakes between sampling events (Table 3).

Results from Bayesian growth modeling are reported in Table 4. We evaluated several length-based metrics to compare with L_{inf} from growth models. We found, through bootstrapping different sample sizes, that using the lengths of the largest percentage (e.g., largest 2.5%) rather than the largest number of individuals (e.g., largest 15) of Yellow Perch eliminated sample size effects on MML, although small sample sizes had larger variance. Of the three length-based percentile metrics we tested (MML2.5, MML5, and MML10), female L_{inf} was most strongly correlated with the MML of the largest 2.5% females from all sampling gears. The linear relationship was significant ($p < 0.0001$, $R^2 = 0.71$, $F_{1,35} = 84.96$), although it did differ statistically from a slope of one ($p = 0.0014$) and an intercept of zero ($p = 0.039$, Figure 12). Similarly,

male L_{inf} from Bayesian growth models was most strongly correlated with the MML of the largest 2.5% of males from all sampling gears ($p < 0.0001$, $R^2 = 0.76$, $F_{1,35} = 112.8$), and although the slope differed from one ($p = 0.0105$), the intercept did not ($p = 0.1910$, Figure 12). An average L_{inf} from females and males was also most strongly correlated with mean MML of the largest 2.5% of Yellow Perch regardless of sex (MML2.5) from all sampling gears ($p < 0.0001$, $R^2 = 0.76$, $F_{1,35} = 109.6$). This combined linear relationship differed from both a slope of one ($p = 0.018$) and an intercept of zero ($p = 0.028$, Figure 12). Collectively, these results indicated that MML2.5 provided similar information as L_{inf} without having to collect more labor-intensive data such as sex and age estimations. Additionally, in some Yellow Perch populations, MML2.5 may provide a more accurate estimate of maximum size than L_{inf} , particularly in short-lived populations where growth did not plateau and was difficult to model.

Table 3. Mean length (mm) at age for female and male Yellow Perch sampled in each lake-year. A minimum sample size of at least 10 individuals per age group for each sex was required for inclusion (Kritzer et al. 2001).

Lake Year	Females					Males				
	Age 0	Age 1	Age 2	Age 3	Age 4	Age 0	Age 1	Age 2	Age 3	Age 4
Bald Eagle 2019	-	118	155	174	196	-	103	-	154	-
Belle 2020	60	108	162	-	-	60	100	144	-	-
Bemidji 2019	55	100	156	193	223	55	100	152	183	213
Big Sandy 2019	56	112	158	-	-	55	107	148	186	-
Big Sandy 2021	60	110	164	208	-	58	103	153	196	-
Big Stone 2019	81	176	223	261	277	79	163	209	-	-
Carlos 2021	59	86	110	136	161	59	78	93	-	-
Clearwater 2019	73	100	123	-	-	72	90	-	-	-
Cloquet 2019	44	113	158	189	223	44	107	151	-	-
Collinwood 2020	99	165	215	-	-	97	154	-	-	-
Eleventh Crow Wing 2021	61	88	113	151	158	58	89	100	136	-
Fish Trap 2021	61	-	152	172	177	61	-	135	156	166
Green 2019	57	89	112	148	160	58	78	-	-	-
Green 2021	-	91	104	147	168	59	76	86	-	-
Gull 2019	62	95	118	144	166	66	90	104	116	-
Gull 2020	61	95	123	147	162	60	90	106	108	130
Gull 2021	66	89	126	142	165	65	86	106	117	142
Hill 2019	59	89	116	140	154	60	84	-	-	-
Hill 2021	67	104	137	149	155	70	99	115	-	-
Independence 2019	-	117	155	187	206	-	110	141	167	-
Kabekona 2020	70	91	111	133	172	69	93	103	-	-
Little Birch 2019	63	85	124	156	-	63	78	93	116	-
Lower Bottle 2019	56	91	122	160	-	55	87	112	-	-
Marion 2020	121	195	-	-	-	116	170	-	-	-
Minnie-Belle 2020	63	98	124	150	-	62	89	-	-	-
Otter Tail 2019	-	99	147	173	223	64	97	135	-	-
Otter Tail 2021	55	102	148	169	223	55	98	127	-	-
Pelican 2019	60	84	109	164	172	60	80	92	115	-
Pelican 2020	60	85	106	138	196	60	80	90	93	-
Pelican 2021	58	87	106	139	184	57	79	89	93	-
Pike 2019	62	88	105	129	143	63	88	94	104	-
Pleasant 2019	58	99	145	-	-	59	88	121	-	-
Shaokotan 2021	56	138	170	211	-	56	117	148	-	-
Stella 2021	-	103	122	-	-	-	91	-	-	-
Upper Bottle 2019	63	97	136	177	-	59	95	125	-	-
Washington 2019	55	104	147	166	-	-	90	114	151	-
Washington 2021	-	92	115	163	-	62	82	97	136	-

Table 4. Bayesian growth models for female and male Yellow Perch, where L_{inf} was the asymptotic average length and L_0 was the length at age 0. The best fit (based on Bayesian Information Criterion) MCMC model used to estimate growth parameters is also reported: Von Bertalanffy (VB), Logistic (Log), or Gompertz (Gom).

Lake Year	Female			Male		
	L_0	L_{inf}	Model	L_0	L_{inf}	Model
Bald Eagle 2019	65.4	232.9	VB	58.9	190.8	VB
Belle 2020	58.7	227.3	Log	60.1	182.3	Log
Bemidji 2019	53.7	273.1	Gom	54.7	257.6	Gom
Big Sandy 2019	55.3	302.7	VB	54.7	237.5	Gom
Big Sandy 2021	59.5	289.9	Gom	57.7	246.9	Log
Big Stone 2019	86.3	299.1	VB	80.2	279.2	VB
Carlos 2021	59.8	234.9	Log	58.9	169.1	Log
Clearwater 2019	73.0	167.5	Log	71.9	117.7	VB
Cloquet 2019	44.8	324.2	VB	44.2	285.7	VB
Collinwood 2020	99.1	253.5	Log	97.2	214.2	Log
Eleventh Crow Wing 2021	58.5	260.6	Gom	58.6	271.4	Log
Fish Trap 2021	60.6	183.7	Log	61.0	172.7	Log
Green 2019	58.6	212.9	Gom	57.8	141.9	Log
Green 2021	56.5	247.5	Log	59.3	125.0	Gom
Gull 2019	70.5	233.2	Log	69.3	146.2	VB
Gull 2020	60.7	220.4	VB	60.2	134.0	VB
Gull 2021	61.2	191.9	Log	64.1	205.1	VB
Hill 2019	59.1	188.1	Gom	59.7	157.1	VB
Hill 2021	66.0	161.5	Log	69.9	168.3	VB
Independence 2019	71.3	214.7	Log	71.7	191.7	Log
Kabekona 2020	65.0	285.9	Log	69.4	142.7	VB
Little Birch 2019	58.5	264.0	Log	62.6	196.8	Log
Lower Bottle 2019	57.9	224.2	Log	54.8	172.2	VB
Marion 2020	121.0	282.6	Gom	115.7	194.7	Gom
Minnie-Belle 2020	62.9	199.6	Gom	61.9	118.0	Log
Otter Tail 2019	58.5	274.4	Gom	64.1	254.5	Gom
Otter Tail 2021	54.9	285.8	VB	55.6	244.6	Gom
Pelican 2019	57.1	256.7	Log	59.9	141.8	VB
Pelican 2020	58.4	285.8	Log	60.5	103.0	VB
Pelican 2021	59.1	282.8	Log	57.3	96.7	VB
Pike 2019	63.5	227.8	Gom	64.1	110.0	VB
Pleasant 2019	57.7	191.4	Log	58.5	176.8	Log
Shaokotan 2021	56.8	224.4	VB	55.7	185.7	VB
Stella 2021	65.1	142.7	VB	57.1	106.9	VB
Upper Bottle 2019	62.0	251.0	Log	58.7	154.4	Log
Washington 2019	53.9	200.6	Log	57.9	172.4	Log
Washington 2021	59.1	234.7	Gom	58.7	180.2	Log

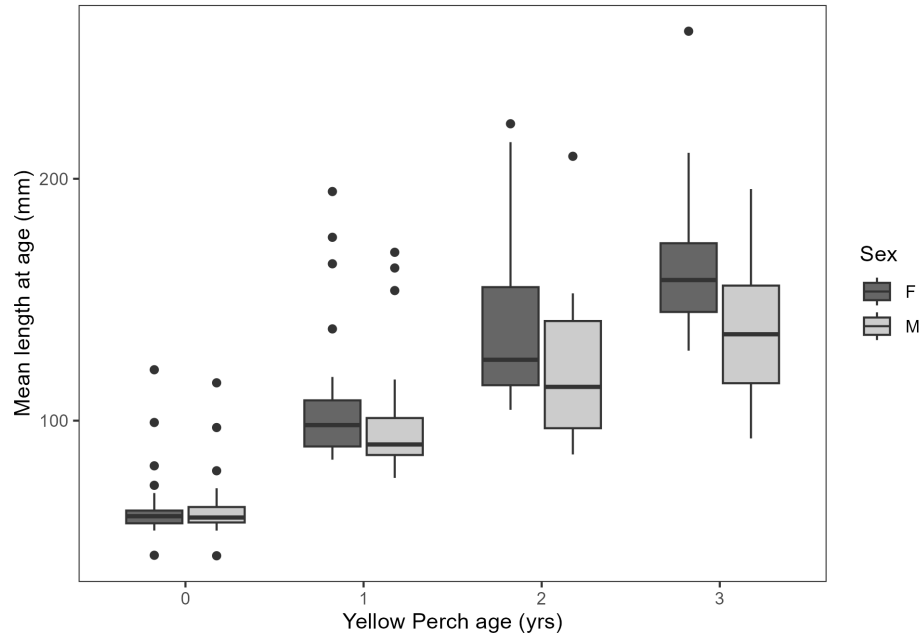


Figure 11. Boxplot distribution of the mean length (mm) at age (yrs) for populations in this study. Ages were estimated in the fall prior to spawning. Dimorphic differences were biologically minimal at age 0 (< 1 mm) and increased each subsequent year.

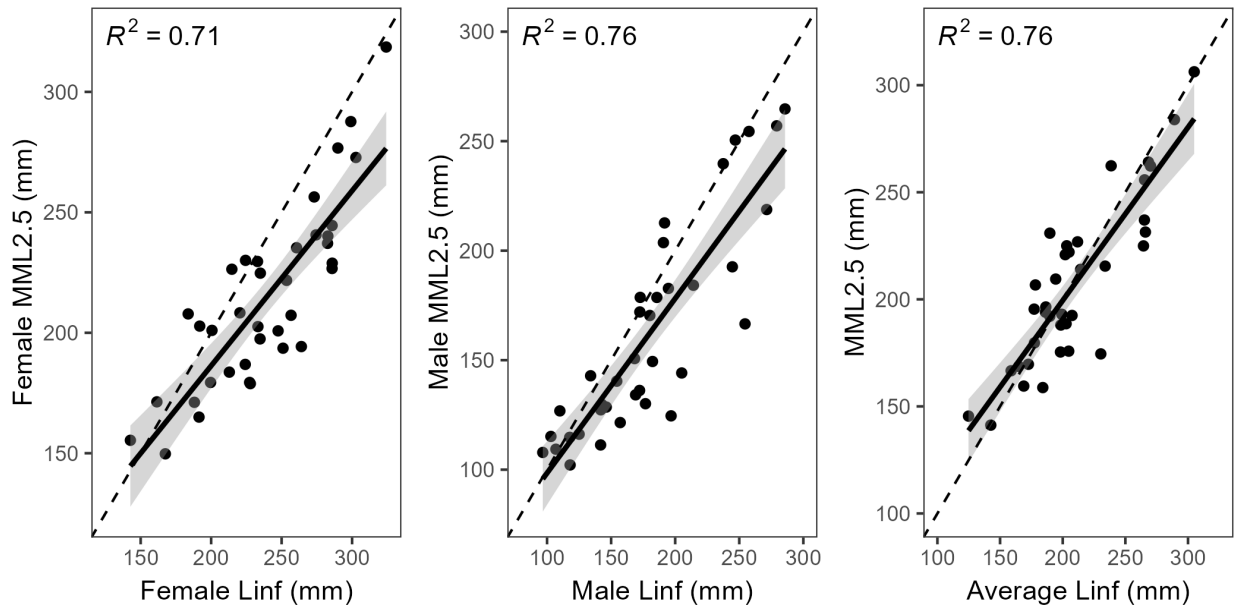


Figure 12. Yellow Perch mean maximum length of the largest 2.5% of fish sampled (MML2.5) compared against Linf from Bayesian growth models for females (left panel), males (middle panel), and all Yellow Perch irrespective of sex (right panel). In the right panel, Linf from Bayesian growth models was averaged for females and males. The dashed line represents a 1:1 line, the solid line represents a linear regression, and shading represents the 95% confidence interval of the linear regression.

MML2.5 for females was, on average, 53 mm greater than the MML2.5 for males. Similarly, results from a paired t -test indicated that, on average, female L_{inf} was greater than male L_{inf} by 59 mm. Both comparisons highlight the effects of dimorphic growth whereby the largest individuals in Yellow Perch populations were predominantly females. When comparing longevity between sexes, the MMA of the oldest 2.5% of females across all gears was significantly greater than the MMA of the oldest 2.5% of males for each lake-year (Wilcoxon rank sum test, $W = 950.5$, $p = 0.0041$), with an average difference of 1.1 yrs (Figure 13).

We evaluated the effects of sample size on MML-based metrics (MML2.5, MML5, and MML10), un-

derstanding that in most lakes standard gill-net data would be used without supplemental experimental sampling gears, so sample sizes may commonly be less than the minimum collected for this study ($n \geq 300$). We found that MML2.5 and MML5 required larger samples sizes ($n \geq 150$) to stabilize variance compared to MML10, which needed a standard gill-net sample size of approximately 100 to stabilize variance, making it a more useful metric for lakes that have mid-catch rates of Yellow Perch. Additionally, MML10 was preferable as a management metric because it was simpler to calculate the number of fish to include in the metric (upper 10%) and to remember the minimum sample size ($n = 100$). MML10 was strongly correlated

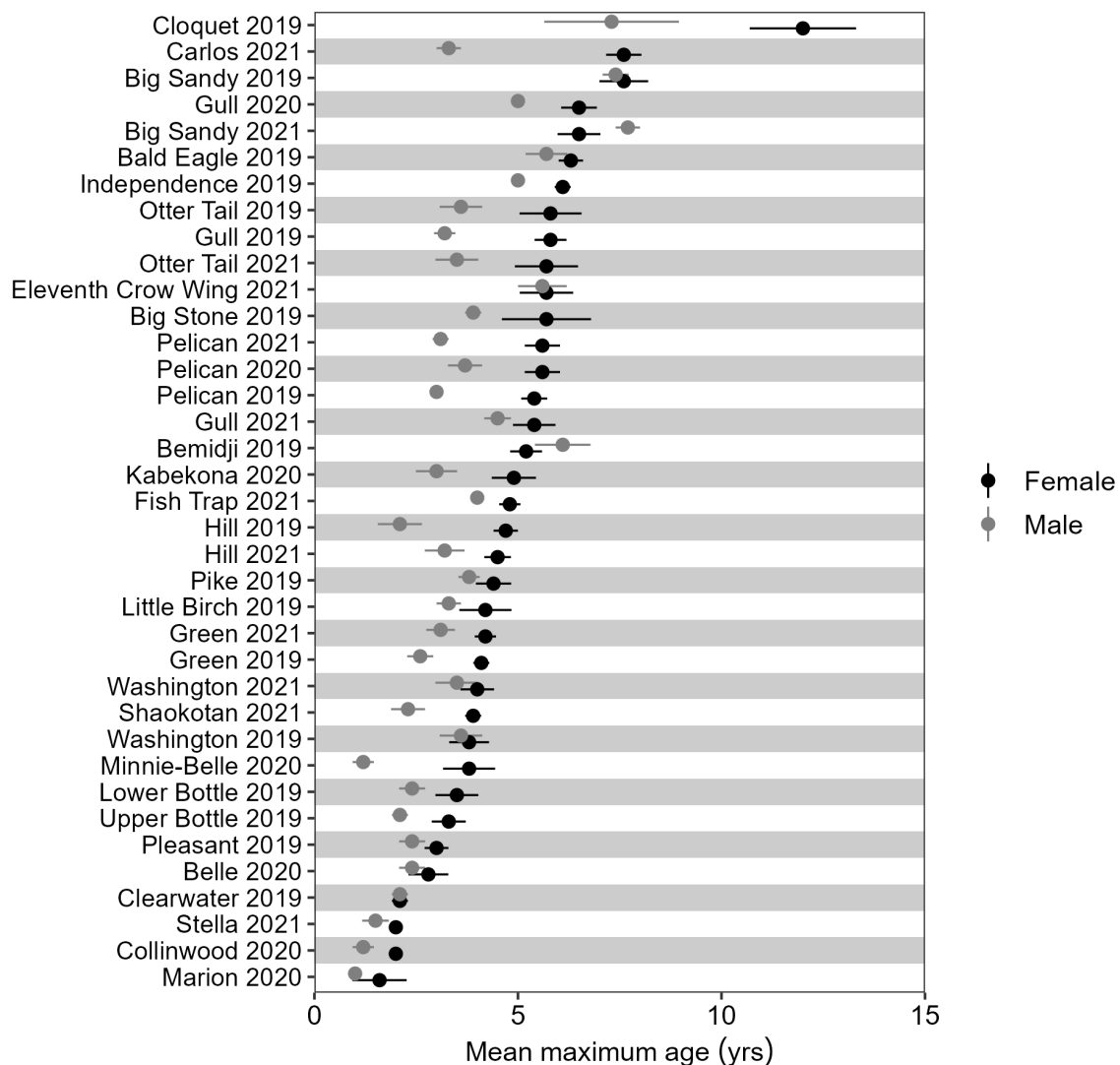


Figure 13. Yellow Perch mean maximum ages in years (yrs) of the oldest 2.5% of females and the oldest 2.5% of males in each lake-year using all gears and assigned ages for all fish. Error bar estimates are the 95% confidence interval. The median value of 3.9 yrs is also shown (dashed line).

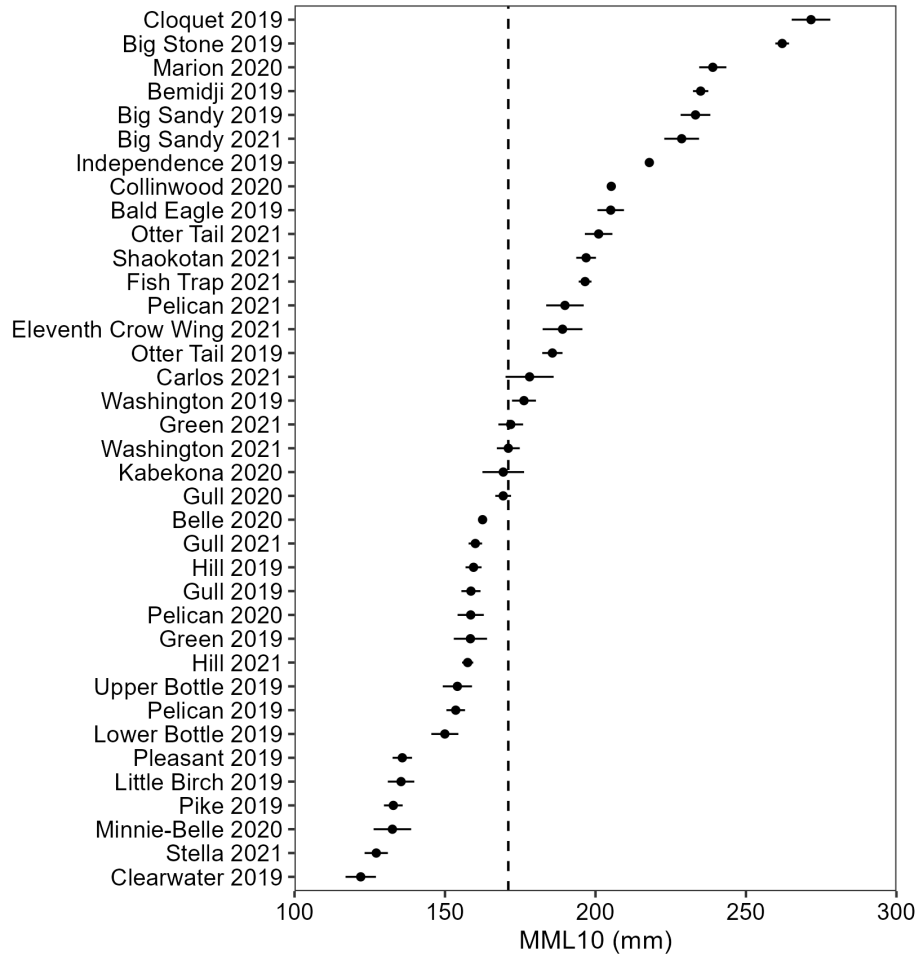


Figure 14. Mean maximum length of largest 10% of Yellow Perch (MML10) from all gears in each study lake and year. Error bars represent 95% confidence intervals. The median value of 171 mm is also shown (dashed line).

with MML2.5 ($p < 0.0001$, $R^2 = 0.92$, $F_{1,35} = 389.1$) and with the average L_{inf} for females and males ($p < 0.0001$, $R^2 = 0.65$, $F_{1,35} = 65.43$), although the correlation was lower than with MML2.5 and deviated more strongly from a slope of one ($p = 0.0049$).

MML10 varied across sampled populations from 122 to 272 mm and the median was 171 mm (Figure 14). MML10 was also positively correlated with female L_{50} ($p < 0.0001$, $R^2 = 0.42$, $F_{1,34} = 25.1$, Figure 15). Natural log-transformed MML10 was positively correlated with natural log-transformed catch per unit effort from standard gill nets ($p < 0.0001$, $R^2 = 0.59$, $F_{1,35} = 50.43$) indicating that populations with a larger maximum size were more likely to being caught in standard surveys, especially at MML10 > 175 mm (Figure 15). In our study lakes, MML10 was also positively correlated with MMA2.5 ($p < 0.0001$, $R^2 = 0.38$, $F_{1,35} = 21.87$), indicating that longevity was an important characteristic of pop-

ulations that reached larger maximum sizes.

Female survival estimates from the fine-mesh gill nets varied from 17.7% to 44.5% with a median value of 33.3% (Figure 16). Female survival estimates from the standard gill nets varied from 23.5% to 75.3% with a median value of 41.8% (Figure 17). Survival estimates for fish sampled by fine-mesh gill nets were significantly lower than survival estimates for fish sampled by standard gill nets (Wilcoxon rank sum test, $W = 36$, $p = 0.011$). Based on the criteria used to model catch curves, populations included in the analysis for fine-mesh gill nets were generally slow-growing and smaller-bodied, while populations included in the analysis for standard gill nets were generally faster-growing and larger-bodied. Because of the criteria used for modeling (a minimum of three age-classes after the peak catch), populations with higher longevity were overrepresented in the data and likely represent-

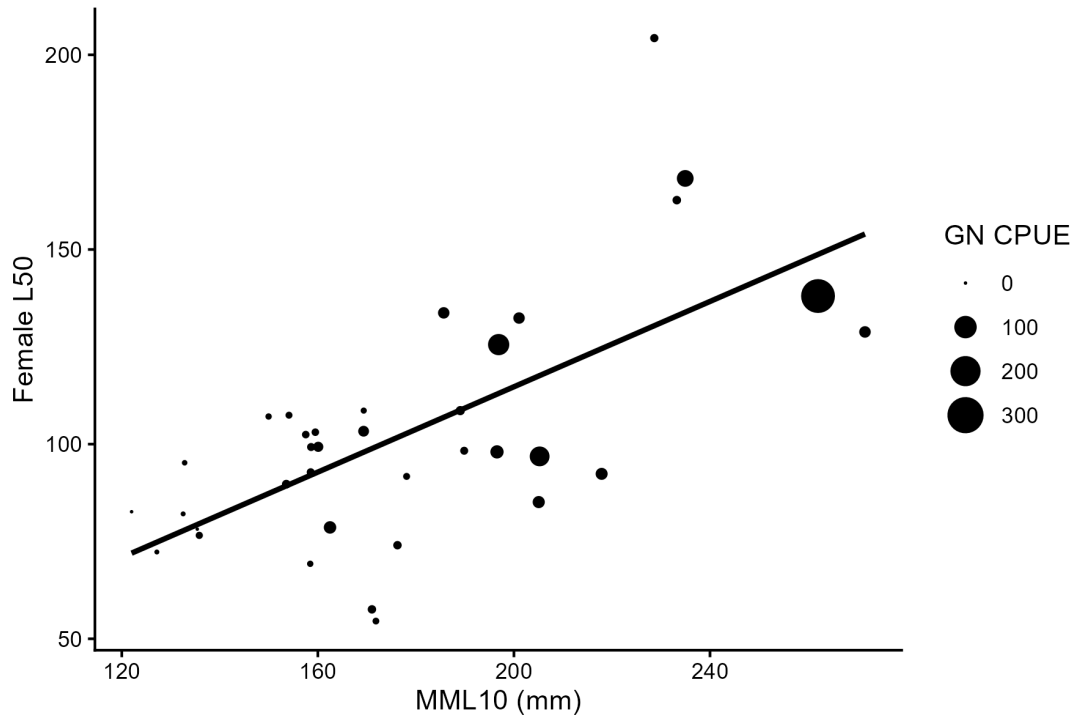


Figure 15. Relationship between mean maximum length of the largest 10% (MML10) of Yellow Perch from all gears and estimated female length at 50% maturity (female L50). The size of the points indicates catch rates in the standard gill-net survey (GN CPUE).

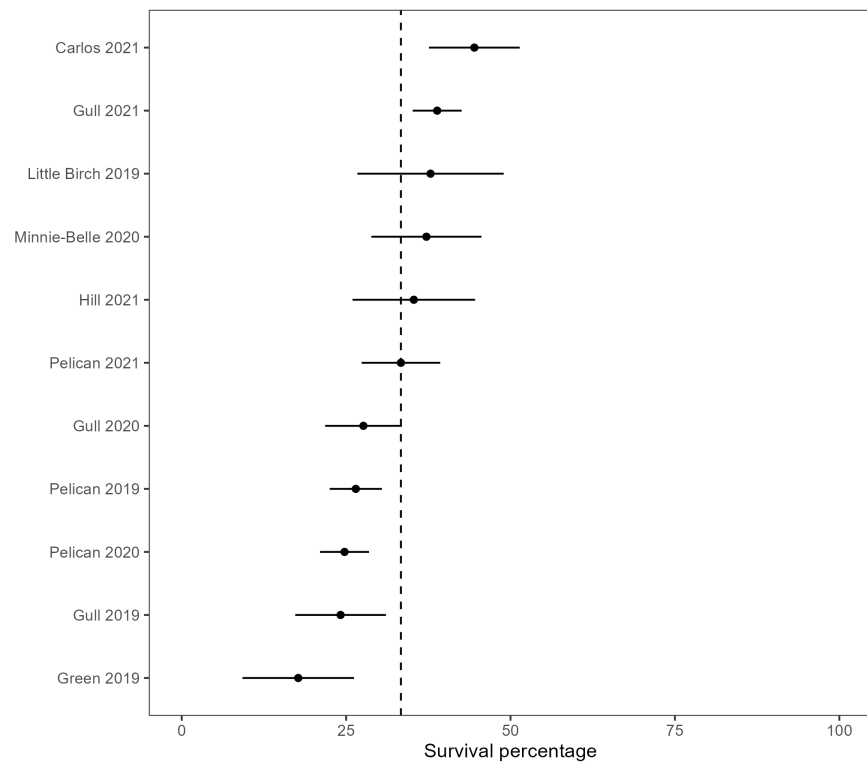


Figure 16. Chapman-Robson survival estimates for female Yellow Perch captured with fine-mesh gill nets, using populations where there were at least three age-classes sampled after the peak catch with a mean length < 200 mm (the maximum length caught in the largest 19.05-mm fine-mesh gill net mesh size). Error bars are the 95% confidence interval. The median value of 33.3% is also shown (dashed line).

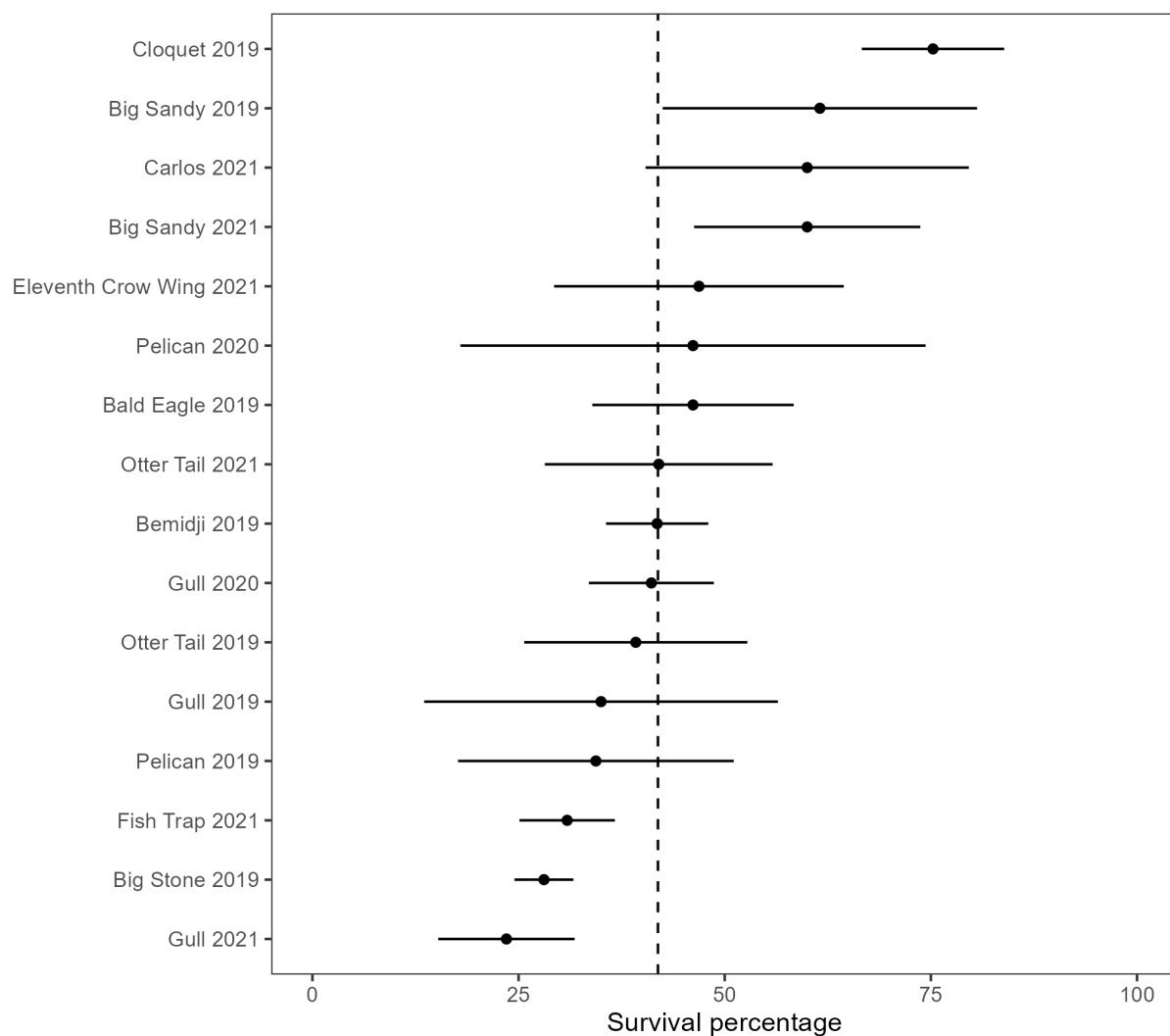


Figure 17. Chapman-Robson survival estimates for female Yellow Perch captured with standard gill nets. Populations included in analysis include only those sampled where at least three age-classes were present after the peak catch that had a mean length > 144 mm (the minimum length caught in the 19.05-mm smallest standard gill-net mesh size). Error bars are the 95% confidence interval. The median value of 41.8% is shown with a dashed line.

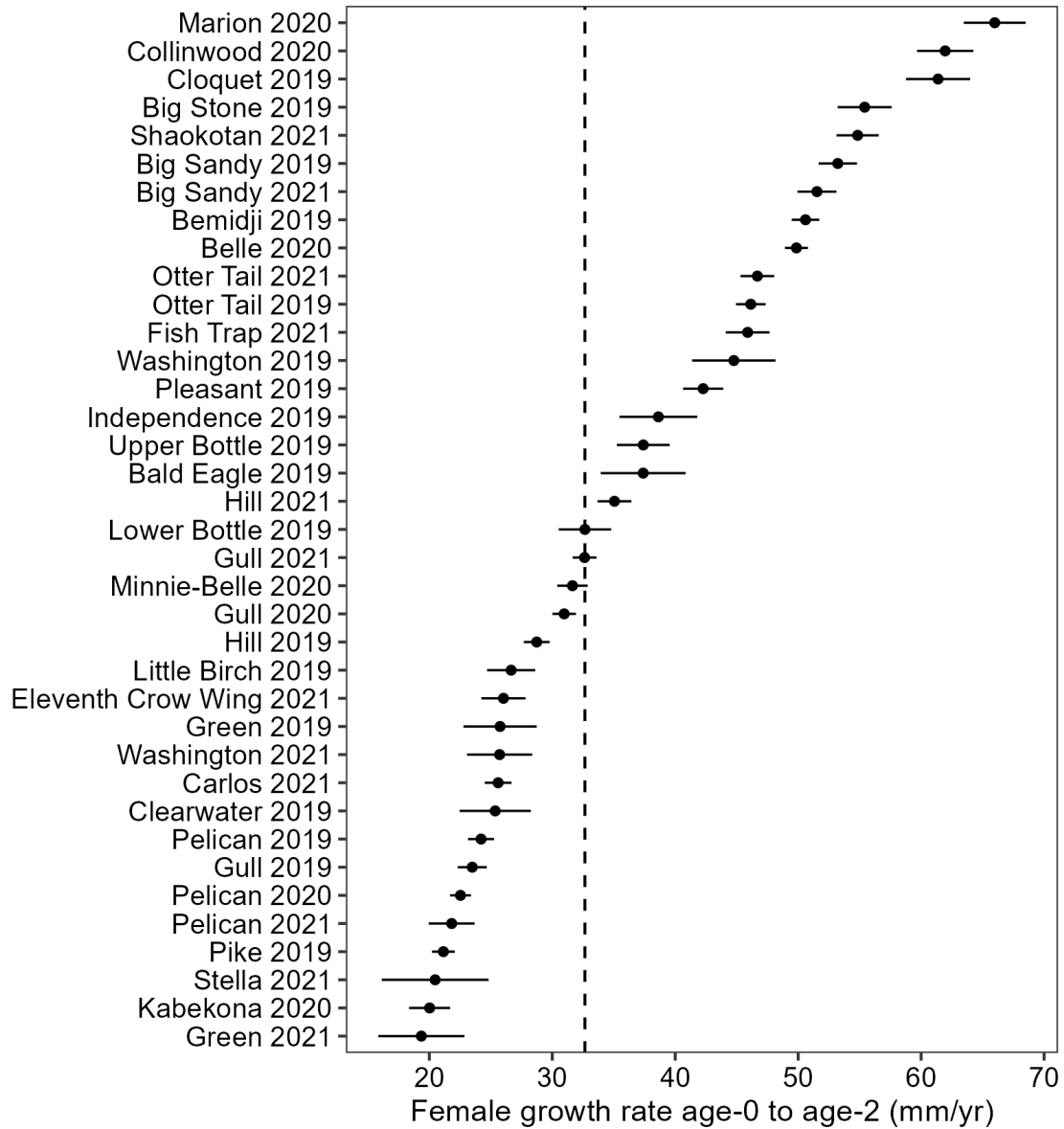


Figure 18. Female growth (mm yr⁻¹) from age 0 to age 2 for lake-years sampled as part of this study. Confidence intervals are $\pm 2 \times \text{SE of the slope}$ from a linear regression. The median value of 32.7 mm is also shown (dashed line).

ed a “best case scenario” for mortality estimates.

Linear growth from age 0 to age 2 differed among populations, ranging from 19.4 mm yr⁻¹ to 66.0 mm yr⁻¹ (Figure 18). Female growth from age 0 to age 2 was not correlated with the average length-at-age 0 L_0 from Bayesian growth models ($p = 0.08$, $R^2 = 0.08$, $F_{1,35} = 3.2$) but was correlated with MML10 ($p < 0.0001$, $R^2 = 0.54$, $F_{1,35} = 40.61$). Because simple linear regression analysis indicated that female growth and MMA2.5 were individually positively correlated with MML10, a multiple regression analysis was conducted with these variables using MML10 as a response variable. The multiple regression with the lowest BIC included positive slope estimates for female growth and MMA2.5. The overall model was significant ($p < 0.0001$, $F_{2,34} = 58.87$) and explained 76% of the variability in MML10, indicating that both longevity and high growth rates were important factors associated with Yellow Perch populations that had a larger size structure.

Statewide changes in size structure

We evaluated changes in Yellow Perch size structure over time using data from the MN DNR statewide standard gill-net database and found that MML10 has decreased an average of 5.6 mm from 1994 to 2021 in 344 lakes across Minnesota that had a minimum of three surveys with a minimum sample size of 100 Yellow Perch per survey (Figure 19). MML10 declined 25 mm or more in 17% of lakes and increased 25 mm or more in only 6% of lakes. Among lakes in Minnesota where at least three gill-net surveys were conducted between 1994-2021, the total number of lakes surveyed annually has not changed ($p = 0.172$, $R^2 = 0.07$, $F_{1,25} = 1.974$). However, among lakes in Minnesota where at least three gill-net surveys were conducted between 1994-2021, the number of lakes with Yellow Perch catch rates of ≥ 100 per net has declined significantly ($p = 0.00059$, $R^2 = 0.38$, $F_{1,25} = 15.45$). This trend indicates that more populations are falling below the minimum sample size needed to calculate MML10, suggesting that other metrics and/or larger sample

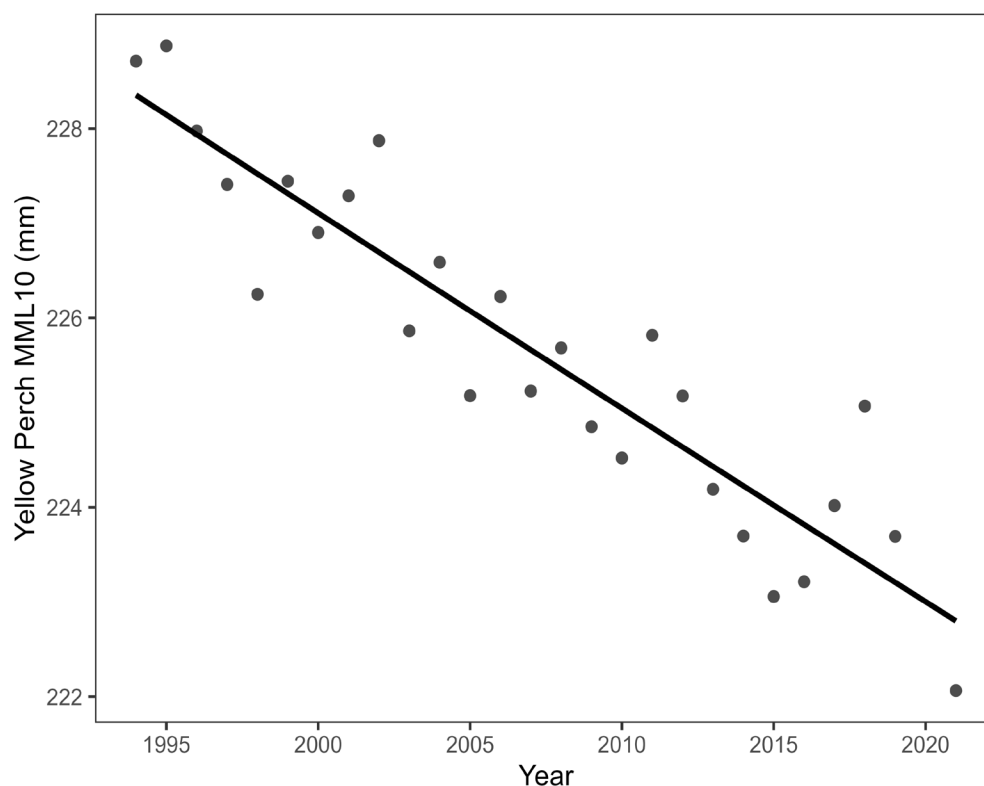


Figure 19. Average change in mean maximum length of the largest 10% of individuals (MML10) in statewide standard gill net surveys from 1994 to 2021 ($n = 344$ lakes). Points represent the average estimated MML10 for all lakes sampled within each year, and the line represents the back-transformed statewide trend from the mixed-effects model. The year 2020 was omitted from the analysis because fewer lakes were sampled that year due to the Covid-19 pandemic.

sizes (i.e., using experimental sampling gears) may be necessary to assess changes in size structure for lakes with low catch rates in standard gill nets.

Discussion

Our objectives were 1) to develop sampling and analysis tools for evaluating indirect metrics of Yellow Perch populations and 2) to understand the range of Yellow Perch population characteristics in Minnesota Lakes. Three important findings of the study meet these objectives and provide tools for fisheries management. First, fine-mesh gill nets and boat electrofishing can be used to supplement standard gill net collection of Yellow Perch, and the experimental gears result in comparable biological characterization of populations despite some statistical differences. This means both or either gear can be deployed to obtain supplemental Yellow Perch population information, allowing fisheries managers to select the sampling method most practical for supplemental data needs. Second, a relatively simple metric, MML10, is correlated with more complex metrics such as L_{inf} and female L_{50} and can be used as an initial assessment tool to evaluate populations, using standard or experimental data collection. Third, we documented variation in Yellow Perch population characteristics across Minnesota lakes, yet an analysis of MML10 over time using a broader statewide dataset indicated significant declines in the size structure of Yellow Perch statewide, likely causing changes to catchability of populations in standard gill nets.

Given the widespread decrease in size structure impacting Yellow Perch populations, fisheries managers will likely continue to face challenges in interpreting declining Yellow Perch catch rates in standard gill nets. Fisheries managers can choose from a menu of options developed in this study to further investigate the low or changing Yellow Perch catch rates, with options ranging from simple additional analysis of standard data already available to intensive supplemental sampling using additional gears and including collection of sex, maturity, and age data. Fisheries managers may also engage in additional investigation of Yellow Perch progressively, beginning with lower effort options based on data on-hand, such as MML10 from existing survey data, then continuing to additional data collection, such as experimental sampling, as necessary to meet management data needs.

Boat electrofishing and fine-mesh gill nets were

both effective sampling gears for capturing Yellow Perch larger than 50 mm, and boat electrofishing also captured Yellow Perch smaller than 50 mm. Comparatively, the minimum length of Yellow Perch captured in standard gill nets was 140 mm. In this study, over 90% of lakes had a female length at maturity smaller than 140 mm and 80% of lakes had standard gill-net catches composed of greater than 80% females, indicating that standard gill nets in many lakes may sample only a subset of mature fish that may not be representative of the overall population.

Sampling crews noted additional considerations associated with deploying gear types in different lakes. For instance, known high densities of Rusty Crayfish *Faxonius rusticus* deterred management staff from using fine-mesh gill nets in some lakes. Other survey crews found that boat electrofishing resulted in low catch rates despite high effort and preferred to set fine-mesh gill nets. For example, staff from the Hutchinson Area Fisheries Office attempted to sample Yellow Perch using both fine-mesh gillnetting and boat electrofishing in 2019 and determined that boat electrofishing yielded low sample sizes despite high effort, so fine-mesh gill nets were exclusively used in subsequent lake-years. There may also be additional workload considerations associated with different gear types. For example, boat electrofishing required only one trip to the lake but could be time consuming and inefficient if catch rates were low. In contrast, fine-mesh gillnetting required two trips to the lake and time to remove fish from nets but may be more efficient for catching the minimum sample sizes required in this study ($n = 300$). Given that data resulting from both experimental gears is comparable, fisheries managers can deploy the experimental gear most practical for the given circumstances.

In addition to fish being collected with different experimental gears, processing of fish varied among gear types in ways that may have impacted length measurements. Fish captured in standard gill nets and fine-mesh gill nets were processed fresh, but fish captured with boat electrofishing were frozen, thawed and then processed. The difference in processing resulted from the practical circumstances around the sampling types. First, electrofishing was often conducted in the evening and intensive fish processing in the night was not reasonable compared to daytime retrieval and processing of fish sampled in gill nets. Second, when fish are frozen shortly after being captured (as with boat electrofishing) they can be thawed

with minimal additional decay compared to fish caught in nets that may be deceased for several hours before being retrieved (as with gill nets).

The total length of Yellow Perch may decline by approximately 0.7-2.5% when freezing and thawing fish prior to measurement (Engel 1974; Mike McInerney, unpublished data), so declines in length associated with freezing may have decreased average L_{50} estimates for boat electrofishing samples by approximately 1-2 mm. Therefore, the average difference in L_{50} between boat electrofishing and fine-mesh gillnetting may have been approximately 11 to 12 mm for females and 3 to 4 mm for males if all fish had been processed fresh. Despite these differences between experimental gear types, estimates of A_{50} and L_{50} were biologically similar within a lake, particularly when compared to the range of estimates between lakes. Therefore, if freezing fish sampled via boat electrofishing is more practical than processing the fish immediately following capture, it can be done with likely minimal impact on data interpretation.

We documented an unexpected difference in length of Yellow Perch sampled in the same mesh size of different gears. The median length of Yellow Perch sampled in fine-mesh gill nets was statistically larger than the median length sampled in standard gill nets in the 19.05-mm mesh common to both nets. One reason for this consistent difference may be that standard gill nets were generally set in the summer compared to fine-mesh gill nets that were set in September, so continued fish growth might account for some length differences. However, both fine-mesh gill nets and standard gill nets were set at the same time in Big Stone Lake and there were still significant differences in the length distribution and median lengths between gill-net gears, with the median approximately 19 mm larger for fine-mesh gill nets.

The difference in net material between the two gill net types is another possible explanation for the observed length difference. Fine-mesh gill nets were made of monofilament mesh while standard gill nets were made of multifilament knotted-nylon mesh. Yellow Perch that were too large to wedge in the monofilament mesh may have become more easily entangled by their teeth or gill plates in monofilament nets relative to the multifilament mesh. The extent to which net material may cause these differences is unknown, however, a comparison study of net materials in Lake Erie found that Yellow Perch catch per unit effort

was higher in monofilament than multifilament gill nets, but there was not a statistical difference in size (Hendersen and Nepszy 1992). In contrast, a comparison study of net materials in Lake Michigan found statistically larger lengths of Yellow Perch were captured in monofilament nets compared to multifilament nets, but the difference in mean length was only 5 mm (Smith et al. 2022).

While the resulting impact on modeled life history was minimal compared to across-lake differences, within lakes the sex and maturity status of fish sampled by the two experimental gears did differ. More mature females were sampled with fine-mesh gill nets than with boat electrofishing, although males tended to comprise a greater proportion of fine-mesh gill-net samples overall. These results indicate that there may be distinct behavioral differences between sexes, with females more likely to occupy nearshore (< 2 m) habitats sampled with boat electrofishing and males more likely to occupy deeper (> 3 m) habitats sampled with fine-mesh gill nets. Additionally, females occupying deeper habitats sampled with fine-mesh gill nets may mature at smaller sizes compared to females occupying shallower habitats. Evidence of population segregation by sex or size has been documented in other Yellow Perch populations. Doll et al. (2020) found that the proportion of females sampled in gill nets in the Indiana waters of Lake Michigan varied from 10 to 95% over the course of the season. Rada-baugh et al. (2010) found significant differences in movement and depths across seasons for different Yellow Perch sizes and sexes in both a complex and simple lake. Additionally, Sandheinrich and Hubert (1984) found that females were more likely to occupy warm, shallow waters while males were more likely to occupy cool, deeper waters in an Iowa lake.

We found strong evidence of sexual size dimorphism (SSD) in all 28 populations in this study, similar to other studies that have found growth differences between male and female Yellow Perch (Malison et al. 1988; Purchase et al. 2005; Rennie et al. 2008; Uphoff and Schoenebeck 2012). Males matured earlier at smaller sizes, grew slower, reached a smaller MML, and had a shorter MMA. Interestingly, we detected statistical evidence of SSD at all ages, although differences were < 1 mm at age 0, and increased with each subsequent age-class. SSD has been associated with the onset of maturation (Malison et al. 1985; Shewmon et al. 2007; Rennie et al. 2008) and in our study, most male populations were maturing at the end of their

first summer (age 0), which may explain why statistical differences were detected even at young ages. SSD in Yellow Perch is associated with hormones including estrogens and androgens that cause physiological differences between sexes (Malison et al. 1986; Goetz et al. 2009; Lynn et al. 2009). Studies have found that male Yellow Perch have lower consumption rates and less efficient energy conversion of food (Malison et al. 1988; Rennie et al. 2008) and higher anaerobic activity (Schoenebeck and Brown 2012). Our study also suggests that SSD may also result in higher rates of mortality, with females outliving males by 1.1 years on average.

Statistical models for estimating and mortality and survival, including the Chapman-Robson method we applied, rely on important assumptions about the population analyzed (Dunn et al. 2002). The assumption that the population has a stable age structure is unlikely in Yellow Perch populations because their recruitment is inconsistent year-to-year due to environmental and ecosystem conditions (e.g., Arranz et al. 2015; Dembkowski et al. 2016). Further, age structure is likely destabilized by inconsistent mortality across the sizes of fish recruited to the gears applied in this study, given size-dependent predation (e.g., Post and Evans 1989), winter- and summer-kill events (e.g., Phelps et al. 2019), and variation in angling pressure among lakes (e.g., Cook et al. 1997). Our results demonstrate differences in the size and sex of fish sampled by different gears, and interconnections between sex, size, maturity, and age of individuals within populations. We addressed the known constraints of our dataset for mortality and survivability estimation by filtering it to a subset less likely to materially violate the above assumptions. This limited analysis to only the female data collected with fine-mesh and standard gill nets from about half of the lake-year surveys. Still, the resulting survival estimates should be treated with caution because almost all populations had catches with fewer than 10 individuals for age-classes older than age 5, but Dunn et al. (2002) and Smith et al. (2012) both recommended that all age-classes should be included in the Chapman-Robson analysis rather than applying criteria for right truncation. Finally, it should be noted that neither fine-mesh gill nets nor standard gill nets captured the entire range of Yellow Perch sizes and ages, except for the smallest-bodied populations, so each gear is only partially representative of overall mortality.

Estimates of female survival were approximately

10% higher for Yellow Perch sampled with standard gill nets compared to fine-mesh gill nets, perhaps because fish were larger in the standard gill nets (> 140 mm) and less susceptible to predation. In contrast, populations modeled in the fine-mesh gill nets were smaller-bodied (< 200 mm) and may have been more susceptible to predation. Natural mortality, including predation, was likely the main source of mortality for populations modeled from fine-mesh gill nets because most of these populations were too small to be targeted by anglers. Mortality estimates of populations from standard gill nets also likely included fishing mortality for at least some of the populations, including Bemidji, Big Sandy, Big Stone, and Otter Tail. Our estimates of survival are similar to the mark-recapture estimate of 35% from a slow-growing population in South Dakota (Schoenebeck and Brown 2011), and to catch-curve estimates from several South Dakota lakes that varied from 24% to 66% (Isermann et al. 2007). In our analysis, longer-lived populations were overrepresented because due to the data filtering we applied, so these estimates likely represent “best-case scenario” survival estimates compared to shorter-lived populations with few age-classes. These low catch rates of older fish may explain the higher error estimates in standard gill nets, which were generally modeled on populations age 3 or age 4 and older.

We were surprised by a lack of asymptote in the length at age of Yellow Perch populations sampled. Traditional growth modeling methods rely on a plateauing of length at age, but the generalized framework developed by Smart and Grammer (2021) provided a flexible approach more appropriate for this dataset. The tradeoff is that the Bayesian methods we applied, and examination of multiple growth models to determine methods most appropriate for different age-structured populations, are relatively inaccessible to fisheries management staff at the time of this publication. However, the correlations between parameters from the models and easier to obtain estimates, such as MML10, allow for approximations of similar information with less intensive statistical methods. The reality of managing multiple sportfish populations across thousands of water bodies, including adapting to changes in climate, land use, and invasive species, is that fisheries management staff need tools for assessing populations that do not require extensive time and expertise. This study does not prescribe any one approach for assessing a Yellow Perch population, but the findings further delineate the network of interrelated life

history traits present in Yellow Perch in Minnesota.

Fisheries managers can gain insight about Yellow Perch populations by leveraging the correlations among life history traits documented in this study. We found significant positive correlations between length at maturity, proportion of females in standard gill nets, age at maturity, and MML. Similar to this study, life history metrics including age and length at maturity were found to be correlated in Great Lakes stocks of Yellow Perch (Feiner et al. 2017), indicating that this pattern is likely consistent across different populations. These relationships indicate that not all metrics may need to be sampled to make inferences about populations. For example, if a Yellow Perch population has a relatively longer MML10, it is likely that this population also has a relatively longer length at maturity and later age at maturity. Alternatively, if Yellow Perch sex is evaluated from standard gill nets and the percentage of females is greater than 90%, it is likely that maturity occurred earlier and at smaller sizes so that catch rates in standard gill nets may only represent a small proportion of the overall population. One challenge associated with evaluating sex from summer gill nets was that in two of the southernmost lakes (Collinwood and Marion), surface temperatures were so warm in July and August that fish deteriorated and sex could not be accurately evaluated. In most lakes, however, sex could be differentiated during summer surveys, although maturity was challenging to evaluate and was not assessed in summer fish.

One of the most significant findings of this study was evaluating MML10 using a larger long-term statewide dataset and discovering that this metric has steadily declined from 1994 to 2021. Because MML10 was correlated with metrics like female L_{50} and MMA2.5, we hypothesize that the life history of Yellow Perch has also changed. A shift in size structure over time likely has reduced catchability of Yellow Perch in standard gill nets and may explain decreased statewide catch rates over time (Bethke and Staples 2015). Results from a multiple regression analysis also indicated that MML10 was strongly correlated with longevity and growth, suggesting that statewide populations may have shorter lifespans and/or are growing slower compared to the past. Longevity and growth of Yellow Perch and of the closely related Eurasian Perch have been correlated with water temperature/latitude and lake productivity (Abbey and Mackay 1991; Heibo et al. 2005). For example, Yellow Perch maximum body size was positively correlated to lake

surface area and negatively correlated to growing degree days in a study of 72 Ontario lakes (Purchase et al. 2005). Water temperatures and lake productivity are changing in Minnesota lakes (e.g., Olmanson et al. 2008; Jane et al. 2021; Schoenebeck et al. 2026), so future work will explore these and other variables to better understand correlations with Yellow Perch life history traits.

Management recommendations

As a result of this project, we recommend different management strategies when additional information is needed to evaluate Yellow Perch populations. A simple and informative metric that does not require additional sampling is the calculation of MML10 using standard gill-net data. MML10 less than 175 mm is likely indicative of a smaller-bodied population that may be less susceptible to being captured in standard gill nets. Additionally, evaluating MML10 over time can be used to determine if the size structure has changed, altering catchability in standard gill nets and potentially affecting catch rates. One caveat for using MML10 is that a minimum sample size of 100 is recommended for calculating this metric and over time fewer lakes have met this minimum threshold. Assessing size structure in lakes with lower catch rates of Yellow Perch may require evaluating different metrics and/or supplementing standard gill-net surveys with additional sampling. Another metric that could be used to confirm a smaller-bodied size structure is to evaluate the sex of Yellow Perch captured in standard gill nets and calculating the percentage of females. A high percentage of females (> 90%) in standard gill nets may indicate a more stunted population that is not representatively sampled in standard surveys.

If more information is needed for evaluating small-bodied Yellow Perch populations, we recommend using additional sampling gears such as boat electrofishing and/or fine-mesh gill nets to collect fish less than 140 mm. For example, in lakes with low catch rates in standard gill nets, managers may want to evaluate whether Yellow Perch are present but are too small to be caught in the minimum mesh size. Either experimental gear can be used to assess populations and can be selected based on the purpose of sampling, the presence of invasive species, effectiveness of boat electrofishing in individual lakes, and individual office workload. Depending on management objectives, these gears can be used to collect supplemental Yellow

Perch data such as comprehensive size structure, length at maturity, age at maturity, number of age-classes, and growth. For example, evidence of high mortality could be indicated by an early age at maturity and/or the presence of few age-classes (provided that adequate sample sizes have been obtained, see MN DNR 2018). Calculated metrics from these experimental gear types can be compared to the overall gradient we documented in this project to assess a population relative to other sampled Yellow Perch populations. Finally, due to dimorphic growth, we strongly recommend that sex should be evaluated for any Yellow Perch where age structures are collected, including those fish that are sampled during standard surveys.

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