An evaluation of Walleye stocking strategies in tributary reservoirs

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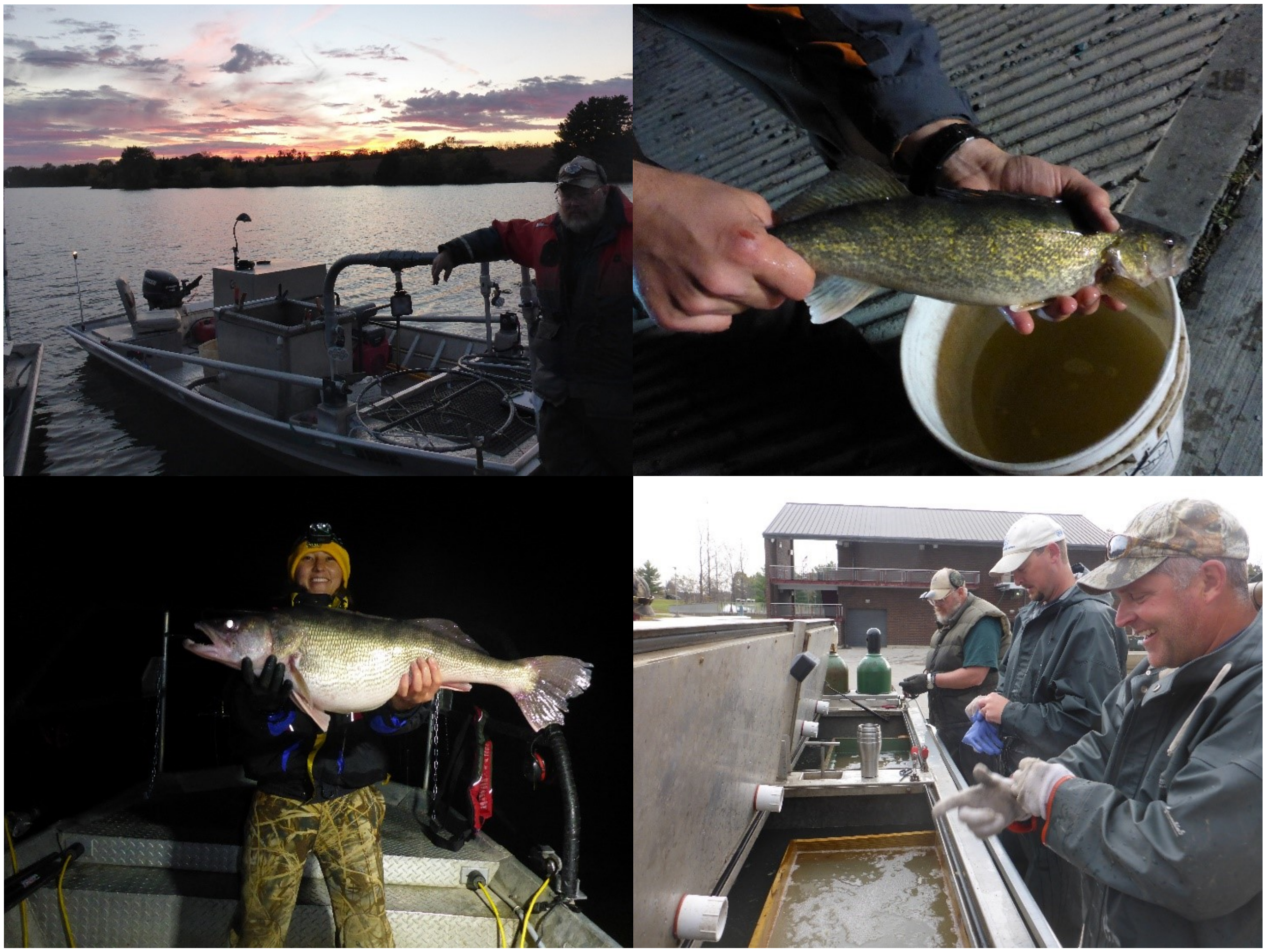
Study 7041 Completion Report
Federal Aid to Sport Fish Restoration
Iowa Fisheries Research



Rebecca M. Krogman
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Iowa Department of Natural Resources
Kayla Lyon, Director

WILDLIFE & SPORT FISH RESTORATION

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Executive Summary

Walleye are an important recreational fish species in Iowa and, along with black bass, are targeted by more anglers than any other taxon (Responsive Management 2019). Each year, the Iowa Department of Natural Resources (DNR) produces over 150 million fry; over 1 million fingerlings; and hundreds of thousands of advanced fingerlings in its hatcheries for stocking throughout the state (Clouse et al. 2011, 2014-2019; Iowa DNR 2012; Rudacille et al. 2013), and Walleye stocking requests continue to increase. Stocking in many locations, such as reservoirs, is necessary to maintain a Walleye population due to lack of natural recruitment in those systems (e.g., Mitzner 1992). The cost of producing each size of Walleye differs, with fry being the cheapest to produce (up to $0.00269/fish stocked) and advanced fingerlings being the most expensive (up to $1.83/fish stocked). Survival of stocked fish to the adult stock and contribution to the recreational fishery affect ultimate cost per fish to the angler. Thus, evaluation of survival of each size is necessary to ensure stocking strategies are cost-effective. Unnecessary grow-out or stocking of fish in inappropriate locations/times results in wasted hatchery resources, ultimately costing the angler.

Walleye stocking evaluations have been conducted in the Midwest for decades, with numerous size-at-stocking evaluations indicating increased survival for fingerlings exceeding 5 inches in length but concurrent increases in production cost (Kampa and Jennings 1998). In Iowa, small fingerlings (4-6 inches) experienced higher first-year mortality than fry-stocked Walleye (McWilliams and Larscheid 1992; Mitzner 1992; Flammang 2000; Walter and Sobotka 2008), resulting in only a 10% contribution of fingerling-stocked fish to overall year-class abundance in natural lakes (McWilliams and Larscheid 1992). Despite this lesser contribution, fingerling stocking may be able to provide more stable year-classes than relying on fry success alone. Limited information on larger fingerling (7-8 inches) Walleye implies that survival to Age 1 may be substantially greater than small fingerlings (Kampa and Hatzenbeler 2009), which could make advanced fingerling culture more cost effective. Unfortunately, results from other states are unclear due to conflicting results and wide variation in sizes examined (e.g., Koppelman et al. 1992; Santucci and Wahl 1993; Parsons and Pereira 2001; Kampa and Hatzenbeler 2009).

In Iowa, Walleye culture in concrete ponds and raceways advanced enough to produce fish with higher survival over the first winter than Walleye fingerlings raised in earthen ponds and stocked at a similar size (Mitzner 1992; Mitzner 2002). Since then, Iowa DNR has further improved Walleye intensive culture techniques, yielding larger advanced fingerling Walleye than have ever been produced in the past (8-10 inches). This merits a renewed investigation of optimal Walleye size-at-stocking. Initial Age-0 survival and survival to adulthood should be investigated for various fish sizes across multiple lakes and reservoirs, along with associated cost per recruit, to provide better stocking recommendations for Walleye.

The objective of this project was to conduct one stocking evaluation that examines the contribution of different sizes of Walleye to lentic recreational fisheries by June 30, 2021.

Based on the findings detailed in Parts 1 and 2 below, I recommend the following regarding Walleye stocking into impoundments and reservoirs in Iowa:

- Prior to Walleye stocking into an impoundment, the waterbody's characteristics (i.e., water quality and fish community) should be examined to determine: A) whether Walleye in general would likely be successfully established through stocking; and B) whether Walleye should be stocked as fry or as advanced fingerlings. Generally, waterbodies with high crappie densities, high Largemouth Bass densities, and high total dissolved and suspended solids were not as Walleye-friendly regardless of size-at-stocking. Fry stocking was more successful in warmer summertime water temperatures and much less successful when Largemouth Bass densities were high.
    - Advanced fingerling stocking is recommended if **Largemouth Bass density exceeds 21.5 fish/hour** of electrofishing, if Walleye stocking occurs, as fry stocking will likely be ineffective. Advanced fingerling stocking is also recommended if crappie density exceeds 90 fish/net-night from modified fyke nets, for the same reason.
    - Walleye stocking is not recommended if total dissolved solids exceed 300 mg/L or total suspended solids exceed 60 mg/L, unless other variables are conducive to Walleye recruitment to adulthood.
    - Walleye friendliness was calculated for all significant publicly-owned impoundments for which data were available. The values presented in this report can be used for individual lakes to compare whether

predicted catch will be greater using fry-stocked or fingerling-stocked fish, and to assess how practical Walleye stocking may be at an individual lake relative to other locations. These formulas are not prescriptive, but rather comparative, to help fisheries managers choose the most efficient stocking method and select more Walleye-friendly locations for establishing fisheries. Because lake characteristics alter the catch curve predictions, changes over time can affect Walleye friendliness of a location.

- Fall nighttime electrofishing catch rates of Age-0 Walleye can serve as an index of year-class establishment, explaining over 92% of variation in catch rates of the same fish at Age-2. Since this electrofishing typically occurs prior to advanced fingerling stocking and indexes fry stocking success, it is called the Fry Index. If the Fry Index exceeds 0.22 Age-0 fish/min, there is a 95% chance of capturing fish from that year-class at Age-2. **If the Fry Index exceeds 0.50 Age-0 fish/min, there is a 95% chance of capturing 5 Age-2 fish/hour of electrofishing two years later. In other words, there is a 95% chance that a year-class has been established through fry stocking, and advanced fingerling stocking is not needed.**
- Walleye population dynamics can rapidly respond to changing conditions, including changes in population density, forage base, and exploitation rate. Although the intended density target was achieved and exceeded, Walleye in Big Creek Lake likely experienced density-dependence when Walleye density was high and Gizzard Shad were absent, resulting in depressed growth, low condition, increased natural mortality, reduced exploitation, and ineffectiveness of regulations. However, at lower Walleye densities, the centrarchid/percid forage supported Walleye growth and condition equivalent to when Gizzard Shad were present. We did not detect many changes in water quality or zooplankton, except for a reduction in turbidity when Gizzard Shad disappeared. Regulations provided variable outcomes over time, and the preferred regulation for the current scenario (high-density Walleye with Gizzard Shad) depends on angler preferences. Big Creek Lake's Walleye fishery provided a useful demonstration of how rapidly a population can respond to changes in density and forage, and therefore how dynamic fishery management needed to be.
- Based on our analysis of Big Creek Lake, **a reasonable management target density for a Walleye population** with a centrarchid- or percid- forage base in a mesotrophic to eutrophic, medium-sized reservoir in the central U.S. **may be greater than 2.9 fish/ha but less than 13.8 fish/ha**.
- Density-dependent reductions in growth were detected using the growth index ω, which is calculated using von Bertalanffy growth parameters. The reduction at Big Creek Lake during a period of limited forage and high adult Walleye density was 50 mm/year. **Use of the growth index to monitor Walleye populations could help management biologists determine more specific, reasonable adult densities for their own waterbodies**, as optimal density likely differs among lakes due to system-specific characteristics such as forage base, water quality, and a host of other factors.

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PART 1: COMPARISON OF FRY-STOCKED AND ADVANCED FINGERLING-STOCKED WALLEYE

ABSTRACT

Walleye *Sander vitreus* are an important recreational species in impoundments and large reservoirs of Iowa, where they are typically stocked by Iowa Department of Natural Resources (DNR) to maintain fishable populations. Iowa DNR's hatcheries produce Walleye as fry stocked in summer and advanced fingerlings stocked in fall. The cost of producing each size of Walleye differs, with fry being much cheaper to produce than advanced fingerlings. However, larger size at the time of stocking enhances survival. This study was conducted to evaluate recruitment to adulthood (Age-2) and cost-effectiveness of Walleye stocked as fry and advanced fingerlings into impoundments and reservoirs of Iowa, as well as to identify lake characteristics that affected recruitment to adulthood and determine whether Age-0 catch rates could index stocking success and later recruitment to adulthood. Both fry and advanced fingerling Walleye were stocked into seven study locations for five years, between 2011-2018. Fish were recaptured in fall and spring using nighttime electrofishing at each study location and assigned to their year-class and size-at-stocking. Sampling occurred twice during fall, once before and once after advanced fingerling Walleye stocking, allowing estimation of the number of fry-stocked fish that survived to fall. Cost-effectiveness of each size by the end of the first fall was calculated, yielding the number of fish obtained per dollar spent by Iowa DNR. Generally, advanced fingerlings had more reliable cost effectiveness and were more successful in certain waterbodies than fry-stocked fish, but fry stocking had greater potential for large year-classes in the right conditions. Catch curves with explanatory variables (along with fish age) were fitted using general linear modeling, revealing that size-at-stocking affected recruitment to adulthood (indicated by predicted catch of Age-2 Walleye). In addition, Walleye catch was affected by water quality and fish community variables: summertime water temperature, total suspended and dissolved solids, crappie density, and Largemouth Bass density. Certain variables affected the sizes-at-stocking differentially, particularly Largemouth Bass density, and could be used to determine how appropriate Walleye stocking of either size might be for an Iowa impoundment. Finally, early fall electrofishing catch of Age-0 Walleye was highly correlated with catch of Age-2 Walleye two years later, and a Fry Index was established for determining fry stocking success. The Fry Index must exceed 0.50 Age-0 fish/minute of nighttime electrofishing in order to be 95% confident that Age-2 Walleye catch will exceed 5 fish/hour two years later.

INTRODUCTION

Walleye *Sander vitreus* provide recreational fishing opportunities throughout their range in North America, which spans to every coast as a result of glacial events, colonization, and transplantation (Billington et al. 2011). In the U.S. Walleye fishing drew over 3.8 million anglers in 2016 (USFWS and USCB 2016), and was particularly important in the Midwest and northern latitudes (Schmalz et al. 2011). In Iowa, Walleye are targeted by 43% of Iowa's licensed anglers, typically in interior lakes and reservoirs like Big Creek Lake (Responsive Management 2019). Although Walleye are native to both riverine and lacustrine habitats in Iowa, they do not have self-sustaining populations in most reservoirs due to lack of suitable spawning habitat (Bozek et al. 2011) and are maintained through stocking of cultured Walleye (Kerr 2011). Over 148 million Walleye fry and 1.5 million fingerlings were produced and stocked in 2019 by Iowa Department of Natural Resources to provide fishing opportunities statewide (Iowa DNR 2019), giving Iowa one of the largest Walleye stocking programs in North America (Kerr 2011).

The cost of producing each size of Walleye differs, with fry being the cheapest to produce (up to $0.00269/fish stocked) and advanced fingerlings being the most expensive (up to $1.83/fish stocked) (Clouse et al. 2011, 2014-2019; Iowa DNR 2012; Rudacille et al. 2013). Cost effectiveness, especially of large fingerlings, has been frequently questioned by researchers (Kampa and Jennings 1998). Intensively cultured fish in particular require different culture techniques (e.g., indoor raceways with ongoing flow, feeding) compared to extensively cultured fish raised in outdoor ponds (Olson et al. 2000) or to fry which can be stocked immediately after hatching. However, larger size at the time of stocking could enhance survival. Survival of stocked fish to adulthood ultimately drives contribution to the recreational fishery and therefore cost per fish to the angler. Thus evaluation of survival to adulthood of each size is necessary to ensure stocking strategies are cost-effective. Unnecessary grow-out or stocking of fish in inappropriate locations results in wasted hatchery resources (Trushenski et al. 2018).

Survival of various sizes of stocked Walleye has been evaluated numerous times in the Midwest, with mixed results (Kampa and Jennings 1998). Fry stocking has been successful in some cases (e.g., McWilliams 1990; McWilliams and

Larscheid 1992; Mitzner 1992), but most often outcomes were highly variable (Jennings and Philipp 1992). In Iowa, small fingerlings (4-6 inches) experienced higher first-year mortality than fry-stocked Walleye (McWilliams and Larscheid 1992; Mitzner 1992; Flammang 2008; Walter and Sobotka 2008), resulting in only a 10% contribution of fingerling-stocked fish to overall year-class abundance in natural lakes (McWilliams and Larscheid 1992). When both fry and small fingerlings were stocked simultaneously in the Okoboji lakes, fry-stocked Walleye outnumbered fingerling-stocked Walleye from the same year-class by 2.4 to 22.8 times after the first year (McWilliams 1990). Likewise, small fingerlings (20-40 mm) contributed weaker year-classes compared to fry stockings in South Dakota lakes (Lucchesi 2002) and Iowa natural lakes (McWilliams 1990). However, small fingerlings (25-51 mm) had greater survival than both fry and advanced fingerlings stocked into Missouri impoundments (Koppelman et al. 1992); advanced fingerlings (91-122 mm) also had greater return at Age 1 and 2 than fry. Brooks et al. (2002) made similar conclusions for Illinois lakes, finding small fingerlings (50-mm) to have greater survival and cost-effectiveness than either medium fingerlings (100 mm) or fry, and Pratt and Fox (2003) made similar conclusions for Ontario lakes, finding small fingerlings to have greater return as adults than medium fingerlings. Larger fingerlings appeared to have higher survival (Santucci and Wahl 1993; Kampa and Hatzenbeler 2009; Raabe et al. 2020), but previous studies had never evaluated advanced fingerlings at the size recently produced in Iowa. Rathbun Fish Hatchery's intensive culture methods regularly produce Walleye exceeding 200 mm by mid-October (Johnson and Summerfelt 2015).

Environmental and water quality characteristics can affect natural recruitment, stocking success, and subsequent Walleye densities. For example, probability of establishing a reproducing Walleye population in the U.S. and Canada through stocking depended on lake area, maximum depth, and pH (Bennett and McArthur 1990). In addition to surface area, Nate et al. (2003) identified mean depth and substrate size as important indicators of Walleye habitat in Wisconsin lakes, while storage ratio was important in Kansas reservoirs (Erickson and Stevenson 1972). Hansen et al. (2015) suggested water temperature degree-days, conductivity, and shoreline development were important for predicting where natural recruitment occurred (or where fry stocking may be especially effective). Predator and forage densities and composition can also affect Walleye survival. Stocked Walleye survival may be reduced by cannibalism or competition by conspecifics and other percids (Chevalier 1973; Forney 1976) or predation by adult piscivores (e.g., Largemouth Bass: Santucci and Wahl 1993). Most importantly, these factors may affect different sizes of Walleye differentially, making some lakes more appropriate for fry stocking and others more appropriate for advanced fingerling stocking (Santucci and Wahl 1993).

Finally, stocking of Walleye at different sizes occurs at different times of the year. Fry are typically stocked shortly after hatching, which occurs in late April or early May in Iowa. Advanced fingerlings are not ready until October, when water temperatures decline below 13.3°C. Thus, there is time after fry stocking to assess whether a year-class was established in a lake. Recruitment bottlenecks of Walleye fry occur during summer (likely before mid-July: Boehm 2016; Gostiaux 2018), so early fall assessment of fry stocking success could be useful to determining whether advanced fingerling stocking is needed at a particular location. Again, this assessment could reduce unnecessary stocking of costly advanced fingerling Walleye, thereby making the hatchery investment more efficient (Trushenski et al. 2018).

Therefore, the objectives of this study were to assess recruitment to adulthood (Age-2) and cost-effectiveness of Walleye stocked as fry and advanced fingerlings into impoundments and reservoirs of Iowa, to identify lake characteristics that affected recruitment to adulthood, and to determine whether Age-0 catch rates could index stocking success and later recruitment to adulthood.

METHODS

STUDY LOCATIONS

Study locations ranged from a large, turbid oxbow lake (i.e., Lake Manawa) to relatively complex reservoirs (e.g., Pleasant Creek Lake), varying in physical and water quality characteristics (Table 1). The locations were meant to represent a range of environmental conditions common to Iowa's significant publicly-owned impoundments and reservoirs. (Reservoirs, as defined by Iowa DNR, include the large impoundments created by dams for flood control.) Walleye were stocked into each study location at both fry and advanced fingerling sizes for five years in a row, beginning in 2011 at Big Creek Lake and 2014 at all other study lakes. Both sizes of fish were produced by Rathbun Fish Hatchery each year following consistent culture and stocking methods over time (Clouse et al. 2011, 2014-2019; Iowa DNR 2012;

Rudacille et al. 2013). Fry were stocked at a target density of 2,000-3,000 fish/acre in late April - early May each year. Advanced fingerlings were grown out until October each year and stocked at a target density of 5-10 fish/acre in mid-late October when water temperatures had fallen below 13.3°C. Advanced fingerlings stocked into Big Creek Lake were freeze-branded for year-class/size-at-stocking identification prior to stocking; unique fin clips were used at other study lakes (Table 2). These marks were unique and long-lasting enough to identify a fish as having been stocked at advanced fingerling size during subsequent years. The day of marking, a subsample of approximately 100 fish was set aside for length and weight measurement to estimate fish condition (as relative weight W_r) and probable survival rate of advanced fingerling Walleye.

Table 1. Study locations stocked with fry and advanced fingerling Walleye from 2011-2018, by management district. Physical characteristics (SA = surface area, Z_{max} = maximum lake depth, and Z_{mean} = mean lake depth), number of electrofishing sites, and target stocking numbers are shown (N_{Fry} = number of fry stocked, N_{Adv} = number of advanced fingerlings stocked).

District	Lake	Code	SA (ha)	Sites	Z_{max} (ft)	Z_{mean} (ft)	Years of Stocking	N_{Fry}	N_{Adv}
Boone	Big Creek Lake	BIC77	357	8	53.4	19.4	2011-2015	2,442,600	8,142
Mt. Ayr	Lake Icaria	ICA02	648	6	30	11.1	2014-2018	1,943,400	6,478
Mt. Ayr	Little River Lake	LRI27	743	7	42	13.1	2014-2018	2,229,000	7,430
Macbride	Lake Macbride	MAC52	889	8	47	16	2014-2018	2,667,000	8,890
Cold Springs	Lake Manawa	MAN78	747	8	11.1	6.1	2014-2018	2,240,400	3,734
Macbride	Pleasant Creek Lake	PLC57	401	5	55.5	15.8	2014-2018	1,203,300	4,011
Mt. Ayr	Twelve Mile Lake	TMI88	595	6	42	16.8	2014-2018	1,784,100	5,947

Table 2. Marks used to identify advanced fingerling-stocked Walleye by year-class. Brands were placed on the right side of the fish using freeze-branding techniques immediately prior to stocking.

Year-Class	Brand		Fin Clip
2011	|	Single bar	Left Pelvic
2012	‖	Double bar	-
2013	O	Open circle	-
2014	●●●	Triple dot	Left Pectoral
2015	^	Chevron	Right Pectoral
2016			Left Pelvic
2017			Right Pelvic
2018			Left Pectoral

DATA COLLECTION

Walleye were sampled numerous times throughout the year with nighttime electrofishing. First, an early fall (late September to mid-October) nighttime electrofishing survey was completed at each study lake to determine fry-stocked Walleye catch rates. Electrofishing was conducted using a boat electrofishing unit (pulsed DC output) with one to two netters. Sampling was completed when water temperatures ranged between 10 and 18.3°C and began 20-30 minutes after dusk. Sampling sites were fixed over time at each study lake; each site received 15 minutes of pedal time electrofishing. The number of sites depended on lake surface area (Table 1). Fish were measured (total length, mm), weighed (g), and examined for marks (either freeze brands or fin clips). Marked fish were assigned to their respective year-class, and unmarked fish were assumed to have been fry-stocked. Natural recruitment was assumed to be negligible. The first and second dorsal spines were removed from up to 5 fish per 10-mm length bin (per lake, per year) from fry-stocked fish for age estimation. Next, a second fall nighttime electrofishing survey was completed at least one week after advanced fingerling Walleye were stocked, allowing fish some time to disperse through the lake (Weber et al. 2019). Finally, spring nighttime electrofishing was conducted when water temperatures again exceeded 10°C. Identical methods were used as the early fall sample.

Age was estimated using dorsal spines collected from subsampled fry-stocked fish. Dorsal spines were mounted in epoxy and sectioned using a high-speed precision saw following the recommendations of Koch and Quist (2007). Sectioned spines were examined using a microscope, and a double-blind reading process was used to determine age estimates, followed by a tie-breaking process. Age-length keys were developed for fry-stocked fish by lake/season, allowing estimation of age for all measured fish. Age was assigned to marked fish based on their respective marks. All fish with age estimates were assigned to their year-class based on age at time of capture. I combined data across years at an individual lake because the study had a relatively short duration and I did not expect growth to change drastically.

DATA ANALYSIS

Cost-effectiveness of sizes-at-stocking

Catch rates were calculated for each study location by fish age and size-at-stocking. Because effort varied among samples, catch was normalized by calculating catch rate as number of Walleye per minute of nighttime electrofishing. The catch rate, plus one, was natural log-transformed prior to mean calculations, then back-transformed for reporting. A series of general linear mixed models were fit to the catch curve using fish age, plus a combination of lake, season, year-class, and size-at-stocking as fixed effects (GLIMMIX Procedure, SAS 9.4). I included season because I expected spring and fall electrofishing catch rates to possibly differ, and I included year-class in case the survival of hatchery products from a particular year may have differed (e.g., if fish were in particularly poor condition or small). Year of sampling was included as a random effect. Akaike's information criterion, corrected for small sample sizes (AICC), was determined for each model, and the model with the lowest AICC was considered the best. Models with an AICC within 4 points of the best model (ΔAICC) were considered similar in performance to the best model. I also calculated model weights based on the likelihood of each model (W_i) and reported the number of parameters in each model.

I assumed advanced fingerling Walleye survival immediately post-stocking depended on predation probability, which was dependent on length (Grausgruber and Weber 2020). The number of advanced fingerlings assumed to be present during the post-stocking sample was calculated as the number stocked, less the proportion which experienced mortality due to predation. Next, by using a ratio of advanced fingerling:fry-stocked fish captured during late fall, I estimated the number of fry-stocked fish surviving to late fall, according to the following formula:

$$n_{Fry} = \frac{Catch_{Fry} \cdot n_{Advanced}}{Catch_{Advanced}}$$

The number of fry-stocked and advanced fingerling-stocked Walleye alive by late fall was then divided by their respective cost to stock (number of fish stocked*cost/fish), using annual costs estimated by Rathbun Fish Hatchery (Clouse et al. 2011, 2014-2019; Iowa DNR 2012; Rudacille et al. 2013). Cost-effectiveness of each size was calculated as number of fish per dollar spent for each lake-year, then averaged across years.

Lake factors affecting optimal size-at-stocking

Differences among lakes were apparent based on overall and size-specific catch rates, preliminary general linear models, and overall and size-specific fish established per dollar. Thus, a second set of models was examined, fitting the catch curve with physical lake characteristics, fish community metrics, and summertime water quality data from the year of stocking (Table 4), along with the significant variables from the previous modeling step. Size-at-stocking was also allowed to interact with each variable (except age), in case a lake characteristic affected the sizes-at-stocking differentially. Because the number of potential models was high, an automated backward selection process was used with n-fold model cross-validation (n=5) (GLMSELECT Procedure, SAS 9.4). No intercept was allowed. After the best model was identified, it was re-fit with sampling year added as a random effect to ensure a more proper fit (GLIMMIX Procedure, SAS 9.4).

Water quality data were compiled from Iowa DNR's Ambient Lake Monitoring Program (LMP). The LMP has collected summertime water quality data from significant publicly-owned waterbodies annually since 2000. Three times per year between May and August, the LMP collected midday epilimnetic samples from the deepest point in the main reservoir. Secchi depth was measured on-site with a 152-mm disk, and water temperature, pH, dissolved oxygen, and turbidity were measured on-site as an epilimnetic average (mean readings from surface to metalimnion). Combined water samples of the entire epilimnion were collected for laboratory analysis of chlorophyll-*a* concentration, total suspended solids, and total dissolved solids. In the case of a non-detectable reading for a given parameter, the value was set to half the detection limit. Water quality data from specific lake-years were joined by Walleye year-class, thereby associating Walleye catch to the year of stocking.

Morphometric and physical data were compiled from agency data derived from lake mapping (L. Bruce and J. Lorenzen, Iowa Lake Mapping Program, personal communication) and joined by lake. Morphometric variables included mean depth, maximum depth, watershed area, lake area, watershed-to-lake surface area ratio, mean basin slope of the lake, volume development, shoreline development, and maximum wind fetch. Measures of distance and area were natural log-transformed prior to inclusion in modeling. In addition, land use within the watershed was represented by percentage cover by deciduous vegetation, corn, and residential development (Iowa DNR, unpublished data). Physical data were joined by lake.

Fish community metrics included catch per unit effort of Black and White Crappies combined (fish/net-night in modified fyke nets), Bluegill (fish/hour of electrofishing), and Largemouth Bass (fish/hour of electrofishing). All data were derived from the Iowa DNR's Fisheries Management Data Portal. Each year of the study was associated with catch from the most recent sampling that had been conducted; in some cases, the fish community was sampled every year and in others, sampling was intermittent or irregular. Catch rates were natural log-transformed prior to inclusion in modeling. Fish community data were joined by lake-year-class, associating Walleye catch with the best available fish community sample present when the Walleye were stocked.

The distribution of water quality, physical, and fish community variable values was examined within the study lake dataset and the entire population of Iowa impoundments and reservoirs. If the study lakes' range of values (maximum and minimum) for a variable did not overlap at least 50% of the interquartile range of the population, the variable was excluded from modeling. This step ensured that the resulting models would be more applicable to all Iowa impoundments and reservoirs, not only a subset with values of a significant variable in a narrow range.

Using the resulting model, input variables were held at their global means (average value across all impoundments), and catch curves were modeled for both fry- and advanced fingerling-stocked Walleye. Next, each input variable was varied across the range of possible values (based on the population of impoundments and reservoirs) while holding other variables at their global means, and the catch of Age-2 Walleye was estimated.

Finally, the fall-season models for each size-at-stocking were applied to all significant publicly-owned impoundments and reservoirs using recently collected water quality, physical, and fish community data. Fry and advanced fingerling catch at Age-0 were predicted, and all waterbodies were ranked in descending order of catch for each size-at-stocking. Walleye "friendliness" was determined using the predicted catch curve intercept (Age-0 catch rate with fall electrofishing) divided by the "best-case scenario" of a theoretical impoundment which optimized each input variable's value. This yielded a "Walleye friendliness" index that may help identify better or worse choices for future Walleye stocking. The Friendliness index has a theoretical maximum of 1.

Utility of fall nighttime electrofishing as an index

Finally, the utility of early fall nighttime electrofishing to index year-class establishment was examined first by correlating Age-0 catch with Age-2 catch, two years later. A significant correlation could imply that fry detection during the first fall can adequately define the presence of a year-class later on (Pearson's ρ). However, a year-class may also be supported by concurrent advanced fingerling stocking. Thus, if the correlation was significant, it was followed by a quantile regression analysis instead of a linear regression, allowing the catch of Age-2 Walleye to be *greater* than would be predicted by Age-0 catch, but not less (QUANTREG Procedure, SAS 9.4). Specifically, the lower bound was fitted above which 95% of the data fell (i.e., the 5% quantile). The intersection of that line with Age-2 = 0 was then back-calculated. Early fall Age-0 catch rates greater than that intersection would have a 95% chance or greater of indicating an adult Walleye year-class two years later.

RESULTS

Stocking and subsequent sampling was completed according to plan, with a few exceptions. Specifically, habitat improvements at Pleasant Creek Lake disallowed post-advanced fingerling stocking sampling during one year, due to an inaccessible boat ramp (2015). During two years, advanced fingerling stocking at Lake Icaria was cancelled due to fingerling shortages and high early fall electrofishing catch rates of fry-stocked fish. Finally, pre-advanced fingerling stocking sampling was not conducted during the first two years of the study at Big Creek Lake. A total of 77 sites were sampled during fall and 59 sites were sampled during spring, resulting in capture of 15,786 Walleye through the duration of the study (Figure A 1). A total of 11,348 Walleye captured were not marked and assumed to be stocked as fry (or belonged to a year-class from before the stocking study, in which case they were ignored in additional analyses). A total of 4,438 fish were marked and assumed to be stocked as advanced fingerlings in a known year.

Advanced fingerling Walleye condition (W_r) ranged from 68.4 - 135.4 at the time of stocking (mean ± standard error = 93.1 ± 0.2), while total length ranged from 70 - 295 mm (218.3 ± 0.9 mm; Figure 1). Mean total lengths each year were associated with post-stocking predation mortality rates of 5.2 - 18.2% (Grausgruber and Weber 2020).

COST-EFFECTIVENESS OF SIZES-AT-STOCKING

Fish were captured after advanced fingerling Walleye stocking for five subsequent years at each study lake, with the exception of locations where advanced fingerling stocking was cancelled. Multiple catch curves were fit to both fall and spring electrofishing data (post-advanced fingerling stocking in the fall, and the subsequent spring), where the null model was dependent only on fish age. The best catch curve model explaining differences in catch of Walleye over time included an interaction between lake and size-at-stocking (Type III test of fixed effects $F = 7.95$, df = 13, p-value < 0.0001) and season of capture ($F = 10.65$, df = 1, $p = 0.0012$; Table 3). The interaction effect indicated that size-at-stocking had variable effects depending on which lake the fish were sampled from. Annual and mean Age-0 electrofishing catch rates by size-at-stocking implied that there may be important differences among lakes (Figure 2; Figure A 2). I suspected systematic differences in lake characteristics affected whether fry or advanced fingerlings survived better in each lake. Rather than retain the model using lake as a categorical variable, I conducted a subsequent analysis using available lake characteristics in addition to lake. Seasonal differences in catch rate were expected, with fall yielding higher catch rates than spring (Figure A 3). Notably, year-class was not important, indicating hatchery products (i.e., the stocked fish) did not significantly differ in their contribution over the years of the study, and size-at-stocking was not important without the lake interaction effect, indicating fry or advanced fingerlings were not consistently better or worse than the other.

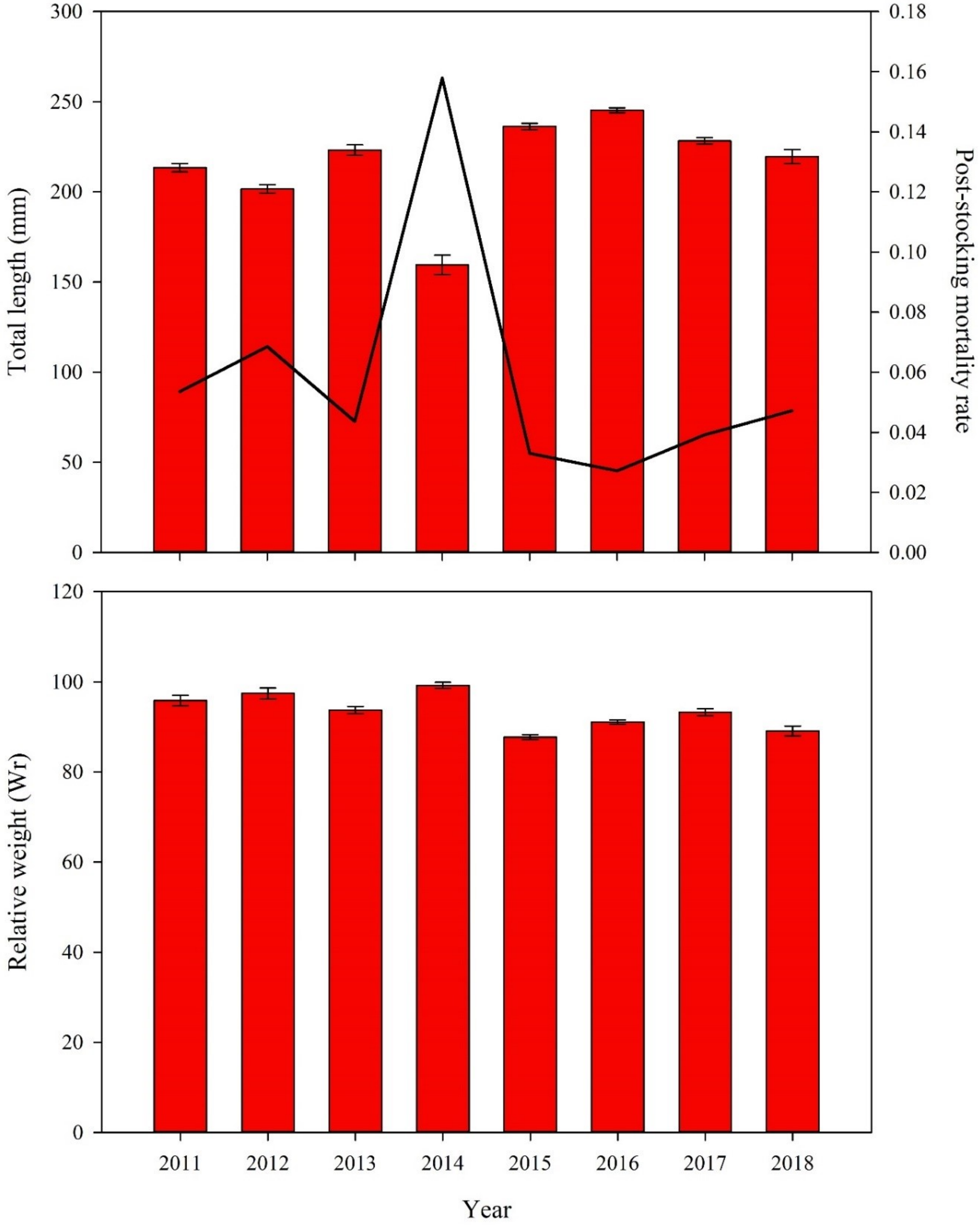

Figure 1. Fish size (total length) and condition (relative weight), and associated post-stocking mortality rate of advanced fingerling Walleye produced by Rathbun Fish Hatchery from 2011-2018.

Calculation of the number of fish surviving to late fall per dollar spent on production revealed that fry stocking was more cost-effective in some lakes, while advanced fingerling stocking was more cost-effective in others (Figure 3). Specifically, fry stocking garnered more fish per dollar over time in Big Creek Lake, Lake Icaria, Lake Macbride, and Pleasant Creek Lake. Advanced fingerling stocking garnered more fish per dollar in Little River Lake and Twelve Mile Lake. The two strategies appeared to be equally cost-effective over time in Lake Manawa. Confidence intervals were tighter for advanced fingerling estimates, implying that fry stockings had less reliable outcomes. This was occasionally the case for specific lakes; for example, fry stocking was extremely successful one year at Pleasant Creek Lake, making the lake's average appear to favor fry stocking (Figure A 4). However, fry stocking was frequently unsuccessful at Pleasant Creek Lake during the study. The same can be said of Big Creek Lake. Erratic fry stocking outcomes in an individual lake could indicate locations where a Fry Index is especially important before advanced fingerling stocking is pursued.

Table 3. Akaike's Information Criterion, adjusted for small sample sizes (AICC), ΔAICC, model weight (W_i), and number of parameters (K) of general linear models predicting Walleye catch (fish/minute of electrofishing) using fish age, lake, season, year-class, and size-at-stocking.

Model	AICC	ΔAICC	W_i	K
Age + Lake*Size-at-stocking + Season	-73.94	0	0.81	16
Age + Lake*Size-at-stocking + Season*Size-at-stocking	-69.92	4.02	0.11	17
Age + Lake*Size-at-stocking	-69.24	4.70	0.08	15
Age + Lake*Size-at-stocking + YearClass + Season	-49.63	24.31	0.00	24
Age + Lake*Size-at-stocking + YearClass	-47.53	26.41	0.00	23
Age + Lake*Size-at-stocking + Season*Size-at-stocking + YearClass	-45.67	28.27	0.00	25
Age + Lake + Season	-44.02	29.92	0.00	9
Age + Lake + Size-at-stocking + Season	-43.57	30.37	0.00	10
Age + Lake	-39.74	34.20	0.00	8
Age + Lake + Size-at-stocking	-39.30	34.64	0.00	9
Age + Season	-38.30	35.64	0.00	3
Age + Size-at-stocking + Season	-36.32	37.62	0.00	4
Age + Season*Size-at-stocking	-31.86	42.08	0.00	5
Age + Size-at-stocking	-30.03	43.91	0.00	3
Age + Lake + YearClass + Season	-19.28	54.66	0.00	17
Age + Lake + Size-at-stocking + YearClass + Season	-18.76	55.18	0.00	18
Age + Lake + YearClass	-17.20	56.74	0.00	16
Age + Lake + Size-at-stocking + YearClass	-16.71	57.23	0.00	17
Age + YearClass + Season	-14.29	59.65	0.00	11
Age + Size-at-stocking + YearClass + Season	-12.59	61.35	0.00	12
Age	-11.27	62.67	0.00	1
Age + YearClass	-10.82	63.12	0.00	10
Age + Size-at-stocking + YearClass	-9.24	64.70	0.00	11

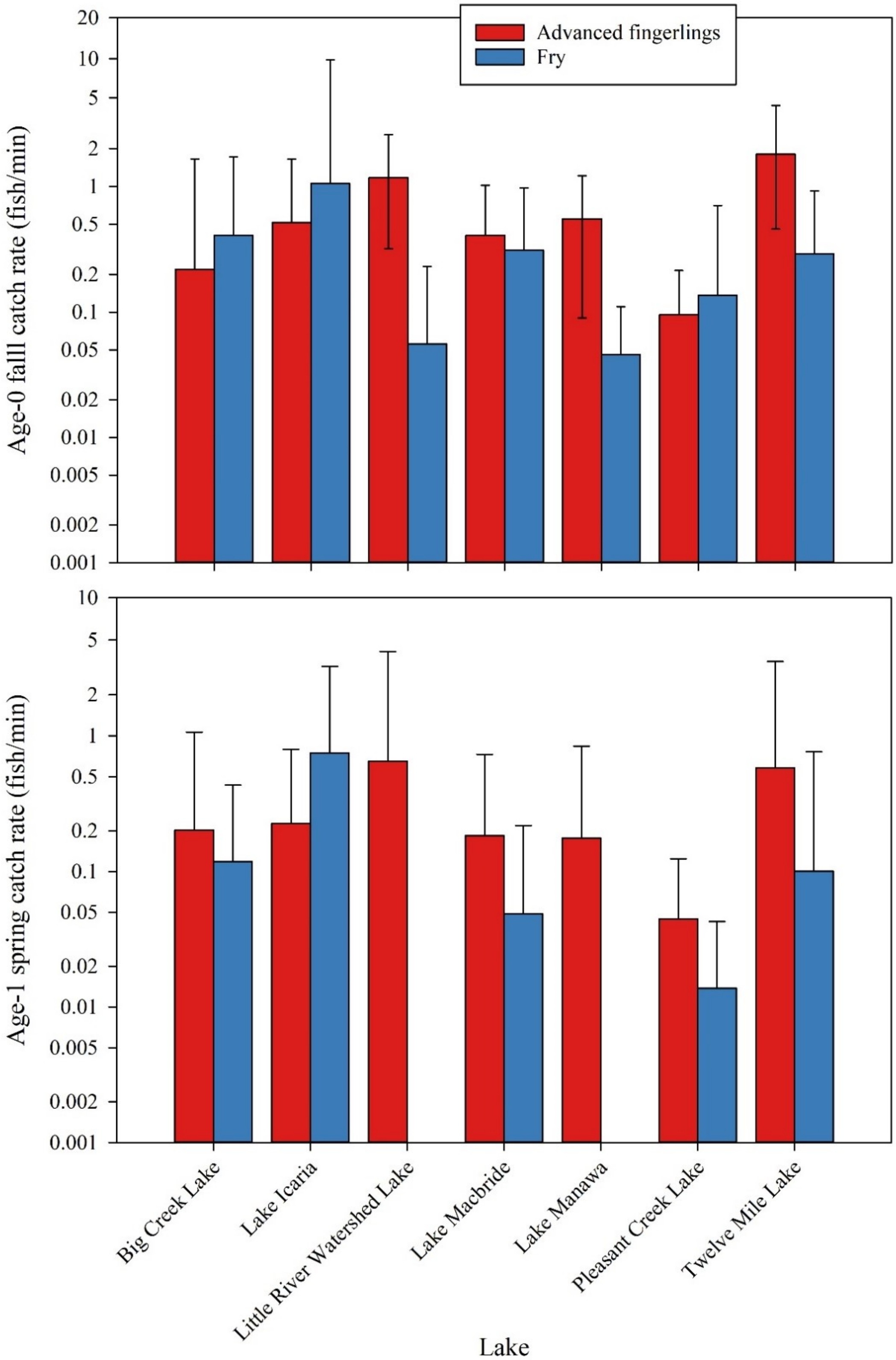

Figure 2. Mean nighttime electrofishing catch rate (fish/minute) of Walleye from seven study locations in Iowa, by size-at-stocking, during their first fall (Age-0) and the following spring (Age-1). No fry-stocked Walleye were captured during spring at Age-1 at Little River Watershed Lake or Lake Manawa during the study. 95% confidence intervals are shown with an error bar; note that lower bounds below zero are not shown.

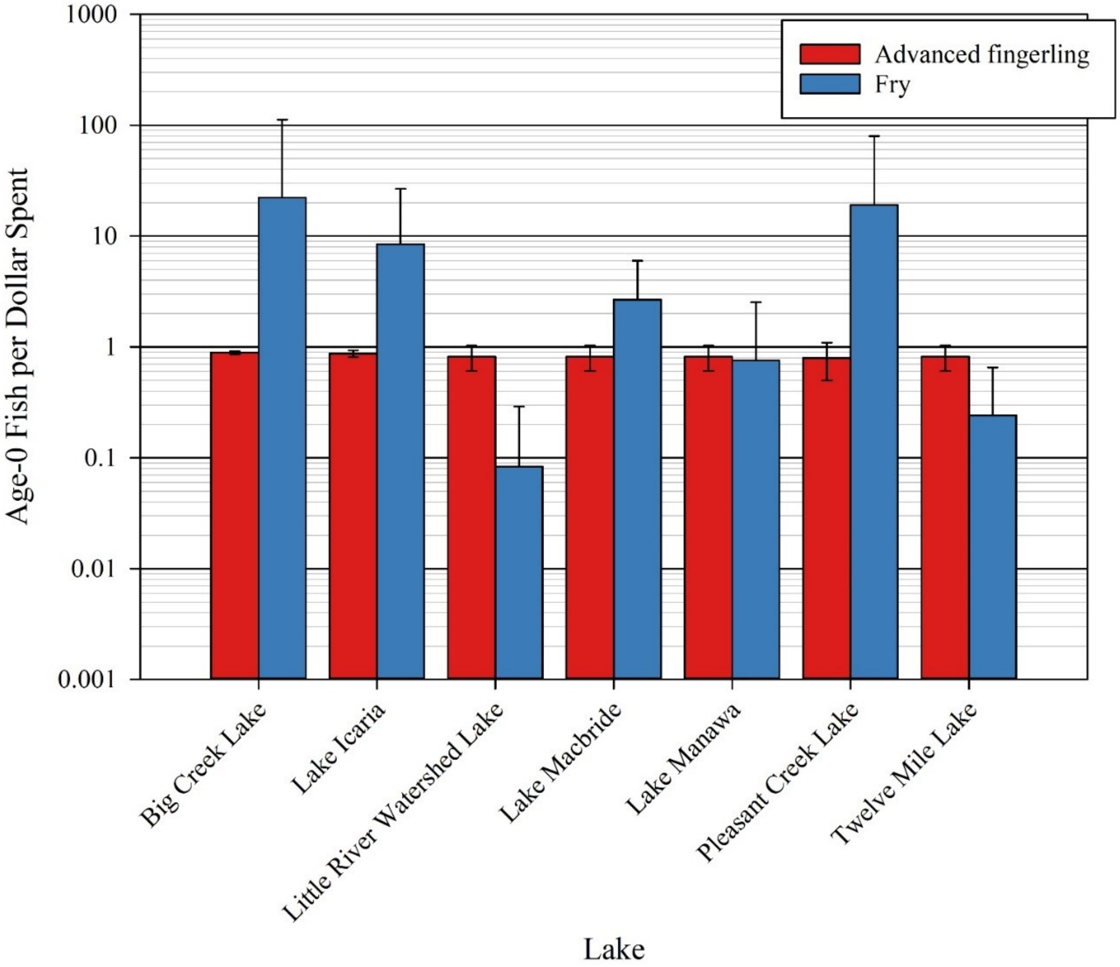

Figure 3. Number of Age-0 Walleye surviving to late fall, per dollar spent on production, by size-at-stocking. Error bars indicate 95% confidence intervals. Lower bounds of error bars below zero are not shown.

LAKE FACTORS AFFECTING OPTIMAL STOCKING CHOICES
Variables of interest for describing lake characteristics were examined within the study lakes and across all significant publicly-owned impoundments (n = 7) and reservoirs with data available (n = 92). Several morphometric variables were excluded from the analysis because their range of values in the study lakes did not cover at least 50% of the interquartile range of Iowa’s impoundments and reservoirs (Table 4).

Table 4. Environmental and morphometric variables considered that may affect fry or advanced fingerling-stocked Walleye, including their range within the study lakes and their range across all significant publicly-owned impoundments and reservoirs (All). All distance and area variables are presented in log-adjusted form.

Variable	Units	Study Lakes					All					Included
		Min	Q1	Median	Q3	Max	Min	Q1	Median	Q3	Max	
Water temperature	*C	20.63	22.50	23.43	24.73	28.03	16.37	22.60	23.63	24.57	27.33	Y
Depth, Secchi	m	0.20	0.73	0.92	1.68	3.17	0.11	0.60	0.87	1.36	5.37	Y
Total dissolved solids	mg/L	133.33	153.33	176.67	253.17	376.67	85.33	160.00	196.67	261.60	438.67	Y
pH		7.68	8.07	8.30	8.43	8.72	7.30	8.13	8.33	8.53	9.33	Y
Dissolved oxygen	mg/L	4.50	6.17	7.37	8.82	11.03	3.40	7.51	8.64	9.89	17.80	Y
Total suspended solids	mg/L	2.60	7.03	8.63	14.33	68.17	0.60	7.71	11.40	16.67	94.00	Y
Chlorophyll a	ug/L	3.10	12.65	24.50	32.22	101.67	0.60	12.00	26.54	46.12	147.88	Y
Turbidity	NTU	2.40	6.33	8.60	13.32	54.97	0.15	7.02	11.61	18.85	150.77	Y
Mean depth	m	0.70	1.03	1.51	1.58	1.66	0.09	0.77	0.98	1.25	2.08	Y
Maximum depth	m	1.93	2.21	2.48	2.74	2.83	0.92	1.69	1.94	2.21	3.16	Y
Basin slope		9.80	12.00	12.60	15.32	20.80	1.40	11.30	16.80	23.60	39.80	Y
Watershed surface area	ha	6.73	6.92	8.65	8.82	9.89	1.40	5.63	6.73	7.71	11.86	N
Lake surface area	ha	5.09	5.53	5.71	5.76	5.89	1.46	2.37	3.22	4.27	8.45	N
Watershed:lake surface ratio		3.17	5.18	18.23	25.92	62.37	0.67	17.15	28.13	50.66	207.51	Y
Volume development		0.85	0.86	1.03	1.13	1.13	0.81	1.06	1.15	1.30	1.89	N
Shoreline development		2.84	3.07	3.72	4.34	4.89	1.36	2.05	2.47	3.12	7.86	N
Fetch	m	7.83	7.89	8.38	8.46	8.52	5.69	6.51	6.93	7.54	9.55	N
Percent cover deciduous	%	1.96	2.36	4.43	11.88	29.08	0.14	2.81	8.73	18.32	78.14	Y
Percent cover corn	%	5.38	6.10	12.06	26.58	41.48	0	7.27	16.74	30.75	52.10	Y
Percent cover residential	%	0.38	0.56	0.93	1.52	10.90	0.08	0.46	0.76	1.49	22.38	Y

The best-fitting model of a catch curve with environmental, physical, and fish community factors included age, several water quality variables, and several fish community variables plus interactions with size-at-stocking (Model *F* = 22.49, df = 11, *p*-value < 0.0001). Notably, lake was not included as a categorical variable in the final model, indicating that systematic differences were not lake-specific but rather predictable using lake characteristics. The resulting formulas by size-at-stocking were as follows based on fall nighttime electrofishing.

Advanced fingerling model:

$$Ln\left(Catch_{Walleye} + 1\right) = 0.9272 - 0.06246 * Age - 0.03188 * CPUE_{Crappie} - 0.02504 * CPUE_{Largemouth\ Bass} - 0.00458 * WaterTemp - 0.00151 * TDS - 0.00339 * TSS$$

Fry model:

$$Ln\left(Catch_{Walleye} + 1\right) = 0.9272 - 0.06246 * Age - 0.03188 * CPUE_{Crappie} - 0.1196 * CPUE_{Largemouth\ Bass} + 0.005433 * WaterTemp - 0.00123 * TDS - 0.00339 * TSS$$

The formulas were as follows based on spring nighttime electrofishing.

Advanced fingerling model:

$$Ln\left(Catch_{Walleye} + 1\right) = 0.8610 - 0.06246 * Age - 0.03188 * CPUE_{Crappie} - 0.02504 * CPUE_{Largemouth\ Bass} - 0.00458 * WaterTemp - 0.00151 * TDS - 0.00339 * TSS$$

Fry model:

$$Ln\left(Catch_{Walleye} + 1\right) = 0.8610 - 0.06246 * Age - 0.03188 * CPUE_{Crappie} - 0.1196 * CPUE_{Largemouth\ Bass} + 0.005433 * WaterTemp - 0.00123 * TDS - 0.00339 * TSS$$

In all models above, variables were defined as:

$Age =$ fish age
$CPUE_{Crappie} =$ modified fyke net catch per net-night +1 of Black and White Crappie, natural-log transformed
$CPUE_{Largemouth\ Bass} =$ electrofishing catch per hour +1 of Largemouth Bass, natural-log transformed
$WaterTemp =$ mean summertime water temperature from ambient lake monitoring, in °C
$TDS =$ mean summertime total dissolved solids from ambient lake monitoring, in mg/L
$TSS =$ mean summertime total suspended solids from ambient lake monitoring, in mg/L

When input variables were held at their global means across all impoundments and reservoirs (Table 5), the fry and fingerling models predicted reasonable catch curves (Figure 4). The effects of higher crappie or Largemouth Bass densities were negative; however, Largemouth Bass density was more important for fry-stocked Walleye than advanced fingerling-stocked Walleye. When electrofishing catch rate of Largemouth Bass exceeded 21.5 fish/hour, fry stocking no longer produced greater returns, and advanced fingerling stocking is recommended (Figure 5). Warmer summer temperatures had a positive effect on fry-stocked Walleye (Figure 6). Both total dissolved solids and total suspended solids had negative effects on Walleye catch at Age-2, with a slight difference between fry-stocked Walleye and advanced fingerling-stocked Walleye (Figure 7). Walleye stocking may not be recommended if total dissolved solids exceeds 300 mg/L or if total suspended solids exceeds 60 mg/L during the summer, although other factors should also be accounted for.

Table 5. Parameters used to explain catch curves of fry- and advanced fingerling-stocked Walleye. Mean, standard deviation, minimum, and maximum values were calculated across all significantly publicly owned impoundments and reservoirs in Iowa.

Parameter	Mean	Standard Deviation	Minimum	Maximum
$\text{CPUE}_{\text{Crappie}}$ (natural-log)	2.53	1.01	-0.25	4.72
$\text{CPUE}_{\text{Largemouth Bass}}$ (natural-log)	4.07	0.79	1.79	5.36
Water temperature	23.33	1.40	19.73	26.47
Total dissolved solids	205.93	78.48	99.41	428.66
Total suspended solids	12.88	7.98	0.60	52.00

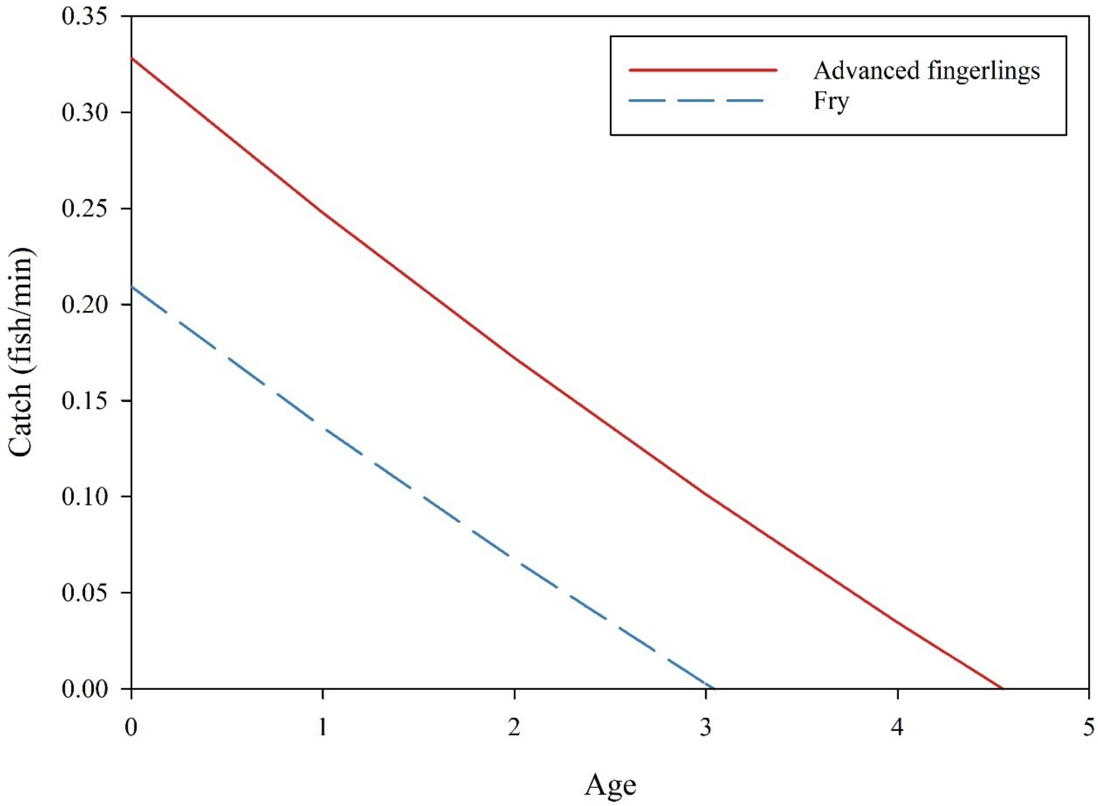

Figure 4. Predicted catch of Walleye (fish/min) with fall nighttime electrofishing, by age and size-at-stocking, across all Iowa significant publicly-owned impoundments and reservoirs.

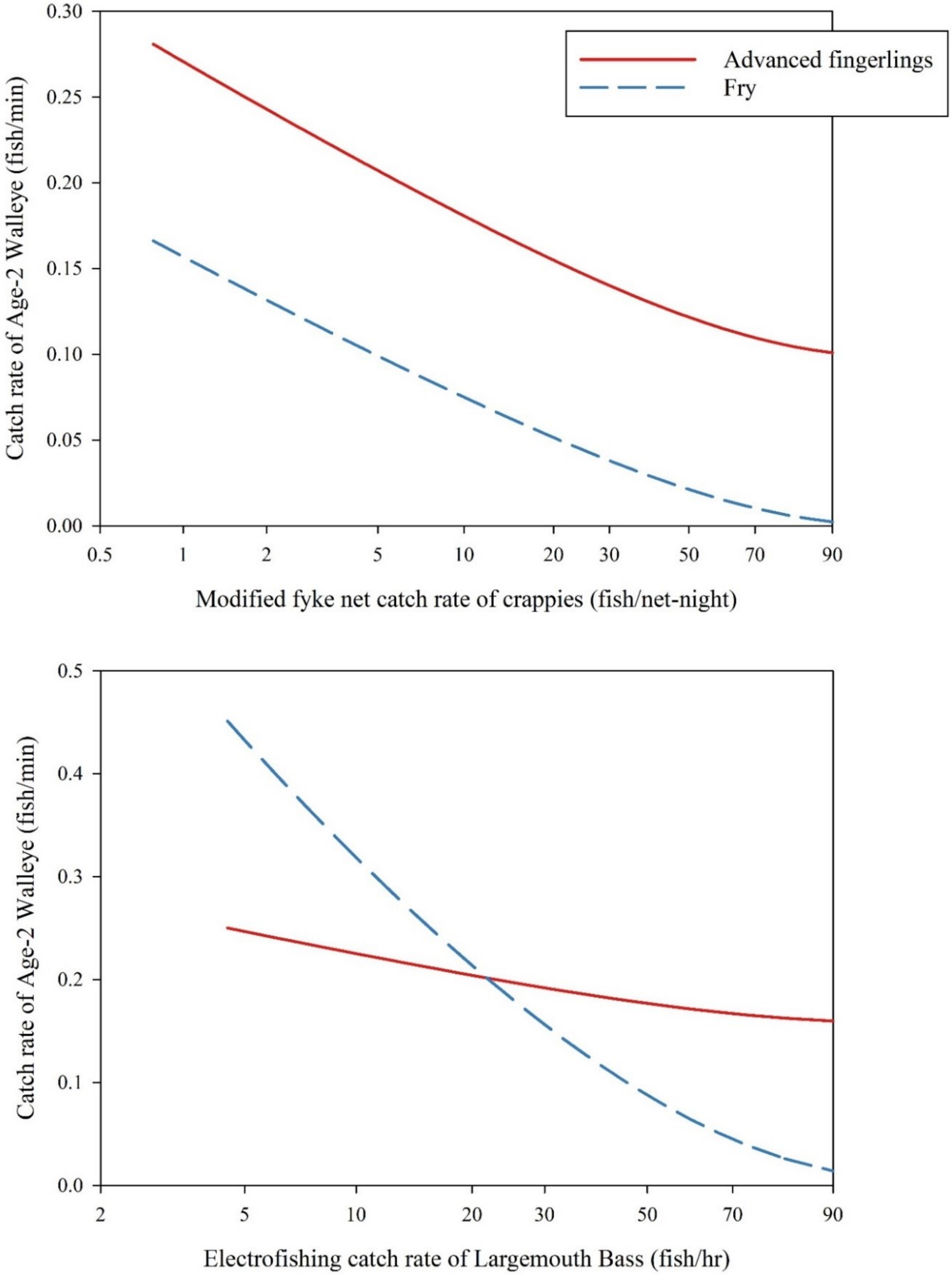

Figure 5. Fall electrofishing catch rate of Age-2 Walleye (fish/min) predicted using water quality and fish community metrics (held at global means) across a range of catch rates of crappie (top panel) and Largemouth Bass (bottom panel), by Walleye size-at-stocking.

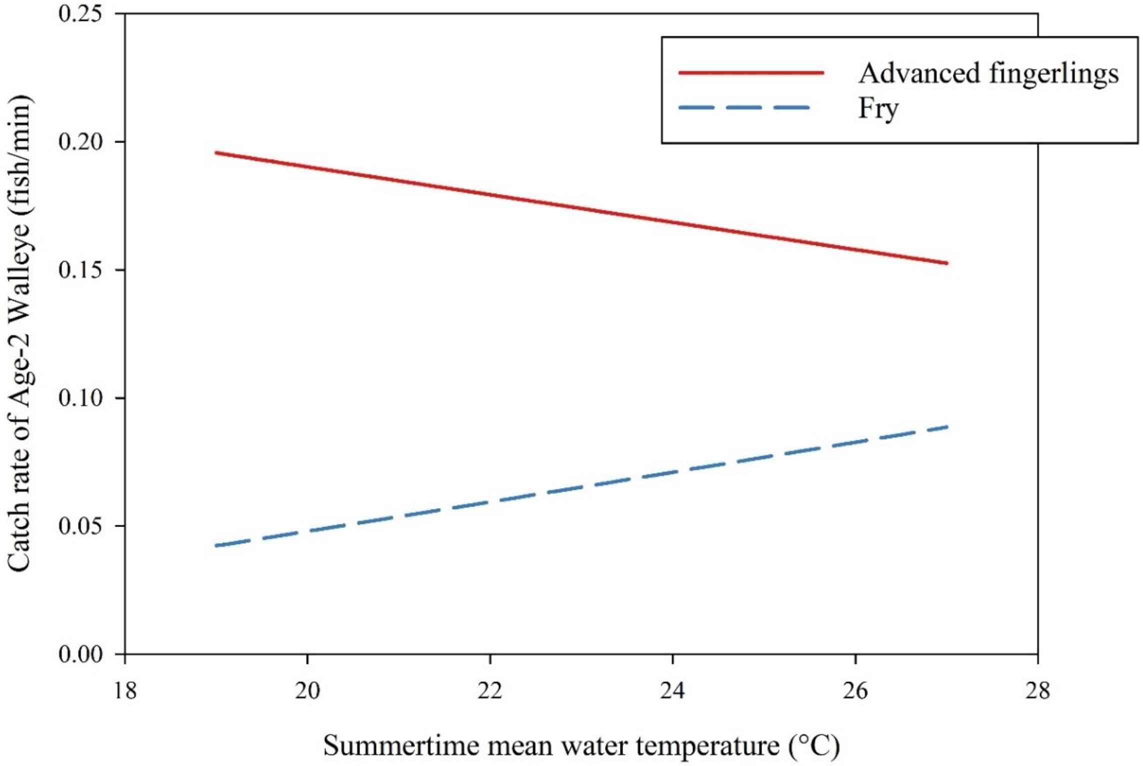

Figure 6. Fall electrofishing catch rate of Age-2 Walleye (fish/min) predicted using water quality and fish community metrics (held at global means) across a range of water temperatures, by Walleye size-at-stocking.

“Walleye-friendliness” of all significant publicly-owned impoundments and ranks was calculated and ranked for both fry and advanced fingerling stocking (Table A 1). The index was calculated using a baseline optimal impoundment characterized by advanced fingerling stocking into a cool temperature, low dissolved and suspended solids, and low Largemouth Bass and crappie densities. Ranks and the Walleye Friendliness Index are not definitive but meant to serve as a guide for how effective walleye stocking might be, given each lake’s characteristics, and can change over time if the fish community changes (e.g., a weak Largemouth Bass year-class or crappie year-classes) or if a lake is renovated (e.g., a significant reduction in suspended solids).

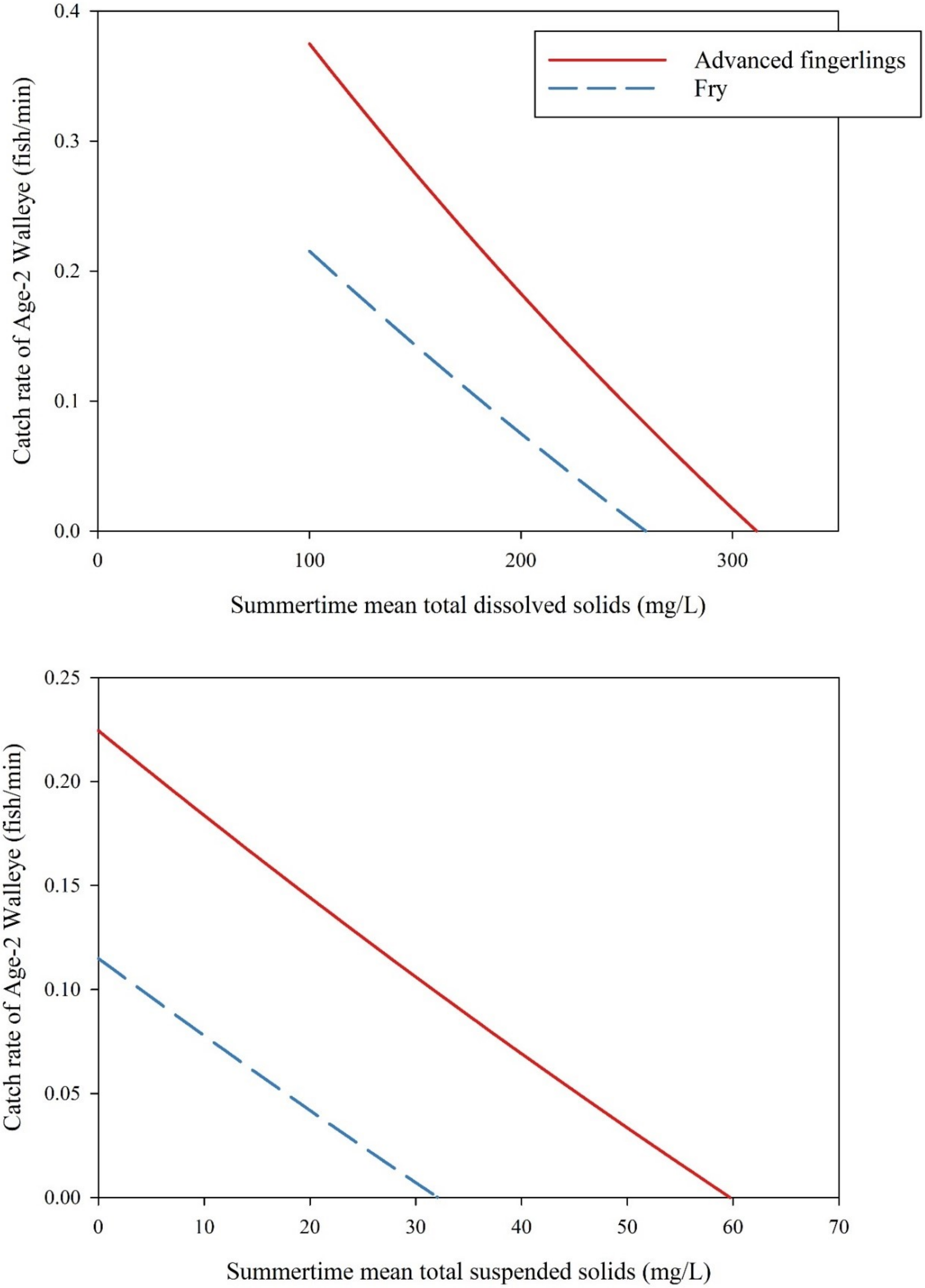

Figure 7. Fall electrofishing catch rate of Age-2 Walleye (fish/min) predicted using water quality and fish community metrics (held at global means) across a range of concentrations of dissolved solids (top panel) and suspended solids (bottom panel), by Walleye size-at-stocking.

UTILITY OF FALL NIGHTTIME ELECTROFISHING AS AN INDEX

Catch of Age-2 Walleye two years later was significantly correlated with early fall Age-0 Walleye catch established through fry stocking (Pearson's ρ = 0.9289, p-value < 0.0001). The quantile regression model predicted catch of Age-2 Walleye (two years later) using catch of fry-stocked Age-0 Walleye in fall using a simple model. The 5% regression line was:

$$Catch_{Age-2} = 0.3687 \cdot Catch_{Age-0} - 0.0709$$

where catch is a natural-log transformation of the catch per minute of electrofishing plus one.

Back-calculation of the Age-0 catch below which predicted Age-2 catch is zero yielded an estimate of 0.22 fish/min. If early fall electrofishing catch of Age-0 Walleye is above 0.22 fish/min, there is a 95% chance a year-class has been established by fry stocking (Figure 8). This was named the Fry Index. Establishment of a year-class is still possible if the Fry Index is below this level, but probability is less than 95%. Alternatively, to achieve a catch rate of 5 Age-2 Walleye/hour, the Fry Index must be greater than 0.50 fish/min. If early fall electrofishing catch is above 0.50 fish/min, there is a 95% chance that a year-class has been established which will yield catch rates of Age-2 Walleye over 5 fish/hour, two years later. Likewise, other management targets (in terms of Age-2 Walleye catch per effort) may be defined by following the quantile regression line.

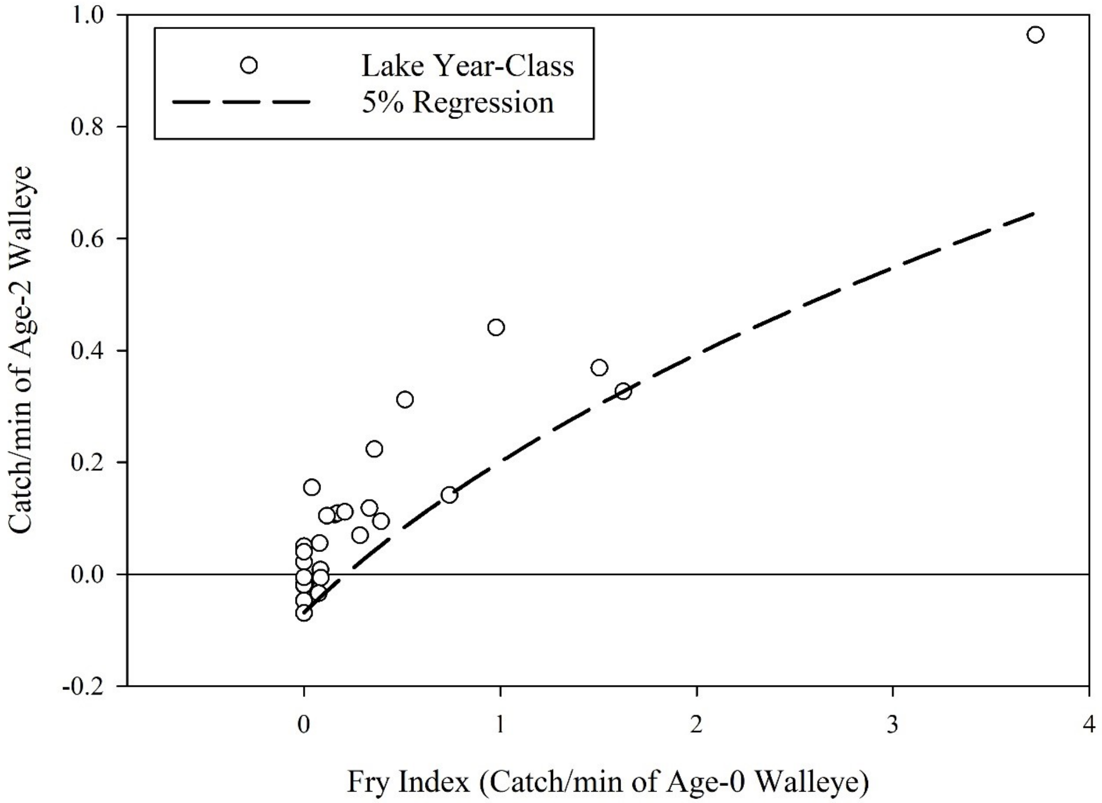

Figure 8. Catch of Walleye at Age-2, as indexed by catch at Age-0 by nighttime electrofishing in the fall, prior to any advanced fingerling Walleye stocking. The lower bound line (determined by a 5% quantile regression) is shown.

DISCUSSION AND MANAGEMENT IMPLICATIONS

This study determined stable cost-effectiveness of advanced fingerling-stocked Walleye by late fall and greater recruitment to adulthood (Age-2) compared to fry-stocked Walleye. These findings are similar to previous research in Illinois (Santucci and Wahl 1993), Iowa (Mitzner 2002), and Wisconsin (Kampa and Hatzenbeler 2009), and has held true generally according to a recent literature review (Raabe et al. 2020). For example, Santucci and Wahl (1993) found that large fingerling Walleye (186-216 mm) had greater survival to Age-1 and Age-2 in small impoundments in Illinois than Walleye stocked as fry, small fingerlings (48-61 mm), or medium fingerlings (132-145 mm). Likewise, advanced fingerling Walleye stocked into Iowa's natural lakes had greater survival over time than fry (Weber and Weber 2020). Large fingerlings (178-203 mm) stocked in Wisconsin lakes had better recruitment to Age-1 than small fingerlings (25-51 mm) and provided more stable year-classes (Kampa and Hatzenbeler 2009). In contrast, fry stocking had more variable outcomes, but could produce substantial year-classes intermittently (Mitzner 2002; Lucchesi 2002). Although this study did not evaluate fry stocking density as a factor (consistently stocking 2,000-3,000 fry/acre in all study lakes), stocking density has not consistently been shown to relate to year-class strength (Forney 1976; Carlander and Payne 1977), and our raw results implied that in most locations the fry stocking was either successful or unsuccessful in an individual year.

Lake characteristics had significant effects on whether fry or advanced fingerling stocking would be successful (as indicated by number of Age-2 adults caught by electrofishing), and the interaction effects with size-at-stocking in catch curve models implied that one size was not consistently better or worse the other. Instead, important variables included fish community and summertime water quality characteristics. Fry-stocked fish, which were stocked during early summer, benefitted from warm water temperatures which could be conducive to growth in the range observed in this study (Raabe et al. 2020). Both sizes were negatively affected by solids polluting the water. It is possible that suspended and dissolved solids affected recruitment by reducing the thermal-optical habitat area ideal for Walleye foraging, as water clarity is known to affect Walleye recruitment (Raabe et al. 2020). Walleye are visual predators and require habitat that simultaneously provides cool temperature, adequate dissolved oxygen, and adequate water clarity for feeding (e.g., a Secchi depth of 1-3 m: Raabe et al. 2020). Crappie and Largemouth Bass densities were also important, likely because both fish can predate on or compete with young Walleye. Largemouth Bass density had an especially strong effect reducing fry-stocked Walleye success, and I recommend no fry stocking if Largemouth Bass electrofishing catch rates exceed 21.5 fish/hour. Likewise, Grausgruber and Weber (2021) determined that predation was the most important factor affecting advanced fingerling Walleye survival post-stocking in Iowa natural lakes. Walleye stocking tends to be less successful when Largemouth Bass densities are high (Santucci and Wahl 1993; Fayram et al. 2005; Grausgruber and Weber 2020; Raabe et al. 2020) or when forage densities are low (Kampa and Jennings 1998). Although summer zooplankton densities were not evaluated in this study, fry stocking success may also be affected by zooplankton abundance post-stocking; past research in this area has yielded inconsistent conclusions (Kampa and Jennings 1998).

Final catch curve models did not include any physical lake characteristics (e.g., lake area, lake shape indices). However, that result is partially due to exclusion of variables with inadequate coverage by the suite of study lakes; because study lakes did not span a substantial portion of the possible range of values for those variables, I could not rightly make conclusions on their effect on Walleye stocking success in impoundments with this study. I expected mean or maximum lake depth may be important, as has been shown by previous studies (Bennett and McArthur 1990; Parsons and Pereira 2001; Nate et al. 2003; Jacobson and Anderson 2007), but these morphometric indicators did not explain enough additional variance to remain in the final models. Generally, Walleye-friendly lakes tend to be similar to each other in physical characteristics whether they supported self-sustaining or stocked populations (Nate et al. 2003). In addition, Walleye stocking tends to be less successful in locations with storage ratios less than 1.0 (Erickson and Stevenson 1972; Johnson et al. 1985; Willis and Stephen 1987), small surface area (<100 ha; Bennett and McArthur 1990; Nate et al. 2003; Jacobson and Anderson 2007; Raabe et al. 2020), and muck substrates (Nate et al. 2003). Emigration potential of larger Walleye should also be considered and may be affected by spillway design, dam operations, and seasonal flows (see Part 2). Prior to stocking Walleye into a lake, the lake's characteristics should be examined to determine the following: A) whether Walleye in general would likely be successfully established through stocking (i.e., Walleye friendliness); and B) whether Walleye should be stocked as fry or as advanced fingerlings.

Cost-effectiveness of each size-at-stocking varied depending on lake characteristics. Despite the greater reliability of advanced fingerling-stocked Walleye in general, fry stocking was more cost-effective in specific lake conditions and was more influential in establishing highly abundant year-classes (e.g., Lake Icaria). Thus, fry stocking success can drive year-class establishment (Carlander et al. 1960; Payne 1975; Mitzner 1992; McWilliams and Larscheid 1992; Mitzner 2002), and early fall electrofishing catch rate can be used as a fairly reliable index of that year-class's presence. Since this electrofishing occurs prior to advanced fingerling stocking and indexes fry stocking success, it is called the Fry Index. If the Fry Index exceeds 0.22 fish/min, there is a 95% chance of capturing fish from that year-class at Age-2. In other words, there is a 95% chance that a year-class has been established through fry stocking, and advanced fingerling stocking is not needed. If driving the electrofishing boat at walking speed (4.8 km per hour/3 mi per hour) as indicated in Iowa DNR's standard sampling protocol (Iowa DNR, no year), this equates to approximately 2.8 fish/shoreline km (4.4 fish/mi). However, this is an absolute minimum for acceptable fry capture (yielding >0 Age-2 adult Walleye). If the management goal is a target density of adult Walleye, then a more reasonable number may be that which leads to at least 5 Age-2 adult Walleye per hour of electrofishing; using the same regression line, the target fry catch rate is 0.50 fish/min or 6.25 fish/km (10 fish/mi). This estimate is identical to that suggested for assessing fry recruitment success in Wisconsin lakes (Hansen et al. 2015). The Fry Index presented in this study is specifically a lower-bound model, in which there is potential for year-class establishment without high fry catch; these year-classes were likely supported or established by remedial advanced fingerling stocking. Because advanced fingerlings are more costly to produce, it is wise to conduct nighttime electrofishing in early fall and calculate the Fry Index to guide advanced fingerling stocking decisions.

I did not detect an effect of year-class on Walleye stocking success, implying the advanced fingerling size and condition at the time of stocking (i.e., the hatchery product) did not significantly alter outcomes over time. Mitzner (1992) and McWilliams and Larscheid (1992) found disparate overwintering mortalities between fry and fingerling-stocked fish during the first winter, leading to dominance by fry-stocked fish by the next spring compared to fingerlings grown out in nursery ponds (i.e., extensively reared). However, this was not the case for intensively reared fingerlings (Mitzner 1992; McWilliams and Larscheid 1992) like the ones used in the current study. Since those earlier studies were conducted, the mean size and condition of advanced fingerling Walleye has increased through improved culture methods, and it was typical for the mean length of fish stocked to exceed 200 mm as suggested by Santucci and Wahl (1993). Likewise, Larscheid (2005) recommended stocking fingerlings at least 127 mm to enhance survival, and Flammang (2008) recommended fingerlings exceed 178 mm. Studies that found poorer survival of fingerling-stocked Walleye were conducted using smaller fingerlings (e.g., Koppelman et al. 1992; Olson et al. 2000; Pratt and Fox 2003). Although overwintering mortality of advanced fingerling Walleye during the first year is still quite substantial (Grausgruber and Weber 2021), Iowa's advanced fingerling program recently has been shown to produce fish that survive at a higher rate than fry-stocked fish over time (Weber and Weber 2020).

Previous stocking studies in Iowa have used the ratio of fingerling-stocked fish to fry-stocked fish to calculate the number of fry-stocked fish alive by late fall (Mitzner 1992; McWilliams and Larscheid 1992; Mitzner 2002). However, initial mortality of intensively reared Walleye can be important and would affect this ratio calculation (McWilliams and Larscheid 1992); specifically, post-stocking mortality due to predation could quickly reduce the number of advanced fingerlings present (Grausgruber and Weber 2020). To account for this, the number of advanced fingerling Walleye likely to alive by the time of the post-stocking electrofishing sample was adjusted by predicted mortality due to predation. This adjusted number was then used to calculate the number of fry alive and consequent numbers of fish established per dollar. I recommend using this adjustment in future stocking studies to more accurately assess cost-effectiveness. I also acknowledge that cost-effectiveness in this study was based on partially limited dispersal of advanced fingerling Walleye because follow-up sampling was delayed by only one week. According to a recent study in Iowa natural lakes, advanced fingerling Walleye dispersed in 13 days (Weber et al. 2019). This could have affected our cost-effectiveness analysis by artificially inflating recapture rates of advanced fingerling-stocked fish and reduced our estimates of fry-stocked Walleye surviving to late fall. Future investigations of cost-effectiveness using a ratio of fish captured should delay sampling after stocking by two weeks instead of one to allow for complete dispersal of stocked fish (Weber et al. 2019). In addition, long-term survival and recruitment to adulthood may not be reflected by survival to the first fall (McWilliams and Larscheid 1992), so assessment of contribution by different stocking methods should be delayed to at least Age-1 if not Age-2 (e.g., Weber and Weber 2020). In the current study, I utilized a catch curve approach in order to garner information from all ages recaptured during the study, rather than relying on survival to the first fall or ratios of fish captured age Age-0.

The formulas presented in this report can be used for individual lakes to compare whether predicted catch will be greater using fry-stocked or fingerling-stocked fish, and to assess how practical Walleye stocking may be at an individual lake relative to other locations. These formulas are not prescriptive, but rather comparative, to help fisheries managers choose the most efficient stocking method and select more Walleye-friendly locations for establishing fisheries. Because lake characteristics alter the catch curve predictions, changes over time can affect Walleye friendliness of a location. For example, a decline in Largemouth Bass or crappie densities may provide an opportunity for stocking Walleye in a new location, and a lake renovation resulting in a significant reduction in suspended and dissolved solids could create more Walleye-friendly habitat. Finally, natural recruitment potential of Walleye may need to be re-examined as lake conditions and habitat change over time (Hill 2001) such as following a lake renovation. For example, reduced productivity and elevated water temperatures may contribute to Walleye declines, whereas addition of spawning substrates may enhance natural recruitment (Raabe et al. 2020). Regular contributions from natural recruitment would likely far exceed stocking, making supplemental stocking minimally effective (<5% of the time: Kampa and Jennings 1998) and even suppressive on adjacent year-classes (Li et al. 1996), allowing resources invested in fish culture to be allocated elsewhere (Trushenski et al. 2018).

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APPENDIX

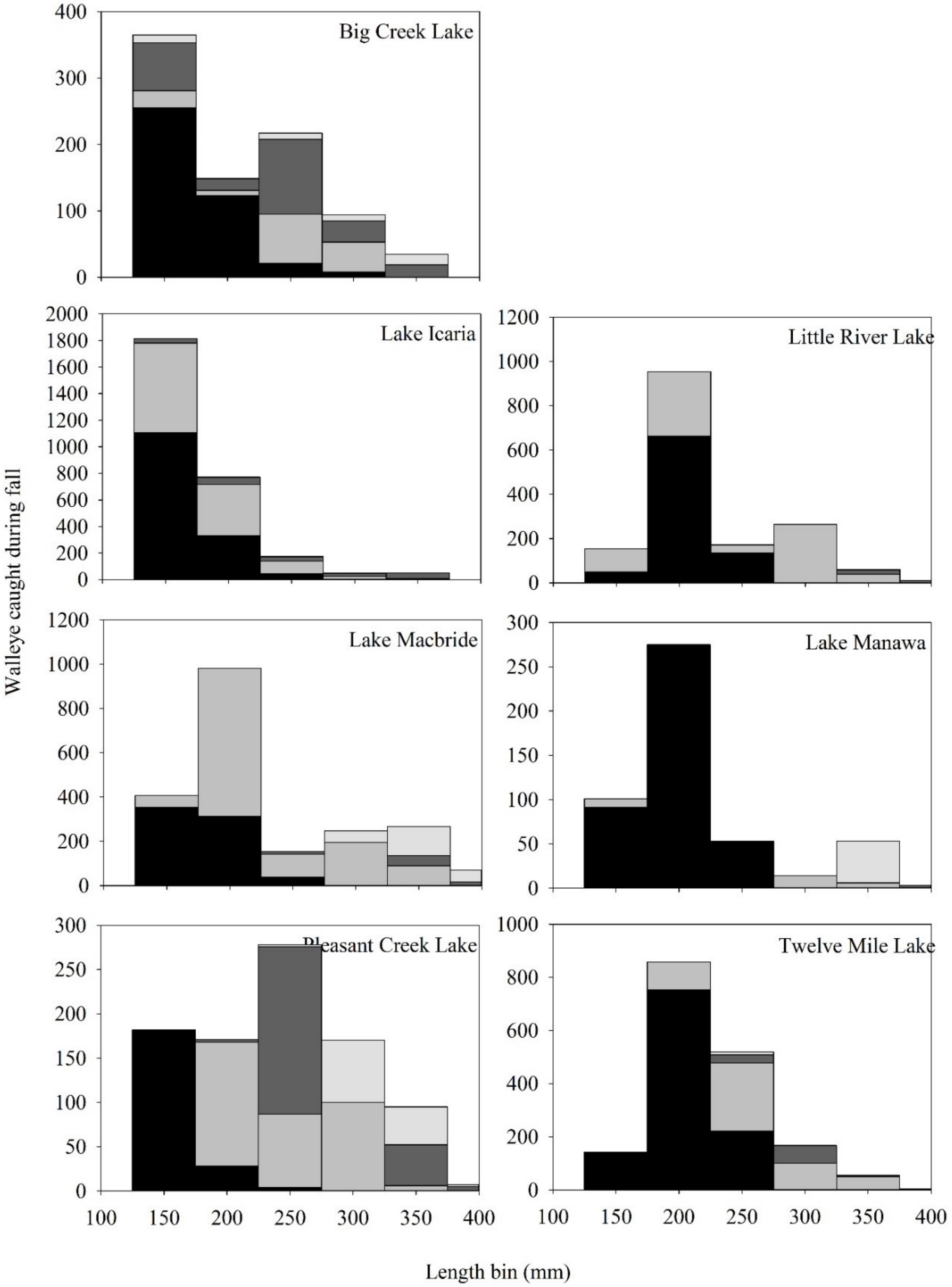

Figure A 1. Number of Age-0 to Age-3 fish captured during fall nighttime electrofishing at study lakes, by length bin and age. Age is indicated by the color of the bar, with the youngest (Age-0) shown in black.

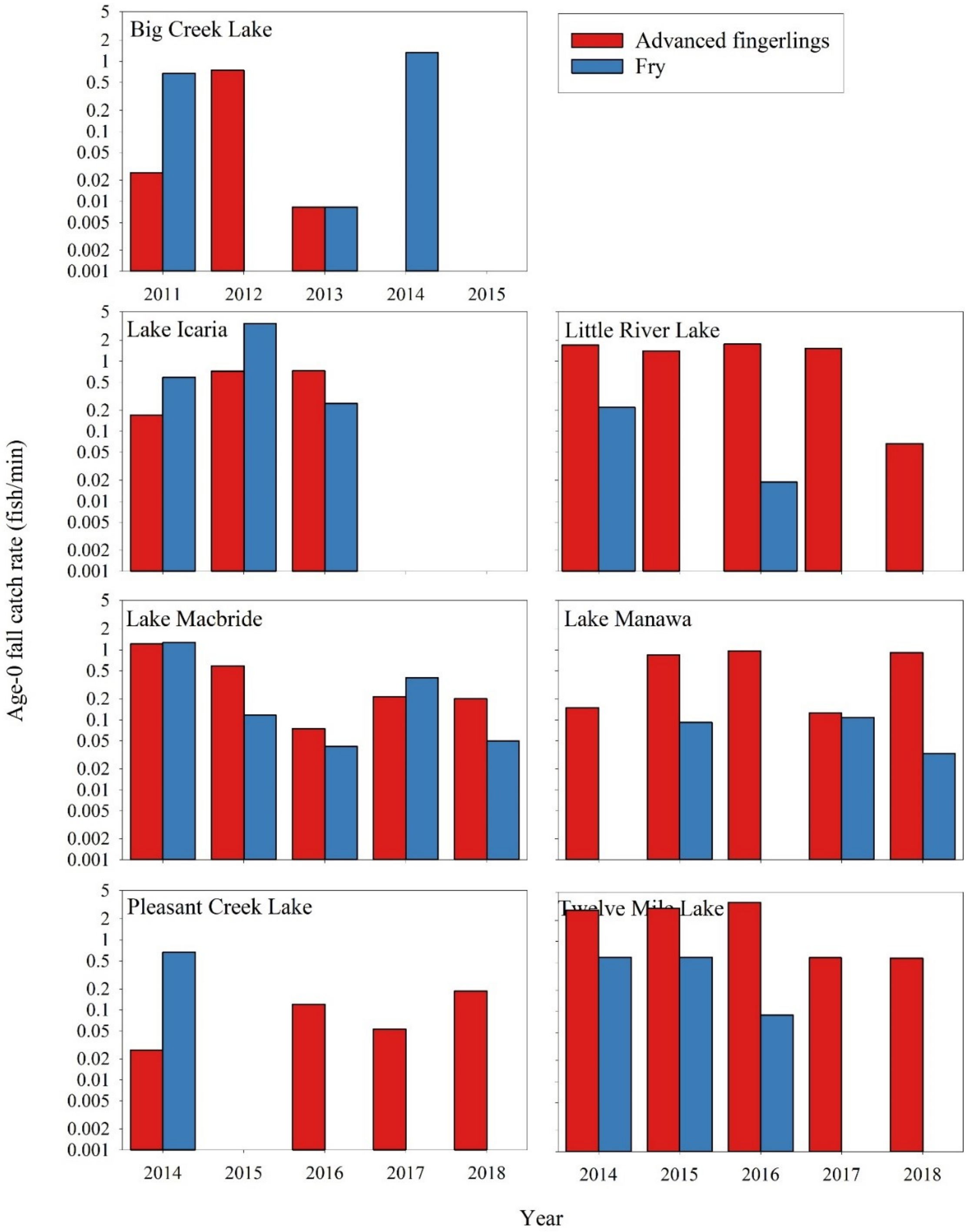

Figure A 2. Fall nighttime electrofishing catch rate of Age-0 Walleye from study lakes, by size-at-stocking.

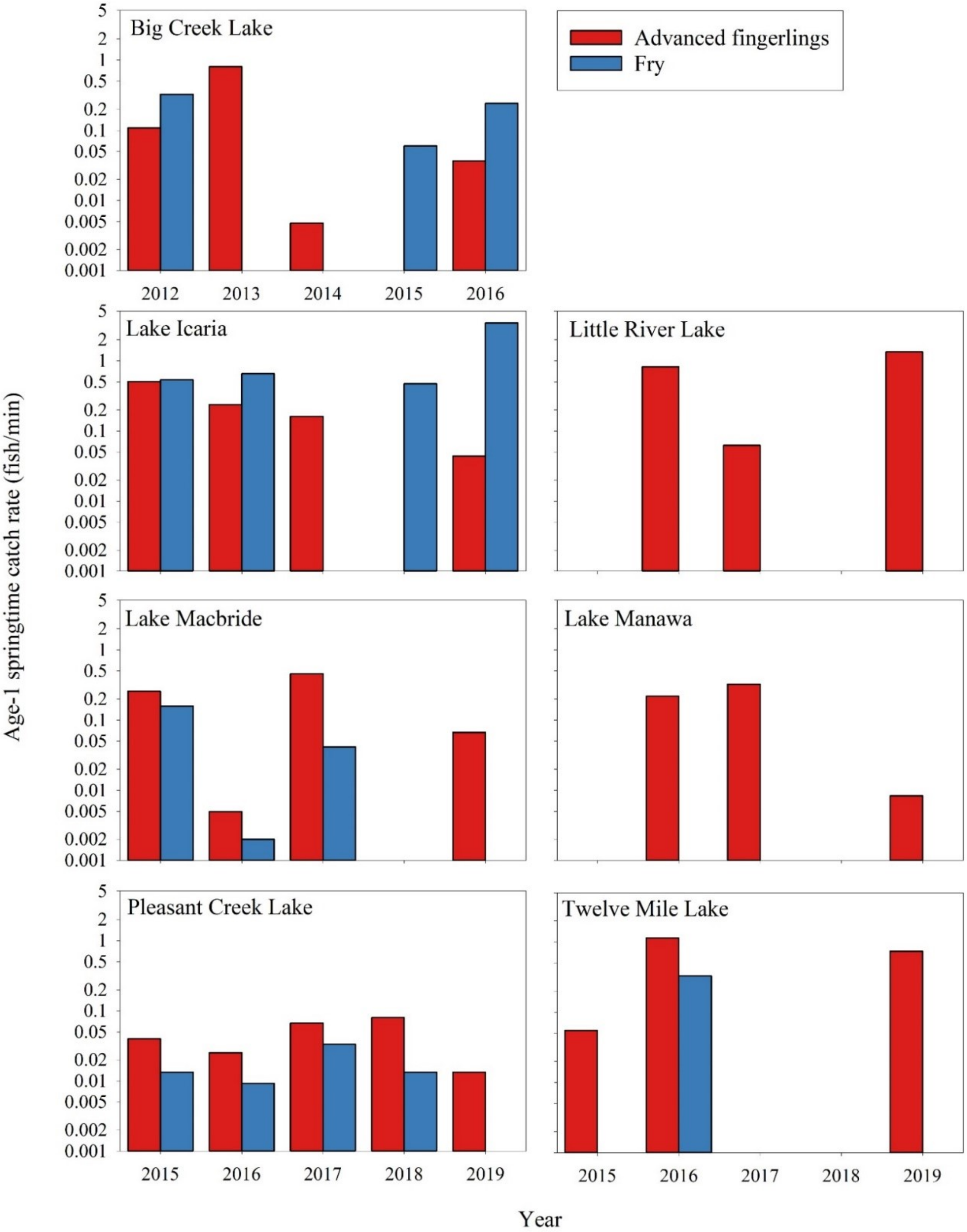

Figure A 3. Spring nighttime electrofishing catch rate of Age-1 Walleye from study lakes, by size-at-stocking.

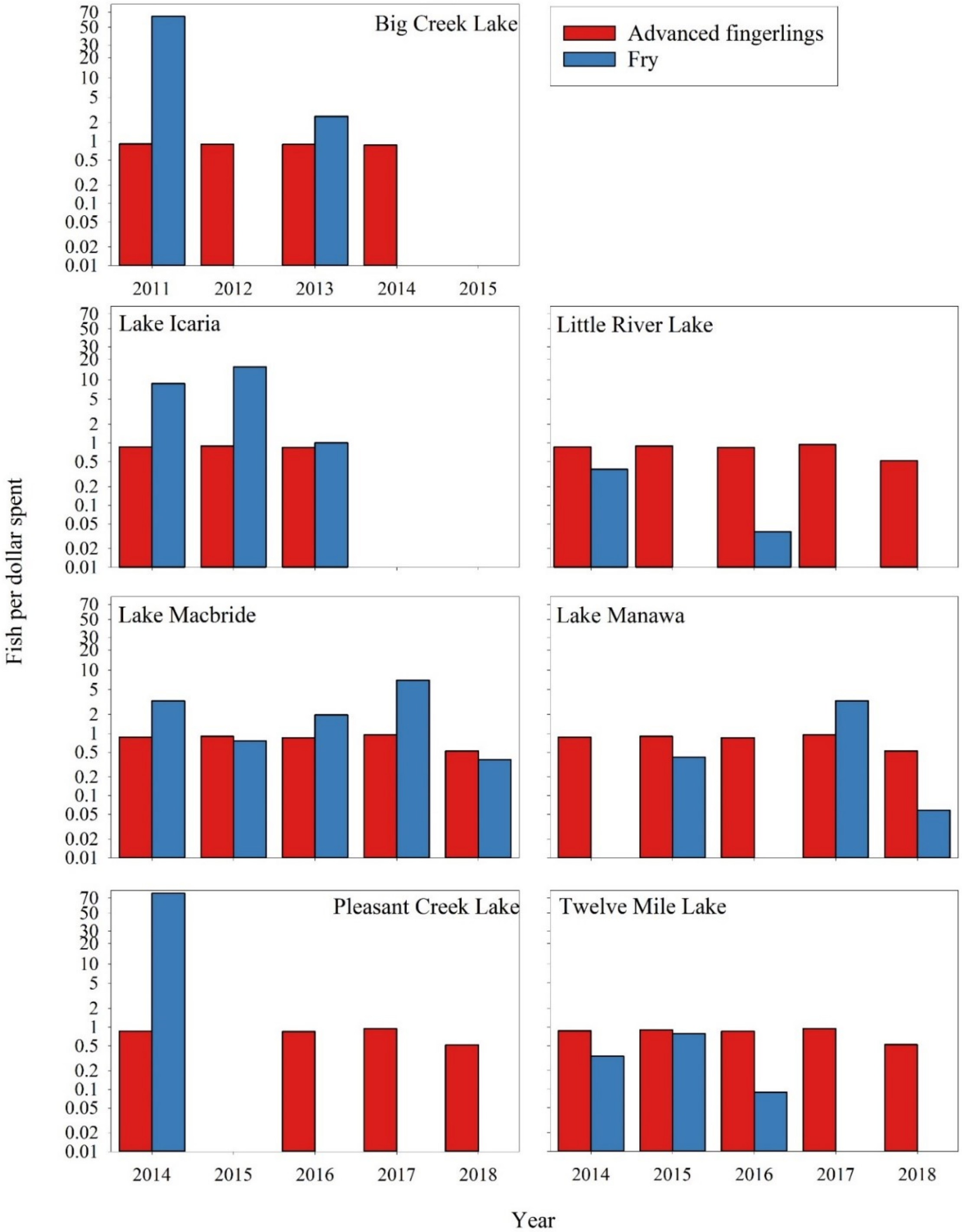

Figure A 4. Age-0 Walleye established per dollar spent during production, by late fall of the year of stocking.

Table A 1. Significant publicly-owned lakes and their characteristics, ranked for Walleye-friendliness, in alphabetical order. WaterTemp = mean summertime water temperature (°C), TDS = mean summertime total dissolved solids (mg/L), TSS = mean summertime total suspended solids (mg/L), CPUE_{LMB} = Largemouth Bass catch rate (fish/hr) from electrofishing, $\text{CPUE}_{\text{Crappie}}$ = Black and White Crappie catch rate (fish/net-night) from modified fyke netting

Lake Code	Lake	County	Water Temp	TDS	TSS	CPUE_{LMB}	$\text{CPUE}_{\text{Crappie}}$	Fry Rank	Adv Rank	Friendliness Index
ARB79	Arbor Lake	Poweshiek	22.57	308.00	22.00	-	-	-	-	-
ARR78	Arrowhead Pond (Pottawattamie)	Pottawattamie	.	.	.	-	-	-	-	-
BAC61	Badger Creek Lake	Madison	23.40	169.67	32.00	40.10	52.16	45	54	0.25
BAD94	Badger Lake	Webster	20.66	390.00	17.63	208.00	7.75	71	71	0.00
BEA25	Beaver Lake	Dallas	24.77	183.00	20.17	72.65	25.95	47	45	0.27
BEE35	Beeds Lake	Franklin	22.70	370.00	8.53	10.22	12.42	34	68	0.21
BIC77	Big Creek Lake	Polk	21.60	303.33	2.60	28.00	5.02	32	56	0.23
BHO29	Big Hollow Lake	Des Moines	24.73	260.00	13.27	76.00	1.00	42	43	0.28
BWH93	Bob White Lake	Wayne	24.37	136.67	52.00	37.00	7.49	31	40	0.29
BWO40	Briggs Woods Lake	Hamilton	24.63	203.33	15.77	85.64	20.25	53	50	0.26
BRC94	Brushy Creek Lake	Webster	19.84	385.39	8.00	64.83	1.42	68	65	0.11
CAS86	Casey Lake (Hickory Hills Lake)	Tama	23.90	196.67	5.83	-	-	-	-	-
CEN53	Central Park Lake	Jones	23.29	251.70	8.33	124.16	3.43	59	46	0.26
CSP15	Cold Springs Lake	Cass	26.47	173.33	7.57	120.50	8.50	38	31	0.36
COR52	Coralville Reservoir	Johnson	22.83	320.00	14.87	41.10	19.77	65	67	0.10
CRC47	Crawford Creek Impoundment	Ida	22.79	244.75	6.33	9.56	20.00	5	38	0.40
DIA79	Diamond Lake	Poweshiek	22.40	166.67	18.03	55.17	47.43	41	36	0.31
DCR71	Dog Creek Lake	O'Brien	22.63	310.00	6.70	-	-	-	-	-
DWI08	Don Williams Lake	Boone	19.73	350.00	8.53	50.00	11.42	67	66	0.10
EOS20	East Lake (Osceola)	Clarke	24.00	153.46	13.33	56.28	19.50	25	25	0.38
EAS77	Easter Lake	Polk	24.30	286.67	12.63	25.94	29.77	46	64	0.17
ESH41	Eldred Sherwood Lake	Hancock	20.97	321.42	6.87	85.43	-	-	-	-
FOG80	Fogle Lake	Ringgold	23.79	138.97	9.20	-	-	-	-	-
GCA64	Green Castle Lake	Marshall	23.54	193.94	5.07	46.40	-	-	-	-
GVA88	Green Valley Lake	Union	23.04	103.33	25.33	87.72	22.53	36	18	0.41
GRL01	Greenfield Lake	Adair	23.59	174.61	5.67	82.19	42.96	44	33	0.33
HAN06	Hannen Lake	Benton	23.80	170.81	18.67	6.20	16.67	2	21	0.56
HAW62	Hawthorn Lake (Barnes City Lake)	Mahaska	25.17	130.83	13.00	-	-	-	-	-
HGR85	Hickory Grove Lake	Story	23.80	217.33	10.83	47.63	7.57	28	35	0.31
HOO91	Hooper Area Pond	Warren	24.50	155.26	9.33	44.00	12.61	12	17	0.42

Lake Code	Lake	County	Water Temp	TDS	TSS	$CPUE_{LMB}$	$CPUE_{Crappie}$	Fry Rank	Adv Rank	Friendliness Index
IND89	Indian Lake	Van Buren	25.70	183.33	19.20	72.67	37.84	50	52	0.25
KEP52	Kent Park Lake	Johnson	25.01	177.66	11.20	87.40	16.14	39	34	0.33
LKE89	Lacey Keosauqua Park Lake	Van Buren	24.21	133.21	19.00	-	-	-	-	-
AHQ91	Lake Ahquabi	Warren	25.00	150.00	8.17	66.27	9.54	16	15	0.43
ANI15	Lake Anita	Cass	26.23	154.00	25.83	68.12	26.95	40	42	0.29
BDL54	Lake Belva Deer	Keokuk	24.13	156.67	5.80	66.11	2.90	11	8	0.48
DAR92	Lake Darling	Washington	25.47	195.67	14.67	31.85	62.49	27	49	0.26
GEO44	Lake Geode	Henry	23.23	217.33	3.47	36.40	2.72	10	22	0.40
HEN45	Lake Hendricks	Howard	24.10	147.33	19.10	44.99	3.21	9	13	0.45
ICA02	Lake Icaria	Adams	23.15	126.78	12.07	35.69	19.59	8	10	0.46
IOW48	Lake Iowa	Iowa	25.73	160.00	10.00	-	-	-	-	-
KEO62	Lake Keomah	Mahaska	23.90	216.00	8.13	212.00	5.29	64	41	0.29
MAC52	Lake Macbride	Johnson	25.67	180.91	5.87	57.07	9.90	17	26	0.37
MEY96	Lake Meyer	Winneshiek	23.47	296.67	8.83	67.71	9.85	62	63	0.16
MIA68	Lake Miami	Monroe	24.81	124.66	17.67	184.44	12.00	51	23	0.39
ORI01	Lake Orient	Adair	23.23	137.43	28.67	-	-	-	-	-
PAH60	Lake Pahoja	Lyon	19.89	428.66	23.67	121.54	15.24	72	72	0.00
SMI55	Lake Smith	Kossuth	21.01	263.02	8.33	63.00	12.23	58	58	0.23
SUG89	Lake Sugema	Van Buren	24.53	104.22	8.33	106.18	12.03	18	5	0.50
WAP26	Lake Wapello	Davis	23.83	117.96	8.00	148.59	7.08	29	6	0.49
TFI87	Lake of Three Fires	Taylor	23.25	114.82	13.00	107.25	21.41	33	14	0.44
LTH82	Lake of the Hills	Scott	21.40	227.40	26.00	-	-	-	-	-
LRI27	Little River Watershed Lake	Decatur	22.60	132.41	7.00	97.81	7.12	22	7	0.48
LIT05	Littlefield Lake	Audubon	23.43	173.46	28.53	97.04	21.17	60	47	0.26
LGR82	Lost Grove Lake	Scott	24.13	219.63	6.67	32.16	-	-	-	-
LPI42	Lower Pine Lake	Hardin	23.62	217.14	11.53	49.05	30.57	43	51	0.26
MAP83	Manteno Park Pond	Shelby	21.40	266.94	16.00	50.00	-	-	-	-
MAR50	Mariposa Lake	Jasper	22.77	185.33	12.00	64.19	112.00	52	48	0.26
MEA01	Meadow Lake	Adair	23.60	132.60	19.67	123.57	23.36	49	30	0.36
MIC71	Mill Creek Lake	O'Brien	22.18	259.01	12.67	-	-	-	-	-
MOO47	Moorehead Park Pond	Ida	20.66	280.40	0.60	85.71	25.20	66	60	0.20
MTR01	Mormon Trail Lake	Adair	23.72	119.31	9.33	72.96	21.61	19	11	0.45
NEL24	Nelson Park Lake	Crawford	21.04	304.20	2.20	151.33	8.57	70	61	0.17

Lake Code	Lake	County	Water Temp	TDS	TSS	CPUE_{LMB}	$\text{CPUE}_{\text{Crappie}}$	Fry Rank	Adv Rank	Friendliness Index
NEA27	Nine Eagles Lake	Decatur	22.70	121.74	4.33	93.14	0.78	7	2	0.62
NOD01	Nodaway Lake	Adair	22.63	166.51	10.67	44.00	27.58	23	29	0.37
OLD67	Oldham Lake	Monona	20.40	303.53	9.67	116.75	5.41	69	62	0.17
OTC86	Otter Creek Lake	Tama	23.53	181.69	12.33	34.42	11.87	14	28	0.37
PIC73	Pierce Creek Lake	Page	23.15	168.84	14.67	-	-	-	-	-
PLC57	Pleasant Creek Lake	Linn	23.44	205.34	4.53	60.91	3.28	20	24	0.39
POL56	Poll Miller Park Lake	Lee	22.44	179.21	12.53	-	-	-	-	-
PRO83	Prairie Rose Lake	Shelby	23.25	193.45	8.67	175.58	17.63	63	39	0.29
RAT04	Rathbun Reservoir	Appanoose	23.05	137.11	6.53	9.40	17.76	1	4	0.60
RHA59	Red Haw Lake	Lucas	20.89	129.84	6.00	201.07	1.75	35	3	0.54
RRO63	Red Rock Reservoir	Marion	24.77	383.33	18.60	13.00	19.14	54	70	0.12
ROC63	Roberts Creek Lake	Marion	22.82	268.65	7.53	6.00	31.39	4	53	0.41
ROC50	Rock Creek Lake	Jasper	24.37	205.89	22.67	19.89	59.84	26	57	0.25
ROG06	Rodgers Park Lake	Benton	23.51	235.43	22.33	73.13	-	-	-	-
SAY77	Saylorville Reservoir	Polk	22.57	416.67	16.60	15.80	2.36	55	69	0.12
SIL28	Silver Lake (Delaware)	Delaware	.	.	.	60.81	21.57	-	-	-
SBL27	Slip Bluff Lake	Decatur	24.75	99.41	4.00	112.00	1.33	6	1	0.63
SPR39	Springbrook Lake	Guthrie	21.56	266.13	8.20	110.00	-	-	-	-
SUM88	Summitt Lake	Union	23.50	113.26	25.53	-	-	-	-	-
THY88	Thayer Lake	Union	23.48	151.89	9.33	172.00	25.00	57	32	0.36
THM88	Three Mile Lake	Union	23.80	145.75	11.00	15.39	13.42	3	9	0.49
TMI88	Twelve Mile Creek Lake	Union	23.34	140.26	8.00	124.03	13.82	37	16	0.42
UGR86	Union Grove Lake	Tama	23.77	200.18	16.53	103.22	31.40	61	55	0.24
UPI42	Upper Pine Lake	Hardin	23.49	249.93	13.67	48.54	14.79	48	59	0.22
VIK69	Viking Lake	Montgomery	24.94	146.06	9.00	71.77	15.44	21	19	0.41
VOL33	Volga Lake	Fayette	22.72	222.47	17.33	35.60	9.53	30	44	0.28
WOS20	West Lake (Osceola)	Clarke	23.13	134.01	6.00	57.63	21.90	15	12	0.45
WOA62	White Oak Lake	Mahaska	23.15	161.82	8.00	-	-	-	-	-
WIP59	Williamson Pond	Lucas	24.64	117.08	22.33	39.00	27.50	13	20	0.40
WIL43	Willow Lake	Harrison	23.69	261.17	6.00	65.65	-	-	-	-
WIL87	Wilson Park Lake	Taylor	.	.	.	111.09	22.53	-	-	-
WIN87	Windmill Lake	Taylor	22.78	136.11	21.00	41.33	38.40	24	27	0.37
YSM24	Yellow Smoke Park Lake	Crawford	23.42	235.80	4.53	131.27	3.82	56	37	0.30

PART 2: MODELED WALLEYE REGULATION OUTCOMES IN A MIDWESTERN RESERVOIR WITH VARYING FORAGE AND WALLEYE DENSITY (BIG CREEK LAKE, IOWA)

One of the original objectives of this study was to increase Walleye density at Big Creek Lake through stocking. This was achieved, but other factors besides stocking may also have been important (e.g., installation of a fish barrier, drought during key fry-stocked Walleye years). Subsequent changes in population dynamics also occurred, altering the fishery. Finally, additional changes in forage also had drastic impacts on the Walleye population. A manuscript documenting the increase in Walleye density at Big Creek Lake, as well as comparison to historical and later conditions, was drafted for submission to the proceedings of the 2021 Walleye Symposium, which was held at Midwest Fish and Wildlife Conference in January 2021. The manuscript was submitted for inclusion in a special issue of North American Journal of Fisheries Management and is included below in journal format. It should be cited as:

Krogman, RM, B Dodd, A Otting, MJ Weber, and RE Weber. *In revision*. Modeled Walleye regulation outcomes in a Midwestern reservoir with varying forage and Walleye density. Submitted to North American Journal of Fisheries Management, Special Issue (2021 Walleye Symposium).

ABSTRACT

In a put-grow-take fishery, Walleye *Sander vitreus* management may require length-based regulation and depends on population dynamics such as growth, which in turn depends on forage. Big Creek Lake, an important Iowa Walleye fishery, underwent forage changes twice within two decades. Concurrently, Walleye density changed due to increased stocking and reduced emigration, resulting in four scenarios: A) low-density Walleye with Gizzard Shad *Dorosoma cepedianum* forage, B) low-density Walleye with centrarchid/percid forage, C) high-density Walleye with centrarchid/percid forage, and D) high-density Walleye with Gizzard Shad forage. We examined Walleye population dynamics and relative effects of four length-based regulations during each period using sampling data from 1998-2000, 2006-2008, 2013-2015, and 2019. Walleye in Big Creek Lake likely experienced density-dependence when Walleye density was high and Gizzard Shad were absent, resulting in depressed growth, low condition, increased natural mortality, reduced exploitation, and ineffectiveness of regulations. At lower Walleye densities, the centrarchid/percid forage supported Walleye growth and condition equivalent to when Gizzard Shad were present. Fishing regulations for enhancing Walleye size distribution or yield differed over time due to shifting population dynamics and angler exploitation, and were notably ineffective during Period C. The preferred regulation for the current scenario (high-density Walleye with Gizzard Shad) depends on angler preferences for higher catch or larger fish. Big Creek Lake's Walleye fishery provided a useful demonstration of how rapidly a population can respond to changes in density and forage, and therefore how dynamic fishery management needed to be.

INTRODUCTION

Walleye *Sander vitreus* provide recreational fishing opportunities throughout their range in North America, which spans to every coast as a result of glacial events, colonization, and transplantation (Billington et al. 2011). In the U.S. Walleye fishing drew over 3.8 million anglers in 2016 (USFWS and USCB 2016), and was particularly important in the Midwest and northern latitudes (Schmalz et al. 2011). In Iowa, Walleye are targeted by 43% of Iowa's licensed anglers, typically in interior lakes and reservoirs (Responsive Management 2019). Although Walleye are native to both riverine and lacustrine habitats in Iowa, they do not have self-sustaining populations in most reservoirs due to lack of suitable spawning habitat (Bozek et al. 2011) and are maintained through stocking of cultured Walleye (Kerr 2011). Over 148 million Walleye fry and 1.5 million fingerlings were produced and stocked in 2019 by Iowa Department of Natural Resources to provide fishing opportunities statewide (Iowa DNR 2019), giving Iowa one of the largest Walleye stocking programs in North America (Kerr 2011). Because many fisheries are put-grow-take opportunities, management goals typically focus on achieving target densities of catchable Walleye or enhancing size distribution, rather than improving spawning potential or enhancing recruitment.

Walleye fisheries require adequate forage to support early life survival and growth over time. That forage base is typically composed of percids (e.g., Yellow Perch *Perca flavescens*), salmonids (e.g., Cisco *Coregonus artedi*), centrarchids (e.g., Bluegill *Lepomis macrochirus*), cyprinids (e.g., shiners *Notropis* spp.), and clupeids (e.g., Alewife *Alosa pseudoharengus* and Gizzard Shad *Dorosoma cepedianum*). Specifically, clupeids are often a dominant component of

Walleye diet when present, regardless of Walleye age (Carlander 1997; Quist et al. 2002; Ward et al. 2007; Wuellner et al. 2010), and are associated with greater Walleye growth (Hartman and Margraf 1992; Quist et al. 2004; Wuellner et al. 2010; VanDeHey et al. 2014). Walleye prefer small-bodied clupeids when they are available as forage. For example, Gizzard Shad composed the bulk of biomass in Walleye diets in Lake Sharpe, South Dakota (Wuellner et al. 2010), Glen Elder Reservoir, Kansas (Quist et al. 2002), and Lake Erie (Knight et al. 1984; Hartman and Margraf 1992). In Lake McConaughy, Nebraska, clupeids composed 95% of Walleye stomach contents in reservoir sampling, although Yellow Perch and White Sucker *Catostomus commersonii* were also available (Porath and Peters 1997). Prior to Gizzard Shad introduction to Oneida Lake, New York, the primary forage species was Yellow Perch (Forney 1974); afterward, Gizzard Shad became a significant component of Walleye diet (Lantry et al. 2008).

Besides forage, management of Walleye fisheries may also entail fishing regulation, establishment of seasons, and gear restrictions (Brousseau and Armstrong 1987; Isermann and Parsons 2011). Length-based limits are typically used to prevent overharvest, enhance population structure, maintain favorable population dynamics, and maximize yield or other fishery metrics (Brousseau and Armstrong 1987), and have successfully done so (Fayram et al. 2001; Stone and Lott 2002). For instance, a 356-mm minimum length limit in South Dakota produced both increased yield and fish harvest within two years of regulation (Stone and Lott 2002). However, length limits have also resulted in reduced growth and poor fish condition; severe declines in growth following implementation of a minimum length limit could result in stockpiling of Walleye below the legal size, prolonging the time for fish to enter the fishery and increasing the proportion of fish lost to natural mortality (Serns 1978; Munger 2002; Larscheid and Hawkins 2005). A MLL led to stockpiling in Big Crooked Lake, Texas (a 381-mm MLL: Serns 1978), and Meredith Reservoir, Texas (a 407-mm MLL: Munger 2002). Although the number of fish below the MLL increased in Big Crooked Lake, condition, growth, and mean length of angler-caught Walleye decreased (Serns 1978). In Meredith Reservoir, total Walleye abundance and angler catch rates increased but harvest did not, and fish below the MLL proliferated (Munger 2002). Interestingly, stockpiling may have been avoided in Lake Francis Case, South Dakota, because some harvest of smaller fish was allowed; the MLL was seasonal and effective only during the months of highest fishing pressure (Stone and Lott 2002). This approach led to increased catch rates of Walleye > 356 mm, but no changes in relative weight or growth. Alternatively, length-based regulations may have no measurable effect on Walleye growth, size distribution, or catch rate but could preclude anglers from harvest, reducing exploitation without a tradeoff of benefits (Isermann 2007). Inappropriate regulations unsuited to the population being managed can do more harm than good (Brousseau and Armstrong 1987). Therefore, understanding how populations with variable characteristics respond to different regulations is an important component of effective fishery management.

We wanted to examine the relative effects of different length-based regulations on a Walleye fishery in the presence and absence of Gizzard Shad. Big Creek Lake in central Iowa provided a single location with a variable history of Gizzard Shad presence/absence and concurrent Walleye population dynamics. Like Oneida Lake, Big Creek Lake underwent a substantial forage base change twice during a two-decade time span, potentially altering the Walleye fishery. During the late 1990s, Gizzard Shad were abundant, composing about 60% of the catch from fishery management sampling efforts (Iowa DNR, unpublished). Angler complaints suggested the panfish fishery was poor and catch rates of Walleye were low (McWilliams 2003). Then, the Gizzard Shad were completely eradicated during a severe winter from 2000-2001 (McWilliams 2003); no shad were detected during standardized fish sampling from 2001 to 2015. The forage base reverted to Yellow Perch, Bluegill, Black Crappie *Pomoxis nigromaculatus*, and White Sucker, which had been present since impoundment (Paragamian 1977). Creel surveys immediately following the elimination of shad revealed a renewed panfish fishery again dominated by Bluegill and crappies (McWilliams 2003). However, Gizzard Shad reappeared in spring 2015, becoming abundant once again by 2017.

The Big Creek Lake Walleye fishery was regulated only by a 5-fish bag limit until 2002, when a minimum length limit of 381 mm was implemented, along with a reduced daily bag of 3 fish with only 1 fish exceeding 508 mm (McWilliams 2003). During subsequent years, anglers complained about difficulty catching legal-sized Walleye (Dodd and Otting 2008). Adult Walleye density was also low based on mark-recapture estimates from spring fishery sampling (Dodd and Otting 2012; Table 6), eventually leading to decisions to increase stocking and install a physical fish barrier on the spillway to reduce emigration (Dodd and Otting 2012). Walleye densities increased, far surpassing management goals by 2015 (Dodd and Otting 2012). However, angler complaints continued regarding the lack of legal-size Walleye, and stockpiling below the minimum length limit was suspected. After Gizzard Shad were detected the second time in 2015, Walleye growth and condition seemed to improve, while density remained high (Weber and Weber 2021; Table 6).

Table 6. Stock-size Walleye abundance estimates (with 95% confidence intervals [CI]) over time based on repeated mark-recapture sampling during spring using a Schnabel estimator (Krebs 1989), and their associated density in Big Creek Lake, Iowa.

Year	Population Estimate	Lower 95% CI	Upper 95% CI	Mean Density (#/ha)	Source
2007	665	449	1,025	1.86	Dodd and Otting (2008)
2008	1,048	748	1,521	2.94	Dodd and Otting (2008)
2010	1,171	925	1,519	3.28	Dodd and Otting (2012)
2011	1,545	1,262	1,972	4.33	Dodd and Otting (2012)
2015	4,936	4,101	6,151	13.83	Unpublished data
2017	11,084	7,385	17,296	31.05	Weber and Weber (2021)
2018	3,509	2,648	4,764	9.83	Weber and Weber (2021)
2019	7,332	4,628	13,574	20.54	Weber and Weber (2021)

The Walleye fishery in Big Creek Lake is one of the most important in the state due to its proximity to a major population center (Des Moines and its suburbs) and its longheld reputation as a Walleye destination (McWilliams 2003). It was one of the most-visited recreational waterbodies in Iowa, drawing 376,000 household trips in 2019 (Iowa DNR, unpublished data). Thirty-seven percent of recreational visitors indicated they fished at Big Creek Lake during their trip (Jeon et al. 2014). Thus, the reservoir receives a substantial amount of fishing pressure, and adaptive fishery management is needed to adjust to an ever-changing fishery and fish community.

Our objectives were to 1) evaluate Walleye growth, condition, and mortality at low and high Walleye densities in the presence and absence of Gizzard Shad, and 2) model the effectiveness of various length-based fishery regulations under each scenario. Because Big Creek Lake is a put-grow-take fishery with no natural recruitment, we were most interested in protection of stocked fish to desirable sizes, measuring regulation effectiveness by proportional size distribution indices and the number of fish achieving target lengths. We hypothesized that the Walleye population in Big Creek Lake achieved different growth and mortality under different scenarios, yielding variable effectiveness of proposed length regulations over time.

METHODS

STUDY AREA AND HISTORY

Big Creek Lake is a 357-ha reservoir located just north of Des Moines, Iowa (Figure 9). First impounded in 1972, Big Creek Lake provides additional flood control above Saylorville Reservoir and features a chute-style spillway at the end of a canal. We selected four time periods reflective of different Gizzard Shad-Walleye scenarios in Big Creek Lake. From 1998-2000, Walleye were low in abundance and supported by an abundant Gizzard Shad forage base. From 2006-2008, Walleye were low in abundance and supported by alternative species for forage with no Gizzard Shad present. From 2013-2015, Walleye were high in abundance and still dependent on alternative forage. In 2019, Walleye were high in abundance and supported by a new Gizzard Shad forage base. We referred to each of these time periods as A (1998-2000), B (2006-2008), C (2013-2015), and D (2019).

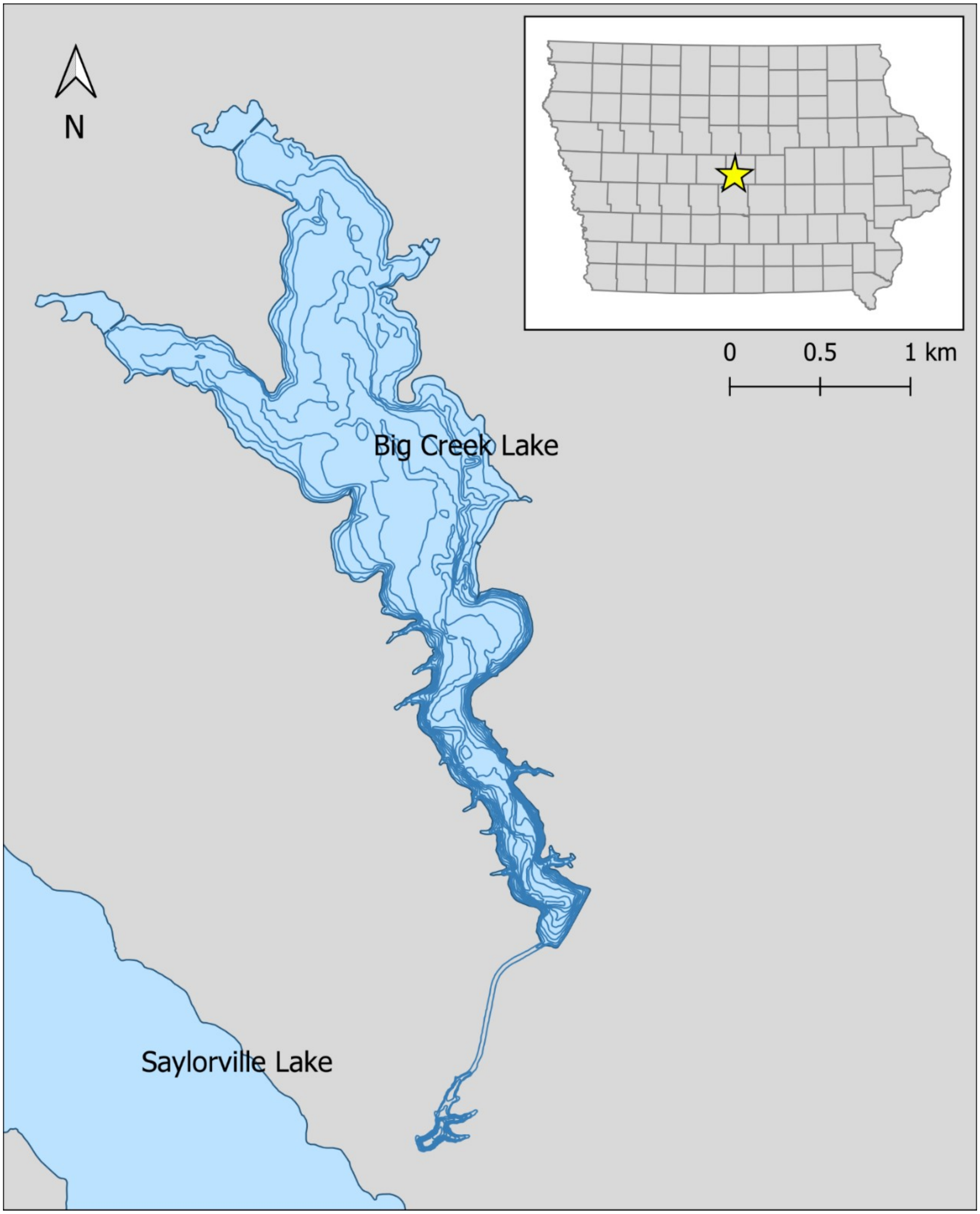

Figure 9. Big Creek Lake, Iowa. Bathymetric lines indicate 1.5-m increments in depth.

DATA COLLECTION

Fish Sampling

Walleye were collected using boat electrofishing, modified fyke nets, and gill netting. Electrofishing was conducted at night during spring using pulsed DC output, with 60 Hz pulse frequency, 25% duty cycle, and an average current output of 8 Amps. A Coffelt Electrofisher Mark-22 control box was used during Period A, and an ETS Electrofishing control box was used thereafter. In addition, sampling was conducted later in the spring to early summer during Period A. Electrofishing was typically conducted for 15 minutes, although non-standard effort was also recorded, at eight standard transects representing a variety of habitat around the reservoir.

Gill net sampling included both single-mesh nets and experimental nets over time. During Period B, gill nets consisted of either 38- or 64-mm nylon mesh hung 1.8 m deep. Gill nets used during 2006 and 2007 were 48.8 m long but were shortened in 2008 to 24.4 m due to the steepness of the lake basin and net entanglement in woody debris. During Periods C and D, single-mesh gill nets (64-mm nylon mesh) and experimental gill nets (monofilament, with mesh 25, 38, 51, 64, and 102 mm) were set in pairs at the same sites. Gill nets were set perpendicular to shore and soaked for 3 hours in the evening during spring.

Modified fyke nets were used during Period A; nets had a 0.7×1.3-m rectangular trap, a 12.2-m lead, and 19 mm-bar square mesh. Nets were always set during late spring/early summer for 24 hours. We used fyke net and gill net data in age and growth analysis and length-weight models but did not use these data for catch curve calculations due to inconsistency in application. Combining samples from multiple gears with varying size selectivity can improve growth curve estimation, reducing size-related bias and increasing precision of parameter estimates (Wilson et al. 2015).

Age and Growth

Fish captured with any gear were measured (total length) and weighed. Calcified structures were removed from Walleye during each time period and examined for age and growth estimation. During Period A, scales were removed from all Walleye sampled by both electrofishing and fyke nets. During Periods B-D, dorsal spines were taken from fish captured using both electrofishing and gill nets. Spines were prepared by setting in epoxy-filled tubes and sectioned using a high-speed saw following the recommendations of Koch and Quist (2007). A double-blind read was used to determine age estimate for both scales and spines, followed by a tie-breaking process. Although both scales and dorsal spines can underestimate the age of older fish (relative to otoliths; Phelps et al. 2017), estimates derived from these structures were considered acceptable because the majority of fish examined were relatively young (5 years or younger). Otoliths were not collected by Iowa DNR during any time period and were not available for analysis.

DATA ANALYSIS

Length, Weight, and Body Condition

Length-weight relationships were modeled by fitting a series of models using the equation $W = aL^b$, where W = weight (g), L = total length (mm), b = growth coefficient, and a = arbitrary intercept value, base 10. We used linear regression with log-transformed lengths and weights (GLMSELECT Procedure, SAS 9.4), inputting data from all gears. Several models were tested, allowing a and b to vary by time period, allowing one parameter to vary by time period, or allowing neither to vary by time period. Akaike's information criterion (AIC) was determined for each model, and the model with the lowest AIC was retained.

Based on the final model, a and b parameters were used to calculate condition according to the relative weight equation, in which W_S was defined by Murphy et al. (1990; $W_s = 10^{-5.453} \times L^{3.18}$). Changes in condition over time were determined by fitting a general linear model predicting relative weight with time period and its interaction with fish total length. If the model and period effect were significant based on the F-test ($\alpha = 0.05$), pairwise comparisons of least-square mean values were made between time periods (t-test, $\alpha = 0.05$, with Bonferroni adjustment).

Age and Growth

Growth was modeled by fitting a series of von Bertalanffy growth functions using back-calculated length at the most recent annulus (Vaughan and Burton 1994), as $L_t = L_\infty\left(1 - e^{-K(t-t_0)}\right)$, where L_t = total length at time t, L_∞ = asymptotic length, K = growth coefficient, and t_0 = time when length equals zero. Data from all fish were used, recognizing that older fish could have experienced different forage/Walleye density scenarios throughout life. We chose to accept this legacy effect to support more realistic asymptotic length estimation, rather than exclude older fish from the model; that said, the majority of fish captured during each time period were younger, reflecting more recent years' conditions. In addition, we constrained the upper bound of the asymptotic length to the maximum size of fish observed in the dataset, plus 51 mm; this further supported realistic asymptotic length estimation while recognizing that our sampling may not have captured the largest possible fish. Several growth models were tested, allowing the asymptotic length L_∞ and t_0 to vary by time period, allowing one of the parameters to vary by time period, or allowing none of the parameters to vary by time period. The growth coefficient was held constant because it has been demonstrated to be consistent under density-dependent growth (Beverton and Holt 1957). AIC was determined for each model, and the model with the lowest AIC was retained. Data from all gears were used to fit each model (Period A: electrofishing and modified fyke nets; Periods B-D: electrofishing and gill netting; Wilson et al. 2015). We used nonlinear regression with starting parameter value ranges based on rangewide growth of Walleye determined by Quist et al. (2003); starting values were kept constant across modeling efforts (NLMIXED Procedure, SAS 9.4). Based on the final model, von Bertalanffy parameters were used to calculate growth index as $\omega = K \cdot L_{\infty}$. Values of ω can be interpreted as mm/year of growth (Gallucci and Quinn 1979). We focused on fish age-5 and younger during Periods B-D so that growth patterns reflected the conditions of only one time period rather than multiple time periods.

Mortality

During Periods B-D, age-length keys were developed using all fish captured with electrofishing each year, and catch curves were developed for all fish recruited to the gear (Age-2+). We excluded Period A because electrofishing occurred later in the year and may not have been comparable. Instantaneous mortality (*Z*) was calculated for each period by calculating the weighted mean slope of the catch curve. Instantaneous natural mortality (*M*) was calculated using the method of Lorenzen (1996), as suggested by Maceina and Sammons (2016), as $M = 3 \cdot (W_{\infty}^{-0.288})$, where W_{∞} is calculated based on the population's length-weight relationship, using the L_{∞} established during von Bertalanffy growth modeling. Fishing mortality was calculated as the difference between total and natural mortality rates ($F = Z - M$). All rates were converted to total annual and conditional estimates, and exploitation μ was calculated as $\mu = \frac{F \cdot A}{Z}$.

Regulation Modeling

Four fishing regulations were modeled for Walleye in Big Creek Lake using a yield-per-recruit model (Fisheries Analysis and Modeling Simulator: Slipke and Maceina 2014). Regulations included:

- No length-based limit (statewide standard regulation for Walleye)
- Minimum length limit (MLL) of 381 mm (15"), with a bag limit of 1 fish over 508 mm (20"; current regulation in place at Big Creek Lake)
- MLL of 533 mm (21")
- Protected slot limit (PSL) of 432-559 mm (17-22"), with a reduced bag limit above the slot of 1 fish (special regulation used in Storm Lake and Spirit Lake, Iowa)

These regulations were considered because they were either in place regulating a Walleye fishery in Iowa or were requested by anglers to enhance the fishery at Big Creek Lake. Regulation modeling inputs included parameters from length-weight models, von Bertalanffy growth models, and conditional mortality estimates for Periods B-D. Conditional fishing mortality was allowed to vary from 0.05 to 0.40, while conditional natural mortality was held constant at the level estimated from analysis for that time period. The PSL was modeled over the range of conditional fishing mortality rates (0.05 - 0.40) below the slot, with the commensurate fishing mortality rate above the slot being 6% lower. This was based on the percentage of anglers who may have been affected by a reduced bag limit in a Walleye tag return study in 2010-2011 (Dodd and Otting 2012). The conditional fishing mortality rate within the slot was assumed to be 0%, and recruitment to the fishery was assumed to occur at 250 mm (i.e., stock length). For the MLL with a reduced bag limit at a designated length, the model was set up similar to a slot limit, but with recruitment occurring at the minimum harvestable length and conditional fishing mortality being constant up to the length at which reduced bag limits were instituted. Conditional fishing mortality above that length was set 6% lower. The absence of a length limit was modeled by allowing fish to recruit to the fishery at 250 mm. Yield, size of fish harvested, and number of fish achieving target lengths were the response variables of greatest interest. Therefore, we modeled total annual yield (kg), mean total length of fish harvested (mm), number of fish harvested out of 1,000 recruits, Proportional Size Distribution$_{\text{Preferred}}$ (PSD-P), PSD$_{\text{Memorable}}$ (PSD-M), and PSD$_{\text{Trophy}}$ (PSD-T) as response variables. Lengths designated as Preferred, Memorable, and Trophy were 510 mm (20 inches), 630 mm (25 inches), and 760 mm (30 inches), respectively (Gabelhouse 1984).

RESULTS

POPULATION DYNAMICS

A total of 6,261 fish and 1,049 age structures were collected across all four time periods. The best fitting length-weight model allowed both parameters a and b to vary by period (Table 7). The value of *b* during Period C indicated Walleye grew more isometrically than during other time periods, rather than becoming rounder with greater length (Figure 10).

Likewise, condition of Walleye captured differed between time periods and generally increased with fish length ($F = 397.96$, $p < 0.0001$). Specifically, relative weight was lower during Period C than during all other time periods (all pairwise comparison *t*-values < -5.94, *p*-values < 0.0001; Figure 11). Relative weight during Period D was also lower than during Period B ($t = -6.82$, *p*-value < 0.0001). Unlike other time periods, relative weights decreased with increasing fish length during Period C.

The best-fitting growth model allowed both the asymptotic length L_∞ and t_0 to vary by period, although a second model allowing only asymptotic length to vary was almost identical (AIC was equivalent, but differed by 1 when adjusted for small sample sizes; Table 7). The top model was parameterized, yielding unique estimates of L_∞ and t_0 for each time period. The growth coefficient *K* was 0.1781 across all time periods. Asymptotic lengths overlapped except for Period C, translating to significantly slower-growing fish during Period C (Figure 12). Similarly, growth index ω was similar across time periods, except Period C when it decreased by approximately 49 mm/year (Period A: $\omega = 137.4$, Period B: $\omega = 139.1$, Period C: $\omega = 89.2$, Period D: $\omega = 138.7$). As a result, fish would not become legal to catch under the current MLL (381 mm) until as late as Age-7, rather than Age-3 as was typical during other time periods.

The remainder of analyses excluded Period A due to sampling differences. Catch curves yielded annual mortality rates ranging from 36% during Period C to 46% during Period D (Table 8). Natural mortality increased during Period C by 13%, whereas fishing mortality decreased substantially during Period C. Mortality estimates were used to guide subsequent regulation modeling.

Table 7. Akaike's Information Criterion (AIC), ΔAIC, weight (W_i), and number of parameters (K) of length-weight and von Bertalanffy growth models for Walleye in Big Creek Lake, Iowa, from four time periods. Period A: 1998-2000, Period B: 2006-2008, Period C: 2013-2015, and Period D: 2019

Model	AIC	ΔAIC	W_i	K
Length-weight				
$a_{(\text{Period})}L^{b(\text{Period})}$	-18,528	0	1.00	9
$aL^{b(\text{Period})}$	-18,322	206	0.00	6
$a_{(\text{Period})}L^{b}$	-18,271	257	0.00	6
aL^b	-17,000	1,528	0.00	3
Growth				
$L_{\infty(\text{Period})} + K + t_{0(\text{Period})}$	11,356	0	0.50	9
$L_{\infty(\text{Period})} + K + t_0$	11,356	0	0.50	6
$L_\infty + K + t_{0(\text{Period})}$	11,910	554	0.00	6
$L_\infty + K + t_0$	12,614	1,258	0.00	3

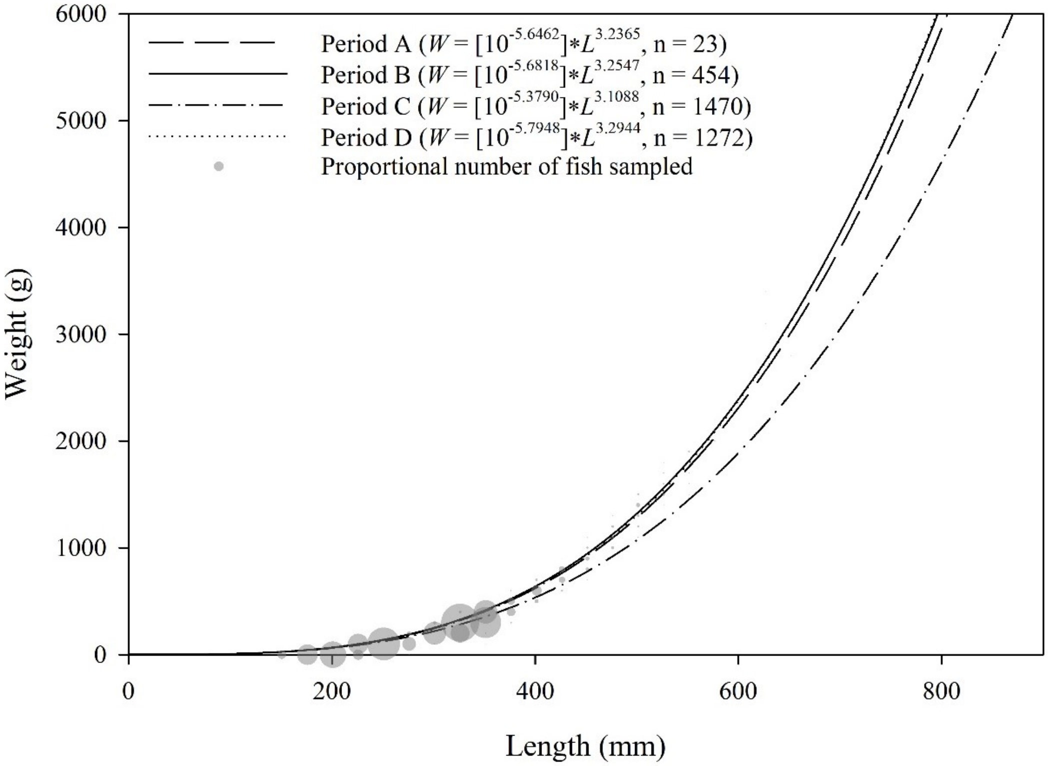

Figure 10. Length-weight model for Walleye in Big Creek Lake, Iowa, during four different time periods. Period A: 1998-2000, Period B: 2006-2008, Period C: 2013-2015, and Period D: 2019. A semi-transparent bubble plot shows how many fish were sampled and used in the modeling process, indicated by relative bubble size.

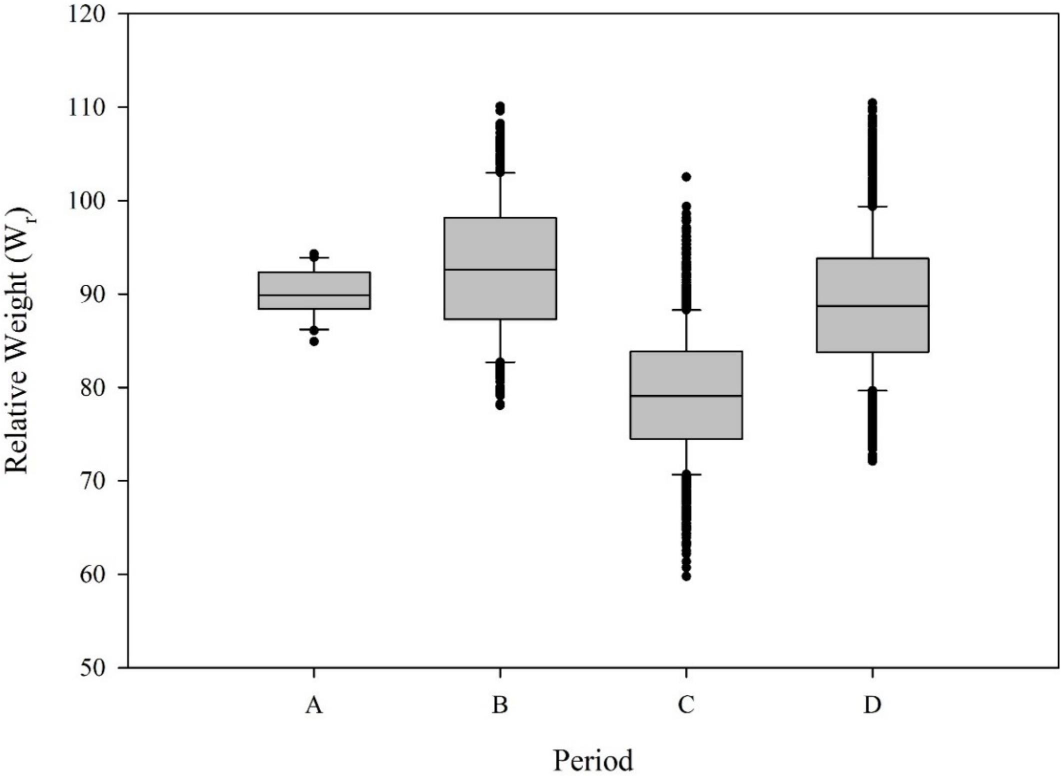

Figure 11. Distribution of relative weights of Walleye in Big Creek Lake, Iowa, during four different time periods. Period A: 1998-2000, Period B: 2006-2008, Period C: 2013-2015, and Period D: 2019

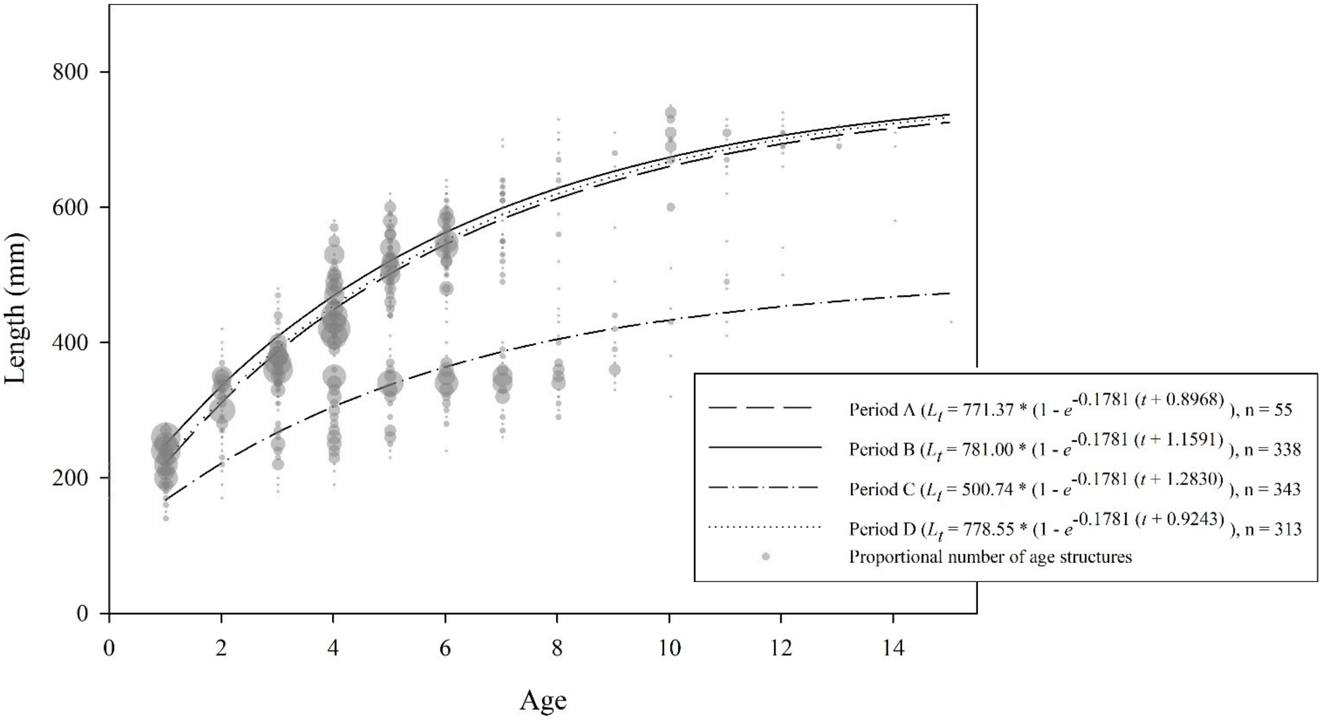

Figure 12. Walleye growth in Big Creek Lake, Iowa, during four different time periods. Period A: 1998-2000, Period B: 2006-2008, Period C: 2013-2015, and Period D: 2019. A semi-transparent bubble plot shows how many age structures were used in the modeling process, indicated by relative bubble size.

Table 8. Mortality rate estimates for Walleye Age-2-15 captured by spring nighttime electrofishing in Big Creek Lake, Iowa, during three different time periods. Period B: 2006-2008, Period C: 2013-2015, and Period D: 2019

Parameter	Abbreviation	B	C	D
Total annual survival	S	0.6122	0.6437	0.5449
Total annual mortality	A	0.3878	0.3563	0.4551
Total annual natural mortality	v	0.1995	0.3289	0.1895
Total annual fishing mortality	u	0.1884	0.0274	0.2656
Instantaneous mortality	Z	0.4907	0.4406	0.6071
Instantaneous natural mortality	M	0.2524	0.4066	0.2528
Instantaneous fishing mortality	F	0.2383	0.0339	0.3543
Conditional natural mortality	n	0.2230	0.3341	0.2234
Conditional fishing mortality	m	0.2121	0.0333	0.2983

REGULATION MODELING

Regulations were variably effective in altering yield and proportional size distribution across time periods. Notably, Periods B and D were very similar and are summarized together. The current 381-mm MLL at Big Creek Lake enhanced size distribution slightly more than if no LL was in place, but was not as effective as a higher MLL (Figure 13). The higher MLL examined (533-mm) had the greatest positive effect on size distribution, increasing the proportion of preferred- and memorable-size fish even at high fishing mortalities, while also maximizing annual yield (Figure 14). However, this regulation also reduced the percentage of fish harvested below 20%, indicating the majority of fish would die of natural causes before being subject to harvest. The mean size of fish harvested would also be maximized by this MLL. The PSL allowed more fish to be harvested, primarily below the slot, but would likely have resulted in growth overfishing at the fishing mortality we estimated for Period D (e.g., yield declined when fishing mortality exceeded 0.25 under a PSL). None of the regulations examined appeared to increase size distribution or yield substantially during Period C. However, greater harvest could have been allowed if no length limit was in place. Likewise, a PSL would have allowed harvest of the slow-growing fish during Period C, which were stockpiling at lengths below the slot.

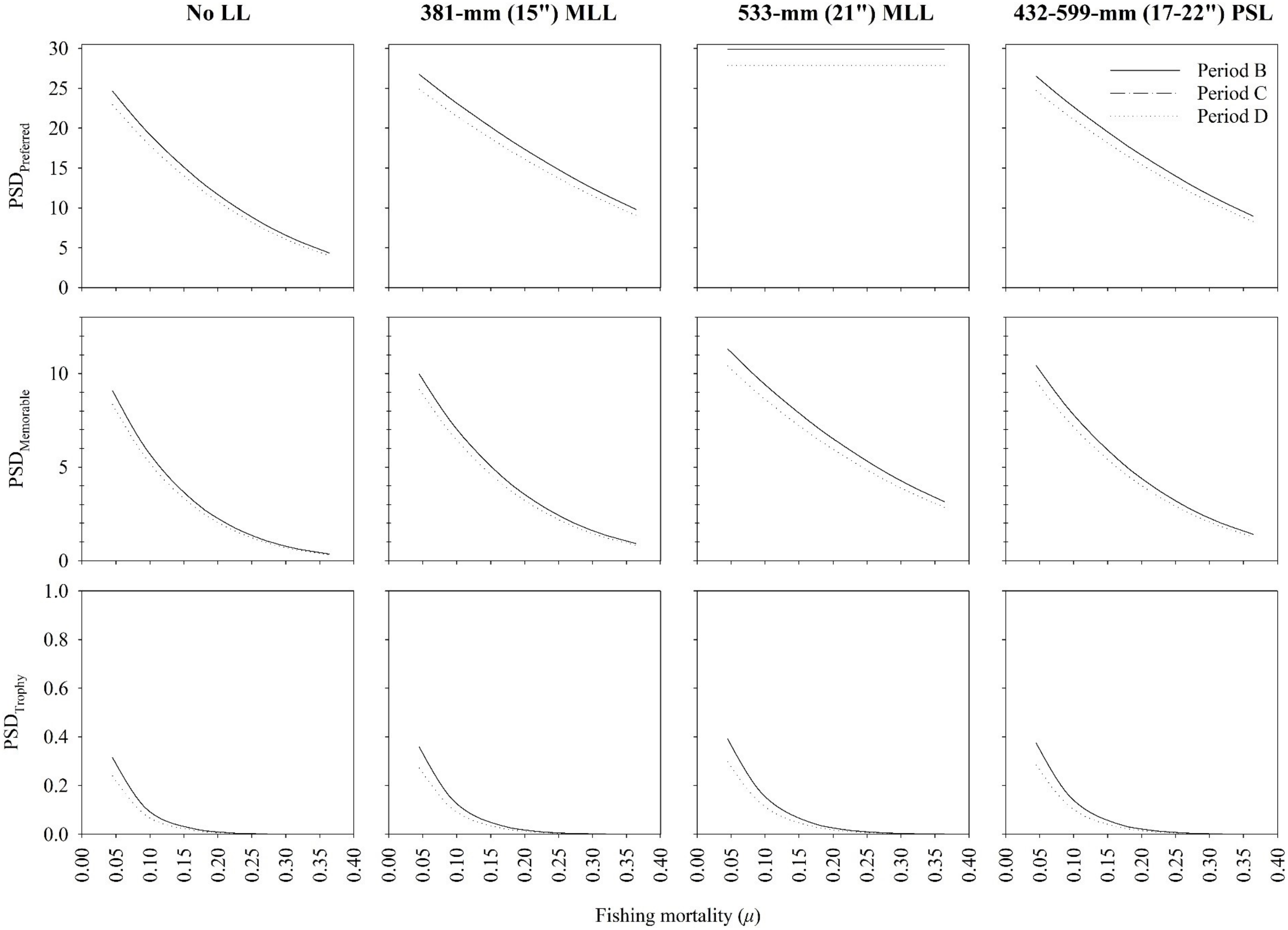

Figure 13. Proportional size distribution (PSD) of Walleye in Big Creek Lake, Iowa, under four different length-based regulations, during three different time periods. Period B = 2006-2008, C = 2013-2015, D = 2019. Note that all PSD values for Period C were equal to zero.

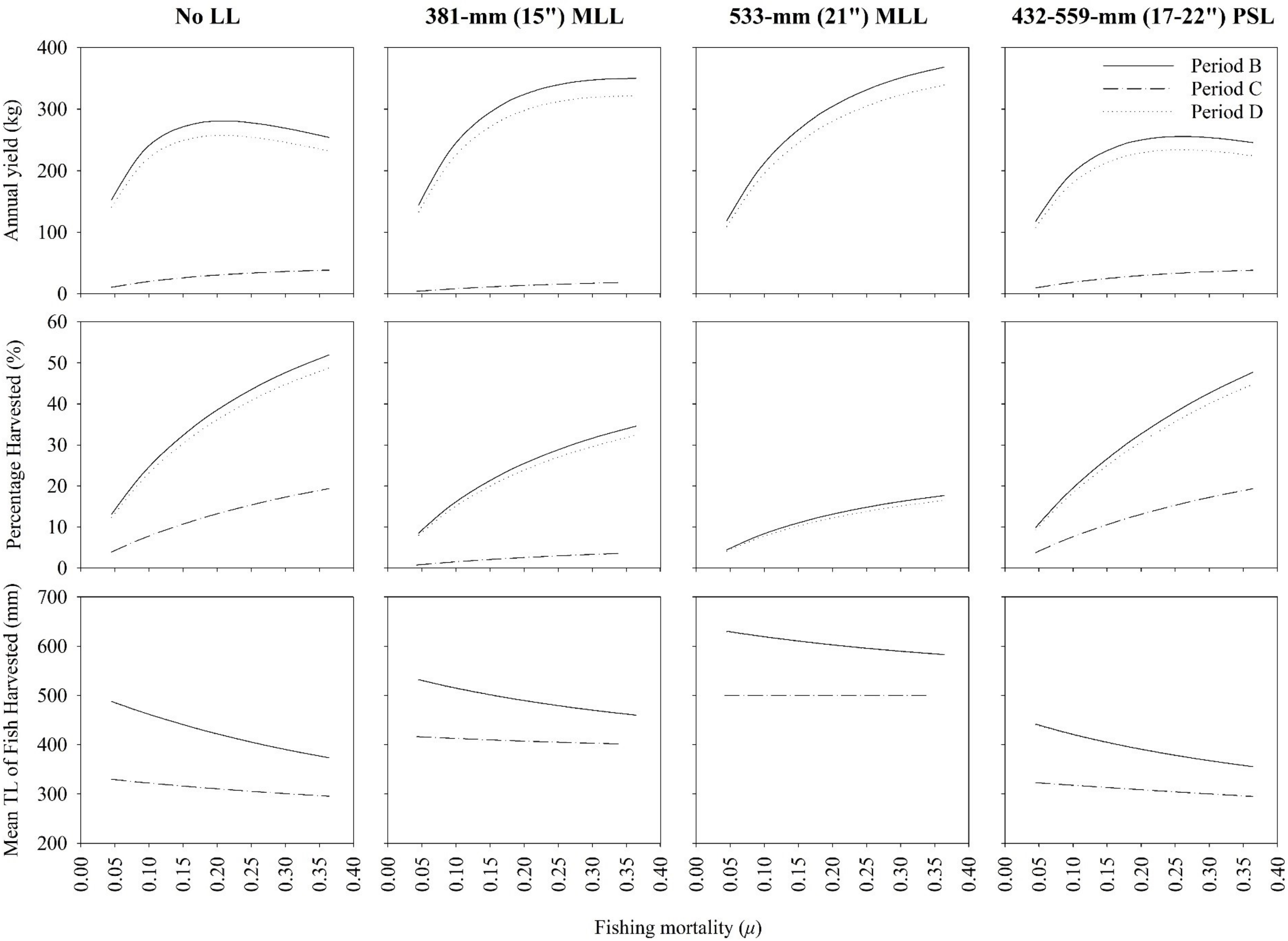

Figure 14. Predicted annual yield based on 1,000 fish, percentage of fish harvested, and mean total length (TL) of fish harvested for Walleye in Big Creek Lake, Iowa, under four different length-based regulations, during three different time periods. Period B = 2006-2008, C = 2013-2015, D = 2019. Note that values for Period C under the 533-mm MLL were equal to zero.

DISCUSSION AND MANAGEMENT IMPLICATIONS

Walleye in Big Creek Lake appeared to experience density-dependent growth during Period C, when Walleye density was relatively high and Gizzard Shad were absent. Adult densities during Period C and D were between the 50th and 75th percentiles for North American Walleye populations (Baccante and Colby 1996). In contrast, densities during Periods A and B fell below the 25th percentile. Increased Walleye densities have been associated with reduced growth in other lakes and reservoirs in Wisconsin (Nate et al. 2000; Sass et al. 2004), Ontario (Craig et al. 1995; Kaufman et al. 2009), Lake Erie (Knight et al. 1984; Hartman and Margraf 1992), and Pennsylvania (Kocovsky and Carline 2001). Likewise, density-dependent growth has been observed in numerous other fish species (Lorenzen and Enberg 2002). During Period C, Walleye early growth rate ($\omega = 89.2$) was similar to the lower values observed in many northern Wisconsin lakes documented by Sass et al. (2004) and in far northerly populations of Ontario and Saskatchewan (Quist et al. 2003). It was also similar to Walleye growth observed in Midwestern reservoirs with a centrarchid- or percid-dominated forage base (Santucci and Wahl 1993). In a comparison among three Ontario lakes, an unexploited lake with high Walleye density had the slowest growth, differing from the other lakes by almost 60 mm/year ($\omega = 100.2$ versus 157.4-158.8; Craig et al. 1995). This was similar to our findings; we detected a reduction of over 50 mm/year in growth in Big Creek Lake during Period C. Region-wide density-dependence of Walleye growth was not apparent in Wisconsin (Sass et al. 2004) or Kansas (Quist et al. 2003). Rather, the density at which density-dependent effects occur likely differs among lakes due to system-specific characteristics such as productivity, forage base, water quality, or a host of other factors (Sass et al. 2004), making appropriate growth or asymptotic length targets specific to a particular waterbody (Lorenzen and Enberg 2002; Sass et al. 2004).

Walleye growth during Period B was similar to when Gizzard Shad were present (Period D), implying native forage was adequate to support the low-density Walleye population present at the time, and density-dependent growth was not occurring. In fact, growth was faster than observed in other centrarchid- and percid-dominated impoundments (Santucci and Wahl 1993). Lake Mendota's Walleye population was likewise supported by Yellow Perch and Bluegill with no decline in growth after a Walleye stocking program that increased the density of Walleye > 278 mm from 1.7 to 3.8 fish/ha (Johnson et al. 1996). In the absence of Gizzard Shad, Walleye growth would likely decline once again at the current population density (Wuellner et al. 2010). Based on our analysis of Big Creek Lake, a reasonable target density for a Walleye population with a centrarchid- or percid- forage base in a mesotrophic to eutrophic, medium-sized reservoir in Iowa may be greater than 2.9 fish/ha but less than 13.8 fish/ha. Target densities are useful for fishery management and should provide adequate catch rates without incurring density-dependence in growth rate.

GIZZARD SHAD EFFECTS

Walleye growth and condition increased after Gizzard Shad became available during Period D. Similar to Periods A and B, growth was similar to other Midwestern Walleye populations (Michaletz 1998; Sass et al. 2004), but slower than the standardized rangewide growth ($\omega = 183$ mm/year; Quist et al. 2003). For instance, Walleye in Missouri reservoirs with Gizzard Shad grew to between 83 and 140 mm during their first year (Michaletz 1998). Growth in Lake of the Woods, Minnesota, and Lewis and Clark Lake, South Dakota, were 105 and 125 mm/year, respectively (Quist et al. 2003). Within Iowa, Big Creek Lake was most similar to Clear Lake ($\omega = 121$). Other lakes and reservoirs in Iowa (i.e., Black Hawk Lake, Lake Macbride, and Spirit Lake) had greater growth ω, but typically reached a lower asymptotic length. Our models may have yielded more similar results, with a lower asymptotic length and more rapid growth, had we not constrained the growth coefficient K to be stable over time; we retained this constraint in order to better examine density-dependent growth patterns within Big Creek Lake (Beverton and Holt 1957).

Although Gizzard Shad enhanced overall Walleye growth in Big Creek Lake during Period D, additional fishery impacts of shad should also be considered. Prior to Gizzard Shad re-introduction, Walleye catch rate peaked in May and June, but some harvest continued throughout the year (Dodd and Otting 2012). This seasonality is typical (Quist et al. 2010). However, when Gizzard Shad were established, the fishery contracted to primarily encompass the spring and early summer. Harvest rates were seven times greater from April to July than other months (Weber and Weber 2021), and anglers reported reduced Walleye catch rates during the ice season. Low angler catch during parts of the year can be attributed to the seasonal peaking of Gizzard Shad availability, which in turn affects Walleye catchability (VanDeValk et al. 2008) and condition (Ward et al. 2007). In Angostura Reservoir, South Dakota, adult Walleye condition declined steadily from spring through summer, until Gizzard Shad hatched (Ward et al. 2007). In addition to shortening the

Walleye season, Gizzard Shad can alter foraging pressure on desirable sport fish species: during periods of low shad abundance, Walleye may shift to native species, depressing other species like Yellow Perch and Bluegill (Hartman and Margraf 1992).

Big Creek Lake was historically known as a panfish fishery featuring Bluegill and Black Crappie (Putnam 1976), which declined when Gizzard Shad became established (McWilliams 2003). When shad disappeared after Period A, the recreational fishery redeveloped into one dominated by crappies and Bluegill, attracting 262 angler-hours/ha during the openwater season (McWilliams 2003). Given the renewed presence of Gizzard Shad, the panfish community should be monitored, as Gizzard Shad are known to compete directly and indirectly with Yellow Perch, Bluegill, and other panfish (Dettmers and Stein 1992; Schaus and Vanni 2000; Vanni et al. 2005; Detmer et al. 2019). However, a negative impact on panfish is not consistently shown, especially if zooplankton densities remain high (e.g., Yellow Perch: VanDeHey et al. 2014), and crappie size distribution and fishery quality seem to have improved in recent years (B. Dodd, unpublished data).

FISHING REGULATION EFFECTIVENESS OVER TIME

Fishing regulations for enhancing Walleye size distribution or yield in Big Creek Lake differed over time due to shifting population dynamics and angler exploitation. An increased MLL could have improved size distribution somewhat during Periods B and D, while preventing growth overfishing, concurring with findings from Dodd and Otting (2008). Brousseau and Armstrong (1987) suggested a MLL was appropriate for Walleye if the population had low reproduction (or recruitment of stocked fish), fast growth of young fish, low natural mortality, and high fishing mortality. Increased MLLs can increase both adult Walleye abundance and size distribution (Stone and Lott 2002) and reduce overexploitation (Fayram et al. 2001; Quist et al. 2010). Based on our results, an increased MLL would have enhanced size distribution and abundance of larger fish during Period B. At the time, Dodd and Otting (2008) recommended a shift in regulation to a higher MLL, but the regulation change was hindered by legislative inertia. Therefore, the decision was made to increase stocking rates and install a physical barrier on the reservoir spillway to reduce escapement as alternative approaches for achieving a higher-density Walleye population.

We found that stockpiling occurred during Period C, with few fish reaching and exceeding the 381-mm MLL. Accordingly, fishing mortality was low, likely due to density-dependent growth effects. Length-based regulations may not have substantive effects on Walleye populations unless exploitation rates are high (e.g., over 35%; Fayram et al. 2001). Thus, while length regulations may not have negative effects, they may also fail to deliver benefits such as increasing size distribution at low exploitation rates (Isermann 2007). Even with adjustments in exploitation, metrics such as yield can be unresponsive in the presence of density-dependent growth (Lorenzen and Enberg 2002). We observed minimal predicted benefits of various length regulations during Period C, and likely negative effects of the existing 381-mm MLL (e.g., reducing the percentage of fish harvested). Plans were being made at the end of Period C to initiate the removal of the existing 381-mm MLL to allow angler harvest sublegal fish, and attempt to reduce Walleye density to a level that could be supported by the available forage. However, the discovery of Gizzard Shad in 2015 ended that process due to anticipated improvements in Walleye growth.

During Period D, Walleye growth and exploitation increased once again. An increased MLL could be effective if the management objective is to increase yield and the mean length of fish harvested, whereas a PSL could be effective if the management objective is to maximize proportion of fish harvested. A PSL is most appropriate when the Walleye population has good natural reproduction (or recruitment of stocked fish), slow growth, high natural mortality of young fish, and high angler effort (Brousseau and Armstrong 1987). Although we have not yet observed a reduction in growth, future increases in Walleye density or alterations in the forage quality could suppress Walleye growth, so monitoring is essential. At this time, an increased MLL would likely enhance size structure most effectively, but a PSL could become more appropriate if stockpiling recurs, or if anglers prefer harvesting smaller fish that would be sublegal under an increased MLL. In addition, a PSL could be more appropriate if natural mortality is higher than we estimated, as implied by a recent tagging study (Weber and Weber 2021). However, any PSL would need close monitoring to ensure yield does not drop due to growth overfishing. It is unknown whether anglers at Big Creek Lake prefer to catch many, smaller fish or fewer, larger fish, but recent legislative changes simplified regulation adjustments for Walleye, black bass, and trout. This change gave fisheries managers in Iowa the flexibility needed to better respond to dynamic fish populations.

A NOTE ON INCREASED WALLEYE DENSITIES

Walleye density in Big Creek Lake increased after stocking both fry and advanced fingerlings and a physical fish barrier was installed on the reservoir spillway. Fry stocking was highly successful in 2011 and in 2012, during a drought when no water was passing over the spillway for most of the year. In combination with the new barrier, increased stocking led to establishment and retention of several large year-classes of Walleye. Annual strong year-classes can drastically alter size distribution due to density-dependent growth (Daugherty and Smith 2012), and repeated stocking of Walleye in Ontario resulted in extremely high biomass and reduced growth (Kaufman et al. 2009). Similarly, Walleye growth in Lake Erie declined during years of high abundance and strong year-classes (Hartman and Margraf 1992). Walleye density appeared to increase in Big Creek Lake between Period C and D as well, and it is possible the stocking regime should be reduced to account for increased Walleye density. The current Walleye density is being fully supported by the existing Gizzard Shad forage base without inhibiting Walleye growth, and the population density is within the range of other Walleye populations (75th percentile: Baccante and Colby 1996). However, both advanced fingerlings and fry are being stocked and it remains unknown if the forage base can support further increases in Walleye density. Future monitoring of fry stocking success or failure can guide decisions regarding late fall advanced fingerling stocking rates in an adaptive stocking strategy to improve cost-effectiveness and minimize reliance on limited annual hatchery production of Walleye (Johnson et al. 1996; Trushenski et al. 2018).

We believe that the unexpected recruitment of fry-stocked Walleye to the fishery and the fish barrier were the primary drivers of increased Walleye densities in Big Creek Lake during Periods C and D. Prior to barrier installation, adult Walleye were observed crowding the swift current immediately upstream of the spillway to take advantage of foraging opportunities (Dodd and Otting 2012), as suggested by Paller et al. (2006). Monitoring of Walleye emigration over four years revealed minimal to no emigration from Big Creek Lake when the barrier was present; in contrast, 21.9-46.5% of tagged Walleye emigrated from a nearby reservoir with no barrier during the same time period (Weber and Weber 2021). We are unaware of any other substantial changes in Big Creek Lake's fish community or environmental conditions that could explain the changes in Walleye density. For instance, Largemouth Bass population densities have not changed abruptly based on fisheries management sampling (B. Dodd, unpublished data), which could alter survival of stocked Walleye (Santucci and Wahl 1993; Fayram et al. 2005). Emigration can contribute a substantial portion of fish loss in reservoirs (Louder 1958; Lewis et al. 1968; Axon and Whitehurst 1985; Paller et al. 2006; Kuklinski 2014; Weber and Flammang 2019), and increases exponentially at higher discharges (Weber and Flammang 2019; Weber and Weber 2021) that are typically occur during spring (Paller et al. 2006; Weber and Weber 2021). In Rathbun Lake, Iowa, up to 26% of the Walleye population could emigrate in a year with prolonged spring discharges (Weber et al. 2013; Weber and Flammang 2019). Physical fish barriers can provide a cost-effective reservoir management tools, especially if the fishery is maintained or supplemented by stocking. Subsequent improvement in stocking efficiency translates directly to hatchery production cost savings (Trushenski et al. 2018), improving agency effectiveness and achieving sportfish density goals rapidly.

Our study was based on historical data that presented some challenges and potential limitations. Fish sampling and age data were collected using different techniques during Period A than during other time periods; for instance, electrofishing was conducted later in the spring and early summer, and modified fyke nets were deployed instead of gill nets. We also had more limited documentation of the low population density of Walleye during that time, with no formal mark-recapture study having been conducted. For these reasons, we did not use population dynamics data from Period A in regulation modeling. We did use fish data collected using both netting and electrofishing for growth analysis and length-weight models because gears with varying size selectivity can be effectively combined to improve parameter estimates (Wilson et al. 2015). Finally, the study was conducted over time at a single location, so there could have been some time dependence in the dataset. Specifically, older fish captured during one time period could have been alive and captured during a previous time period, experiencing multiple scenarios throughout life. We did not evaluate changes in growth using back-calculation methods in this study, but it is possible that growth patterns changed within individual fish as they experienced different density-dependent or forage effects. To alleviate this issue, we spaced time periods several years apart, although some of the transitional years in between periods did have data available. Nonetheless, we recognize that inclusion of older fish in growth model fitting could have hidden scenario-specific changes in growth that affected younger fish differently or more drastically, and that time periods were not truly independent. This reflects a common reality for these types of management evaluation scenarios.

The Walleye fishery in Big Creek Lake provided a useful demonstration of how rapidly a population can change in response to changes in their environment and forage base. Over two decades, the reservoir experienced four unique scenarios revolving around Walleye density and Gizzard Shad availability. The current status of the fishery demands some additional evaluation to ensure continued quality fishing provision for anglers. Specifically, the seasonality of Walleye fishing should be evaluated to better understand how Gizzard Shad presence has altered catchability, and angler satisfaction and interest in Walleye size or catch should be surveyed via creel. Angler effort seems to have increased in response to the improved Walleye population in Big Creek Lake, and appropriate regulation decisions may shift quickly over time in response to increased exploitation (Allen et al. 2013). In addition, the status of fisheries for other sportfish, especially Bluegill and crappies, should be evaluated to determine whether those anglers are satisfied and monitor changes in fishery quality. The Walleye population also needs to be monitored to detect density-dependent declines in growth ω, condition, and asymptotic length (Lorenzen and Enberg 2002; Sass et al. 2004). Growth of younger fish in particular could be used as a rapid indicator that the reservoir is approaching or has exceeded is optimal Walleye density (Sass et al. 2004). Likewise, the Gizzard Shad population should be monitored to recognize and respond to any changes, such as another winter kill.

Fisheries management must be as flexible as the populations are dynamic. Historical regulatory limitations inhibited responsive management in the past, leading to inappropriate regulation or lack of regulation of important fisheries like Big Creek Lake. Unexpected changes in year-class abundance, fishing pressure, water quality, or forage should be met with timely management action such as adjustment in stocking and harvest regulation (Johnson et al. 1996). In Iowa, that now entails a public meeting reviewing the justification for change and gauging public opinion, followed by posting of the new regulation at affected fishing accesses. Special regulations require additional work including a public information program and increased enforcement following implementation (Brousseau and Armstrong 1987). Anglers must be willing to comply with established limits, as well as to harvest legal fish both large and small to make a length limit effective. Probable outcomes of any special regulation should be predicated not only on fish population modeling but also on expected angler behavior, and regulations with limited effects on management objectives should be avoided for simplicity. Finally, regulation changes should be monitored carefully to ensure they are achieving management objectives as predicted; Walleye populations can be highly variable, requiring a true reflection of regulation-related changes to derive from a thoughtful multi-year evaluation (Isermann 2007).

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