Age and Growth of Crappies in Alabama Reservoirs and Evaluation of the Statewide Minimum-Length-Limit

By

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Abstract

Black Crappies *Pomoxis nigromaculatus* and White Crappies *P. annularis* in Alabama are currently regulated with a 229-mm minimum length limit (MLL) and a 30 fish/person/day bag limit. With the recent increased angler use of technologies that may allow anglers to target crappies more efficiently, evaluation of current regulations was warranted. We used electrofishing to collect 6,125 crappies between 2022 and 2024. We enumerated, measured morphometrics, sexed, and aged all fish. We estimated growth, mortality, and recruitment in all reservoirs and these data were variable among reservoirs. We developed reservoir-specific age-structured Beverton-Holt equilibrium yield models. We ran models using four MLLs to observe predicted population effects with multiple regulation scenarios, which included an assumed "no MLL." Reservoirs characterized by fast growth and low conditional natural mortality had the most favorable tradeoff associated with a MLL that maximized yield, limited decreases in harvest, and increased the number of memorable sized crappies. In five reservoirs, we split up data collected from the upper riverine versus the lower, main lake sections to analyze differences in population data between sections. We found fish collected did not reach the same size in most upper sections, compared to the lower section, possibly indicating growth overfishing in upper sections of these reservoirs, but could also be caused by underlying factors such as variation in habitat, density dependence, species interactions, and sampling bias. These data will be useful for managers to evaluate multiple regulation scenarios among crappie populations in different reservoirs. These data, coupled with angler preferences, would be useful for evaluating the most favorable regulation(s) that also have a biological underpinning.

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List of Abbreviations

ADCNR	Alabama Department of Conservation and Natural Resources
CHLA	Chlorophyll A
CM	Conditional natural mortality
CPUE	Catch per unit effort
K	Growth coefficient in the von Bertalanffy growth equation
L_{inf}	Length estimated from the von Bertalanffy growth equation for an average fish's largest size within a population
M	Instantaneous natural mortality
MLL	Minimum length limit
PSD	Proportional stock density
t0	Hypothetical estimated age at the time of zero length from the von Bertalanffy growth equation
TL	Total length
Wr	Relative weight
Z	Total instantaneous mortality rate

Chapter 1 Introduction and Age, Growth, and Mortality Study of Black Crappies and White Crappies in Alabama

Introduction

Crappies (i.e., Black Crappie *Pomoxis nigromaculatus* and White Crappie *P. annularis*) have a wide geographic range, are popular among anglers, and despite some ecological differences, tend to be managed collectively due to phenotypic similarities. Black Crappie and White Crappie *P. annularis* are native to the Midwest and Southeast United States, throughout the Mississippi River basin and the Great Lakes and north to portions of Canada (Edwards et al. 1982; Kelly and Baumhoer 2014). Both species have been widely stocked outside their native ranges because of their popularity among anglers and can be found in most U.S. states. Each species has distinct habitat uses (Pope and Willis 1997; Spier and Heidinger 2002). Black Crappie is frequently found in less turbid ecosystems often dominated by aquatic vegetation, whereas White Crappie uses turbid-water habitat and areas with little aquatic vegetation present (Edwards et al. 1982; Spier and Heidinger 2002; Slipke and Maceina 2007). Juveniles of both species feed on plankton and insects, but White Crappie transition to fish at a smaller size (150-200-mm total length [TL]) than Black Crappie (200-250-mm TL) (Ellison 1984). The two species are often managed together due to their similar physical characteristics and occasional hybridization (Travnichek et al. 1996; Allen et al. 1998; Maceina et al. 1998; Sammons et al. 2002b).

Crappies provide important recreational and economic opportunities, but management is important because of their often-high exploitation rates. Crappie fisheries are important because non-tournament anglers are more often targeting fish species that they can consume (i.e., crappie) compared to catch-and-release tournament anglers (Poudyal 2022). Crappie tournaments are also becoming more popular, especially with new technologies (e.g., forward-facing sonar). Crappie fisheries are economically beneficial to local communities through job creation and dollars spent by out-of-town anglers (Palm and Malvestuto 1983; Allen et al. 1998; Hutt et al. 2013; Hwang et al. 2021). Crappie anglers are usually harvest oriented (Isermann et al. 2010a) and exploitation is commonly higher than 30-40% across the U.S. (Larson et al. 1991; Allen and Miranda 1995; Parsons and Reed 1998), contributing nearly 5 kg/ha to angler harvest annually (Miranda 1999). Because crappies usually have high exploitation rates, managers often use minimum length limits (MLLs) to try to restructure population dynamics to be more favorable for angler harvest and yield (Novinger 1984; Wilde 1997). The high harvest rates are a management concern but typically only when managers consider the variability in growth rates among ecosystems.

Crappies have variable growth and size structure making them a challenge to manage (Boxrucker and Irwin 2002; Michaletz 2020). Bonvechio et al. (2015) found age-2 White Crappies in a Georgia reservoir ranged from 85- to 362-mm TL. White Crappie grow quicker at young ages compared to Black Crappie (Jackson and Hurley 2005), but both species can reach similar sizes (Kelly and Baumhoer 2014). A myriad of factors (e.g., environmental, hydrological, density dependent variables) are related to crappie growth and size structures (Guy and Willis 1995; Spier and Heidinger 2002). Spier and Heidinger (2002) indicated the physicochemical characteristics (i.e., habitat) of reservoirs are related to different growth and survival patterns of crappies. The physicochemical characteristics of reservoirs vary, making statewide regulations a challenge. For example, Isermann et al. (2002) categorized their fisheries as fast, medium, or slow growth populations in a statewide study on crappies in Tennessee. They found the regulations predicted to be most favorable were not consistent among the fast, medium, and slow growth fisheries. Also, Hurley and Jackson (2002) reported decreased growth rates after a MLL was implemented in Nebraska fisheries. Management regulations have been used with varied success to improve survival and change the size structure of fish populations.

The success of MLLs varies among ecosystems and is influenced by growth and mortality rates, the physicochemical characteristics of the reservoir or river, and angler attitudes. Fast growth in crappie fisheries, coupled with low conditional natural mortality (CM), is predicted to be most favorable for successful length limits. For example, Isermann et al. (2002) used an equilibrium-yield model to estimate size structure and yield among multiple reservoirs and found reservoirs having fast crappie growth responded with increased yield in fisheries, especially when crappie populations had low CM. Secondly, the characteristics of a reservoir have related to the success of regulations on crappie fisheries. For example, angler yield and mortality rates differed between spatial gradients of an Oklahoma reservoir due to different physicochemical characteristics and a closed fishing season in one portion for waterfowl hunting (Stewart et al. 2015). Finally, angler attitudes and willingness to follow regulations also affect regulation success of high harvest fisheries. Illegal harvest, in particular, eliminates the benefits of establishing a MLL (Miranda et al. 2017; Leiblich 2018). For example, Sullivan (2002) reported high rates of illegal harvest of Walleye *Sander vitreus* in multiple fisheries leading to conclusions that MLLs are not beneficial when illegal harvest is expected to be high.

Strong and weak crappie year classes are related to both density dependent and independent factors. Density dependence has been observed in several lentic ecosystems using catch per unit effort (CPUE), density, and related abundance metrics (Allen and Miranda 2001; Allen and Pine 2000; Bunnell et al. 2006). For example, among multiple Ohio reservoirs, crappie recruitment variation was most successfully explained by spawning stock CPUE and chlorophyll concentrations compared to models that included environmental variables alone (Bunnell et al. 2006). Allen and Miranda (2001) found density-dependent mechanisms were important at high stock density, where recruitment was limited despite favorable environmental conditions. Other investigators find high correlations between recruitment and environmental factors. Recruitment variability in crappies often relates to environmental factors (Mitzner 1991; Pope and Willis 1997) including hydrology (Maceina and Stimpert 1998; Sammons et al. 2002a). For example, the density of younger crappies in an Iowa impoundment was positively related to increased water temperature and water storage during spawning times (Mitzner 1991). Crappie recruitment was negatively related to high flow years in reservoirs in Alabama, presumably related to decreased zooplankton levels (Maceina and Stimpert 1998). Trends in crappie recruitment in larger natural lakes tend to be more sporadic (Sammons et al. 2002a), whereas smaller impoundments generally have more consistent recruitment, but slower growth (Guy and Willis 1995).

Crappie mortality can vary due to fishery-specific exploitation and population metrics (Colvin 1991; Webb and Ott 1991; Maceina et al. 1998; Boxrucker and Irwin 2002), and regulations do not always affect sympatric species mortality rates the same (Hale et al. 1999). Allen and Miranda (1995) found total annual mortality for crappies among reservoirs in the southeast were variable (48 to 94%; mean = 75%). Total annual mortality is often related to angler harvest which has led managers to widely use MLLs for crappie populations (Colvin 1991; Webb and Ott 1991). Density dependence factors can also affect annual mortality of fishes. High population density can negatively affect mortality rates due to factors such as food availability and competition for habitat, especially during early years of a fish’s life (Jørgensen and Holt 2013). Species-specific mortality rates and survivorship largely depend on population characteristics in a reservoir (Ellison 1984; Spier and Heidinger 2002). For example, after implementation of a 254-mm MLL in an Ohio reservoir, mortality of age 3-4 Black Crappie declined more than 40%, whereas White Crappie mortality only declined by 12% (Hale et al. 1999).

In this chapter, our objective was to estimate growth, mortality, and recruitment variation of Black Crappie and White Crappie in 13 Alabama reservoirs. We provide metrics of growth and mortality because they are important to managers to ensure adequate fishing quality for anglers. Recruitment variation of crappies has been heavily studied and found to be quite variable. Reasons for variable recruitment are important to understand to ensure populations have adequate recruits to support the fishery. Our first chapter provides foundational data that are then used in subsequent chapters. In the second chapter, we used the growth and mortality estimates to construct equilibrium-yield models to assess the simulated effects of multiple regulation scenarios on crappie fisheries. Building on the first two chapters, the third chapter examines variation in growth, size, age structure, and mortality of crappie between sites from the upper, more-riverine portion and sites of the lower, main lake portion of several reservoirs. Collectively, these data can be used to better inform crappie management decisions and ensure regulations are adequately protecting the sustainability of these fisheries.

Methods

Study areas

We sampled 13 reservoirs across Alabama (Figure 1). The reservoirs were located in multiple catchments, provided a wide range of hydrological and limnological characteristics, and represented most of the ecoregions in Alabama. The climate in Alabama is temperate but variable with average annual precipitation ranging from 96- to 188-cm in the previous twenty-five years (https://www.extremeweatherwatch.com/states/alabama/average-precipitation-by-year, Date accessed: 07.02.2025) The northern portion of the state is characterized by typically rockier uplands and karst topography that transition to the fall line and then to the coastal plains in the southern portion of the state (EPA 2001). The underlying lithology is quite variable but is dominated by limestone, dolomite, shale, and sandstone in the north and sandstone, clay, and sand in the south (EPA 2001). Elevation and relief are much higher in the northern portions of the state and then transition to lower elevation and more-homogenous topography in the south (EPA 2001). Streams in the northern portions of the state are typically faster flowing and more biologically diverse, whereas low lying, slower moving and swampy areas occur in the south (EPA 2001). Selected reservoirs were hydrologically variable, including mainstem impoundments with low water retention times and fluctuation rates and tributary impoundments with high water retention times and water-level fluctuations. Crappie recruitment patterns can vary according to depth and shoreline lengths of reservoirs (Kaczka and Miranda 2013); thus, reservoirs included in this study varied from 12.2 to 47.2 m maximum depth and have 33 to 1,653 km of shoreline (Table 1). The trophic states of the reservoirs were mostly eutrophic, with only three reservoirs classified as mesotrophic (Table 1). Alabama encompasses six Level-III ecoregions (Griffith et al. 2001), and there was at least one reservoir in all but one region (i.e., Southern Coastal Plains ecoregion, Figure 1).

Fish sampling

Crappies were sampled from most reservoirs using electrofishing in autumn and spring, but supplemental sampling occurred in the spring for some reservoirs. Crappies were collected using electrofishing as it samples a wider range of overall crappie size structure when compared to other gears (Sammons et al. 2002a). Electrofishing boats, powered using a Honda EG - 5000 CL generator, were used to sample. Power was regulated by an electrofishing box (Midwest Lake Management, Inc., Polo. Missouri). Electrofishing was conducted using DC current at 60 Hz, duty cycle at 25%, and volts near 200-500; settings were adjusted according to Miranda (2009). Alabama Department of Conservation and Natural Resources (ADCNR) biologists also assisted with reservoir electrofishing sampling. Their boats were powered by a Honda EG – 7000 CL generator, with output regulated by an electrofishing box (ETS Electrofishing Systems, LLC, Madison. Wisconsin) and using standard power settings (Miranda 2009). The first 300 individuals of the target species sampled while electrofishing were collected. Collection numbers are based on Cochran's formula with 90% confidence intervals and a margin of error at 0.05 (Ahmed 2024). Timed transects were not used but effort and location of collections were recorded. Target species for each reservoir was determined in consultation with the ADCNR biologist that managed the fishery and only the most common species in most reservoirs were used for analyses. In two reservoirs (Gantt and Wheeler), we used both species combined due to very similar collection numbers. Fish were sampled over multiple years where possible. This was done to minimize variable recruitment on population rate functions (Allen 1997). Sampling was conducted during autumn to obtain the widest range of ages and sizes; however, spring sampling was also conducted in most reservoirs (n = 10 reservoirs) as it was necessary to obtain the target sample size.

Morphometrics and otolith processing

In the laboratory, we verified the species designation was correct, measured TL, blotted and weighed (g), and sexed each fish. Species designation was verified using color patterns and morphometrics. Black Crappies have random black spots and blotches, whereas White Crappies tend to have vertical black bars on both sides. We also counted spines on the spiny dorsal fin if the color patterns left uncertainty in the species assigned. Black Crappies have 7-8 spines, whereas White Crappies have only 5-6 spines. Fish were measured for TL (1 mm) using a length board. All individuals were weighed (1 g) using a scale (Compass^{TM} CX 2200-gram OHAUS, Parsippany. New Jersey). After weighing the fish, we made an incision from the pelvic to anal fin to determine the sex via macroscopic examination of the gonads.

We removed otoliths from the collected fish and aged them via multiple readers. We removed the sagittal otoliths from each fish and placed them in numbered vials (Ross et al. 2005). Otoliths were removed by cutting the isthmus, scraping away the gill rakers, and finding the “bulb” or widening in the spinal cord. The “bulb” was then cut with 15-cm diagonal cutting pliers and pried open where otoliths were extracted with fine-tipped tweezers. We placed otoliths in numbered vials with 95% ethanol, ensuring both otoliths were covered. We individually aged each fish as age-length keys in crappies are not reliable due to variable TL at ages (Michaletz 2020). Otoliths were read whole view by two independent readers using a viewing microscope (VistaVision, VWR International) and a dark holding dish with 95% ethanol covering the whole otolith (see below).

We sectioned and mounted all otoliths with greater than four annuli following Maceina (1988) and Buckmeier and Howells (2003) with minor modifications. Deviations from these methods included using an electric grinding wheel to grind otoliths once they are mounted to a slide instead of a hand drill grinder. We also used multiple grits of sandpaper after the otolith was mounted and ground to a thin section to make annuli more visible when observing through the microscope. Briefly, the otoliths were broke in half perpendicular to the longitudinal plane through the nucleus using fish skinning pliers. One half of the otolith was then ground using 600-grit sandpaper on the cut side, then mounted to a labeled microscope slide using a hot plate and clear thermoplastic cement (Crystalbond 509, Hatfield). We then placed the slide on the hot plate and a small piece of thermoplastic cement was placed on the slide. Once the cement turned into liquid, the slide was removed and the half that is ground on the flat side was picked up by fine tipped tweezers and placed flat side down onto the slide with the cement surrounding it. The tweezers were then used to build a small "mound" around the edge of the otolith, ensuring the otolith will be flat on the slide while the cement cooled. Next, the half otolith, vertical on the slide, was ground down to approximately a 0.5-mm section using an electric grinding wheel. Then, the section was polished using 600-, 800-, and 1000-grit sandpaper. Lastly, a drop of immersion oil was placed on each section before being viewed under a compound microscope (Boreal 2, Mississauga. Ontario) at 40x power.

Otoliths were read by multiple readers and discrepancies reconciled. First, whole-view age data were recorded on separate data sheets by two readers. Disagreements between readers were reviewed by a third independent reader to resolve discrepancies (Carroll et al. 2019). If all three readers disagreed, the two original readers attempted to reach an agreement (Miller and Storck 1982; Rogers 2024). If readers did not come to an agreement, the age data associated with that otolith were discarded. Sectioning and processing of otoliths occurred after all readers had a chance to view both whole otoliths. Age estimations of mounted otoliths were recorded on separate data sheets by two readers and followed the same protocols for inclusion of the third reader and concert reads. All age estimations were blindly read by each reader (i.e., no knowledge of TL, species, weight, sex, or other readers results).

Data analyses

Size structure and body condition

We examined patterns in size structure and body indices among populations. Size structures of each population were examined by creating length frequency histograms for crappie from each reservoir. We also created and observationally compared length-frequency histograms by sex and between species, where we had sufficient sample sizes of both. The proportion of larger than stock sized crappies to at least stock sized crappies in each population (PSD) was calculated by dividing the number of quality (≥ 250 mm; PSD-Q) and preferred (≥ 300 mm; PSD-P) size crappies by the number of at least stock (≥ 130 mm) size crappies then multiplying times 100 (Gabelhouse 1984). Lastly, relative weights (Wr) were calculated for all individuals (Neumann et al. 2012). Relative weight was calculated using the standard weight equation (Neumann and Murphy 1991). From this equation, we calculated what the fish should weigh based on its log TL. For Black Crappie, the equation -5.618+3.345*(logTL) was used, whereas the equation -5.642+3.332*(logTL) was used for White Crappie. These equations resulted in log (standard weight); hence, we raised the numbers found in these equations to the power of 10 resulting in the standard weight. Once the standard weight was calculated, we divided it by the observed weight of the fish, then multiplied by 100.

We examined variability in PSD between sex and species and statistically compared PSD between reservoirs that were drawn down annually and reservoirs that were not. We hypothesized that there would not be large differences in size structures of the two types of reservoirs. PSD-Q,P was calculated for each sex where samples among sexes were appropriate ($n = 10$ reservoirs). PSD-Q,P was also calculated for each species and compared in reservoirs where both Black and White Crappies were collected. This was limited to 5 reservoirs where we sampled > 125 fish of each species. We then used a t-test to determine if there were differences in PSD-Q values in reservoirs that draw down water levels annually ($n = 6$) versus reservoirs that do not draw down annually (n = 7) ($\alpha = 0.05$). PSD-P was not statistically compared because our samples had small amounts of "preferred" sized crappies in some reservoir collections.

We developed two linear mixed effect models to evaluate the relationship between Wr and sex and Wr and species (i.e., 2 models) while accounting for differences among reservoirs. We used two models because of differences in the reservoirs where we collected sex versus the reservoirs where we had data on both species (i.e., they were not the same). First, Wr among all samples were truncated to >65 (n = 6089) and <115 (n = 6019) to omit outliers that could be due to measurement errors. We also excluded fish that were below 130-mm TL (n = 6001) to omit bias from juveniles. We included only 10 of 13 reservoirs in the analyses because sex was not determined in one reservoir (Coffeeville), was determined for a small portion of our samples in one (i.e., Millers Ferry), and had truncated sex ratios in another (i.e., Mitchell). We excluded eight reservoirs in the analyses comparing mean Wr and species because we only had enough of the two sympatric crappies in 5 of 13 reservoirs. Black and White Crappies were collected in nine reservoirs, but there were too few of one species (< 125, 28% of total sample) collected in four of those reservoirs and therefore, excluded from these analyses. Then, average Wr for each reservoir was observed before statistically testing for differences between sex and between species. Next, we created two linear mixed effects models analyzing Wr as a function of sex, and Wr as a function of species ($\alpha = 0.05$). Lastly, we included a random effect for reservoir in both models to account for differences related to factors we did not measure (e.g., ecoregion).

Growth

We plotted TL at age to examine patterns in differences in length and age and the von Bertalanffy growth equation (von Bertalanffy 1938) to estimate growth differences among reservoirs. We first created TL at age graphs for each reservoir. We then fit the von Bertalanffy growth curve using length-at-age data from each reservoir (i.e., nonlinear least squares analyses). The instantaneous growth rate, which is also the growth coefficient (K) in the von Bertalanffy growth equation, was estimated for each population. Growth parameters were described using the growth curve; 0.5 was added to each age of fish collected in autumn to account for growth since the last annulus (Sammons and Maceina 2008). Parameters K, L_{inf}, and t0 were estimated for each population. K is the growth coefficient; L_{inf} is the estimated average largest size for each population; t0 is the hypothetical age at the time of zero length. We did not collect many crappies < 100-mm TL in our samples (n = 28), causing the growth curve to flatten and estimates of t0 and K to decline to unrealistic values. Therefore, we constrained t0 to -0.05 for most reservoirs (n=12 reservoirs) to get a more accurate estimate of growth. The time it takes for fish to grow to the current 229-mm MLL was also predicted using the von Bertalanffy equation.

Chlorophyll A

To examine among-reservoir differences in growth, we obtained information related to trophic state from each reservoir and developed two linear regression models to assess relationships in TL related to Chlorophyll A (CHLA) by age class. We restricted our analysis to age 3 and age 4 fish as these were common ages among all reservoir samples. CHLA concentration is a measure of trophic state in reservoirs (Carlson 1977) and can explain differences in fish populations among reservoirs (Bayne et al. 1994; DiCenzo et al. 1996). Then, we obtained CHLA concentrations from ADEM reservoir reports where those data were available (n = 10) and averaged CHLA estimates from their last 7 samples (ADEM n.d.). Chlorophyll A values were plotted to check for skewedness. Lastly, we examined relationships between growth and CHLA using two linear regression models analyzing mean TL at age 3 as a function of CHLA amounts and mean TL at age 4 as a function of CHLA amounts ($\alpha = 0.05$).

Mortality

We created catch-curves and calculated multiple estimates of mortality among all reservoirs. First, we made year-class frequency histograms by reservoir to assess at what age fish recruited to our electrofishing gear. Next, we log transformed catch at age (≥ age 2-4 depending on reservoir, Table 6) to develop our catch curve. Then, we estimated the total instantaneous mortality rate (Z) for each reservoir (i.e., population) by measuring the slope of the descending limb of the graph (Maceina 1997). We excluded ages where we did not collect any fish. We also truncated these data following the age where our catch was zero to eliminate bias from long-lived fish that typically reflect few fish. From Z, the equation $S = e^{-Z}$ was used to calculate annual survival, which was used to estimate total annual mortality (Ricker 1975). Instantaneous natural mortality (M) was estimated using equations in excel (Table 7) (Hoenig 1983; Chen and Watanabe 1989; Djabali et al. 1993; Jensen 1996; Lorenzen 1996; Cubillos et al. 1999). We averaged estimates associated with these equations to calculate M. These equations used different reservoir-specific growth and age parameters to estimate M; uncertainty in the parameters most associated with natural mortality in each reservoir made this a more reasonable approach. Finally, CM was described using the equation: $CM = 1 – e^{-M}$.

We used t-tests to determine if there were significant differences between average mortality of male and female crappie and a simple regression model to assess the relationship between mortality and reservoir depth. We excluded Coffeeville, Millers Ferry, and Mitchell reservoirs from the analysis comparing mortality by sex. In Coffeeville and Millers Ferry reservoirs, we lacked a sufficient sample size of male and female fish; in Mitchell Reservoir, 85% of the fish sampled were males. First, we created sex-specific catch curves for each reservoir to get Z. Then, we used the equation 1-exp(-Z) to get total annual mortality. We plotted total annual mortality to assure data were not skewed and used a t-test to assess differences in mean total annual mortality between sexes ($\alpha = 0.05$). Lastly, we built a simple linear regression showing the relationship between total annual mortality and reservoir depth ($\alpha = 0.05$).

<u>Recruitment variability</u>

We developed a multiple regression model to observe underlying relationships associated with year-class strength. First, we calculated recruitment using residuals from catch-curve regressions that provided estimates of strong and weak year classes (Maceina 1997). We created sample-year-specific catch curves then back calculated to years the fish were hatched. This resulted in multiple catch curves for several reservoirs since fish were collected over multiple years (2022-2024). Then, for each reservoir, we averaged residuals from each year fish were hatched to obtain overall residual estimates. Next, water level and retention time data were retrieved for years where we had recruitment estimates (2015-2021) from multiple water management agencies (i.e., Alabama Power; Army Core of Engineers; Tennessee Valley Authority; USGS). We omitted four reservoirs from our analyses due to lack of all hydrology data (Harding), lack of water-level data (Gantt), and lack of data on retention time (Coffeeville and Warrier). Before building our model, we log transformed then standardized our hydrological data (subtracted the mean, divided by SD). Next, we completed a Pearson's correlation coefficient test to examine multicollinearity between hydrological variables (where rho > 0.6 was considered multicollinear). Then, we used regression analysis to examine the relationship between water level and retention time (Guy and Willis 1995; Maceina and Stimpert 1998; Dattilo et al. 2021) and year-class strength of crappies. Finally, we built a multiple regression model examining the relationships between hydrological variables and the residual estimates ($\alpha = 0.05$).

Results

Fish sampling

We sampled 6,125 Black Crappie and White Crappies from October 2022 to May 2024, and target sample sizes were achieved in all reservoirs. Individual reservoir sample sizes range from 303 crappies to 694 crappies (Table 2). In autumn 2022 and spring 2023, 1,749 and 445 crappies were collected, respectively. Autumn 2023 collections yielded 1,444 crappies and the final samples were collected during spring 2024 with a total of 2,487 crappies.

Morphometrics and otolith processing

We found variable length and weight data among reservoirs, but sex ratios were similar in most. Mean TL for all fish collected ranged 201-mm TL to 299-mm TL (Table 3). The mean weight of fish collected among reservoirs was also highly variable (124 g – 449 g) (Table 3). We found the minimum length of fish collected among reservoirs had a wide range (49-mm TL – 225-mm TL), whereas the maximum fish TL among reservoirs did not vary as much (361-mm – 440-mm TL) (Table 3). The minimum weight of fish collected in all reservoirs was less than 50 grams except for Mitchell Reservoir (152 g), and in over half of the reservoirs (n = 8 reservoirs), we collected at least one fish < 10 grams (Table 3). Although minimum weights collected were not variable in most reservoirs, maximum weights of crappie collected among reservoirs varied by more than 600 g (685 g – 1329 g) (Table 3). Sex ratios among reservoirs were relatively consistent, except for in Mitchell Reservoir. Sex was not identified for any fish collected in Coffeeville Reservoir and for most fish collected in Millers Ferry Reservoir (Table 2). Although most reservoirs had relatively similar collection numbers between sexes, Mitchell Reservoir's sample of female crappies only made up 15% of the total sample (Table 2). We collected more females in 7 of 12 reservoirs (Table 2). Also, we collected similar sex ratios in 8 of 12 reservoirs;

where the sex that was collected in less numbers was ≥ 42% of total sample. Coffeeville Reservoir was not included in these comparisons because sex was not determined for any fish.

We collected both Black and White Crappie in most of the sampled reservoirs. Black Crappie were generally more dominant in deeper, clearer reservoirs, particularly in the central and eastern portions of the state, and we collected a total of 4,036 individuals. However, Black Crappie were not found in two reservoirs—Upper Bear Creek and Warrior (Table 2). In contrast, White Crappie was more commonly dominant in run-of-the-river systems and shallower, more turbid habitats, primarily located in western Alabama. We collected 2,089 White Crappie. There were three reservoirs where White Crappie were not collected—Harris/Wedowee, Martin, and Weiss (Table 2). Although we did not collect White Crappie in Weiss, they were observed during sampling but were not the dominant species and therefore, not collected. Additionally, anglers reported catching White Crappie in Harris/Wedowee and Martin reservoirs, though none were detected in our samples. In Gantt Reservoir, both species were collected in nearly equal numbers, with the less dominant species comprising 45% of the total sample (Table 2).

Reader agreement was relatively high in otolith examinations. We extracted and read 6,125 otoliths. At least two of three readers agreed on the age of the fish in 5,269 out of 5,315 pairs (99%) that were read whole. Most disagreements between readers occurred when otoliths had > four annuli (n = 810, 13% of otoliths). We sectioned and mounted these otoliths for reading rather than simply calling them disagreements. Readers disagreed on 88 out of these 810 (89% agreement) otoliths before they were sectioned. After sectioning, reader agreement was 94% (757 out of the 810 otoliths). Only one otolith was discarded due to disagreements. In this case, one otolith was assigned age four, whereas the other was assigned age six for the pair suggesting this may be the result of a processing error.

Data analyses

Size structure and body condition

We found little variation among length-frequency graphs between sex, variability in lengths of the two species, and a trend in lengths among reservoirs. Male and female length frequencies peaked near the same length in most reservoirs (Figure 2). In two reservoirs (Harris/Wedowee Reservoir and Wheeler Reservoir), we observed slight variations in length frequencies, where female length frequencies peaked near 300 mm, and males length frequencies near 250-mm TL (Figure 2). Data were inconsistent when comparing species, with the dominant species length frequency peaking at a longer TL in 60% of reservoirs (3 out of 5), but the less dominant species comprising higher numbers of longer fish in 40% of reservoirs (2 out of 5) (Figure 3). The less dominant species length frequency only peaked at a longer length in one reservoir (Harding) and the two species length frequencies peaked at a similar length (250-mm TL) in another (Bankhead) (Figure 3). In Gantt Reservoir, the count of species sampled was similar, and White Crappies length frequency peaked at a longer TL (280-mm TL) compared to Black Crappies (220-mm TL) (Figure 3). Reservoirs that do not draw down annually had an overall wider range in TLs compared to reservoirs that draw down annually (Table 1; Figure 2).

We found similar PSDs between sex, variability between species, and no difference in PSDs of crappie between reservoirs that draw down annually and those that do not. PSDs were similar between sexes (Table 4). In reservoirs with similar collection numbers of both species, we saw PSDs were higher in the dominant species in 60% of reservoirs (3 out of 5). There was no significant difference in PSD-Q of crappie populations in reservoirs that were drawn down annually versus reservoirs that were not drawn down ($P = 0.52$; $t = 0.67$; $df = 8.59$) (Table 4).

The mean PSD-Q between reservoirs that were not drawn down was 54.4 (SE: 8.9), whereas reservoirs that were drawn down had an average PSD-Q of 47.8 (SE: 4.3).

We built two linear mixed effects models and found little variation in average Wr between sexes and species. Average reservoir Wr for males ranged from 83 to 103 (mean = 90; SD: 6.2; n = 10 reservoirs), whereas Wr for females ranged from 83 to 100 (mean = 88; SD= 5.4; n = 10 reservoirs) (Table 5). In reservoirs with adequate samples of both species, we found reservoir average Wr for Black Crappie ranged from 84 to 97 (mean = 90; SD= 5.6; n = 5 reservoirs), whereas Wr for White Crappie ranged from 81 to 104 (mean = 91; SD= 9.6; n = 5 reservoirs) (Table 5). Using a linear mixed effects model, we found males had a higher body index by 1.58 units (SE: 0.22; t = 7.1; F = 50.48; df = 9), on average, than females. The random effect of reservoirs had a variance of 32.28 (SD= 5.68; n = 10 reservoirs). Lastly, White Crappies had a greater Wr by 0.93 units (SE: 0.37; t = 2.49; F = 6.20; df = 4), on average, compared to Black Crappies. The random effect of reservoirs in this model had a variance of 57.56 (SD=7.59; n = 5 reservoirs).

Growth

Black Crappie and White Crappie growth was variable among Alabama reservoirs (Figures 4-8). The growth coefficient (K) from the von Bertalanffy growth model varied from 0.39 to 0.55 (Appendix A). L_{inf} was highly variable, ranging from 272-mm TL to 397-mm TL (Appendix A). The time it takes for populations to reach the 229-mm MLL varied from 1.78 to 4.65 years old (Appendix A). Mean-length-at-age varied among all reservoirs. Mid-range ages in most reservoirs (ages 2-5) often encompasses length ranges wide enough that TL at ages overlap with each other. For example, age-3 crappies in Eufaula Reservoir (n=112 crappies) ranged from

156-mm TL to 302-mm TL, whereas age-4 crappies (n=281 crappies) ranged from 144-mm TL to 330-mm TL).

Chlorophyll A

We created two linear regression models and found an increase of trophic state index in Alabama reservoirs was not significantly related to mean TLs at age 3 or TLs at 4. As trophic state index increased, we found mean TL at age 3 was not related to CHLA ($P = 0.07$; $r^2 = 0.34$; $t = 2.05$; $F = 2.89$; $df = 9$). Further, there was not significant relationship between Chlorophyll A concentrations in Alabama reservoirs and mean TL at age 4 ($P = 0.33$; $r^2 = 0.12$; $t = 1.04$; $F = 1.08$; $df = 9$).

Mortality

Our year-class histograms indicated consistent recruitment to our sampling gear, but the maximum age collected, and mortality estimates were highly variable among reservoirs. Peaks in catch-at-age and year-class histograms were consistently 2- and 3-year-old fish (Table 6; Figures 9-13). We found the minimum age collected was consistent among most reservoirs (Table 6), whereas the maximum age collected among reservoirs was variable. For example, crappie ages from Millers Ferry Reservoir (n=419) ranged from 0- to 7-years old and crappie sampled from Harris/Wedowee Reservoir (n=694) ranged from 1- to 16-years-old. Our catch-curve analyses indicated estimates of Z ranged from 0.44 to 1.00 yr^{-1} (mean = 0.72 yr^{-1}; SE = 4%) (Figures 14-18; Appendix B). Estimated survival ranged from 37% to 58% (mean = 49%; SE = 2%) (Appendix B). The average total annual mortality among reservoirs was 51% (SE = 2%) (Appendix B). Instantaneous natural mortality among reservoirs ranged from 0.44 to 0.67 yr^{-1} (Appendix B). Conditional natural mortality data ranged from 36% to 49% (Appendix B).

We found male mortality rates were greater than female mortality rates, and reservoir depths had a significant relationship with total annual mortality. Male total instantaneous mortality rates ranged from 0.43 to 1.39 yr^{-1} (mean = 80%; SE: 8%), whereas female total instantaneous mortality ranged from 0.39 to 0.87 yr^{-1} (mean = 58%; SE: 4%) (Appendix B). Estimates of crappie survival ranged from 25% to 65% for males (mean = 46%; SE: 3%), whereas females ranged from 42% to 68% (mean = 56%; SE: 2%) (Appendix B). Mean total annual mortality was 54% (SE = 3%) for males and 44% (SE = 2%) for females (Appendix B). We found male total annual mortality was 9.8% greater (± 4.2%; 95% confidence intervals), on average, compared to females ($P < 0.05$; $t = 5.28$). We found total annual mortality had a significant negative relationship with average reservoir depth ($P < 0.05$; $r^2 = 0.48$; $F = 10.1$).

Recruitment Variability

Recruitment was variable among populations and retention time was negatively related to year-class strength but not water level. We found some populations had one- or two-year classes that comprised over half of our sample. In other reservoirs, recruitment was more consistent from year to year, and residuals from the catch curve did not deviate much from our regression line. Strong and weak year classes did not line up when compared among reservoirs, or among ecoregions. Our multivariable regression model was significant and explained about 12% of the variation in crappie recruitment ($P < 0.05$; $r^2 = 0.12$; $F = 4.46$). The Pearsons correlation coefficient test resulted in water levels and retention time not being multicollinear to each other (rho = -0.04). We found retention time of each reservoir had a significant negative relationship with crappie recruitment ($P < 0.05$; $t = -2.85$). We found water levels during the months of March and April did not have a relationship with recruitment success in crappies ($P = 0.44$; $t = 0.78$).

Discussion

We observed high variability in crappie growth, mortality, and recruitment among Alabama reservoirs, likely driven by a combination of environmental, biological, and hydrologic factors. Similar patterns have been reported elsewhere; for example, Sammons et al. (2000) identified fast-, medium-, and slow-growth crappie populations in Tennessee reservoirs based on criteria from Allen and Miranda (1995). In Alabama, variable growth may be influenced by factors such as prey abundance, density dependence, and water temperature (Guy and Willis 1995; Spier and Heidinger 2002; Michaletz et al. 2012). Michaletz et al. (2012) found that in some Missouri reservoirs, high temperatures reduced White Crappie consumption rates and growth despite adequate forage, while in others, fish continued to feed and grow rapidly under similar thermal conditions. However, when prey availability was limited, growth declined regardless of temperature. The range of habitats across Alabama's multiple ecoregions (Griffith et al. 2001) likely contributes to this variability. Mortality rates were also highly variable among reservoirs, potentially influenced by angler harvest, population structure, and regulatory differences (Colvin 1991; Webb and Ott 1991; Maceina et al. 1998; Boxrucker and Irwin 2002), and our estimates of total annual and conditional natural mortality reflected these trends (Allen and Miranda 1995). Recruitment patterns followed a similarly variable and quasi-cyclic structure (Allen and Miranda 2001), with potential drivers including environmental conditions, population metrics, and hydrology (Mitzner 1991; Maceina and Stimpert 1998; Bunnell et al. 2006). For instance, Bunnell et al. (2006) found that chlorophyll concentrations were strong predictors of larval crappie density, whereas Maceina and Stimpert (1998) associated year-class strength with hydrologic features like short retention times and elevated winter water levels. Together, these findings highlight the complex and reservoir-specific nature of crappie population dynamics, which may be influenced in some cases by sampling bias.

Sample sizes were achieved in all reservoirs with one gear type, but sampling biases could influence our results in some cases. We achieved our target sample sizes for all reservoirs using only electrofishing, but sampling crappies has historically been achieved using multiple gears (Boxrucker and Ploskey 1988). Trap nets have been shown to collect wider ranges in sizes compared to electrofishing in some cases (Boxrucker and Ploskey 1988), but not others (Sammons et al. 2000). Sampling bias could lead to collecting fish only of certain sizes (Laarman and Ryckman 1982; Boxrucker and Ploskey 1988), which would not accurately reflect the whole population. Electrofishing sampling does not sample fish nearly as deep as other gears, such as trap nets. Mcinerny and Cross (2004) found electrofishing was not as efficient as trap nets in collecting larger sized crappies. Also, we expected to collect higher numbers of males in our spring samples due to the behavioral patterns of crappie during spawning times. Male crappies tend to use shallower habitat longer than female crappies, to guard nests and eggs (Siefert 1968), making them more susceptible to electrofishing. We attempted to collect fish during the autumn season for this reason, but in some reservoirs, this was not achievable. In most of our reservoirs, there were no differences in catch between male and females, and we collected wide ranges of TL's indicating minimal bias associated with electrofishing. Contrarily, in one reservoir (i.e., Mitchell) where we were only able to complete spring sampling, our collections were biased towards male fish, and no juvenile fish were collected. Data from that reservoir, therefore, growth coefficients may be biased for Mitchell Reservoir due to the lack of smaller fish. Sampling during a different season or with multiple gears may provide more reliable estimates for reservoirs where sampling bias is present.

As expected, species composition was variable across the state, with one crappie species typically having higher relative abundance in the reservoir we sampled and exhibiting better overall condition. Species compositions may shift over time. For example, in Gantt Reservoir, ADCNR has historically collected mostly White Crappie in their samples (Rob Andress, ADCNR biologist, personal communications), but we collected the two species in very similar numbers (Table 2). Changes in fish species composition may be due to factors such as reservoir age, habitat, flow regimes, and other environmental variation (Loures and Pompeu 2019). Changes in habitat conditions can benefit both crappie species. Alternatively, one species may be preferentially sampled under some environmental conditions (Sammons et al. 2002b) due to changes in effective sampling (Pope et al. 2010; King et al. 2023). Limnological factors such as turbidity also influence crappie species composition in reservoirs. For example, White Crappie often inhabit water that is more turbid, whereas Black Crappie inhabit clearer reservoirs (Edwards et al. 1982; Pope and Willis 1997; Spier and Heidinger 2002; Slipke and Maceina 2007). Alabama has both turbid and clear reservoirs. In reservoirs where we sampled both species, the dominant species exhibited better growth, possibly due to the characteristics of the reservoir being better suited for that species. Hybridization between the two species is also common (Travnichek et al. 1996; Kelly and Baumhoer 2014) which could make identifying the species a challenge and can alter species composition (Fitzpatrick et al. 2015). In our study, we did not complete genetic analyses but simply relied on morphometrics and color patterns.

We had high between-reader agreement via ageing which may relate to the number of readers and because we sectioned otoliths from older fish. Agreement on whole otoliths was relatively high between readers in this study (99%) compared to others (e.g., 91%, Hammers and Miranda 1991; 90%, Mcinerny et al. 2020). Agreement could have been higher in this study due to the inclusion of a third reader that was blind to the other two readers' estimates, which gives another chance for at least two readers to agree if the first readers disagreed. Agreement could also be higher because we sectioned and mounted otoliths when fish were estimated to have over 4 annuli present (Maceina 1988). Although crappie otolith agreement is relatively high in most studies (e.g., 87-99%, Ross et al. 2005; Isermann et al. 2010c), agreement between readers typically decreases after age 3 or 4 (Mcinerny et al. 2020). Maceina (1988) indicated sectioning and mounting of otoliths was important for older or slower-growing fish. Our data support this finding as our percent agreement increased by 5% (from 89 to 94%) after otoliths were sectioned.

Variable size structures and growth of the crappie we sampled may be due to several factors including reservoir type, sampling bias, and hydrology. We collected wider ranges of TLs in our study in storage impoundments compared to the run-of-the river reservoirs. There could be underlying population differences between the types of reservoirs because of differences in hydrological and environmental variables (Guy and Willis 1995; Spier and Heidinger 2002; Baumgartner et al. 2020). These differences could also be a function of sampling bias. Run-of-the river reservoirs tend to be shallower and have more stable water levels when compared to storage impoundments (Baumgartner et al. 2020). Water temperature may also be warmer in shallow reservoirs compared to deep storage impoundments. These physicochemical differences can affect fish behavior and sampling efficiency (Nelson and Little 1987). We did not see improved size structures in shallower reservoirs, possibly due to our sampling timing. During spring and autumn, crappies tend to use shallow-water habitat that would minimize the expected sampling bias between shallower and deeper waters. Further, CHLA may fluctuate more in run-of-the-river reservoirs (i.e., low retention time of nutrients), which could also indirectly affect fish growth.

Chlorophyll A has historically been linked to fish growth, but our results did not agree with that relationship possibly due to other factors that could influence crappie growth, such as water temperature, density dependence, and forage availability. Chlorophyll A typically has a positive relationship with fish growth and density (Breuklelaar et al. 1994; Dicenzo et al. 1995; Zhou et al. 2016). Interestingly, we did not find any relationship with CHLA and TL at age-3 and age-4 fish. Water temperature also typically relates to fish growth (Michaletz et al. 2012; Matthias et al. 2018) but was not observed in this study. Single point measures from our sampling methods likely do not accurately capture water temperatures the fish experience. In future studies, biotags (e.g., Westhoff 2016) or temperature data loggers may allow a more accurate representation of the temperatures the fish are experiencing. Guy and Willis (1995) found high density dependence in smaller impoundments were negatively correlated with growth, whereas natural lakes with lower densities had faster crappie growth. The density of prey species (e.g., gizzard shad) was found to be the most influential factor for crappie growth, even at warm temperatures (Michaletz et al. 2012). Further, at optimal foraging temperatures, low prey abundance resulted in crappie growth to cease or even cause the fish to lose weight. Although we do not have information on prey abundance in our study, a better understanding of these conditions would be useful for understanding the unobserved variability.

PSDs and Wr are often used as a measure of size structure and growth and can also be affected by sampling bias. We expected fast-growing populations to have higher PSDs compared to slower-growth populations. Our data supported this hypothesis; however, sampling biases could have affected our PSD values (Willis et al. 1993). Because electrofishing can be less efficient for sampling large crappies compared to other gears (Mcinerny and Cross 2004), actual PSD values may be higher in some cases, especially for PSD-P. If sampling is biased towards smaller fish, then PSDs would not be accurate because of the lower number of preferred sized fish sampled. Contrarily, PSD values in Mitchell Reservoir may be unrealistically high because of seasonal sampling biases. Alternatively, Wr is less likely to be affected by sampling biases.

Recruitment variability is common in crappie populations. Variable recruitment has been linked to multiple environmental factors, including water temperature, levels, flows, retention time, and CHLA concentrations (Allen 1997; Maceina and Stimpert 1998; Sammons et al. 2002a; Bunnell et al. 2006; Dattilo et al. 2021). In our study, we found water retention time (i.e., amount of time water occurs within the reservoir) had a strong negative relationship with crappie recruitment. Similarly, Datillo et al. (2021) found retention time was also negatively related to Freshwater Drum *Aplodinotus grunniens* recruitment. Maceina and Stimpert (1998) suggested retention time may be related to underlying factors such as turbidity, food availability, and water levels. We did not find water levels were related to recruitment (but see Mitzner 1991; Maceina and Stimpert 1998). Nonetheless, it appears that crappie recruitment in Alabama reservoirs does not benefit from retaining water within the reservoir, and could have negative implications for downriver fisheries (see Dattilo et al. 2021).

Wide ranges of mortality estimates in fish populations among reservoirs can result from several issues. First, gear selectivity may underrepresent younger or smaller fish and flatten catch curves which leads to underestimated mortality. Ageing errors—such as misreading otoliths—can lead to incorrectly assigning fish to younger age classes and steepen the curve which leads to overestimated mortality. Third, low sample sizes or skewed age distributions reduce the reliability of mortality estimates. Fourth, recruitment failure may be misinterpreted as survival of older fish if younger cohorts are missing. Fifth, violating the assumptions of constant recruitment and mortality in catch-curve models can bias estimates. This is likely with crappie and has been observed by Sammons et al. (2000). Lastly, seasonal or behavioral sampling bias, such as missing fish that occupy deeper water or are less active during sampling, may exclude vulnerable individuals (Fischer and Quist 2014). To reduce these biases, researchers tend to use multiple gear types and incorporate seasonal sampling (Boxrucker and Ploskey 1988; Mcinerny and Cross 2004); however, apart from Mitchell Reservoir, we did not see evidence of this concern. It is likely, however, that violation of catch curve models has created some concern with our mortality estimates.

Complications in catch-curve analyses for crappie can lead to issues when estimating mortality. One of the assumptions of a catch-curve is that the population has constant recruitment from year to year (Maceina 1997). Crappies typically do not have constant annual recruitment, rather the populations are thought to be "boom-and-bust" fisheries (Allen and Miranda 2001; Boxrucker and Irwin 2002). In our study, there were signs of constant recruitment in some fisheries (i.e., typically tributary, storage impoundments), where residual estimates did not deviate much from the regression line. In others, residual estimates were distant from residual regression lines. This suggests that recruitment is not constant from year to year in some crappie populations in Alabama, breaking the assumption of constant recruitment for catch-curve analyses which is an issue for mortality estimates. The possible margin of error associated with violating this assumption (Allen 1997) should be taken into consideration when considering management changes for these fisheries. Using alternative models to estimate crappie mortality may be needed to attain accurate estimates.

Management of fish populations depends on multiple factors and variability makes it especially challenging; though, moving forward with regional regulations may be beneficial. Managers typically consider multiple stakeholder groups that have varied opinions on the goals of the fishery (Allen and Miranda 1996). Crappie fisheries are one of the few freshwater fisheries that can be properly managed with harvest and bag restrictions due to harvest focus of most anglers (Isermann et al. 2010a). Management regulations tend not to be as effective for fisheries that are primarily catch and release, assuming high survival (Allen et al. 2008; Myers et al. 2008; Carlson and Isermann 2010; Miranda et al. 2017). Although crappies are heavily sought after for harvest, anglers are becoming increasingly diverse in their opinions on management of these fisheries (Ward et al. 2013), adding to the challenge of fisheries management (Orth 2023). States have often enforced regulations over a large area (i.e., entire state) for both ease of enforcement but also for angler simplicity and clarity (Shamaskin et al. 2023). Recently, studies indicated that variability in fish populations complicate statewide management regulations (Miazga et al. 2022). For example, Sammons et al. (2000) suggested more fishery-specific regulations would be beneficial due to variability in crappie population characteristics among Tennessee reservoirs. Likewise, Pritt et al. (2019) found regulations resulted in various outcomes on crappie fisheries in 44 reservoirs in Ohio. They found trends in regulation responses among reservoir sizes and productivity. Our results, likewise, indicate that managing crappie fisheries in Alabama would benefit from consideration of specific population metrics which appear much more regional. Guy and Willis (1995) suggested ecosystem specific management for Black Crappie in South Dakota reservoirs and this approach could be applicable for Alabama reservoirs. Ecoregion specific management could ease confusion for anglers compared to site-specific regulations, while still benefiting crappie populations.

Chapter I Tables

Table 1-1. List of reservoirs sampled from 2022-2024 to examine size structures, growth, mortality, and recruitment variation to analyze the 229-mm MLL across Alabama. Reservoirs with a * represent the subset of impoundments that were examined for spatial variations in chapter III of this thesis.

Reservoir name	River system	Area (ha)	Mean depth (m)	Max depth (m)	Shoreline length (km)	Winter drawdown amount (m)	Trophic state	Full pool volume (ha-m)
Upper Bear	Bear Creek/ Tennessee	749	6.2	21.3	169	1.2	Eutrophic	4,634
Wheeler *	Tennessee	27,640	4.8	17.4	1,653	1.8	Eutrophic	129,885
Weiss *	Coosa	12,221	3.1	18.9	719	1.8	Eutrophic	37,996
Bankhead	Black Warrior	3,723	9.8	22.6	644	0	Eutrophic	36,511
Harris*	Tallapoosa	4,314	13.4	38.1	438	2.4	Mesotrophic	57,850
Mitchell	Coosa	2,367	9.1	27.4	237	0	Eutrophic	21,648
Martin *	Tallapoosa	15,782	12.8	47.2	1,127	>1.5	Mesotrophic	202,977
Harding	Chattahoochee	2,371	9.8	33.8	251	N/A	Eutrophic	23,091

Warrior	Black Warrior	3,682	7.0	15.2	483	N/A	Eutrophic	24,341
Coffeeville	Tombigbee	3,440	7.0	12.2	483	N/A	Eutrophic	23,534
Millers Ferry	Alabama	6,960	5.9	18.3	830	N/A	Eutrophic	40,926
Gantt	Conecuh	1,112	1.6	12.2	34	N/A	Mesotrophic	1,796
Eufaula *	Chattahoochee	18,284	6.2	28.4	1,030	1.8	Eutrophic	115,257

Table 1-2. Sample size of crappies from each reservoir and between sex and species if applicable (NA indicates these data were not collected in the sample). The 'Total' column may be different than the sum of male and female fish due to immature fish not being counted as male or female. Sex was not determined by ADCNR biologists in two reservoirs (Coffeeville and Millers Ferry Reservoirs).

Reservoir	Males	Females	Black Crappies	White Crappies	Total
Bankhead	214	218	126	309	435
Coffeeville	NA	NA	312	149	461
Eufaula	404	214	620	7	627
Gantt	126	177	142	176	318
Harding	255	174	322	130	452
Harris	334	337	694	0	694
Martin	300	320	655	0	655
Millers Ferry	52	64	83	336	419
Mitchell	271	44	315	2	317
Upper Bear Creek	148	171	0	323	323
Warrior	162	138	0	303	303
Weiss	322	236	582	0	582
Wheeler	243	271	185	354	539

Table 1-3. Morphometric data of fish collected in lower and upper sections. Data include mean length and weights collected, and standard deviations (SD). The minimum and maximum length and weights collected in each section are also listed.

Reservoir	Mean length (mm)	SD length (mm)	Mean weight (g)	SD weight (g)	Minimum length (mm)	Maximum length (mm)	Minimum weight (g)	Maximum weight (g)
Bankhead	263	40	283	146	162	387	48	901
Coffeeville	201	124	124	104	49	383	2	703
Eufaula	244	46	234	136	87	372	6	911
Gantt	240	50	192	111	75	371	4	699
Harding	232	62	209	158	65	440	5	1329
Harris/ Wedowee	256	44	259	132	118	373	17	810
Martin	246	45	222	124	69	404	6	929
Millers Ferry	266	64	285	195	98	392	8	867
Mitchell	299	29	449	142	225	398	152	857
Upper Bear Creek	236	48	184	137	136	374	29	750
Warrior	263	49	258	135	135	361	26	685
Weiss	239	54	231	158	92	410	7	1116
Wheeler	265	61	347	214	89	385	9	1030

Table 1-4. The proportion of larger than stock size crappies to at least stock size crappies in each reservoir defined by dividing the number of quality (PSD-Q) (≥ 250 mm) and preferred (PSD-P) (≥ 300 mm) size crappies by the number of at least stock (≥ 130 mm) size crappies then multiplying times 100.

Reservoir	PSD-Q	PSD-P
Bankhead	59	17
Coffeeville	17	5
Eufaula	47	8
Gantt	44	8
Harding	44	13
Harris	54	17
Martin	47	12
Millers Ferry	58	35
Mitchell	94	51
Upper Bear Creek	31	12
Warrior	65	21
Weiss	45	10
Wheeler	63	33

Table 1-5. Average relative weights (Wr) of crappies collected in each reservoir and distinguished between sex and species in reservoirs. “NA” for these data concludes these data were not collected in the sample. An asterisk indicates small sample size for these data points (Table 2). Crappies under 130-mm TL and any with relative weights less than 65 and greater than 115 were not included in analyses.

Reservoir	Male Wr	Female Wr	Black Crappie Wr	White Crappie Wr	Average Wr
Bankhead	94	94	93	94	94
Coffeeville	NA	NA	91	85	89
Eufaula	92	91	92	NA	92
Gantt	87	86	88	86	87
Harding	90	91	90	NA	91
Harris	91	89	90	NA	90
Martin	87	86	87	NA	87
Millers Ferry	90*	93*	NA	87	86
Mitchell	95	95*	95	NA	95
Upper Bear Creek	90	90	NA	90	90
Warrior	91	90	NA	91	91
Weiss	94	90	92	NA	92
Wheeler	98	96	96	98	97

Table 1-6. Sample sizes of each age among reservoirs sampled. Ages after 11 were not included because there were very low sample sizes in each reservoir of fish past this age (n ≤ 3).

Reservoir	Age 0	Age 1	Age 2	Age 3	Age 4	Age 5	Age 6	Age 7	Age 8	Age 9	Age 10	Age 11
Bankhead	0	40	178	145	45	8	2	10	2	3	0	2
Coffeeville	8	63	171	77	79	40	16	2	3	1	1	0
Eufaula	0	11	63	112	281	72	36	27	19	3	3	0
Gantt	1	19	45	164	47	30	8	3	1	0	0	0
Harris/Wedowee	0	19	58	247	178	88	46	39	9	5	3	1
Harding	3	41	84	153	44	55	38	22	4	4	2	2
Martin	1	25	202	175	100	45	38	17	18	12	12	7
Millers Ferry	1	69	123	104	97	15	5	5	0	0	0	0
Mitchell	0	0	0	32	197	50	16	10	6	1	1	1
Upper Bear Creek	0	19	126	98	41	25	7	3	3	1	0	0
Warrior	0	62	64	119	33	16	3	6	0	0	0	0
Weiss	0	9	216	194	65	59	24	5	4	0	2	2
Wheeler	6	137	178	106	68	29	9	1	3	2	0	0

Table 1-7. Equations used to estimate instantaneous and conditional natural mortality among reservoirs. “tmax” is the maximum age collected in the reservoir; “Linf, k, and t0” are parameters derived from the von Bertalanffy growth equation (Table A.1.); “cv_tl” is the coefficient of variation in length given age; “max_wt” is the theoretical maximum weight of the largest fish in the population and is derived from ‘a’ and ‘b’ from length weight regressions.

Author	Equation
Hoenig	e^ (1.46 - 1.01 * LN (tmax))
Chen & Watanabe	1 / (tmax-1) * LN ((e^ (k*tmax) – e^ (k*to)) / (e^ (k*1) – e^ (k*to)))
Djabali	1.0661 * (L.inf/10) ^ (-0.1172) * k ^ (0.5092)
Jensen	1.5 * k
Lorenzen	3 * (max_wt) ^ -0.288
Cubillos	4.31 * (t0 - (LN(0.05) / k)) ^ -1.01

Chapter I Figures

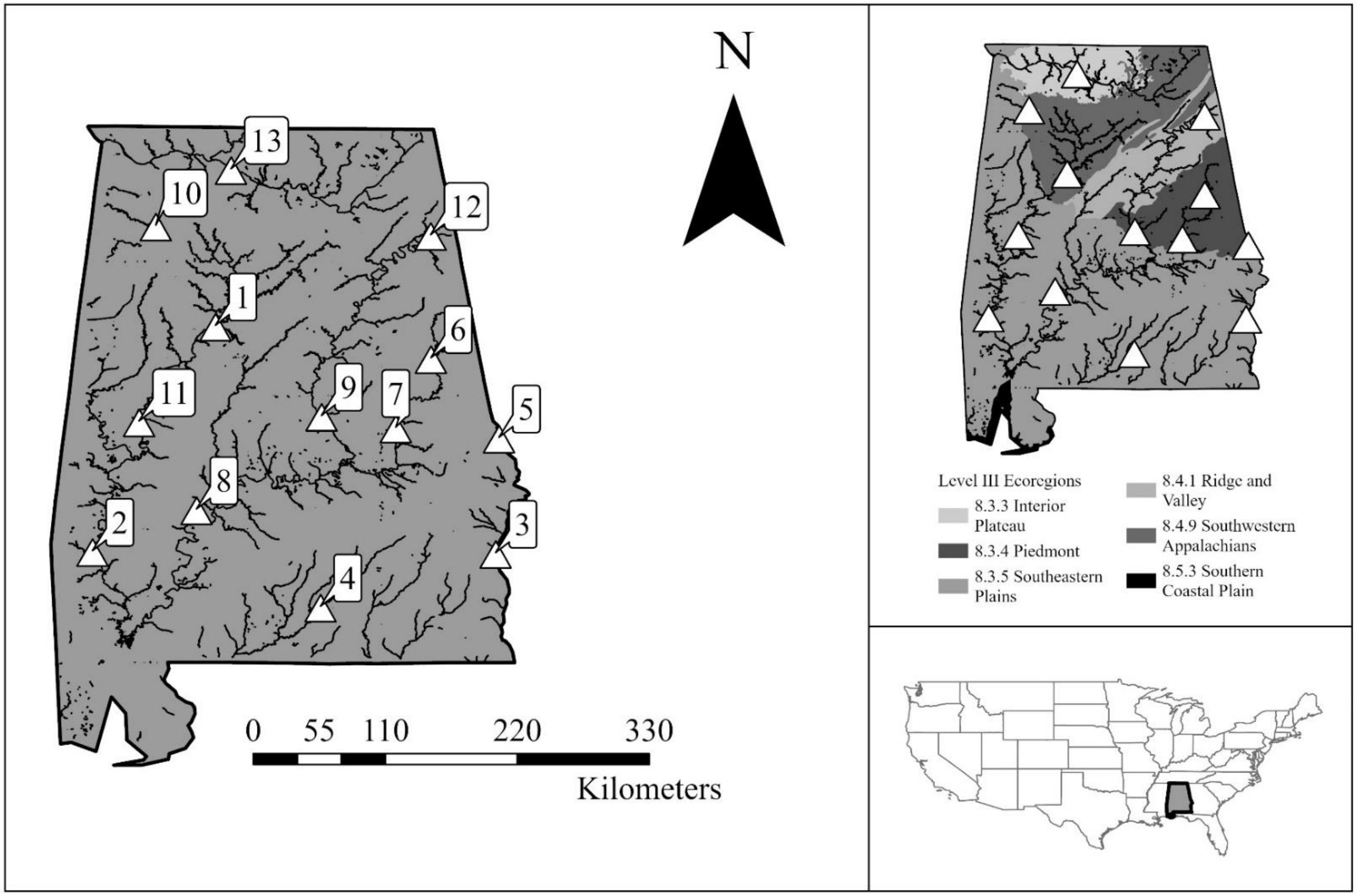

Figure 1-1. Map of reservoirs sampled from 2022-2024. Reservoirs are labeled and reservoir names listed in alphabetical order are 1) Bankhead, 2) Bartletts Ferry/Harding, 3*) Coffeeville, 4) Eufaula/Walter F. George, 5) Gantt, 6) Harris/Wedowee, 7) Martin, 8) Millers Ferry/William B. Dannely, 9) Mitchell, 10) Upper Bear Creek, 11) Warrior, 12*) Weiss, and 13) Wheeler.

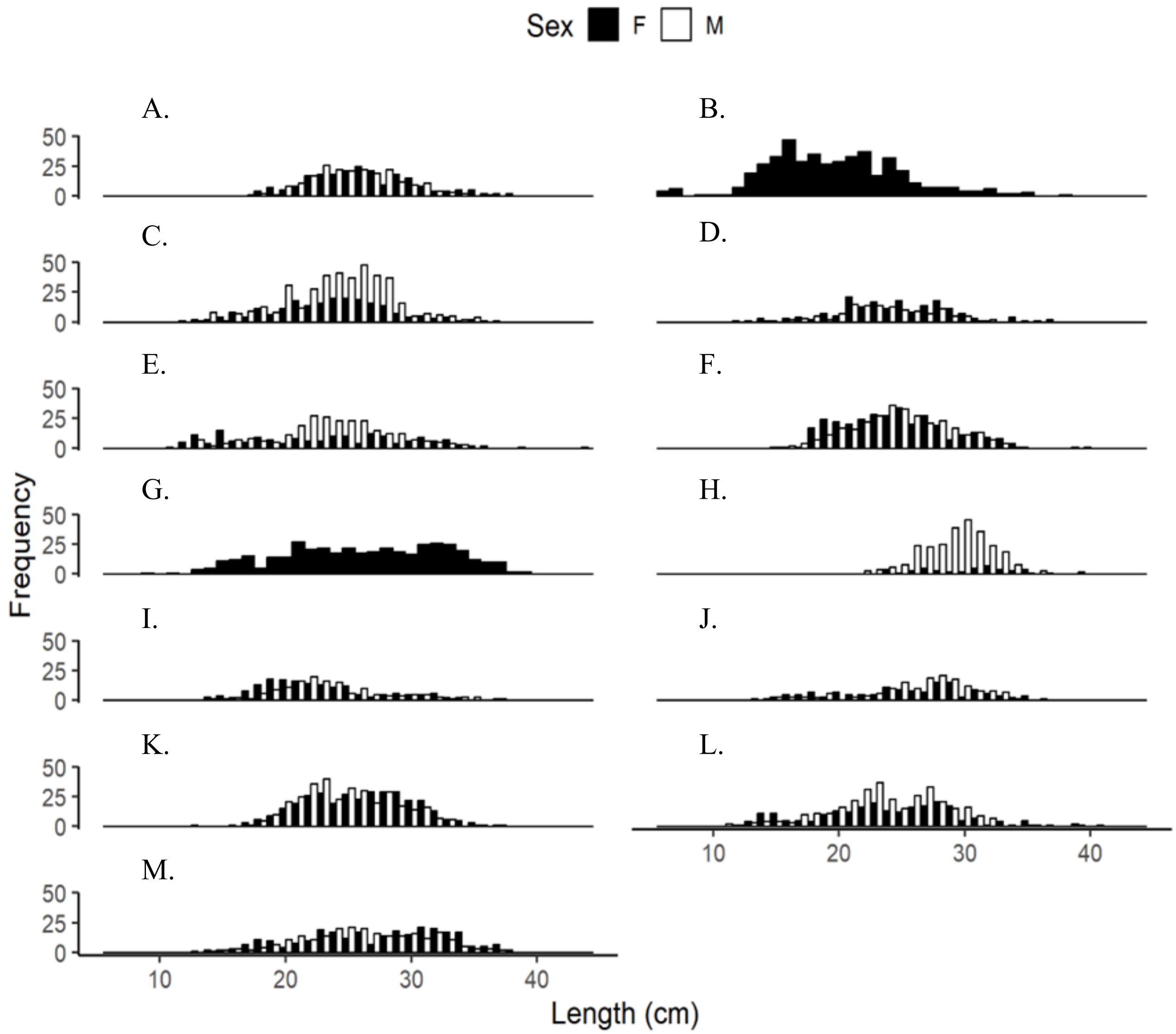

Figure 1-2. Length frequencies (i.e., total length) of crappie populations by sex from each reservoir. Reservoirs are A.) Bankhead, B.) Coffeeville, C.) Eufaula, D.) Gantt, E.) Harding, F.) Martin, G.) Millers Ferry, H.) Mitchell, I.) Upper Bear Creek, J.) Warrior, K.) Harris/Wedowee, L.) Weiss, and M.) Wheeler. Sex was not determined for Coffeeville and Millers Ferry reservoirs (shown as solid black bars) and in Mitchell Reservoir we collected low numbers of females. All length frequencies start at 5-cm on the X-axis.

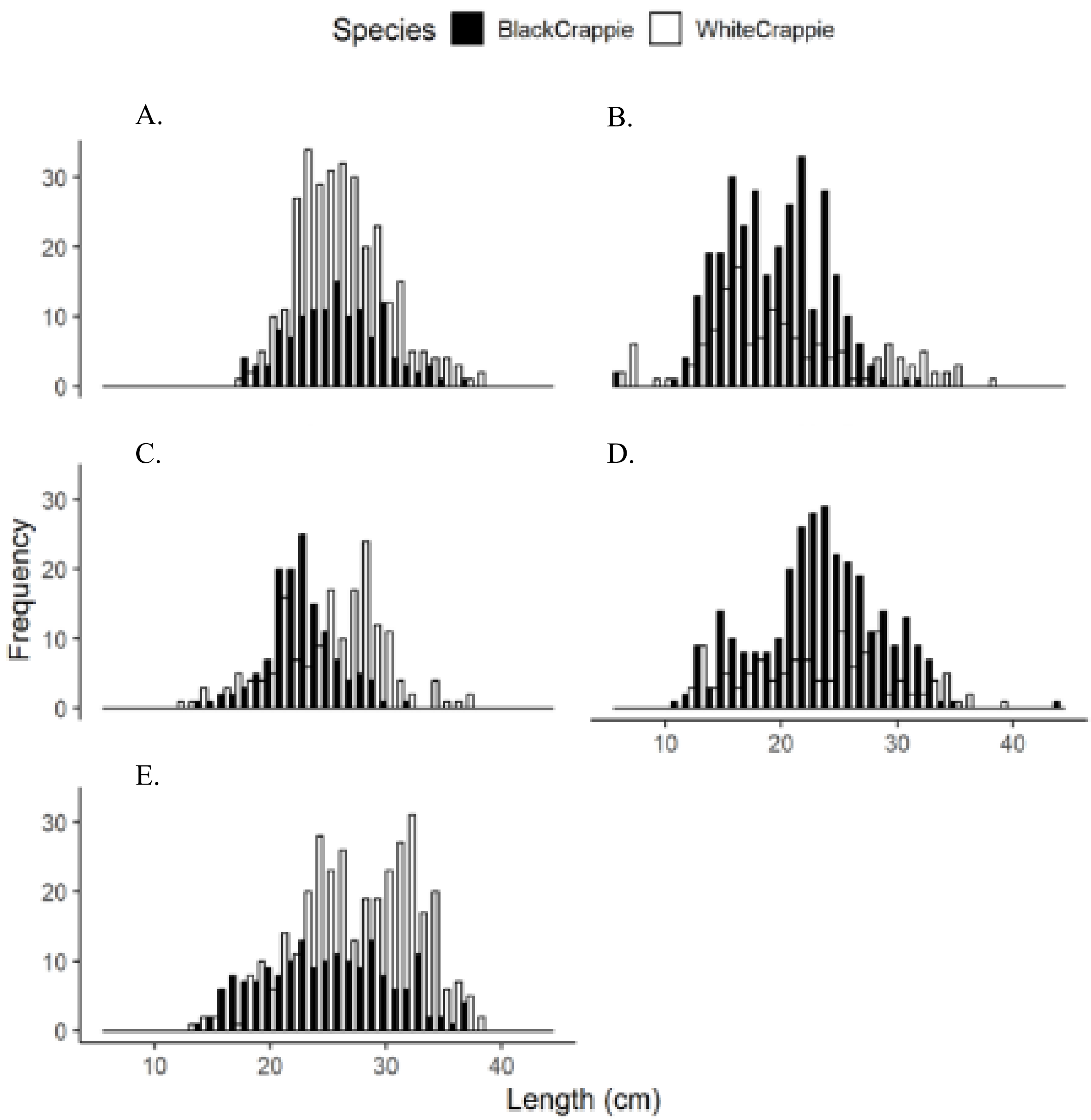

Figure 1-3. Length (i.e., total length) frequencies of Black Crappie and White Crappie populations where there were similar sample sizes of each (Table 2). Reservoirs are A.) Bankhead, B.) Coffeeville, C.) Gantt, D.) Harding, E.) Wheeler. Only reservoirs where the less dominant species made up at least a quarter of the total sample are included. All length frequencies start at 5-cm on the X-axis.

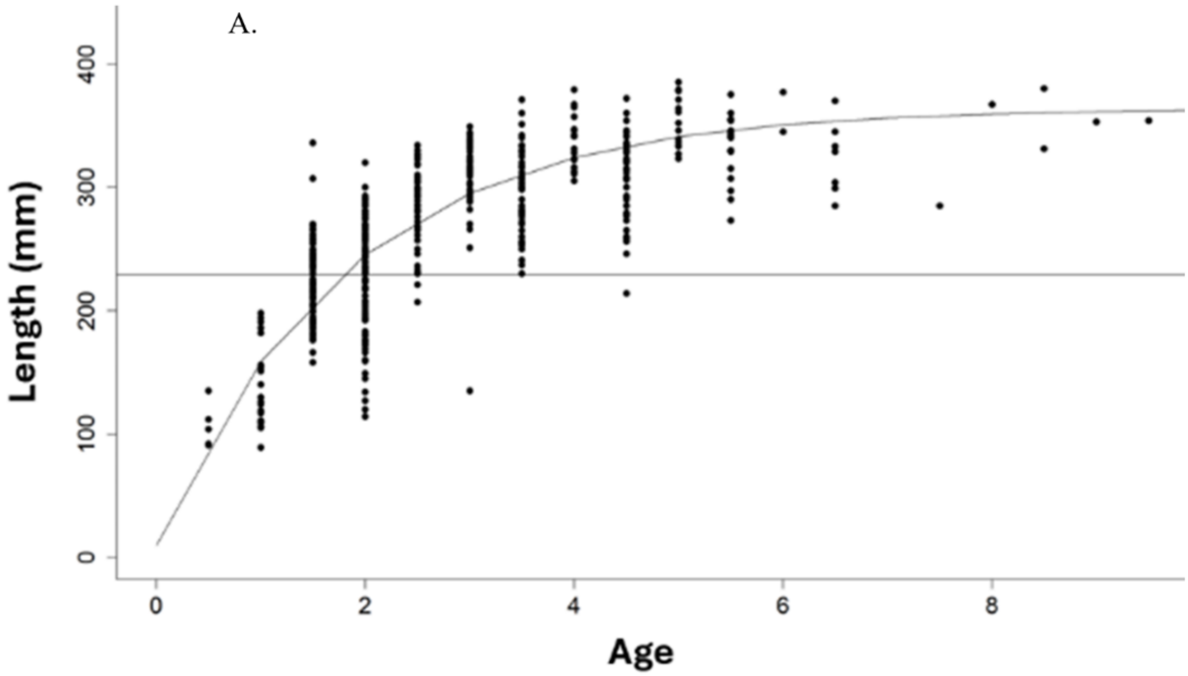

Figure 1-4. Von Bertalanffy growth equation results for the crappie population in Wheeler Reservoir within the Interior Plateau ecoregion. The horizontal line within the graph represents the current statewide 229-mm minimum length limit. Parameters estimated from these results are listed in Table A.1.

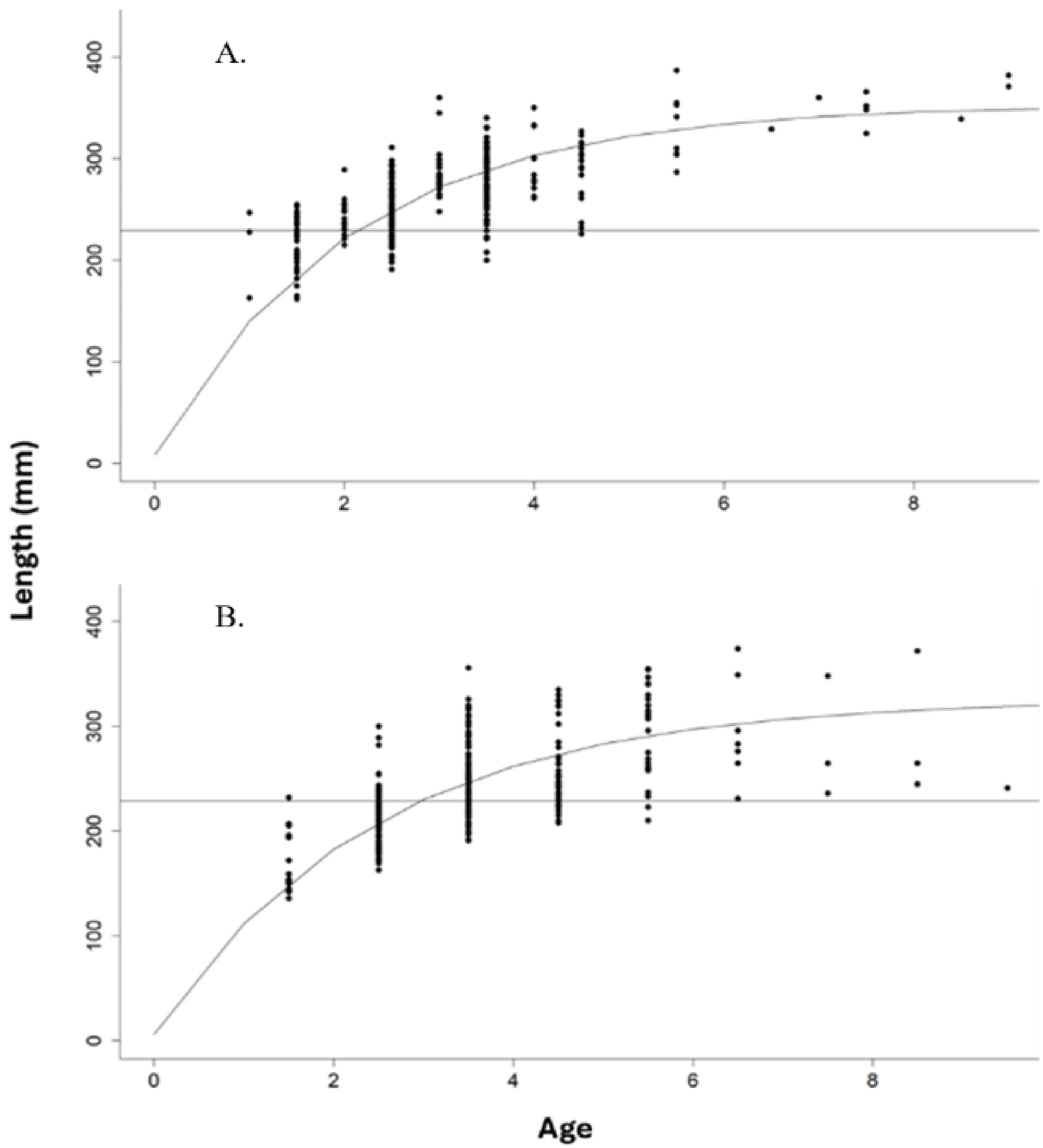

Figure 1-5. Von Bertalanffy growth equation results for crappie populations within the Southwestern Apalachin ecoregion within Alabama. Reservoirs were A.) Bankhead and B.) Upper Bear Creek Reservoirs. The horizontal line within the graph represents the current statewide 229-mm minimum length limit. Parameters estimated from these results are listed in Table A.1.

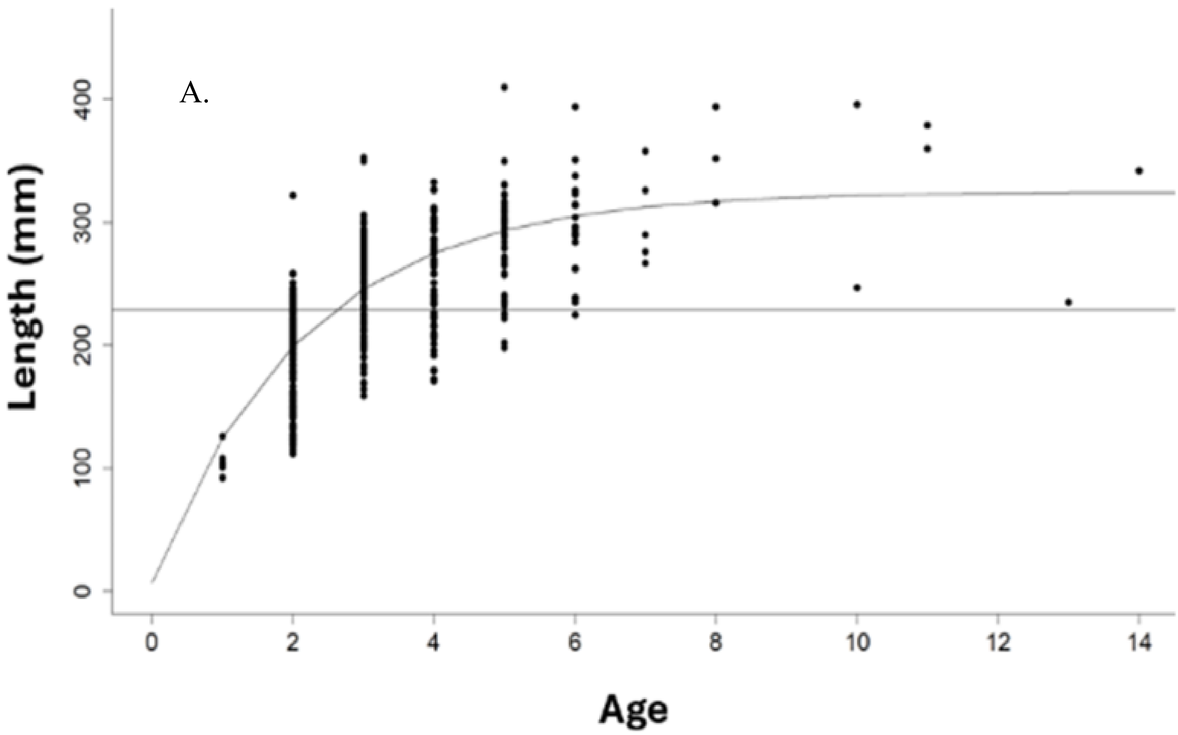

Figure 1-6. Von Bertalanffy growth equation results for the crappie population in Weiss Reservoir within the Ridge and Valley ecoregion. The horizontal line within the graph represents the current statewide 229-mm minimum length limit. Parameters estimated from these results are listed in Table A.1.

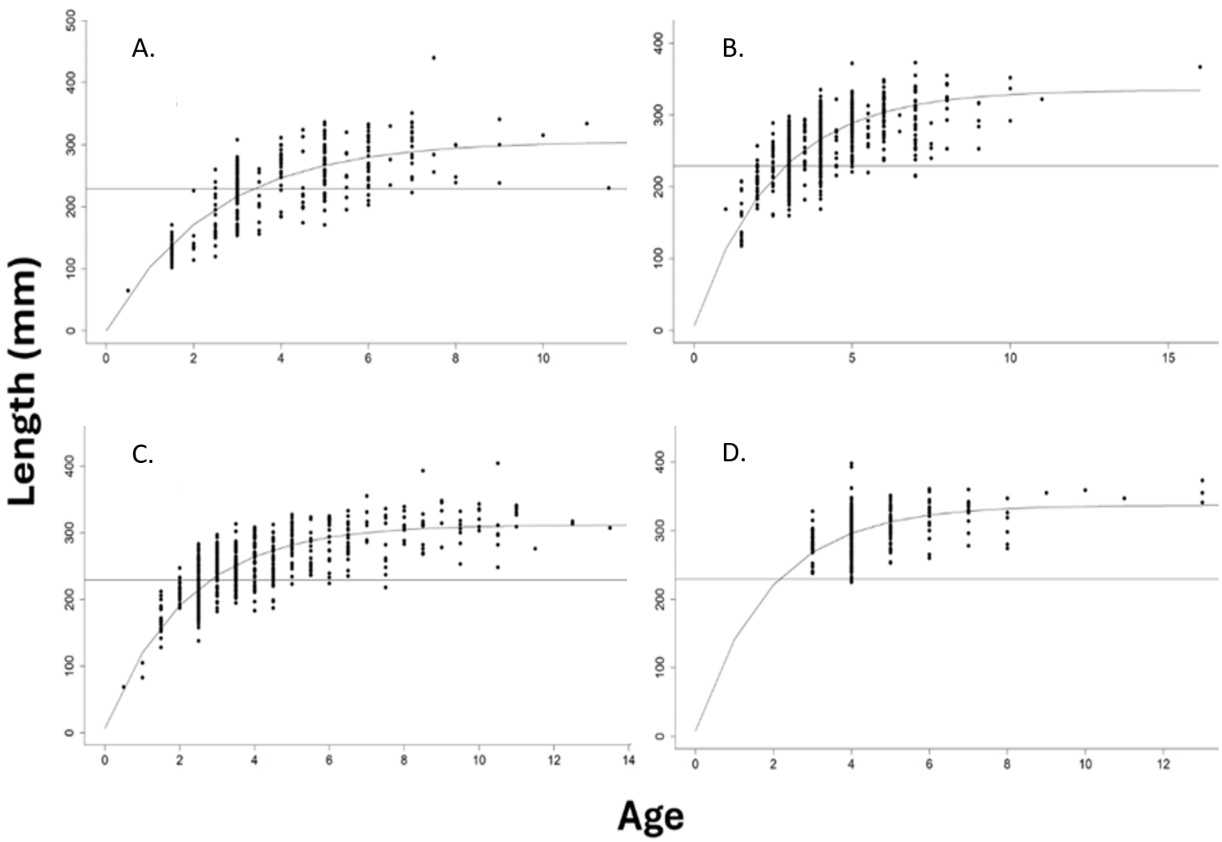

Figure 1-7. Von Bertalanffy growth equation results for crappie populations within the Piedmont ecoregion within Alabama. Reservoirs were A.) Harding, B.) Harris/Wedowee, C.) Martin, and D.) Mitchell Reservoirs. The horizontal line within the graph represents the current statewide 229-mm minimum length limit. Parameters estimated from these results are listed in Table A.1.

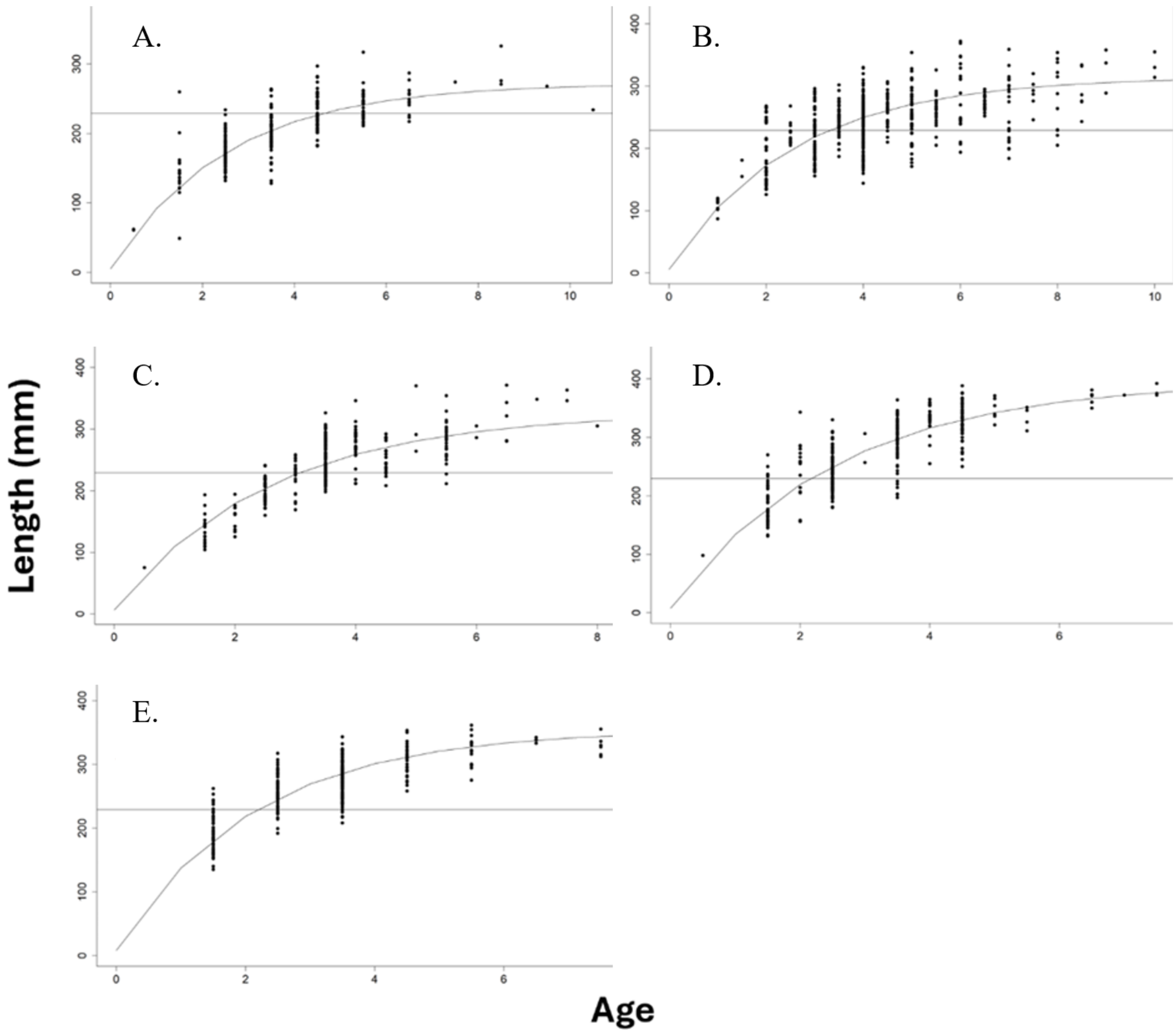

Figure 1-8. Von Bertalanffy growth equation results for crappie populations within the Southeastern Plains ecoregion within Alabama. Reservoirs were A.) Coffeeville, B.) Eufaula, C.) Gantt, D.) Millers Ferry, and E.) Warrior Reservoirs. The horizontal line within the graph represents the current statewide 229-mm minimum length limit. Parameters estimated from these results are listed in Table A.1.

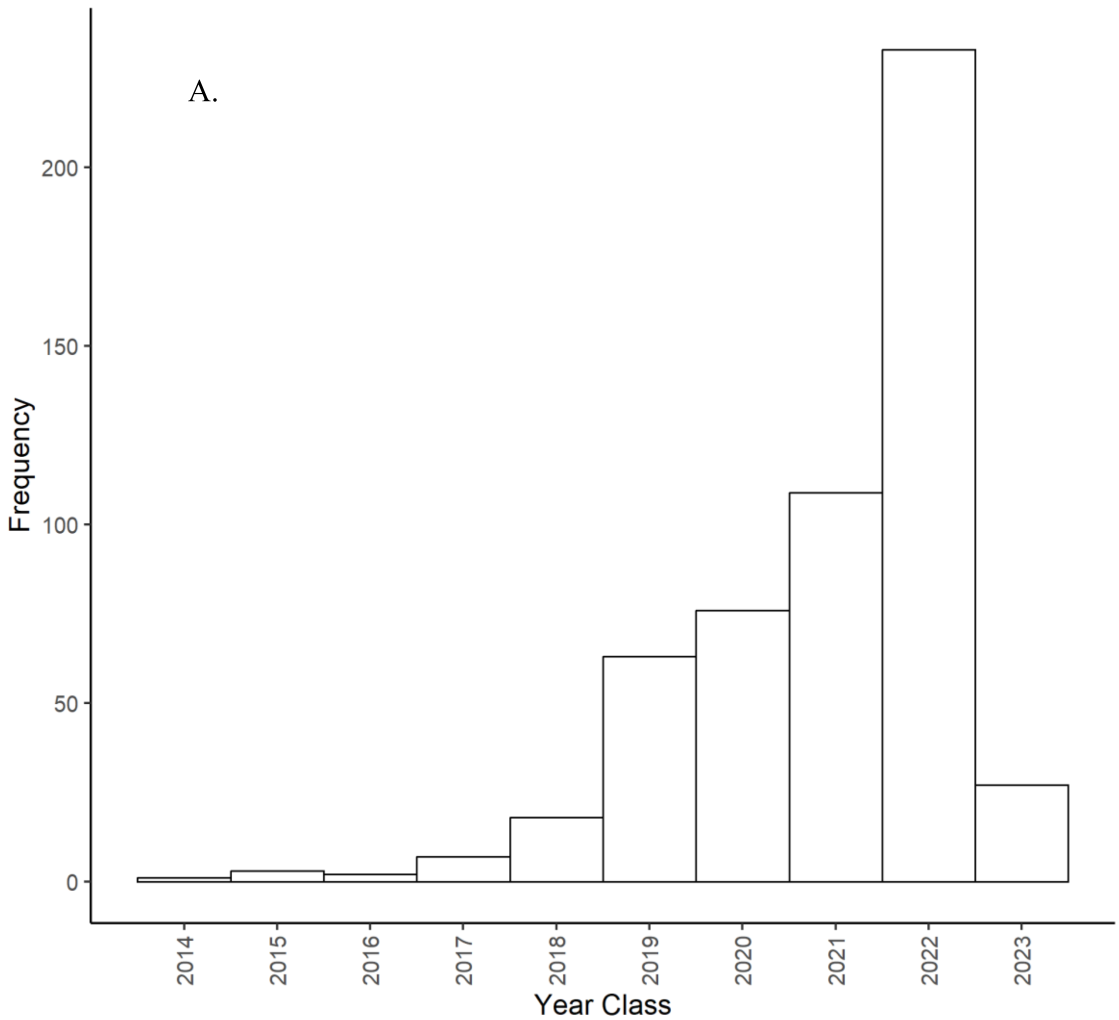

Figure 1-9. Year-class histogram for Wheeler Reservoir within the Interior Plateau ecoregion of Alabama.

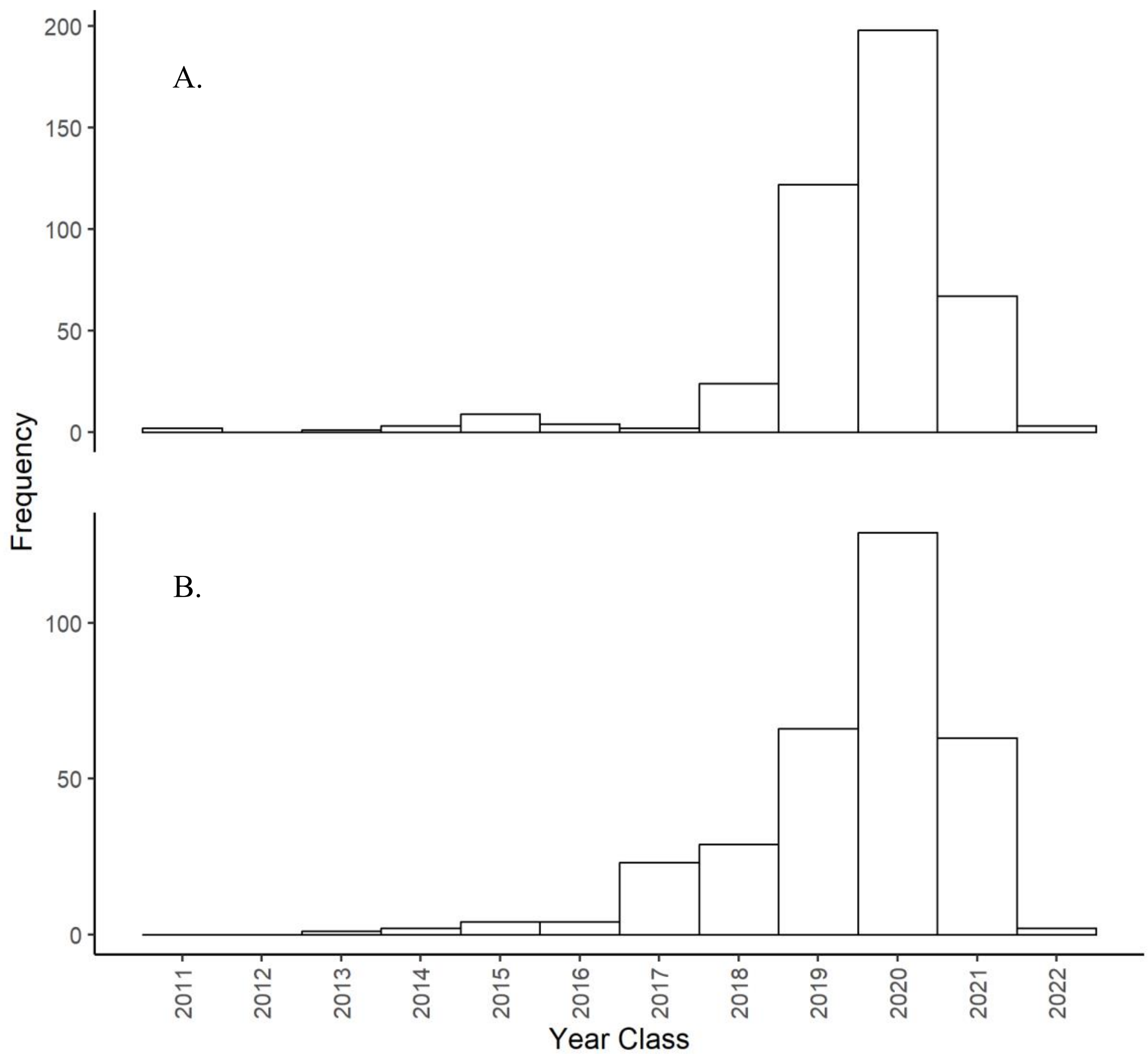

Figure 1-10. Year-class histograms for reservoirs within the Southwestern Apalachin ecoregion within Alabama. Reservoirs were A.) Bankhead and B.) Upper Bear Creek reservoirs.

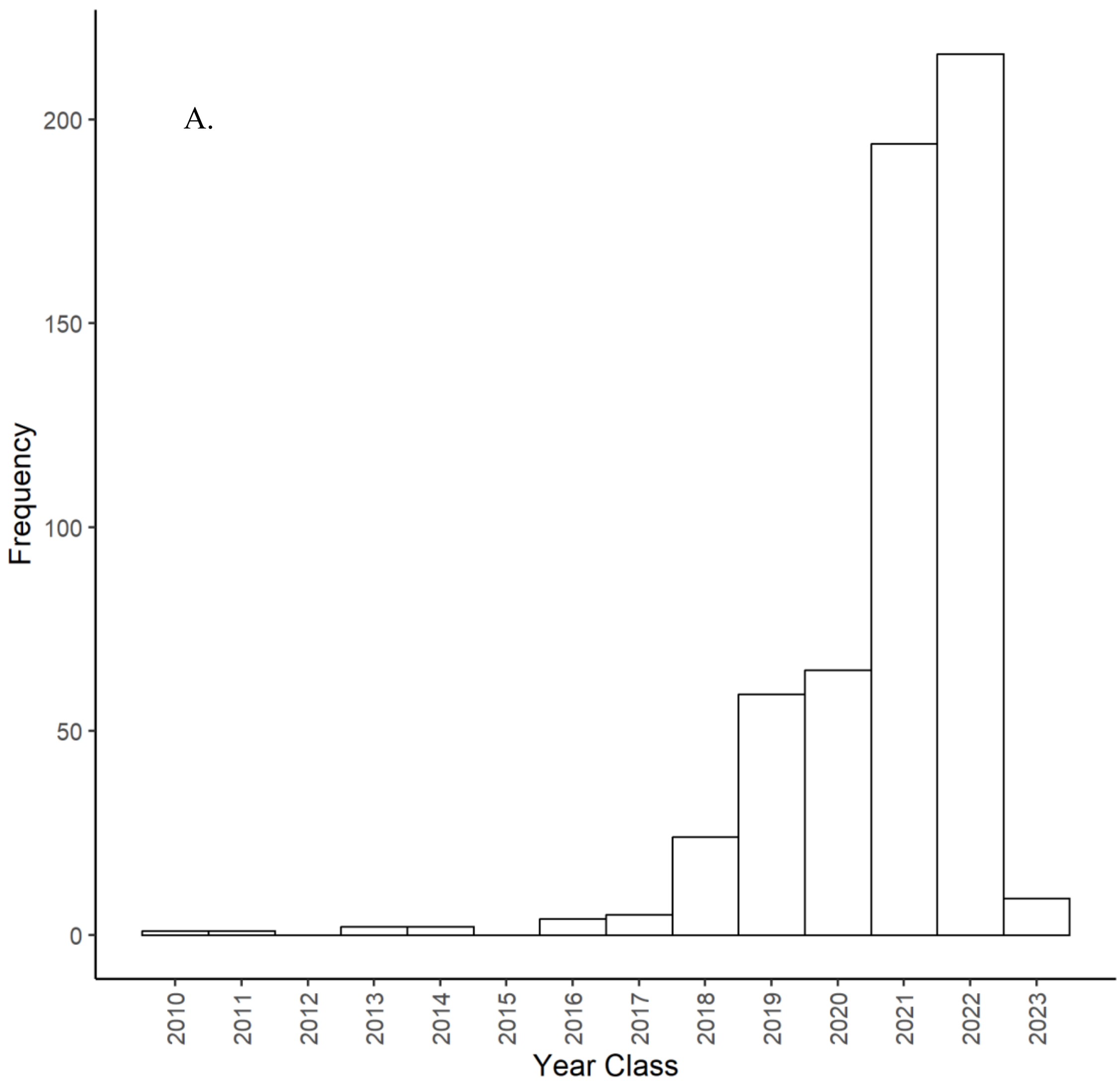

Figure 1-11. Year-class histogram for Weiss Reservoir within the Ridge and Valley ecoregion within Alabama.

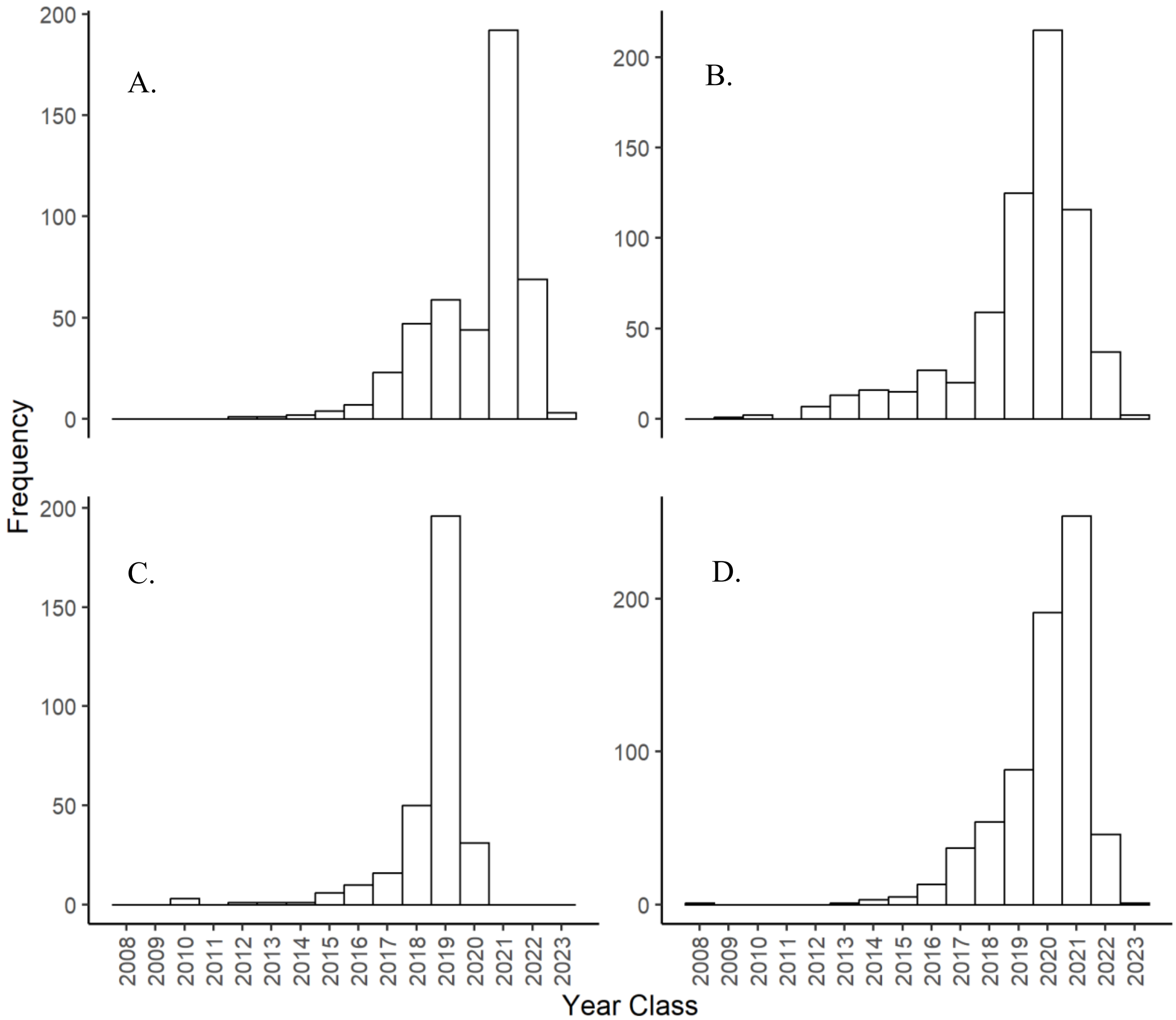

Figure 1-12. Year-class histograms for reservoirs within the Piedmont ecoregion within Alabama. Reservoirs were A.) Harding, B.) Martin, C.) Mitchell, and D.) Harris/Wedowee reservoirs.

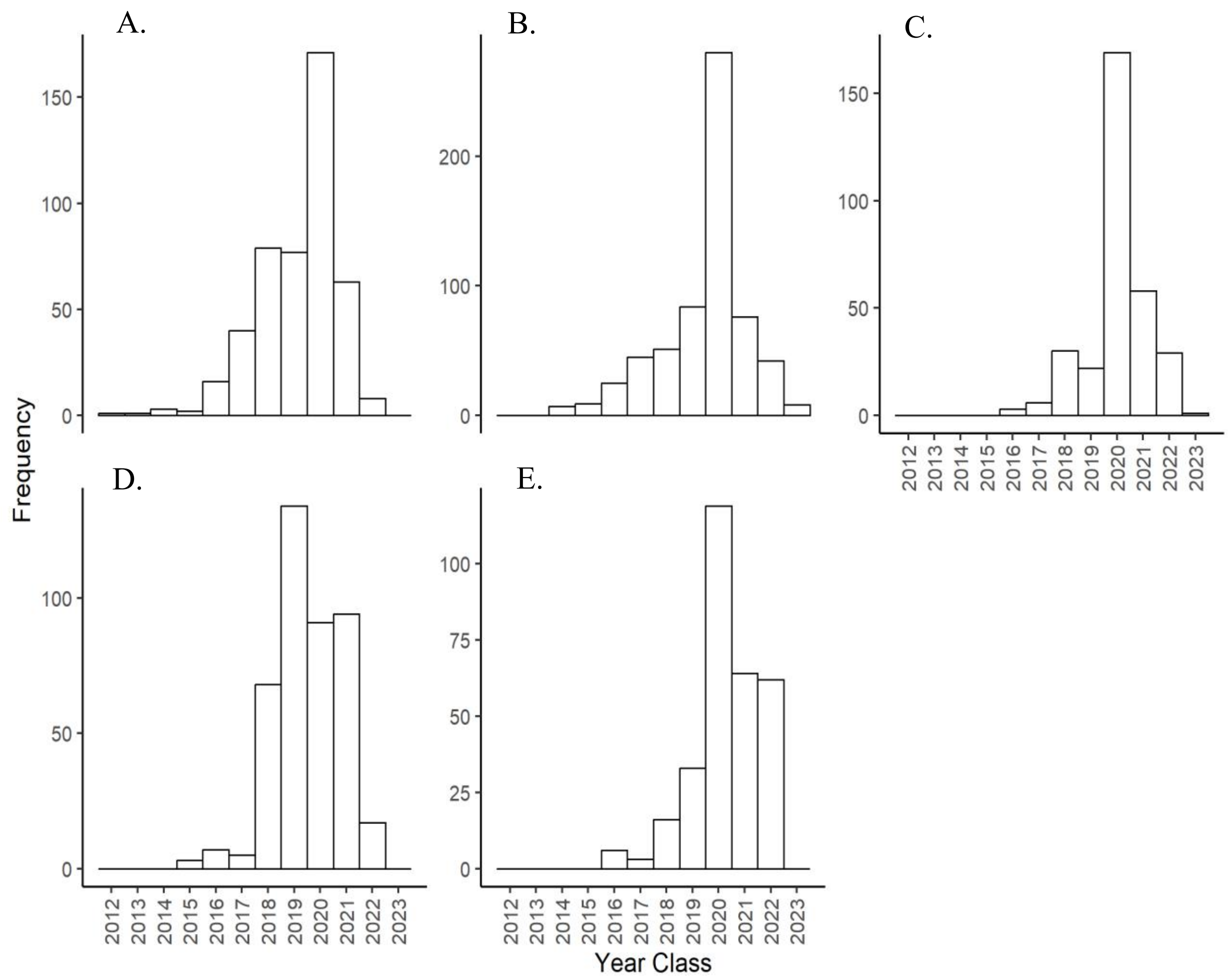

Figure 1-13. Year-class histograms for crappie populations within the Southeastern Plains ecoregion within Alabama. Reservoirs were A.) Coffeeville, B.) Eufaula, C.) Gantt, D.) Millers Ferry, and E.) Warrior reservoirs.

Appendices

Appendix A

Table A.1. Von Bertalanffy growth parameters that were estimated to compare crappie growth among reservoirs (Chapter I) and used as parameters of the Beverton Holt equilibrium yield equation (Chapter II). Age at 0-mm is described as "t0" and had to be manually constrained to -0.05 for most reservoirs; "K" is the growth coefficient; "Linf" is the length (mm) the average crappie in each population will reach at the end of its life. Time to reach the current statewide minimum length limit (229-mm) is also provided.

Reservoir	t0	K	Linf (mm)	Time to 229-mm (years)
Bankhead	-0.05	0.48	353	2.15
Coffeeville	-0.05	0.39	272	4.65
Eufaula	-0.05	0.39	315	3.35
Gantt	-0.05	0.39	327	3.08
Harding	0.00	0.41	306	3.42
Harris	-0.05	0.39	335	2.90
Martin	-0.05	0.46	312	2.84
Millers Ferry	-0.05	0.39	397	2.15
Mitchell	-0.05	0.52	337	2.19
Upper Bear Creek	-0.05	0.40	326	2.97
Warrior	-0.05	0.47	354	2.21
Weiss	-0.05	0.46	325	2.67

Wheeler	-0.05	0.55	364	1.78
State Average	-0.05	0.44	333	2.80

Appendix B

Table B.1. Mortality estimates in all reservoirs. These parameters were used to compare mortality among reservoirs (Chapter I) and used as parameters of the Beverton Holt equilibrium yield equation (Chapter II). "Z" is total instantaneous mortality, "S" is annual survival, "A" is total annual mortality, "M" is instantaneous natural mortality, and conditional natural mortality is "CM".

Reservoir	Z (yr^{-1})	S	A	M (yr^{-1})	CM
Bankhead	0.71	0.49	0.51	0.57	0.43
Coffeeville	0.68	0.51	0.49	0.44	0.36
Eufaula	0.74	0.48	0.52	0.51	0.40
Gantt	1	0.37	0.63	0.53	0.41
Harding	0.54	0.58	0.42	0.5	0.39
Harris/Wedowee	0.69	0.50	0.5	0.49	0.39
Martin	0.44	0.64	0.36	0.54	0.42
Millers Ferry	0.73	0.48	0.52	0.53	0.41
Mitchell	0.78	0.46	0.54	0.58	0.44
Upper Bear Creek	0.72	0.49	0.51	0.54	0.42
Warrior	0.84	0.43	0.57	0.59	0.45
Weiss	0.72	0.49	0.52	0.57	0.43
Wheeler	0.75	0.47	0.53	0.67	0.49
State Average	0.72	0.49	0.51	0.54	0.42

Table B.2. Mortality estimates in all reservoirs. These parameters were used to compare between sex among reservoirs (Chapter I). "Z" is total instantaneous mortality. "S" is annual survival. "A" is total annual mortality.

Reservoir	Z (yr^{-1})		S		A	
	Male	Female	Male	Female	Male	Female
Bankhead	0.76	0.46	0.47	0.63	0.53	0.37
Eufaula	0.87	0.58	0.42	0.56	0.58	0.44
Gantt	1.39	0.87	0.25	0.42	0.75	0.58
Harding	0.56	0.46	0.57	0.63	0.43	0.37
Harris/Wedowee	0.82	0.58	0.44	0.56	0.56	0.44
Martin	0.43	0.39	0.65	0.68	0.35	0.32
Upper Bear Creek	0.78	0.63	0.46	0.53	0.54	0.47
Warrior	0.89	0.62	0.41	0.54	0.59	0.46
Weiss	0.84	0.62	0.43	0.54	0.57	0.46
Wheeler	0.62	0.63	0.54	0.53	0.46	0.47
Average	0.80	0.58	0.46	0.56	0.54	0.44

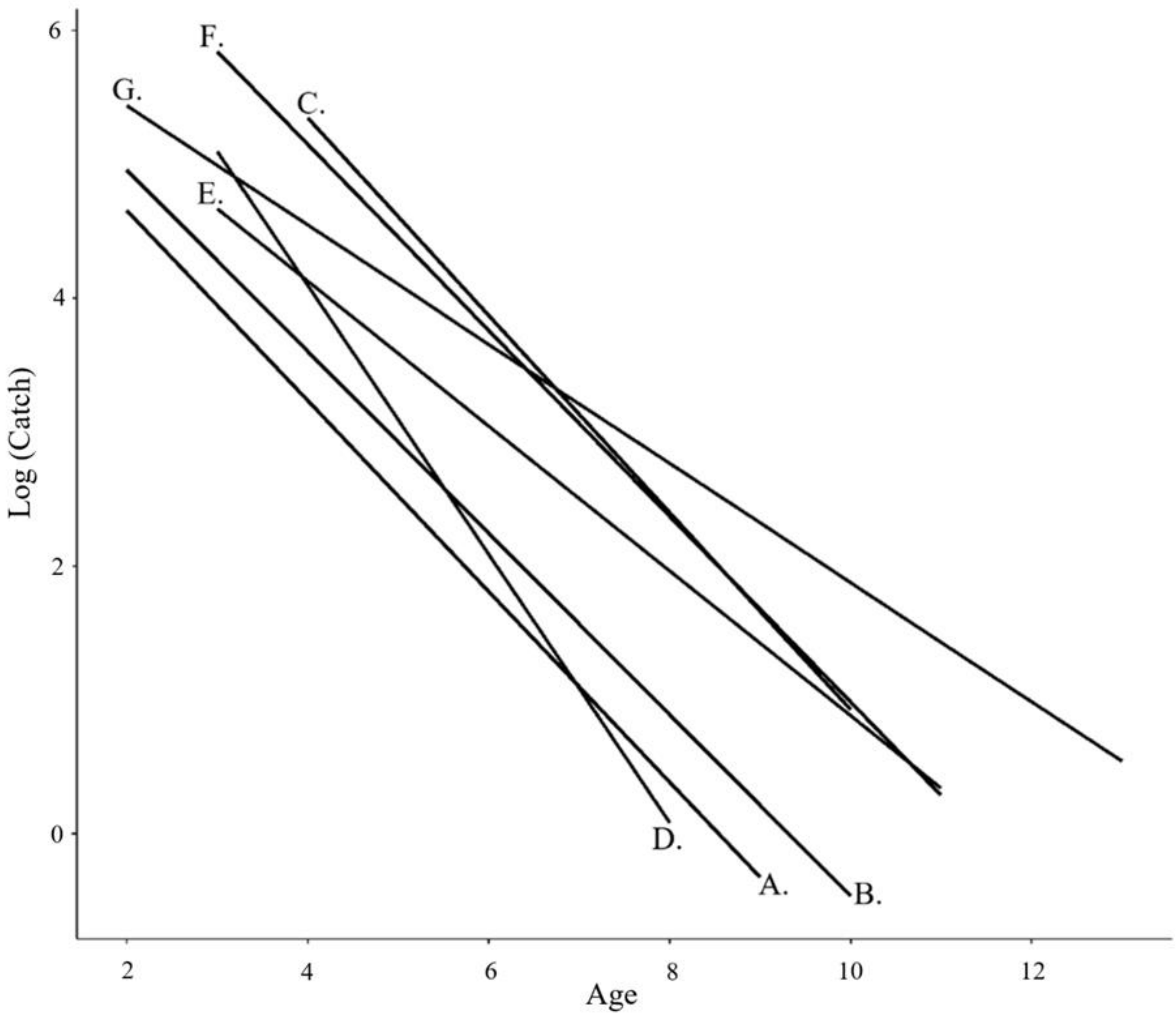

Figure B.1. Catch-curves for 7 of 13 reservoirs. The 7 reservoirs are indicated in alphabetical order: A.) Bankhead, B.) Coffeeville, C.) Eufaula, D.) Gantt, E.) Harding, F.) Harris/Wedowee, and G.) Martin reservoirs.

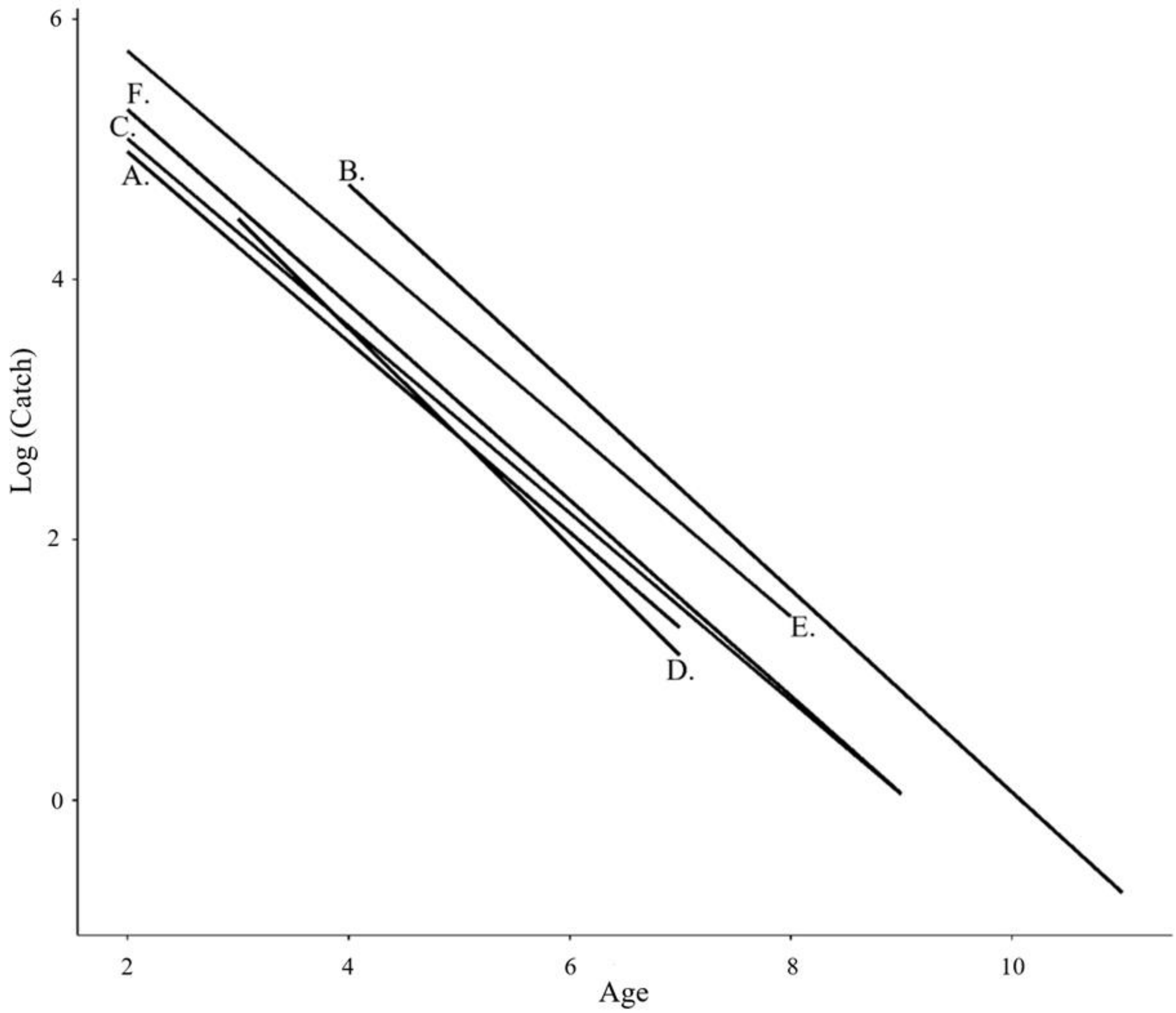

Figure B.2. Catch-curves for 6 of 13 reservoirs. The 6 reservoirs are in alphabetical order : A.) Millers Ferry, B.) Mitchell, C.) Upper Bear Creek, D.) Warrior, E.) Weiss, and F.) Wheeler reservoirs.

Chapter 2 Age structured Modelling to Simulate Multiple Regulation Scenarios on Crappie Fisheries in Alabama

Introduction

Length limits are often implemented to protect and maintain game species populations but can be removed or changed for various reasons (Novinger 1984; Allen and Miranda 1995; Wilde 1997). The purpose of a length limit is to decrease harvest on specified size groups to increase yield, biomass, and number harvested of the fisheries (Wilde 1997). Often, these limits work best on fisheries with low rates of natural mortality, fast growth, and high fishing mortality rates (Novinger 1984; Wilde 1997). These limits are enacted to either fix a reoccurring problem, improve size structure indices, or sometimes to satisfy anglers. Length limits can be removed because the problem has been fixed, population levels have been restored, the minimum length limit (MLL) fails to achieve its objectives, or anglers do not accept the regulations changes (Miranda et al. 2017; Leiblich 2018; Ahrens et al. 2020). For example, a 254-mm MLL on White Crappie in an Oklahoma reservoir was rescinded several years after implementation due to angler complaints and a reduction in angler effort (Boxrucker 2002a).

Human motivation and attitudes towards regulations are one of the most important factors that can determine success or failure of management actions (Ludwig et al. 1993; Sullivan 2002). Harvest restrictions will only work if anglers consistently harvest and do not harvest illegal fish. Unexpected harvest, or declines in harvest, can undermine a MLL, where the limit may provide no benefit or cause adverse effects to a fishery (Miranda et al. 2017; Leiblich 2018). Sullivan (2002) reported an average of 18% of illegal sized Walleye *Sander vitreus* were harvested in a suite of Alberta fisheries, with near 70% maximum kept on a harvest-prone fishery. MLLs do not benefit fish populations when illegal harvest is high; rather, use of either a slot limit or no limit may be preferred under these scenarios (Sullivan 2002; Gwinn et al. 2015). Conversely, Largemouth Bass *Micropterus salmoides* anglers tend to be primarily catch and release fishers in the last couple decades (Myers et al. 2008; Carlson and Isermann 2010), limiting overall effectiveness of length limits to restructure fish populations due to low fishing mortality (Allen et al. 2008; Miranda et al. 2017).

Angler tendencies and social norms can affect MLLs on population fisheries (Ludwig et al. 1993; Sullivan 2002; Bova et al. 2017; Miranda et al. 2017). Size-selective anglers can influence the success of a MLL. For example, recruitment overfishing in Brown Trout *Salmo trutta* populations was evident when anglers only harvested larger, sexually mature fish in a population (Sánchez-Hernández et al. 2016). The authors argue a MLL could limit future recruitment and abundance by forcing anglers to harvest larger fish. Social norms may also affect implementation of regulations, sometimes resulting in detrimental effects. For example, commercial fishermen have historically opposed quotas for the northern subspecies of Pacific Sardine *Sardinops sagax caerulea* (Ludwig et al. 1993). This led to overexploitation and collapse of the fishery, which has been closed for commercial fishing since 2015 (Pacific Fishery Management Council 2017). Recreational anglers can also have adverse reactions when a MLL is imposed as it often causes a short-term decline in yield for a long-term benefit in harvest or catch rates that are not always guaranteed (Ludwig et al. 1993). In a scenario where length limits immediately increased catch rates and size structure of Bull Trout *Salvelinus confluentus* in a Canadian lake, anglers disapproved of regulations, resulting in declines in angler use of the fishery (Johnston et al. 2011). Managers have recently begun focusing on education and how social norms influence angler compliance (Hatcher et al. 2000; Bova et al. 2017).

Various aspects of the fishery (i.e., biological/ sociological factors) can be affected when limiting harvest and establishing length and bag limits. Limits on crappie harvest will alter yield, harvest structure, and angler satisfaction (Colvin 1991). For example, a length limit was imposed on an Oklahoma Reservoir to increase yield and biomass in White Crappie, and effects on angler effort were predicted using typical sportfish population metrics. Angler effort declined more than expected, reducing the benefits from the MLL (Boxrucker 2002a). Additionally, about 50% of crappie anglers in a Mississippi reservoir stated they would fish less or quit fishing altogether if a length limit was imposed. A further 25% would do so if the bag limit were to decrease by 10 fish per day (Dorr et al. 2002). Angler satisfaction is a goal for most fishery managers, but anglers are more likely to accept social norms and what society thinks is ethical, rather than regulations from an authoritative department (Bova et al. 2017). For this reason, outreach to anglers and involving the public in management processes can improve regulation compliance (Jentoft and Mccay 1995; Hatcher et al. 2000). Conversely, multiple groups with different perceptions on how the fishery should be managed can lead to challenges for fishery managers to achieve angler satisfaction (Jentoft and Mccay 1995).

Opinions can vary among anglers regarding preferred-fish and harvestable-fish size (Allen and Miranda 1996) adding sociological constraints when implementing length and harvest limits. Length limits are often put in place to satisfy anglers, especially when they have similar preferences about appropriate regulations (Thurow and Schill 1994; Miranda et al. 2017). Increasingly diverse angler groups do not have the same views of satisfaction (Ward et al. 2013). This can lead to challenges for fishery managers and a “one size fits all” approach will not always be successful in achieving management goals (Orth 2023). Varied angler tendencies can often force regulations to be prioritized where angler concerns are loudest (Jentoft and Mccay

1995; Cox and Walters 2002). Petering et al. (1995) indicated angler satisfaction regarding the length of crappies varied between reservoirs, whereas satisfaction was less affected by the number of crappies caught. Conversely, Webb and Ott (1991) and Miazga et al. (2022) found a MLL was more effective in maintaining angler satisfaction due to few anglers harvesting bag limits, especially when crappies grew quickly. Anglers dissatisfied with regulations can lobby for a regulation change (Thurow and Schill 1994), move to other reservoirs, and shift their target species (Hansen et al. 2015).

Earlier studies have shown MLLs on crappie fisheries have variable success rates, dependent on recruitment, growth, and natural mortality (Colvin 1991; Allen and Miranda 1995; Maceina et al. 1998; Isermann et al. 2002). Often length limits fail to provide benefits to crappie populations (e.g., Larson et al. 1991; Allen and Pine 2000; Hurley and Jackson 2002). Variable recruitment and growth of crappies can often reduce the effectiveness of a MLL, or mask it completely (Maceina et al. 1998; Allen and Pine 2000). Routine surveys failed to detect differences in crappie size structure before and after implementation of a 229-mm MLL in two Alabama reservoirs (Martin and Maceina 2004). However, high recruitment variation may have limited their ability to evaluate the length limit. Length limits tend to be the most beneficial for crappie populations characterized by rapid growth rates and low natural mortality rates (Webb and Ott 1991; Allen and Miranda 1995; Maceina et al. 1998; Isermann et al. 2002; Miazga et al. 2022). Regulations do not perform equally across states or even regions within states due to variations in growth and mortality across systems (Guy and Willis 1995; Isermann et al. 2002; Pritt et al. 2019; Miazga et al. 2022); thus, a statewide MLL may not be effective.

Most crappie fisheries in Alabama are currently managed with a statewide MLL, and we hypothesized that model results would not be consistent among crappie fisheries. Crappies in

Alabama are currently regulated by a 229-mm MLL and 30 fish/angler/day bag limit. Exemptions from these regulations include Bear Creek Reservoir (no MLL), reciprocal waters with Georgia Department of Natural Resources on the Chattahoochee River (no MLL), and Weiss Reservoir (254-mm MLL) (Outdoor Alabama n.d.). These regulations have not been evaluated in nearly 30 years. Biologists are concerned these regulations may provide few population benefits in some reservoirs and not adequately protect populations in others (Neely et al. 2022; Zellers 2022). Correspondingly, our study objective was to simulate how crappie populations across a suite of Alabama fisheries would respond to multiple MLL scenarios. A statewide assessment of the 229-mm MLL is beneficial to determine its effectiveness in protecting these crappie fisheries, while not limiting angler effort, a goal of the state conservation and management agency. Colvin (1991) claimed determining an acceptable compromise between the decrease in harvest and increase in larger fish can be problematic, and could be variable among anglers. For example, Dorr et al. (2002) found half of the anglers they surveyed in a Mississippi reservoir would fish less due to size restrictions; whereas 78% of anglers surveyed in Tennessee reservoirs were in favor of large size restrictions (Sammons et al 2000). We hypothesize favorable regulations will not be consistent across the state due to the variable nature of crappies. We also hypothesize that fast-growth populations could withstand higher exploitation without substantial decreases in the number of memorable sized crappies, whereas high exploitation on slower growth populations would have significant decreases in abundance of memorable sized fish.

Methods

Study areas, field methods, and otolith processing

Our study areas for this chapter were described in Chapter I. Briefly, we sampled 13 reservoirs across Alabama and all 13 reservoirs were used in length-limit modelling. The reservoirs sampled covered eight catchments and represented most of the ecoregions within the state. Five out of six Level-III ecoregions within the state were represented by at least one reservoir. Thus, the reservoirs we sampled were hydrologically and limnologically variable.

Our field methods for this chapter were described in detail in Chapter I. Briefly, ADCNR and Auburn University crews used electrofishing to sample at least 300 crappies from each reservoir. Target species were determined in consultation with ADCNR and the dominant species in each reservoir was used for analyses, except for in two reservoirs. Collection numbers were similar between the two crappie species in Gantt and Wheeler reservoirs, so species were combined for length-limit modelling. We sampled crappies over multiple years during autumn and spring.

Our laboratory methods for this chapter were described in detail in Chapter I. Briefly, we verified the species designation in the laboratory, then recorded morphometric measurements. Each fish was measured to TL, blotted and weighed (g), and sexed by observing reproductive organs. Next, we removed the sagittal otoliths and placed them in numbered vials to be observed by at least two independent readers under a microscope. If otoliths were estimated by either reader to have over four annuli, they were sectioned, mounted to a slide, ground, and polished following the methods of Maceina (1988) and Buckmeier and Howells (2003). Sectioned and processed otoliths were also viewed by two independent readers. Disagreements between readers were reviewed by a third independent reader to resolve discrepancies (Carroll et al. 2019). If all three readers disagreed, the otolith was then concert read by the two original readers (Miller and Storck 1982; Rogers 2024).

Data analyses

An age-structured Beverton-Holt equilibrium yield equation (Ricker 1975) was created over a range of conditional natural mortality (CM) rates to predict the effects of various length limits on yield, harvest, and the number of memorable sized crappies. We assembled an equilibrium yield model in R to examine multiple MLL scenarios. Crappie typically follow a Beverton-Holt growth curve (Allen and Miranda 1995; Maceina et al. 1998; Boxrucker 2002a; Isermann et al. 2002). The Beverton-Holt equilibrium yield equation comprises multiple parameters. Length-weight relationships were derived from pooled electrofishing samples. Other model parameters were produced using age, growth, and mortality data described in Chapter I (Table 1). We saw variable maximum ages sampled among Alabama fisheries (Chapter I), so we used the oldest age collected in each reservoir as the oldest age parameter. The average length at maturity was not determined in this study, thus, we used a mean of 175-mm for all populations (Michaletz 2013; Culpepper III and Allen 2016; Mcinerny et al. 2020). A type II fishery was assumed for all models, where natural and fishing mortality occurs simultaneously (Ricker 1975). The current 229-mm MLL and a 200-, 254-, and 279-mm MLL were used to assess responses to the crappie populations. The 200-mm MLL prediction was used to assess predictions if there was no MLL, as crappies below 200-mm TL are typically not harvested (Travnichek et al. 1997; Allen and Pine 2000). Models were run using a low (30%), medium (40%), and high (50%) estimate of CM for each fishery. Low, medium, and high rates of CM used were based off results from Chapter I of this thesis (range: 36 – 49%) and followed rates used for equilibrium yield models in the southeast (Allen and Miranda 1995; Maceina et al.

1998; Sammons et al. 2000; Miazga et al. 2022). Predicted yield, harvest, and number of crappies at or over memorable size (≥ 300-mm TL) were determined for each population based on our management scenarios.

Reservoirs were classified as fast, medium, and slow growth reservoirs and models were run over a range of perceived exploitation rates. We distinguished each reservoir as a fast, medium, and slow growth reservoir using the time it took each population to reach 229-mm TL (Chapter 1, Appendix A). If populations were predicted to reach 229-mm TL before 2.25 years, then they were considered fast-growth; if they were predicted to reach 229-mm TL between 2.25 and 3 years, then they were labeled as medium-growth; and if they were predicted to reach 229-mm TL after 3 years, then they were labeled as slow growth. Because current exploitation rates of crappies in Alabama reservoirs are unknown, our model results were presented as a mean of estimates using multiple rates within a range of known exploitation rates (0.20 – 0.60) (Allen et al. 1998; Maceina et al. 1998; Sammons et al. 2000).

Results

Fast growth reservoirs

There were 5 reservoirs classified as fast-growth ecosystems for crappie and models predicted a MLL would be favorable under some circumstances. Reservoirs classified as fast growth were Bankhead, Millers Ferry, Mitchell, Warrior, and Wheeler reservoirs. Models for populations in these reservoirs with a 229- or 254-mm MLL and low CM were predicted to still allow relatively high harvest but with an increase in yield and in the number of memorable sized fish in the population. In some fast-growth reservoirs, yield was maximized with a 229-mm MLL, whereas in others, a 254-mm MLL would maximize yield. At high CM, these reservoirs were predicted to have decreased yield and angler harvest with a MLL.

Modeling results across Alabama reservoirs with generally fast crappie growth showed tradeoffs between harvest numbers and the abundance of memorable-sized crappies as MLLs increased and with changes in natural mortality (Table 2). At low natural mortality (CM = 30%), implementing a 229- or 254-mm MLL generally led to modest increases in yield (up to 10%) and notable increases in memorable-sized crappies (20–50%), though harvest declined (typically 13–30%). A 279-mm MLL further increased memorable-sized fish (70–90%) but resulted in larger estimated harvest reductions (up to 43%) and, in some cases, yield (e.g., Mitchell Reservoir, Appendix A). At moderate CM (40%), larger MLLs typically produced larger crappies, but gains in yield were limited (e.g., Wheeler Reservoir, Appendix A). Harvest losses increased up to 47%, at 279-mm MLL. In this scenario, a 229-mm MLL remained the most balanced option, offering some improvement in size structure with minimal yield loss. Under high CM (50%), estimates for most reservoirs indicated that MLLs above 229-mm TL were not favorable. Larger MLLs resulted in significant reductions in yield and harvest (up to 60%), and although they still increased the number of memorable-sized fish, the biological (i.e., decreased harvest numbers) and social tradeoffs would likely be unacceptable for most anglers. A 229-mm MLL offered a moderate increase in large fish with relatively small reductions in yield and harvest. Consequently, the 229-mm MLLs consistently offered the best overall tradeoffs across mortality rates, supporting some increase in memorable-sized crappies with limited negative effects on harvest. Higher MLLs may benefit trophy-focused anglers but result in unacceptable harvest reductions, especially as CM increases.

Medium growth reservoirs

There were 4 reservoirs classified as medium-growth ecosystems for crappie and models for these populations predicted a low MLL would be favorable in some circumstances.

Reservoirs included in this designation were Harris/Wedowee, Martin, Upper Bear Creek, and Weiss Reservoirs. In these reservoirs, a 229-mm MLL was favorable in circumstances when CM was low with modest limits on yield and harvest, and large increases in memorable sized fish. In one reservoir, yield was maximized with the 229-mm MLL (Weiss). No MLL provided the most balanced tradeoff in most of these reservoirs when CM was high because of the substantial loss of yield and harvest.

Modeling results with average, or medium crappie growth showed a less favorable tradeoff between yield and abundance of memorable-sized crappies as MLLs increased and with changes in natural mortality (Table 3). At low CM (30%) and a 229-mm MLL, yield was not decreased by more than 1% for all reservoirs, and was maximized in one (Weiss Reservoir, Appendix A). Although yield was relatively unaffected with this regulation scenario, the predicted number harvested declined (16 – 19%), and the number of memorable sized crappies increased modestly (23 – 26%). There were no circumstances in medium growth reservoirs where a 254-mm MLL maximized yield, with up to 10% reductions in one case (e.g. Martin Reservoir, Appendix A). Further, models with a 279-mm MLL resulted in large yield reductions (17 – 27%). A 254- and 279-mm MLL largely decreased harvest (33 – 55%) and increased memorable sized crappies (≥ 60%) (Table 3). At medium CM (40%), any MLL over 229-mm TL would not be favorable. Yield decreased in all MLL scenarios, but large increases of memorable sized crappies were apparent. With MLLs over 229-mm, harvest was greatly reduced (≥ 43%). Estimates with high CM (50%) indicated any MLL would not be favorable. Reductions were present with a 229-mm MLL in yield (≥ 12%) and harvest (≥ 29%) Therefore, reservoirs with medium and low CM, a 229-mm MLL offered the most balanced trade off with unaffected yield for moderate increases in memorable sized fish and limited decrease in harvest. With high CM, tradeoffs such as large decreases in harvest and yield, are not as favorable with any MLL.

Slow growth reservoirs

There were 4 slow-growth reservoirs and models for most of these populations predicted no MLL would be most favorable in most scenarios of CM. Reservoirs with a slow-growth designation were Coffeeville, Eufaula, Gantt, and Harding Reservoirs. These reservoirs were predicted to have decreases in both yield and harvest in all MLL and CM scenarios, which may outweigh the tradeoff of the increase of memorable sized crappies. Models with a 229-mm MLL in most of these fisheries with low CM predicted low reductions in yield, but large decreases in harvest and low numbers of at least memorable sized fish. Conditional natural mortality rates greater than 30% reduced yield and harvest by substantial amounts with all MLL scenarios in all these fisheries.

Modeling results with slow crappie growth showed tradeoffs between yield and abundance of memorable-sized crappies were not favorable with any MLL and changes in natural mortality (Table 4). At low CM (30%), yield was maximized in all reservoirs with the assumed no MLL, but with only moderate reductions with a 229-mm MLL (up to 17%). With a 229-mm MLL, we saw 17-31% reductions in harvest, but large increases in memorable sized fish (25 – 56%). MLLs larger than 229-mm decreased yield (11 – 44%) and harvest (36 – 59%) further; although, memorable sized fish increased by at least 69% and up to 286% (e.g., Coffeeville Reservoir, Appendix A). At medium CM (40%), large increases of memorable sized crappies were produced with higher MLLs, but yield and harvest were reduced greatly (e.g., Harding Reservoir, Appendix A). With a 229-mm MLL, reductions in yield (up to 27%) and harvest (up to 40%) were prominent. Models predicted similar magnitude differences in memorable sized fish as low CM. Large MLLs with medium CM further decreased yield and harvest, making these scenarios unfavorable, although there were large increases of memorable sized crappies (≥ 68%). Under high CM (50%), MLLs indicated reductions in yield by at least 15% and harvest by at least 29% with any MLL. Although models estimate large increases of memorable sized crappies with high CM, the reductions in yield and harvest probably outweigh the benefits from an increase in memorable sized crappies. Thus, no MLL offered the best tradeoff in slow-growth reservoirs, where yield is maximized across all natural mortality rates. Although large magnitude increases in memorable sized fish may be favorable for trophy anglers, there are still very small amounts of memorable sized fish in these populations, even at low CM and high MLLs (e.g., Gantt Reservoir, Appendix A). Additionally, non-trophy anglers would be limited in harvest if high MLLs were implemented.

Discussion

My modeling results indicate that managing crappie populations may benefit from a river-centric perspective. Catchment-scale differences govern the ecological context in which fish grow, making them an important consideration in fisheries management, even for reservoirs. Catchment characteristics play an important role in influencing fish growth by shaping the thermal, chemical, and biological conditions of aquatic habitats (Gebrekiros 2016; Kataoka and Kashiwada 2021; Lindmark et al. 2022). Impoundments located within the Alabama, Black Warrior, Coosa, and Tennessee catchments seemed to have the most benefit with a 229- or 254-mm MLL in terms of tradeoffs from metrics predicted in models. Land use is one factor that relates to changes in fish growth. Catchments dominated by agriculture or mixed uses (i.e., impoundments on the Alabama, Black Warrior, Coosa, and Tennessee Rivers) often contribute higher nutrient loads, which can boost primary productivity and food availability, leading to faster fish growth (Vondracek et al. 2005). In contrast, forested catchments tend to have clearer water, lower nutrient input, and more stable temperatures, resulting in slower but more consistent growth (e.g., Ozark Highlands, Miller 2019). Model results from reservoirs impounding the Tallapoosa River and Bear Creek were labeled as “medium growth” and resulted in a 229-mm or no MLL being most favorable for anglers. The lack of phytoplankton and zooplankton available for young of year crappies to prey on in these low nutrient catchments may stunt growth (Spier 2002). Steeper, high-elevation catchments typically produce cooler, faster-flowing streams with lower productivity (i.e., impoundments on the Tallapoosa River and Bear Creek), limiting growth (Roni et al. 2014). Model results from the Chattahoochee, Conecuh, and Tombigbee rivers were “slow growth” and ensued no MLL would most likely be best the most favorable tradeoff for anglers of these reservoirs. Soil type and underlying geology influence growth by affecting nutrient runoff and water chemistry. For example, nutrient-rich or easily eroded soils may increase aquatic productivity, whereas sandy or nutrient-poor soils (i.e., impoundments on the Chattahoochee, Conecuh, Tombigbee Rivers) can limit it (Gebrekiros 2016). Finally, hydrology and flow regimes shape habitat quality and food availability (Sabo et al. 2010); relatively stable discharge regimes support consistent foraging and growth for some species (Kelly et al. 2017), whereas ecosystem variables can disrupt feeding and increase stress for some species (Gandini et al. 2014) or promote daily growth in other species (e.g., Neosho Bass *Micropterus velox*, Miller 2019). These changes, which occur both seasonally and annually, can add to the variability in fish growth. Overall, catchment-scale differences govern the ecological context in which fish grow, making them a key consideration in fisheries management. Management at the catchment scale aligns more with our findings and could make it less confusing for anglers and enforcers, compared to reservoir-specific regulations (Shamaskin et al. 2023).

We found responses by crappie populations in Alabama reservoirs were quite variable, largely due to differences in growth and mortality rates. Although trends in predicted harvest and the number of memorable-sized crappies were relatively consistent—as MLL increased, harvest declined, and memorable fish increased—the magnitude of those changes varied among reservoirs. That variation aligns with previous studies that identify growth and conditional natural mortality as key drivers of MLL effectiveness (Brousseau and Armstrong 1987; Colvin 1991; Allen and Miranda 1995; Maceina et al. 1998; Sammons et al. 2000; Isermann et al. 2002). In reservoirs with fast growing crappie populations, yield was often maximized at 229- or 254-mm MLLs compared to no MLL, likely due to the harvest of larger fish contributing more to total weight despite fewer individuals being harvested. In contrast, reservoirs classified as medium- and slow-growth reservoirs typically indicated declines in both crappie yield and harvest with increasing MLLs, while the number of memorable-sized crappies increased. Given that growth parameters have the strongest influence on model outcomes (Brousseau and Armstrong 1987; Sammons et al. 2000; Miazga et al. 2022), and that Alabama crappie populations display high variability in growth (Chapter I), it is not surprising that model predictions were not the same; still, within fast, medium, and slow growth classifications, the patterns we observed were generally consistent.

We found fast growing crappie populations responses to a MLL were favorable via limiting decreases in harvest and yield while allowing an increase in the numbers of memorable sized fish. The reservoirs classified as having fast growing crappie populations with low CM were predicted to withstand larger MLLs possibly due to the number of fish making it to larger sizes quickly and escaping threats of natural mortality when young (Pauly 1980; Lorenzen 1996; Jørgensen and Holt 2013). Differences in young of year crappie growth have been observed in a number of different ecosystems (e.g., Dubuc and DeVries 2002; Spier and Heidinger 2002) and for other centrarchids (e.g., Lemly and Dimmick 1982). Some hypothesize that early rapid growth also benefits over-winter survival (Gebrekiros 2016; Stige et al. 2019; Goodrich and Clark 2023). A liberal MLL may decrease angling pressure on young fish and alleviate growth overfishing (Sammons et al. 2000). A length limit could also help with recruitment in the fishery, protecting some smaller size classes that could contribute to recruitment in years of weak year classes (Webb and Ott 1991). We found the hypothesis of fast-growth populations being able to withstand higher exploitation due to small decreases in the number of memorable sized fish to be correct. This may be due to the abundance of larger fish less than 3-years old, compared to slower-growth populations. However, in our models, the combination of higher MLLs and higher exploitation decreased the number of fish reaching memorable sizes compared to lower exploitation. Thus, high exploitation is not recommended because of the reduction in memorable sized fish in model predictions and the possibility of growth overfishing. (Beamish et al. 2006; Diekert 2012).

The model results for reservoirs classified by medium, or average growth did not favor a minimum length limit with high CM. These reservoir crappie populations were predicted to benefit from a 229-mm MLL due to increases in memorable sized fish without significant reductions in angler yield and harvest. Larger MLLs decreased predicted yield to levels that may not satisfy all anglers in moderate growth crappie populations (Maceina et al 1998; Sammons et al. 2000; Miazga 2022). High exploitation with no MLL (200-mm TL) decreased the number of memorable sized crappies to a level that may not be satisfactory to trophy anglers; therefore, if the goal is to maintain overall angler satisfaction, then a scenario of high exploitation with no MLL would not be beneficial. Weiss Reservoir is also the only population in our study areas that is currently managed with a 254-mm MLL, compared to the statewide 229-mm MLL. We classified Weiss as a medium-growth fishery, but we hypothesized the crappie population could tolerate higher MLL scenarios compared to other medium-growth fisheries. Maceina et al. (1998) found yield was increased with a 254-mm MLL, but only in scenarios of low CM. High exploitation rates negated most of the benefits in yield with a 254-mm MLL. Thus, in reservoirs classified by medium or average growth, a MLL may be unnecessary.

Our model results associated with reservoirs classified by slow-growth populations indicated little to no benefit from any MLL we simulated. Crappie (Isermann et al. 2002; Miazga 2022), Largemouth Bass (Novinger 1984; Wilde 1997), and Walleye (Brousseau and Armstrong 1987) fisheries characterized by slow growth and high CM do not warrant MLLs. Specifically, concerns have been raised about MLLs harming the fishery through forced size-selective harvest and discouraging angler effort (Colvin 1991; Allen and Miranda 1995; Maceina et al. 1998; Sammons et al. 2000; Boxrucker 2002a; Isermann et al. 2002). Coffeeville Reservoir had our slowest crappie growth population, with fish, on average, not reaching the current 229-mm MLL until 4.6 yrs old. Crappies typically do not live longer than 7 to 9 years (Culpepper III and Allen 2016). Anglers have a short amount of time to harvest in Coffeeville Reservoir before these fish die due to natural mortality. In Coffeeville Reservoirs' models, even with a 286% increase in memorable sized crappies with a 279-mm MLL and low CM, we saw that memorable sized crappies are predicted to only make up less than 1% of the population. Due to the small amounts of larger fish in the populations (i.e., slow-growth populations), Miazga et al. (2022) argued liberal daily bag limits could maximize yield. However, growth overfishing may occur easier in these populations (Beamish et al. 2006; Diekert 2012), so managers should use cautious if applying liberal daily bag limits to these fisheries, especially when regulations include a MLL.

Caution should be taken when enacting a MLL on slow-growth populations because growth overfishing can be induced by forcing anglers to be size-selective towards the faster-growth genetics in the population. Growth overfishing, often phrased as "fishing the size structure down," is defined size-selectivity by anglers; eventually, the result is overfishing larger fish or fish that have not reached their full potential (Beamish et al. 2006; Diekert 2012). In crappie fisheries, where anglers and management of this species have historically been harvest oriented (Isermann et al. 2010a), managers are often worried more about growth than recruitment overfishing (Mosel et al. 2015). Growth overfishing is a greater concern crappie are often supplemented by strong year-classes (Colvin 1991; Allen and Pine 2000; Miranda and Allen 2000), which could sustain high exploitation, making it difficult to overfish these populations. Although supplemented by strong year classes, other years may be highly variable (Allen and Miranda 2001; Sammons et al. 2002a; Bunnell et al. 2006) leading to low numbers of harvestable-sized fish. The primary associated concerns are that anglers are forced to harvest larger, faster growth fish, favoring slow-growth genetics, that may decrease the overall size structures of these slow growth populations (Beamish et al. 2006).

Species dominance and the possibility of hybrids in these populations may have influenced our growth and mortality parameters. Most reservoirs predominantly dominated by White Crappie were classified as fast-growth, whereas reservoirs dominated by Black Crappie were classified as medium- or slow-growth reservoirs. Our results indicate growth classifications were somewhat driven by species dominance. For example, in Weiss Reservoir, we only collected Black Crappies, and we classified it as medium growth, but White Crappies also make up a proportion of fish within the reservoir (M. Holley, ADCNR Biologist, personal communication). Maceina et al. (1998) collected both species on Weiss Reservoir and growth was faster than what we observed in our study; however, growth is affected by other factors such as environmental factors, prey abundance, and density dependence, which could vary over time (Guy and Willis 1995; Spier and Heidinger 2002; Michaletz et al. 2012). Hybridization occurs in many centrarchid species and could have also influenced growth parameters (Travnichek et al. 1997; Shen and Wang 2018). Black and White crappies are known to hybridize when sympatric (Travnichek et al. 1996; Miller et al. 2008) Specifically, Travnichek et al. (1996) found a proportion of crappies in 10 Alabama reservoirs included hybrids. Further, Travnichek et al. (1997) found hybrids grew quicker than either parent species. Thus, the collection of hybrids in our study could have influenced growth and mortality parameters and influenced our model results towards being more favorable for a MLL due to faster growth.

We did not observe how specific exploitation rates would affect populations in our study, but previous studies and other states have decreased bag limits for multiple reasons. Decreasing bag limits will decrease the number of fish an angler can harvest, thus decreasing exploitation rates. Decreasing exploitation could result in positive outcomes in crappie fisheries including allowing some fish to reach larger sizes before harvest (Allen and Miranda 1995). Another benefit to decreasing exploitation is possibly increasing angler satisfaction. Anglers do not always have the same perception of fishery satisfaction (e.g., “meat anglers” who try to fill a bag limit versus “trophy anglers” that do not usually keep all fish they catch) (Ward et al. 2013). Trophy anglers could be satisfied with lower exploitation due to the predicted increase in memorable sized fish in a population. Conversely, a proportion of anglers do not achieve the bag limit, especially when the limits are relatively liberal (Meals et al. 2012). In these cases, a small decrease in bag limits may not reduce exploitation; but allow more anglers to achieve a bag limit, increasing overall angler satisfaction (Meals et al. 2012). Changing regulations can affect angler compliance (Allen and Miranda 1996; Johnston et al. 2011; Ward et al. 2013; Poudyal 2022). If the goal of a management agency is focused on managing in a way that is supported by anglers, then it is important to understand angler perceptions prior to changing regulations. Our data indicates catchment-specific regulations and angler preferences may vary among regions. Following up with a creel survey may be beneficial to ensure that angling effort and perceptions align with the management agencies' goals. Data provided in this chapter coupled with angler information would provide a comprehensive view of favorable regulation scenarios for each region.

Chapter II Tables

Table 2-1. Parameters derived from our age and growth analyses for crappie populations for each reservoir that were used in our Beverton Holt equilibrium yield models. The youngest age for each reservoir was held constant at one, and average length at maturity was also held constant at 175 mm TL for all models. Length-weight regressions from each sample were used to derive variables a (y-intercept) and b (slope) for each model.

Reservoir	Linf (mm)	K	t0	Max Age (years)	a	b
Bankhead	353	0.48	-0.05	9	3.0e-06	3.29
Coffeeville	272	0.39	-0.05	10	1.9e-05	2.93
Eufaula	315	0.39	-0.05	10	2.0e-06	3.32
Gantt	327	0.39	-0.05	8	8.0e-06	3.07
Harding	306	0.41	0.00	11	7.0e-06	3.12
Harris/Wedowee	335	0.39	-0.05	16	4.0e-06	3.22
Martin	312	0.46	-0.05	13	5.0e-06	3.17
Millers Ferry	397	0.39	-0.05	7	1.0e-06	3.40
Mitchell	337	0.52	-0.05	13	4.0e-06	3.24
Upper Bear Creek	326	0.40	-0.05	9	2.0e-06	3.32
Warrior	354	0.47	-0.05	7	4.0e-06	3.21
Weiss	325	0.46	-0.05	14	3.0e-06	3.28
Wheeler	364	0.55	-0.05	9	3.0e-06	3.30

Table 2-2. Predicted percent magnitude changes at 30%, 40%, and 50% CM with a 229-, 254-, and 279-mm MLL for fast-growth reservoirs, when compared to the assumed "no MLL" (200-mm). Metrics include predicted yield ("Yield"), predicted harvest ("Harvest"), and predicted number of crappies at or over memorable sized (300-mm) in the population ("N300").

		MLLs (mm) at 30% CM			MLLs (mm) at 40% CM			MLLs (mm) at 50% CM		
Reservoir	Metric	229	254	279	229	254	279	229	254	279
Bankhead	Yield	+ 3%	+ 3%	- 3%	- 2%	- 8%	- 18%	- 8%	- 19%	- 34%
	Harvest	- 13%	- 28%	- 41%	- 18%	- 38%	- 52%	- 23%	- 47%	- 62%
	N300	+ 21%	+ 49%	+ 82%	+ 21%	+ 49%	+ 81%	+ 22%	+ 50%	+ 79%
Millers Ferry	Yield	+ 6%	+ 10%	+ 7%	+ 1%	- 0%	- 7%	- 5%	- 12%	- 23%
	Harvest	- 14%	- 28%	- 38%	- 19%	- 37%	-49%	- 24%	- 46%	- 59%
	N300	+ 21%	+ 46%	+ 72%	+ 22%	+ 46%	+ 71%	+ 22%	+ 47%	+ 70%
Mitchell	Yield	+ 1%	+ 0%	- 8%	- 4%	- 11%	- 24%	- 10%	- 23%	- 40%
	Harvest	- 13%	- 29%	- 43%	- 18%	- 39%	- 54%	- 23%	- 48%	- 65%
	N300	+ 21%	+ 51%	+ 90%	+ 22%	+ 52%	+ 88%	+ 22%	+ 52%	+ 85%
Warrior	Yield	+ 2%	+ 2%	- 5%	- 3%	- 9%	- 20%	-9%	-20%	-35%
	Harvest	- 14%	- 29%	- 42%	-19%	-38%	- 53%	- 24%	- 48%	- 63%
	N300	+ 22%	+ 50%	+ 84%	+ 22%	+ 50%	+ 83%	+ 23%	+ 51%	+ 81%
Wheeler	Yield	+ 1%	+ 1%	- 1%	- 1%	- 5%	- 13%	- 4%	- 13%	- 25%
	Harvest	- 5%	- 17%	- 31%	- 7%	- 23%	- 41%	- 9%	- 28%	- 50%
	N300	+ 9%	+ 31%	+ 59%	+ 9%	+ 31%	+ 59%	+ 9%	+ 31%	+ 58%

Table 2-3. Predicted percent magnitude changes at 30%, 40%, and 50% CM with a 229-, 254-, and 279-mm MLL for medium-growth reservoirs, when compared to the assumed "no MLL" (200-mm). Metrics include predicted yield ("Yield"), predicted harvest ("Harvest"), and predicted number of crappies at or over memorable sized (300-mm) in the population ("N300").

		MLLs (mm) at 30% CM			MLLs (mm) at 40% CM			MLLs (mm) at 50% CM		
Reservoir	Metric	229	254	279	229	254	279	229	254	279
Harris/ Wedowee	Yield	- 0%	- 5%	- 17%	- 5%	- 18%	- 36%	- 12%	- 31%	- 52%
	Harvest	- 16%	- 33%	- 50%	- 22%	- 43%	- 62%	- 29%	- 53%	- 73%
	N300	+ 23%	+ 61%	+ 116%	+ 23%	+ 62%	+ 114%	+ 24%	+ 62%	+ 109%
Martin	Yield	- 1%	- 10%	- 27%	- 8%	- 23%	- 45%	- 15%	- 36%	- 60%
	Harvest	- 19%	- 36%	- 55%	- 26%	- 47%	- 67%	- 33%	- 57%	- 77%
	N300	+ 26%	+ 70%	+ 138%	+ 27%	+ 70%	+ 131%	+ 27%	+ 69%	+ 123%
Upper Bear Creek	Yield	- 1%	- 8%	- 23%	- 7%	- 20%	-40%	- 13%	- 33%	- 55%
	Harvest	- 17%	- 35%	- 53%	- 23%	- 45%	- 65%	- 30%	- 55%	- 75%
	N300	+ 25%	+ 67%	+ 128%	+ 25%	+ 67%	+ 123%	+ 25%	+ 66%	+ 117%
Weiss	Yield	+ 2%	- 4%	- 17%	- 5%	- 16%	- 34%	- 12%	- 29%	- 51%
	Harvest	- 18%	- 33%	- 50%	- 26%	- 44%	- 62%	- 33%	- 54%	- 73%
	N300	+ 25%	+ 60%	+ 116%	+ 26%	+ 61%	+ 113%	+ 26%	+ 61%	+ 108%

Table 2-4. Predicted percent magnitude changes at 30%, 40%, and 50% CM with a 229-, 254-, and 279-mm MLL for slow-growth reservoirs, when compared to the assumed "no MLL" (200-mm). Metrics include predicted yield ("Yield"), predicted harvest ("Harvest"), and predicted number of crappies at or over memorable sized (300-mm) in the population ("N300").

		MLLs (mm) at 30% CM			MLLs (mm) at 40% CM			MLLs (mm) at 50% CM		
Reservoir	Metric	229	254	279	229	254	279	229	254	279
Coffeeville	Yield	- 17%	- 44%	- 75%	- 27%	- 58%	- 84%	- 37%	- 69%	- 90%
	Harvest	- 31%	- 59%	- 84%	- 40%	- 70%	- 90%	- 48%	- 79%	- 94%
	N300	+ 56%	+ 160%	+ 286%	+ 55%	+ 151%	+ 258%	+ 54%	+ 141%	+ 227%
Eufaula	Yield	- 3%	- 13%	- 31%	- 10%	- 27%	- 48%	- 17%	- 40%	- 63%
	Harvest	- 18%	- 39%	- 58%	- 24%	- 49%	- 70%	- 31%	- 59%	- 79%
	N300	+ 29%	+ 80%	+ 155%	+ 29%	+ 79%	+ 147%	+ 30%	+ 78%	+ 138%
Gantt	Yield	- 2%	- 11%	- 27%	- 8%	- 23%	- 43%	- 15%	-36%	- 58%
	Harvest	- 17%	- 36%	- 54%	- 23%	- 46%	- 66%	- 29%	- 55%	- 75%
	N300	+ 25%	+ 69%	+ 129%	+ 26%	+ 68%	+ 125%	+ 26%	+ 68%	+ 118%
Harding	Yield	- 5%	- 17%	- 37%	- 12%	- 31%	- 54%	- 19%	- 44%	- 68%
	Harvest	- 19%	- 40%	- 61%	- 25%	- 51%	- 72%	- 32%	- 61%	- 81%
	N300	+ 30%	+ 86%	+ 170%	+ 31%	+ 85%	+ 159%	+ 31%	+ 83%	+ 147%

Appendices

Appendix A

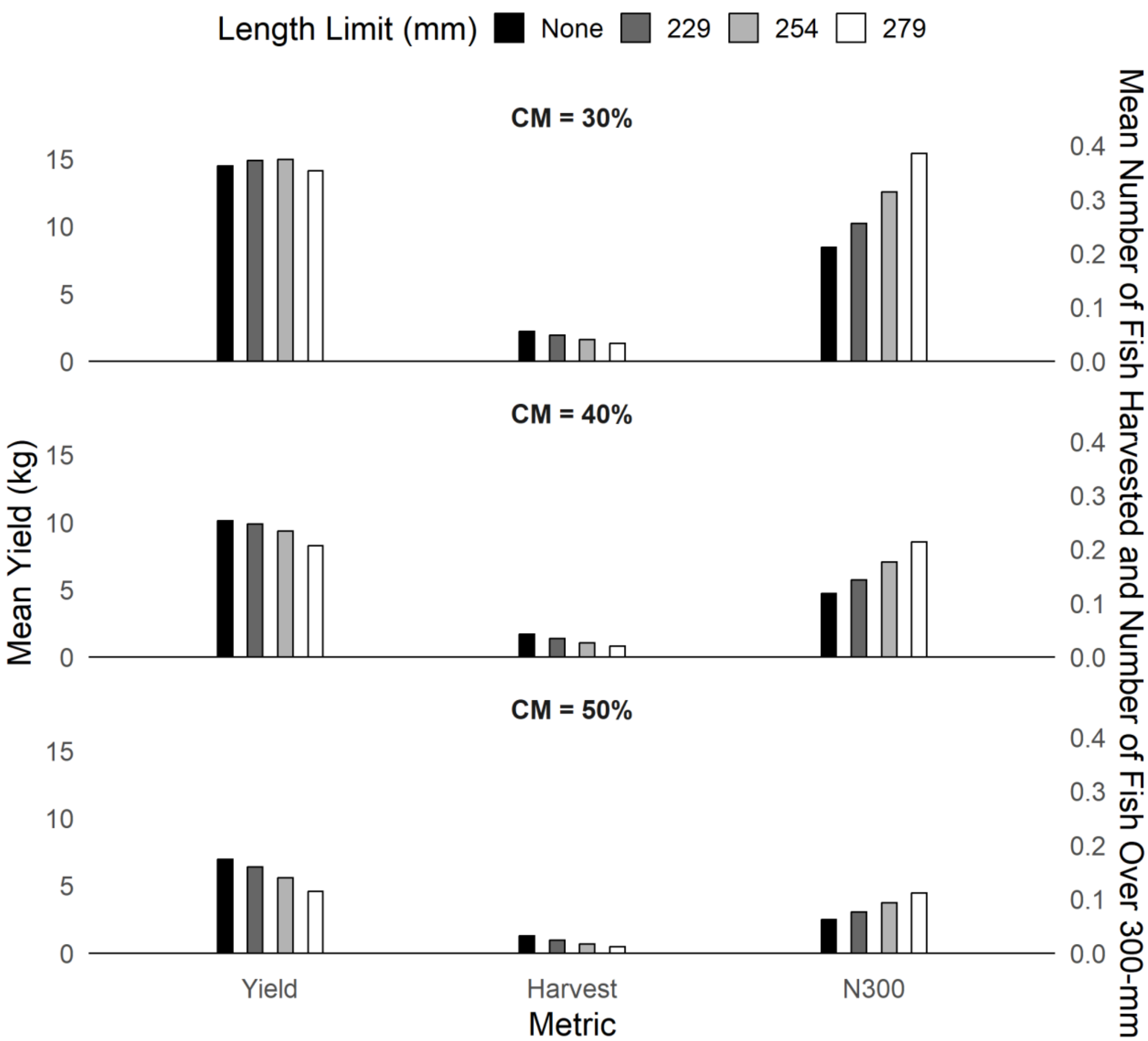

Figure A.1. Mean yield (kg), mean number of fish harvested (per 1 recruit), and mean number of fish over 300-mm ("N300") in the population at an equilibrium of "1" under four different size restrictions and three levels of CM in Bankhead Reservoir, Alabama. Data are averaged over exploitation rates from 0.20 to 0.60.

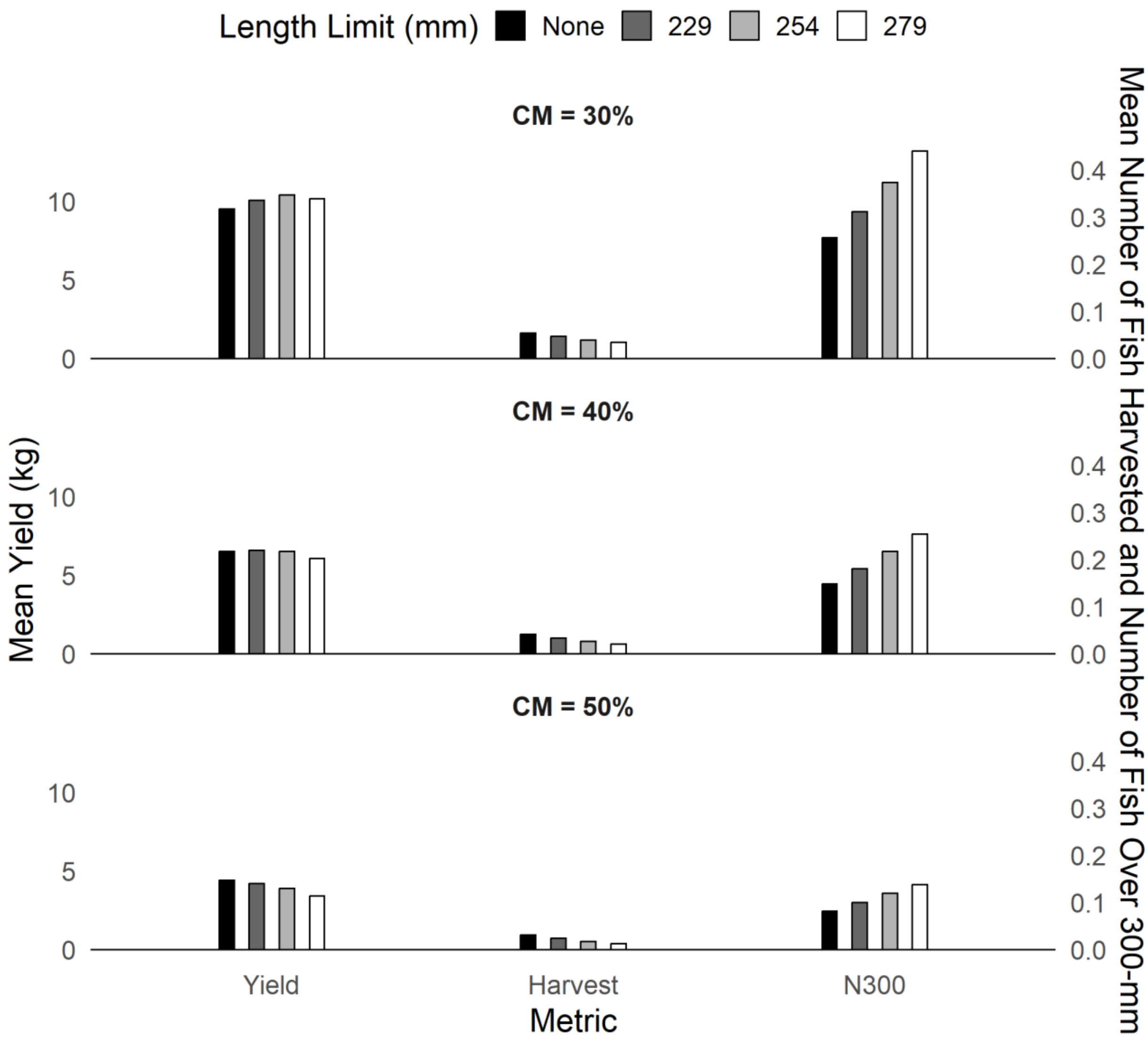

Figure A.2. Mean yield (kg), mean number of fish harvested (per 1 recruit), and mean number of fish over 300-mm ("N300") in the population at an equilibrium of "1" under four different size restrictions and three levels of CM in Millers Ferry Reservoir, Alabama. Data are averaged over exploitation rates from 0.20 to 0.60.

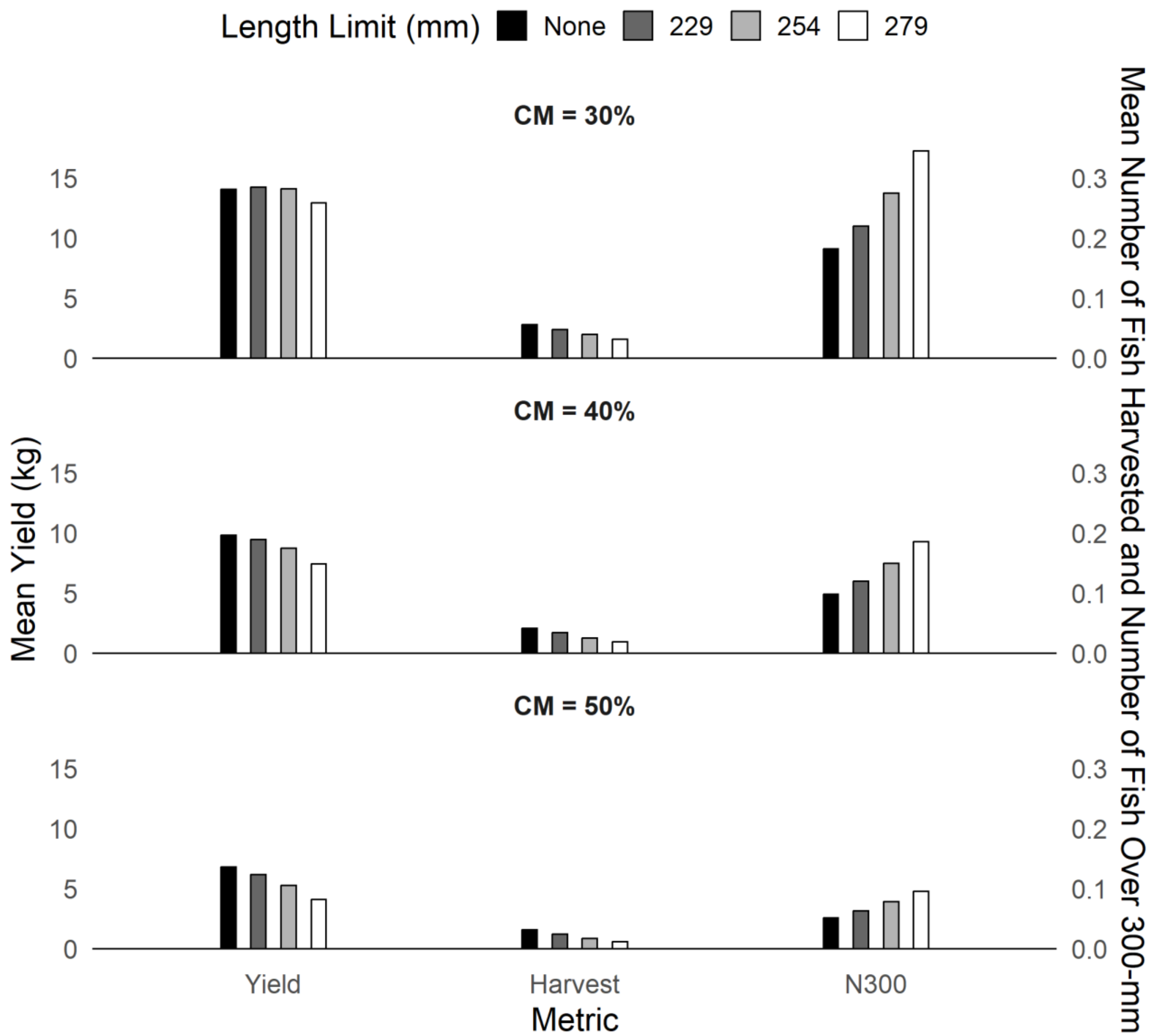

Figure A.3. Mean yield (kg), mean number of fish harvested (per 1 recruit), and mean number of fish over 300-mm ("N300") in the population at an equilibrium of "1" under four different size restrictions and three levels of CM in Mitchell Reservoir, Alabama. Data are averaged over exploitation rates from 0.20 to 0.60.

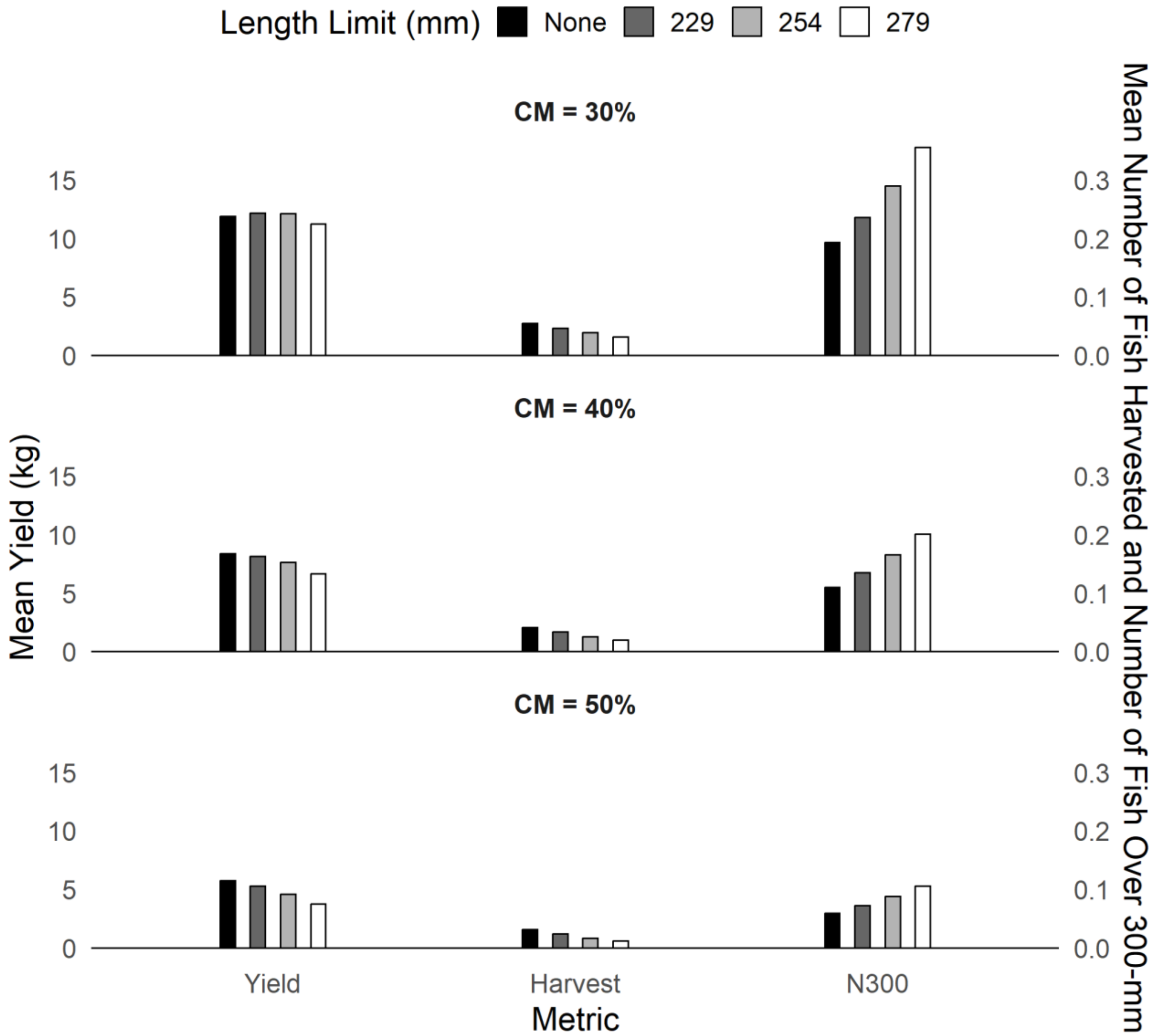

Figure A.4. Mean yield (kg), mean number of fish harvested (per 1 recruit), and mean number of fish over 300-mm ("N300") in the population at an equilibrium of "1" under four different size restrictions and three levels of CM in Warrior Reservoir, Alabama. Data are averaged over exploitation rates from 0.20 to 0.60.

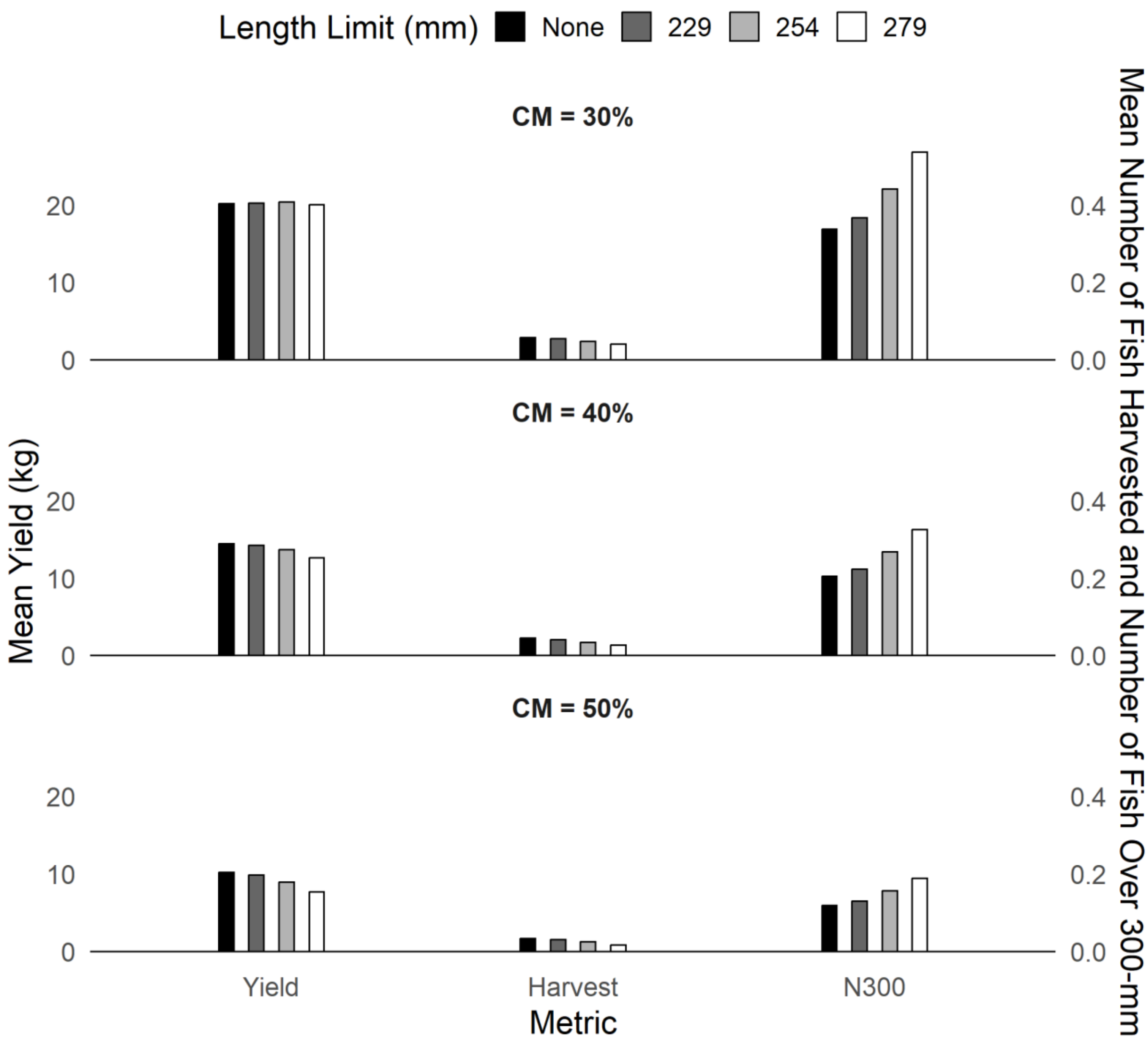

Figure A.5. Mean yield (kg), mean number of fish harvested (per 1 recruit), and mean number of fish over 300-mm ("N300") in the population at an equilibrium of "1" under four different size restrictions and three levels of CM in Wheeler Reservoir, Alabama. Data are averaged over exploitation rates from 0.20 to 0.60.

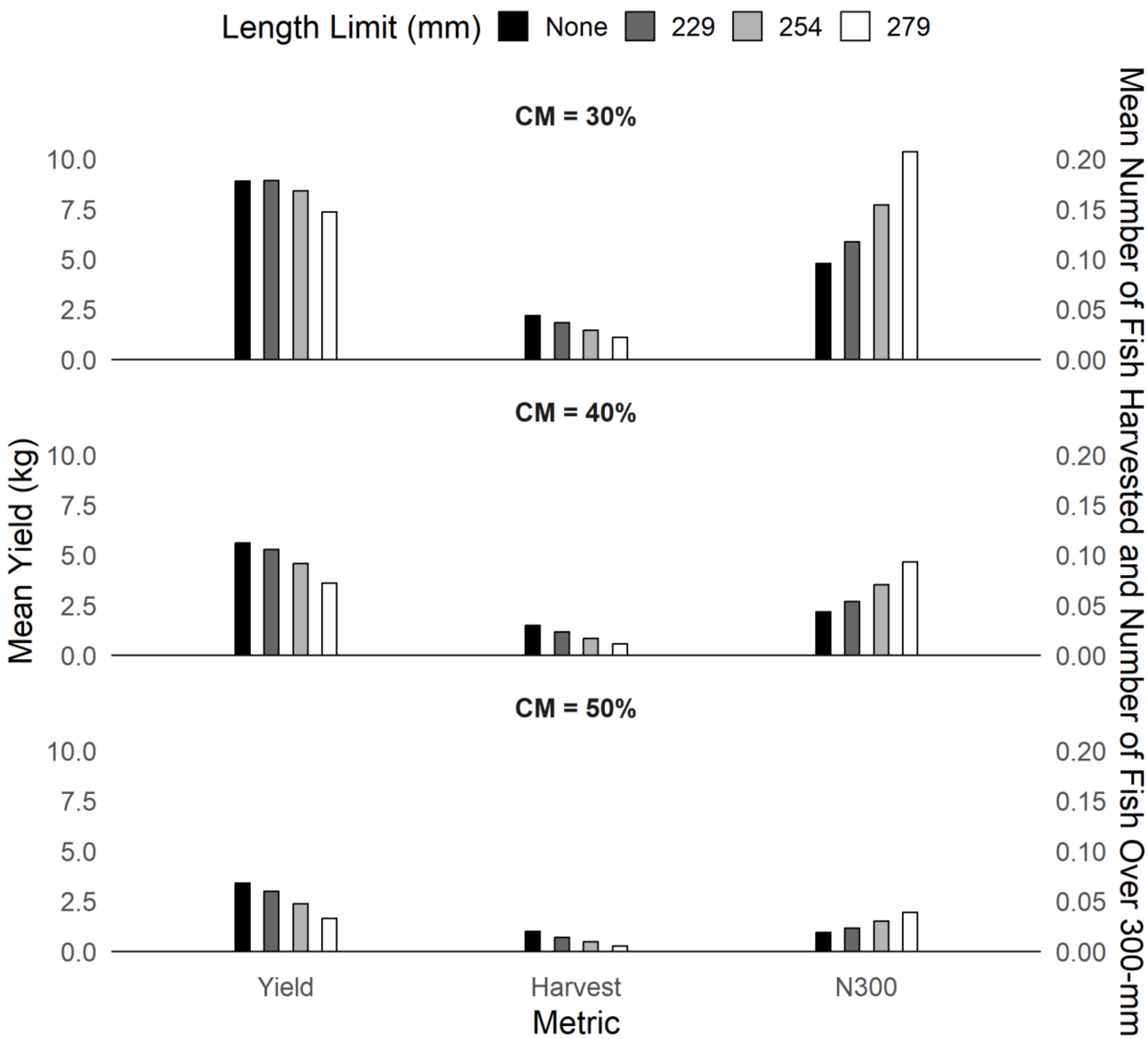

Figure A.6. Mean yield (kg), mean number of fish harvested (per 1 recruit), and mean number of fish over 300-mm ("N300") in the population at an equilibrium of "1" under four different size restrictions and three levels of CM in Harris/Wedowee Reservoir, Alabama. Data are averaged over exploitation rates from 0.20 to 0.60.

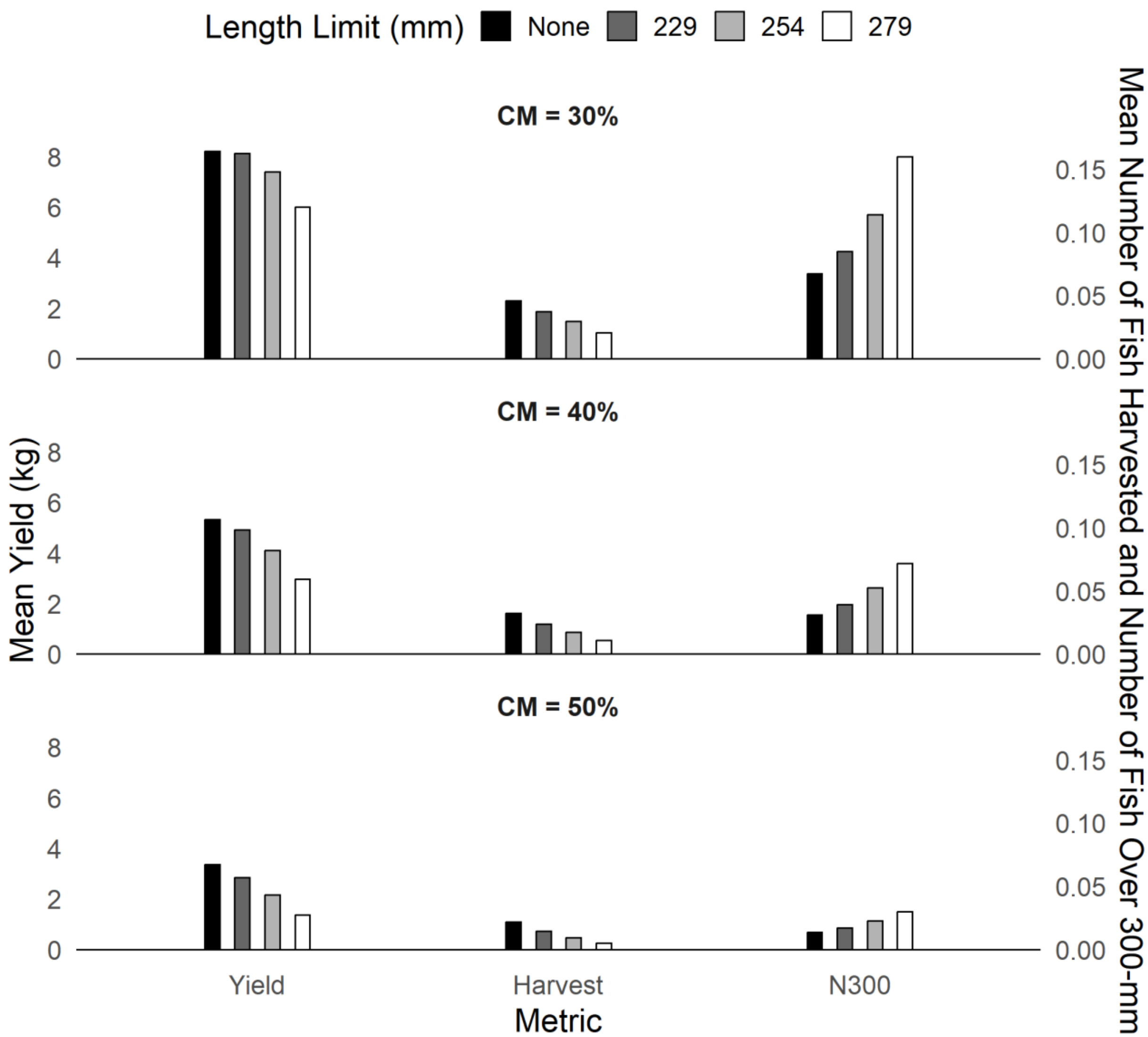

Figure A.7. Mean yield (kg), mean number of fish harvested (per 1 recruit), and mean number of fish over 300-mm ("N300") in the population at an equilibrium of "1" under four different size restrictions and three levels of CM in Martin Reservoir, Alabama. Data are averaged over exploitation rates from 0.20 to 0.60.

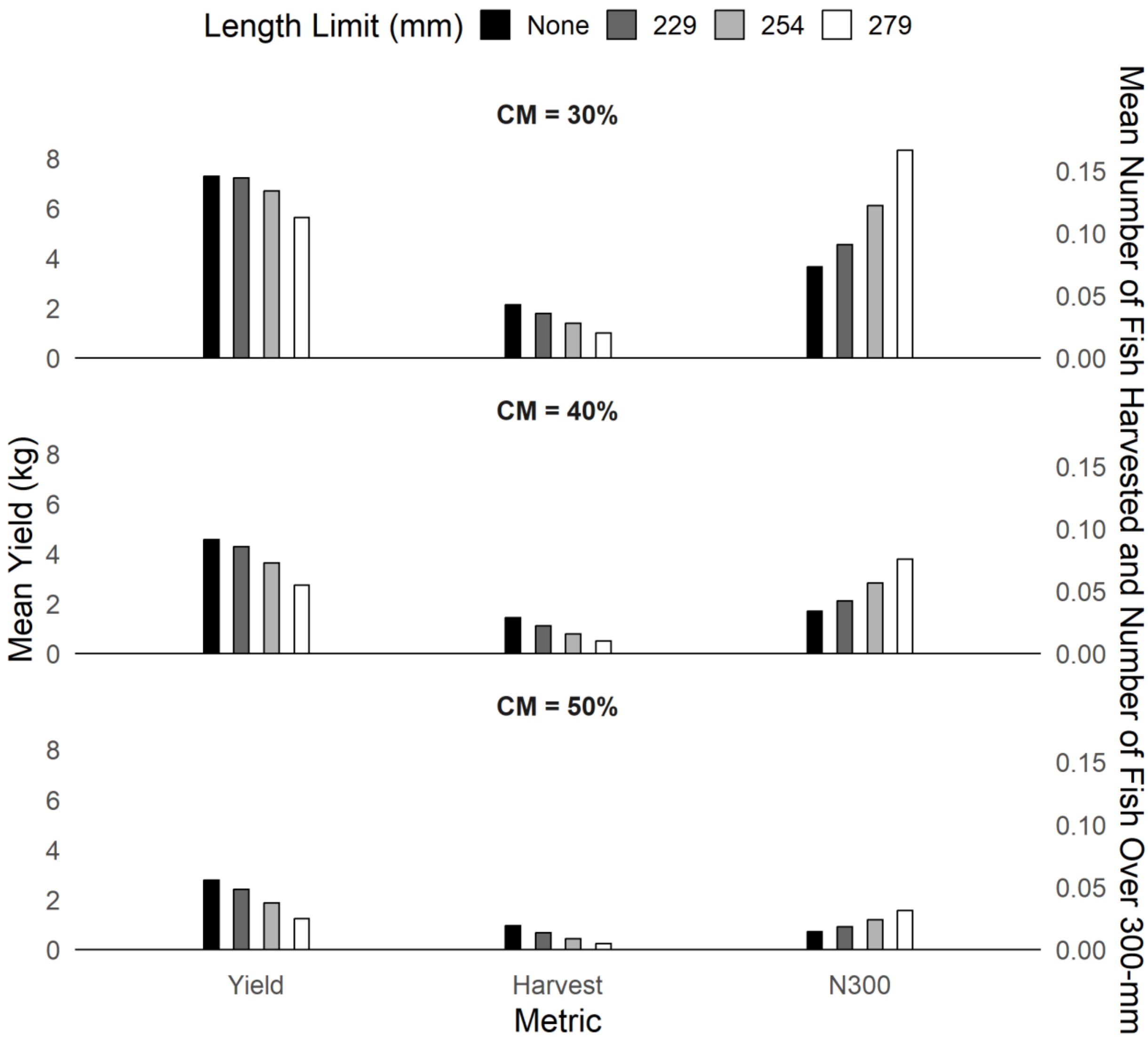

Figure A.8. Mean yield (kg), mean number of fish harvested (per 1 recruit), and mean number of fish over 300-mm ("N300") in the population at an equilibrium of "1" under four different size restrictions and three levels of CM in Upper Bear Creek Reservoir, Alabama. Data are averaged over exploitation rates from 0.20 to 0.60.

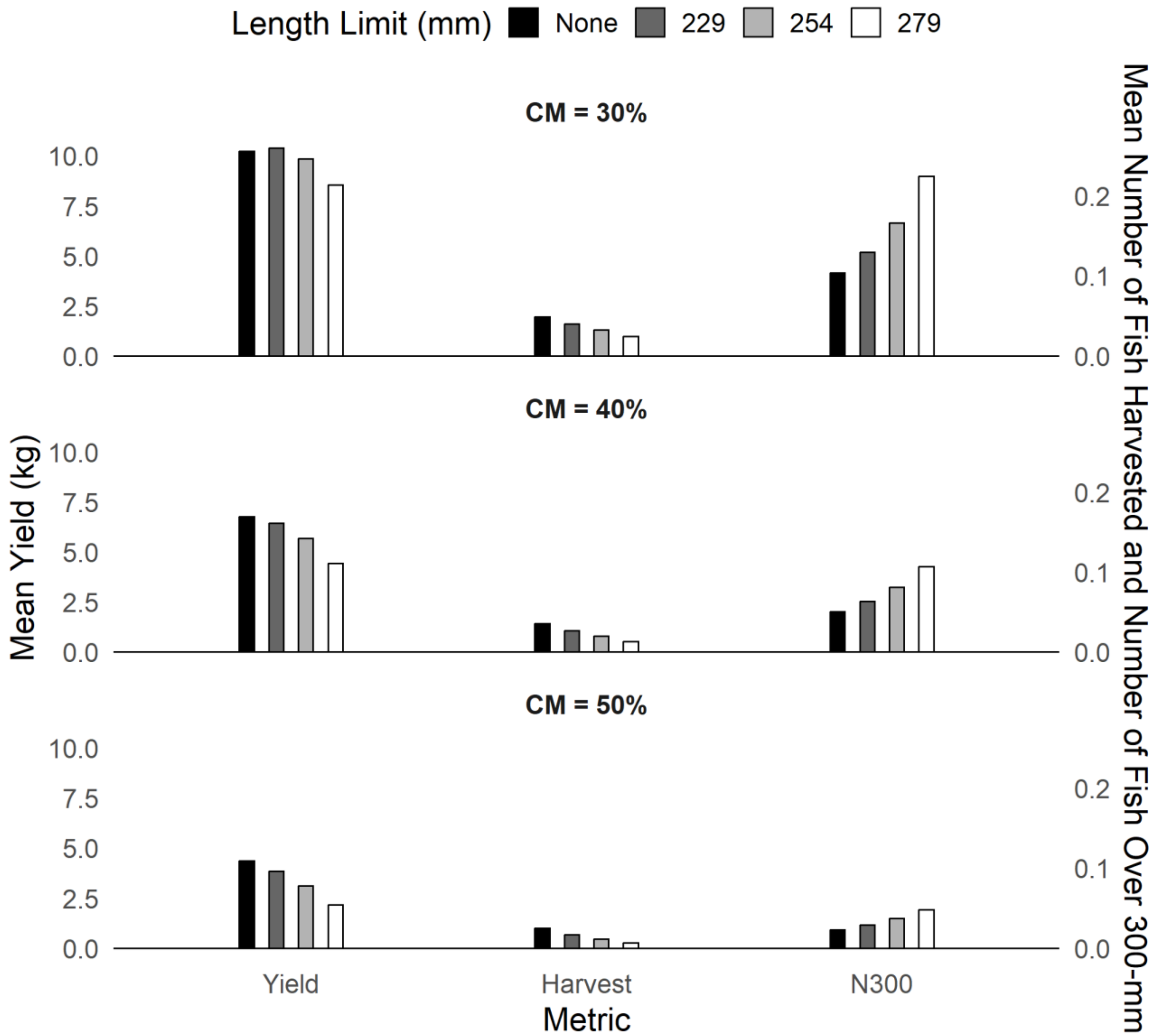

Figure A.9. Mean yield (kg), mean number of fish harvested (per 1 recruit), and mean number of fish over 300-mm ("N300") in the population at an equilibrium of "1" under four different size restrictions and three levels of CM in Weiss Reservoir, Alabama. Data are averaged over exploitation rates from 0.20 to 0.60.

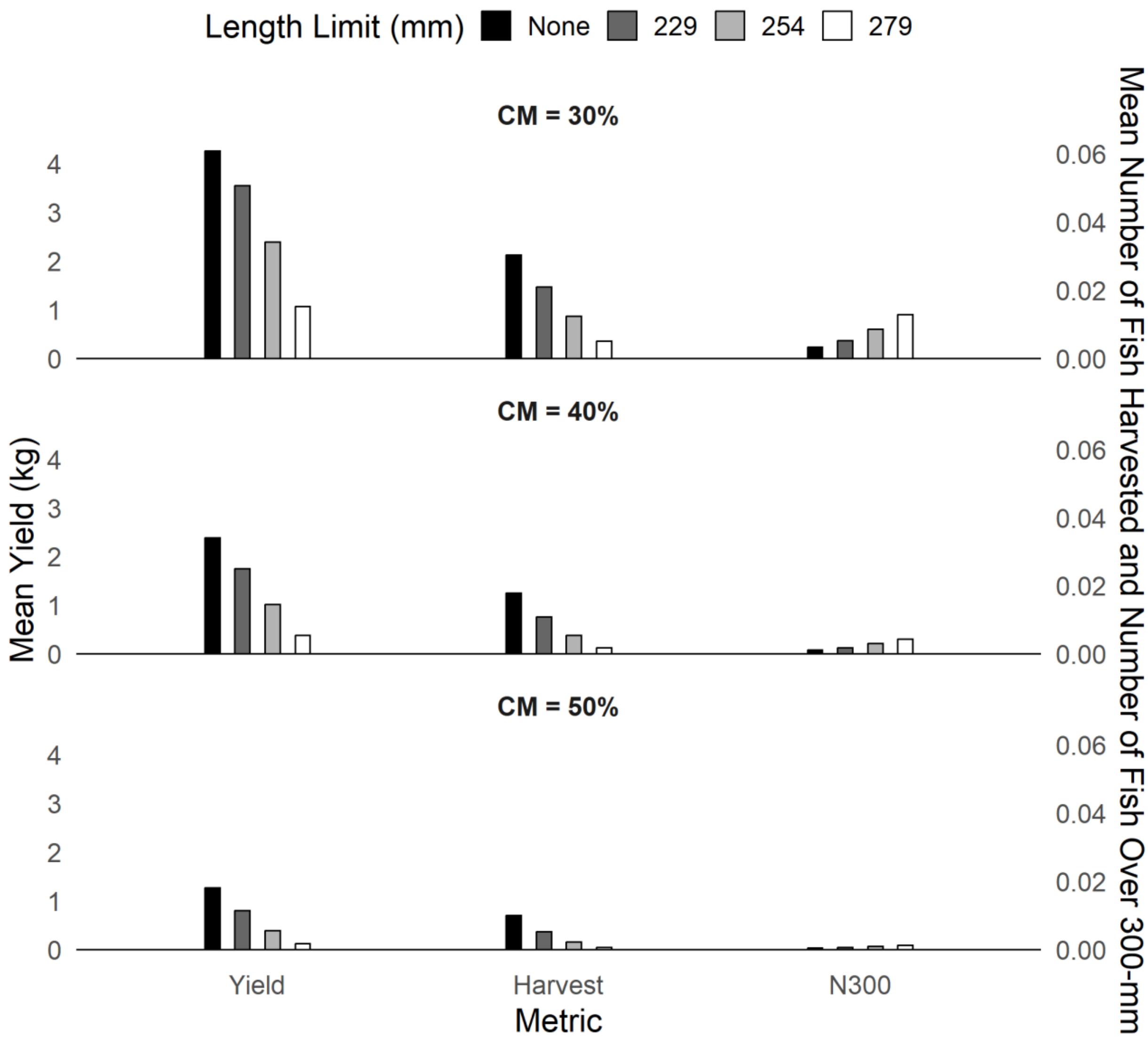

Figure A.10. Mean yield (kg), mean number of fish harvested (per 1 recruit), and mean number of fish over 300-mm ("N300") in the population at an equilibrium of "1" under four different size restrictions and three levels of CM in Coffeeville Reservoir, Alabama. Data are averaged over exploitation rates from 0.20 to 0.60.

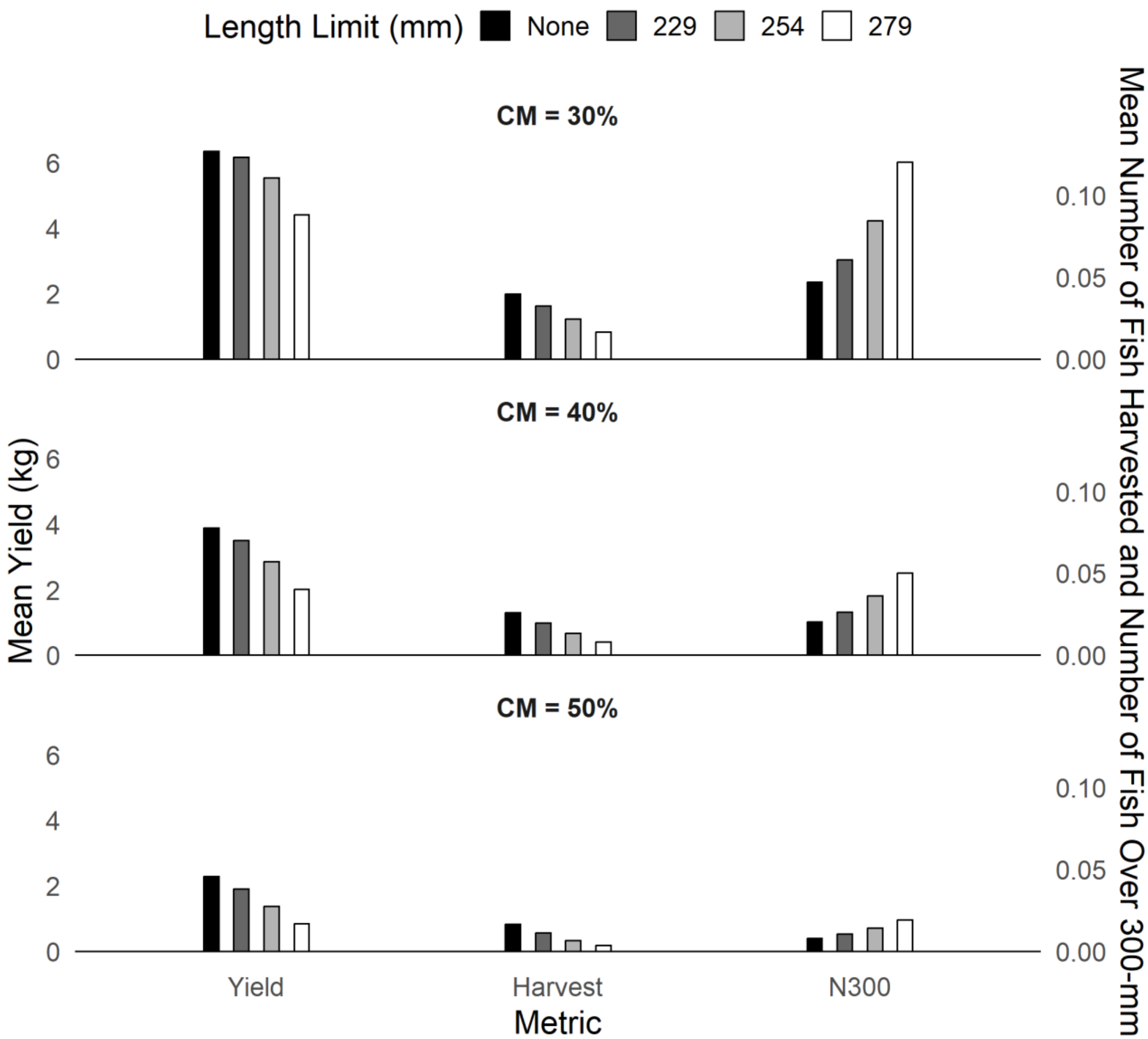

Figure A.11. Mean yield (kg), mean number of fish harvested (per 1 recruit), and mean number of fish over 300-mm (“N300”) in the population at an equilibrium of “1” under four different size restrictions and three levels of CM in Eufaula Reservoir, Alabama. Data are averaged over exploitation rates from 0.20 to 0.60.

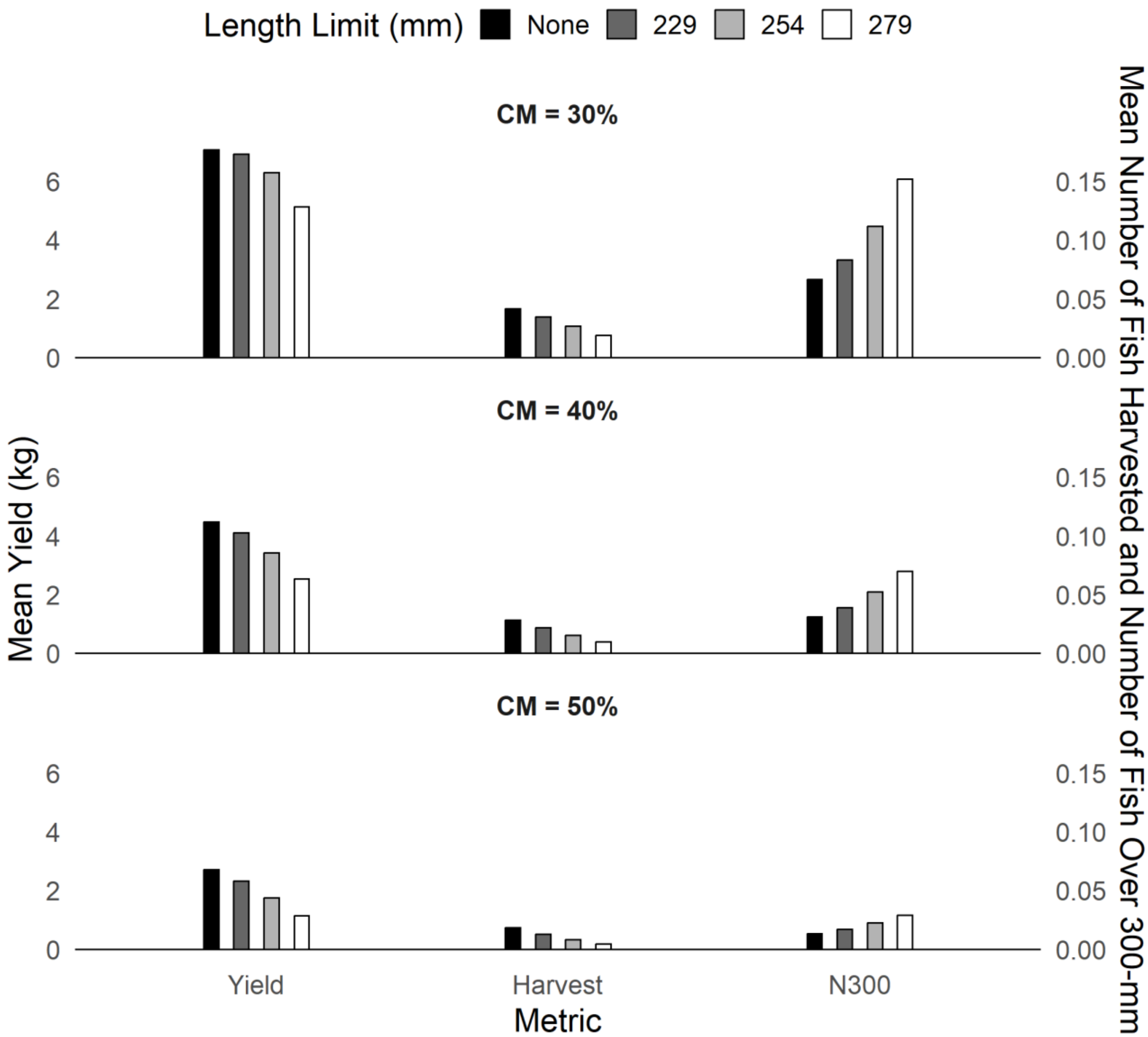

Figure A.12. Mean yield (kg), mean number of fish harvested (per 1 recruit), and mean number of fish over 300-mm ("N300") in the population at an equilibrium of "1" under four different size restrictions and three levels of CM in Gantt Reservoir, Alabama. Data are averaged over exploitation rates from 0.20 to 0.60.

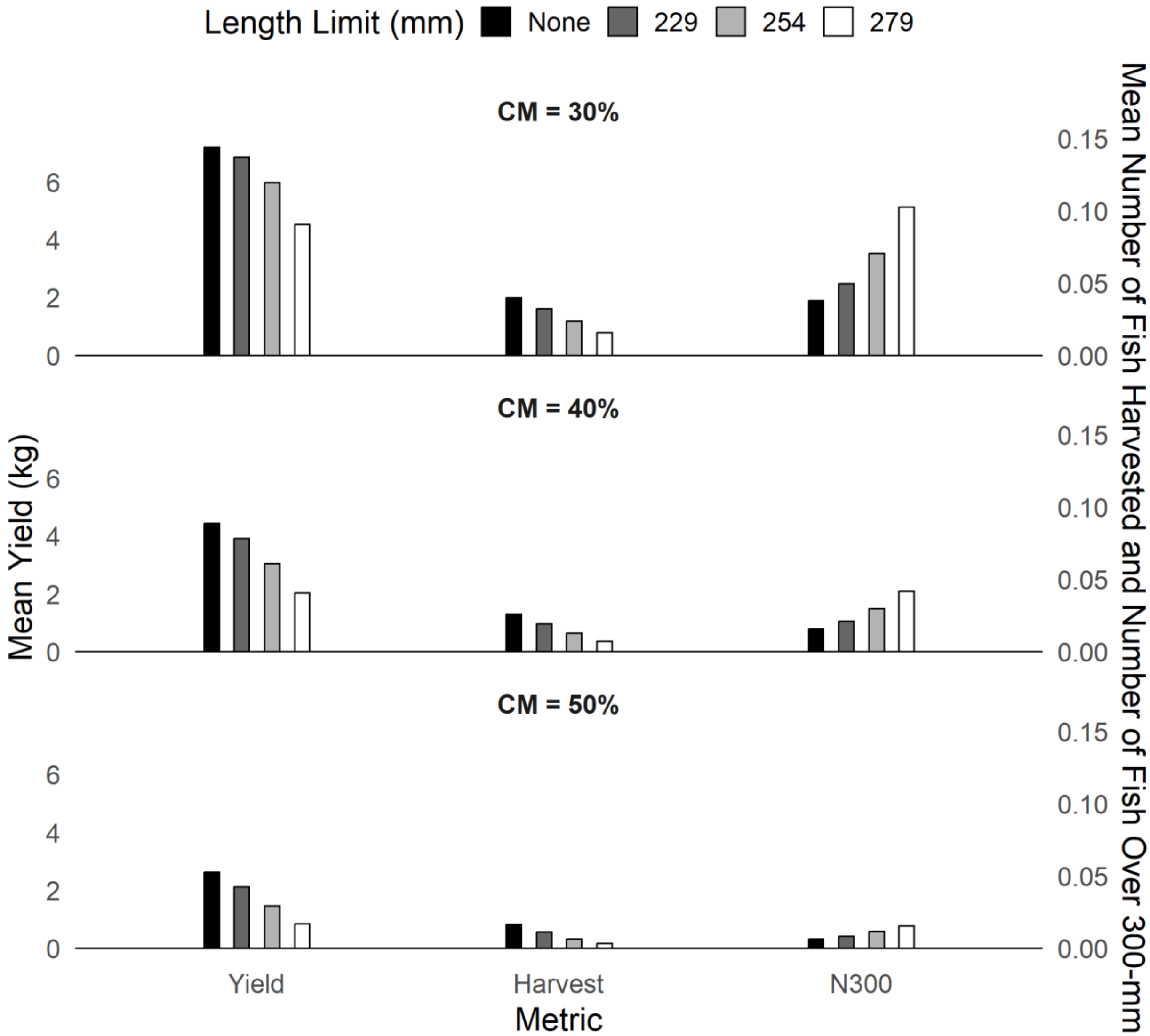

Figure A.13. Mean yield (kg), mean number of fish harvested (per 1 recruit), and mean number of fish over 300-mm ("N300") in the population at an equilibrium of "1" under four different size restrictions and three levels of CM in Harding Reservoir, Alabama. Data are averaged over exploitation rates from 0.20 to 0.60.

Chapter 3 Spatial Variation in Growth, Mortality, and Equilibrium Yield Models between Crappies in Lower and Upper Sections of Five Alabama Reservoirs

Introduction

Changes in the physicochemical conditions within reservoirs (e.g., water temperature, dissolved oxygen, turbidity, nutrient concentrations, and pH) can vary spatially (Buynak et al. 1989; Stewart et al. 2015) and significantly influence fish distributions, assemblage composition, and relative abundance. For example, thermal stratification and hypoxic bottom waters can restrict the vertical habitat available to certain species, often favoring tolerant taxa while excluding those considered more sensitive (e.g., Striped Bass *Morone saxatilis,* Coutant 1987). Summer stratification often creates an anoxic hypolimnia, thereby limiting Largemouth Bass and crappies to the epilimnion or inflowing tributaries (Budnik et al. 2021). For example, hypoxia (<2 mg/L) can dramatically shrink usable habitat for Largemouth Bass and White Crappie in eutrophic reservoirs (i.e., areas of positive growth potential become confined to oxygenated strata, Budnik et al. 2021). As another example, altered nutrient levels and turbidity may shift food web dynamics, reducing prey availability for visual predators or encouraging the expansion or increased abundance of more opportunistic species (Han et al. 2023). In a multi-reservoir survey in North Carolina, Black Crappie catch-per-unit effort (CPUE) was positively correlated with reservoir turbidity (Parker et al. 2023). Likewise, in Louisiana's Anacoco Lake, a shift to predominantly White Crappie was attributed to increased turbidity (Louisiana Department of Wildlife and Fisheries n.d.). Fontes De Oliveira et al. (2005) found that fish composition was more diverse in stream and riverine sites compared to main lake reservoir sites and attributed differences to habitat uses and species interactions. Further, CPUE of crappies was generally lower near the main lake compared to the back of the tributary or embayment in a multi-year study on four Mississippi reservoirs (Kaczka and Miranda 2013). In addition to the influence of physicochemical characteristics, the structure of fish populations may also be influenced by recreational fishing.

Growth and longevity overfishing can affect the overall size structures and underlying genetics of fish populations. Growth overfishing disproportionately reduces the number of large fish in a population because individuals are harvested before reaching older, larger size classes (Beverton & Holt 1957). High fishing pressure, especially in the absence of protective regulations like minimum length limits (MLLs), results in most fish being removed soon after reaching catchable or legal size. This truncates the age and size structure of the population (Hilborn & Walters 1992), reducing the number of large, older fish (Berkeley et al. 2004). Larger fish produce exponentially more and higher quality eggs, so their loss can reduce reproductive output (Duarte ad Alcaraz 1989; Hixon et al. 2014). Additionally, when large fish become rare, the fishery yield declines in both quantity and economic value. Over time, a population dominated by small, young fish may also become more vulnerable to environmental variability and recruitment failure (Anderson et al. 2008). Gear selectivity by anglers can influence the size-selectivity of harvested fish, furthering growth-overfishing problems in a fish population (Diekert 2012). Another type of overfishing that may coincide with growth overfishing of larger size classes is longevity overfishing. Longevity overfishing may occur when anglers select larger fish, and over time, results in decreased sizes of spawning stocks that affect recruitment (Beamish et al. 2006). Minimum length limits could induce this type of overfishing by forcing anglers to be size selective only for these larger size classes. These fish could be the faster growers of a population and may be the most productive in terms of contributing to the spawning stock and sexual maturity. In crappie fisheries, there are typically fast and slow growing crappies within the same population, often causing wide ranges of total length (TL) at ages (Boxrucker and Irwin 2002; Bonvechio et al. 2015; Michaletz 2020). A MLL or size selective anglers could force anglers to harvest the faster-growth genetics from a population (Biro and Post 2008), leaving only slow-growth genetics. In some cases, overfishing can be exacerbated by new technologies.

The efficiency of recent technologies, such as forward-facing sonar, can also be affected by physicochemical variables (Neely et al. 2022); hypothesized to be most efficient in open water. Water depth may also relate to changes in efficiency of modern fishing technologies; thus, crappie exploitation may be greater in the upper versus lower portion of a reservoir, leading to varied success of harvest restrictions. Recent data collected by Alabama Department of Conservation and Natural Resources (ADCNR) indicates that crappies in Alabama have different growth patterns depending on which region of the reservoir they inhabit (D. Abernethy, ADCNR Assistant Chief, personal communication). For example, crappies in Weiss Lake, Alabama had truncated age structures in the upper section of the reservoir (M. Holley, ADCNR Biologist, personal communication), and one hypothesized reason was the use of forward-facing sonar increasing angler exploitation. Thus, in this study, we analyzed multiple reservoirs for differences between crappie populations in the lower and upper sections.

Our study objective was to determine if there were crappie population differences in lower and upper sections of reservoirs, which could be caused by multiple factors. This study builds upon the state agency's previous work by expanding on analyses between lower and upper sections of one or two reservoirs, analyzing if differences between upper and lower crappie populations are a common theme among multiple reservoirs. Upper, riverine portions of a reservoir often encompass only the main channel and tributaries, with little or no deep coves.

Lower, main lake portions of reservoirs have deep coves where crappies may be able to more easily avoid fishing pressure. This hypothesis of growth-overfishing in upper, riverine portions is based on less availability of “open-water” in the upper portions of reservoirs, allowing anglers to presumably exploit crappies easier compared to crappies in the downstream, main lake portions of the reservoirs. With new technologies possibly increasing catch rates of crappies (Neely et al. 2022; Zellers 2022), coupled with some crappie anglers tendency to target the largest crappies to harvest out of the population (Webb and Ott 1991; Miranda and Dorr 2000; Guiot et al. 2024; Cooke et al. 2025), spatial analyses may be useful as a first step to examining if there is evidence of growth overfishing. Because this study examines relationships in the field, we acknowledge possible differences could be due to several factors including increasing catch rates using new technology (Neely et al. 2022; Zellers 2022), other unmeasured factors (i.e., physicochemical factors, angler pressure), or differences in fish assemblage variation that may already be present in these different portions of the reservoirs (Fontes De Oliveira et al. 2005). We view this study as an important first step upon which other evidence may need to be collected or examined.

Methods

Study areas

We sampled 5 reservoirs (i.e., storage impoundments) across Alabama to determine differences between fish populations in upper, riverine and lower, main lake sections of reservoirs (Figure 1). Reservoirs were selected in coordination with ADCNR biologists. We selected reservoirs where there was an apparent difference between upper and main lake sections, where upper sections were more riverine and shallower compared to main lake sections. All but one reservoir (i.e., Eufaula) selected was in the central and northern portions of Alabama, above the fall line. These reservoirs are in ecoregions characterized by rockier uplands and karst topography. Reservoirs represented four of six Level III ecoregions in Alabama (Figure 1). There was one reservoir in each ecoregion, except for the Piedmont Region, which was represented by two reservoirs. Eufaula Reservoir is located in the Southeastern Plains ecoregion and characterized by lower elevation and less relief compared to the other reservoirs. "Run of the river" reservoirs were not included in these analyses due to the similarities in reservoir structure between upper and lower portions.

Fish sampling

We electrofished five reservoirs using similar protocols described in Chapter I. Briefly, ADCNR and Auburn University crews used electrofishing with a goal of sampling at least 300 Black Crappie or White Crappie from each reservoir section. We collected fish from two different portions of these reservoirs to examine possible spatial differences in growth, mortality, and size structures (Figure 1). Although we sampled multiple locations within each reservoir section, we assigned each sample to one section based on our designation criteria. The upper and lower sections were differentiated based on flow (i.e., flow present in upper sections, whereas no flow is apparent in lower, main lake sections) (Figure 2). Target species were determined in consultation with ADCNR and the dominant species in each reservoir was used for analyses, except for in Wheeler Reservoir. Collection numbers were similar between the two species in Wheeler Reservoir, so both species were combined into one group for our analyses. Black and White Crappie are often pooled together for analyses due to minor population differences (e.g., Allen and Miranda 1995; Isermann et al. 2002). Fish were sampled over multiple years during spring and autumn from the majority of reservoirs.

Morphometrics and otolith processing

We measured fish morphometrics and processed otoliths following the methods described in Chapter I. Briefly, fish collected were enumerated, measured (1-mm TL), weighed (1 g) and sexed by observing reproductive organs macroscopically. Species designation was verified in the laboratory. Finally, we extracted, sectioned, mounted, polished, and read the otoliths (n = 3,097 otoliths). Otoliths were not differentiated from Chapter I to keep all readers blind of reservoirs, time of collections, and area of collections.

Data analyses

Size structure and body condition

We assessed possible spatial differences in size structure using length frequencies and PSD-Q,P, and built a linear mixed effects model to determine the relationship between Wr and reservoir section. Length-frequencies of crappies were created for each reservoir section to visually examine spatial patterns among reservoirs. We observed differences between length frequencies to check for any size-specific truncation between the two portions of each reservoir. Then, we used five Kolmogorov-Smirnov tests to determine if the frequency distribution of total lengths was statistically different between the two sections of each reservoir ($\alpha \leq 0.05$). We also calculated PSD-Q,P for each section to check for variation in size structure indices. We plotted PSD-Q,P to determine if these data were skewed and then used a t-test to statistically compare differences between PSD-Q,P in each reservoir section ($\alpha \leq 0.05$). Body index of fish collected was calculated between the two reservoir sections and compared by observing the average Wr of the fish collected in each section (following description in Chapter I). Then, we modelled the relationship between crappie Wr and reservoir section, while accounting for the fact that samples within individual reservoirs could be more similar than samples across reservoirs (i.e., mixed effect, accounting for variation related to sampling different reservoirs) ($\alpha \leq 0.05$).

Growth

We estimated crappie growth in each reservoir section using the von Bertalanffy growth equation (von Bertalanffy 1938), and used a t-test to determine if there were differences in mean growth between reservoir sections. Growth parameters were described using the von Bertalanffy (1938) growth equation; 0.5 was added to each age of fish collected in autumn to account for growth past the last annulus (Sammons and Maceina 2008). The instantaneous growth rate, which is also the growth coefficient, K, in the von Bertalanffy growth equation was estimated for populations in each reservoir section. L_{inf}, which is the estimated asymptotic fish length, was estimated for both reservoir sections, and we examined trends in the range and means from each section. T0, or the average length of each population at the time of hatch, was not compared because hypothetically, these values should be close (i.e., unlike Chapter I where very few young crappies were sampled) and thus, were constrained to -0.05. We calculated the average time it took crappie populations in each reservoir section to reach the current 229-mm MLL using the von Bertalanffy growth equation. These data were also plotted to assess possible skewed data before statistically testing. We used a t-test to determine if there were statistical differences ($\alpha \leq 0.05$) in the mean estimated time it took for crappie populations in each section to reach 229-mm.

Mortality

We created year class histograms and logarithmic catch curves, calculated mortality of crappies, and compared mortality between reservoir sections. We tabulated year classes collected with year-class-frequency histograms. We examined trends in age structure between sections. We used logarithmic catch at each age to form a catch curve for both reservoir sections. From each catch curve, we estimated the total instantaneous mortality rate (Z) for each section by measuring the slope of the descending limb of the graph (Maceina 1997). From Z, the equation $S = e^{-Z}$ was used to calculate annual survival, which was used to estimate total annual mortality

(Ricker 1975). Then, we used a paired t-test to statistically compare ($\alpha \leq 0.05$) estimates of mean total annual mortality between reservoir sections. Instantaneous natural mortality (M) was estimated using several equations within R (Hoenig 1983; Chen and Watanabe 1989; Djabali et al. 1993; Jensen 1996; Lorenzen 1996; Cubillos et al. 1999; Kenchington 2014). Estimates were averaged among these equations for an overall estimate of instantaneous natural mortality. These equations used different reservoir-specific growth and age parameters to estimate M; uncertainty in the parameters most associated with natural mortality in each reservoir made this a more reasonable approach. Conditional natural mortality (CM) was described using the equation: $CM = 1 - e^{-M}$. Finally, we examined trends in natural mortality rates between fish collected in upper and lower portions of the reservoirs.

Age-structured models

Age-structured models were created for each reservoirs section using age and growth data with a constant CM. We used age-structured Beverton-Holt equilibrium-yield models using the same protocols for model building as indicated in Chapter II. Briefly, we assembled an equilibrium yield model in R to examine how each reservoir section is predicted to respond to multiple MLL scenarios. We treated our spatial classifications (i.e., reservoir sections) as separate populations and ran separate models for each. Crappie typically follow a Beverton-Holt growth curve (Allen and Miranda 1995; Maceina et al. 1998; Boxrucker 2002a; Isermann et al. 2002). The Beverton-Holt equilibrium-yield equation comprises multiple parameters. Length-weight relationships were derived from pooled electrofishing samples. We saw variable maximum ages at our sites (Chapter I), so we used the oldest age collected in each reservoir section as the oldest age parameter. The average length at maturity was not determined in this study, thus, we used a mean of 175-mm for all populations (Michaletz 2013; Culpepper III and

Allen 2016; Mcinerny et al. 2020). A type II fishery was assumed for all models, where natural and fishing mortality occurs simultaneously (Ricker 1975). Other model parameters were obtained using the von Bertalanffy growth equation from each portion of the reservoirs (Table 5). Model results were presented as a mean of estimates using multiple rates within a range of known exploitation rates (0.20 – 0.60) (Allen et al. 1998; Maceina et al. 1998; Sammons et al. 2000). We simulated a 200-, 229-, 254-, and 279-mm MLL for each reservoir section. The 200-mm MLL acted as "no MLL" as anglers typically do not harvest crappies under this length when unregulated by size (Travnichek et al. 1997; Allen and Pine 2000). We used the mean CM obtained in Chapter II (i.e., CM = 40%) to assess how MLLs were predicted to affect yield, harvest, and memorable sized fish (≥ 300-mm) in upper and lower reservoir portions.

Results

Fish sampling

We achieved our sample size in most reservoir sections, though some sampling occurred over multiple years and seasons. Black Crappies and White Crappies were sampled 2022-2024 by ADCNR and Auburn University crews. Target sample sizes were achieved in 60% (6 out of 10 sections) of reservoir sections. In the remaining 40% (4 out of 10 sections), we collected at least 85% (≥ 255 crappies) of our target sample size (Table 1). The total number of crappies sampled was 3,097 crappies, with 1,470 and 1,627 crappies sampled from the lower and upper reservoir sections, respectively. Crappies sampled across reservoir sections ranged in count from 255 to 403 fish (Table 1). We sampled 472 crappies in autumn 2022 (ADCNR crew only), no crappies in spring 2023, 504 crappies in autumn 2023, and 2,121 crappies in spring 2024.

Although we considered crappie as single group (i.e., White and Black crappies combined), most of the crappies sampled were Black Crappie. We collected a total of 2,736

Black Crappie and 361 White Crappie. Most (n = 354) White Crappie that we sampled were collected from Wheeler Reservoir. There were seven White Crappie that were collected from Eufaula Reservoir.

Morphometrics and otolith processing

We collected fish with larger TLs and weights in lower reservoir sections, though sex ratios were similar among sections. Mean TLs collected in lower sections (255-mm TL - 275-mm TL) were greater than collected in upper sections (215-mm TL – 271-mm TL) (Table 2). Mean weights of crappies collected were also consistently greater in lower sections compared to upper sections, except for in Wheeler Reservoir (Table 2). The minimum TL fish collected between sections was relatively consistent, with the greatest difference being 67-mm TL between sections (Eufaula Reservoir, Table 2). The maximum TL was also relatively consistent with the greatest difference between fish collected in reservoir sections being 83-mm TL (Martin Reservoir, Table 2). The minimum and maximum weight collected for fish between most reservoir sections was also consistent (Table 2). The only apparent difference in maximum weight of fish collected (> 300 g) between reservoir sections was in Martin Reservoir (431-g difference, Table 2). Sex ratios between sections were relatively consistent, except for in the lower section of Eufaula Reservoir (i.e., 245 males collected, 68 females collected, Table 1).

Data analyses

<u>Size structure and body condition</u>

Our data indicated there was a size structure difference between fish collected in the upper and lower reservoir sections, but body condition was similar. The length frequencies of crappies from each reservoir indicated 80% (4 out of 5 reservoirs) of lower reservoir section samples comprised larger fish (i.e., TL) compared to the upper riverine sections (Figure 3). This trend was not observed in one reservoir (Wheeler), where both sections had a bimodal distribution peaking near the same lengths (250-mm and 310-mm TL) (Figure 3). Five K-S tests indicated that the frequency distribution of lengths collected in all reservoirs lower- and upper-section samples were significantly different ($D > 0.12$; $P < 0.05$). The mean of crappie length distributions varied in lower (mean: 263-mm TL, SD: 8-mm TL) and upper (mean: 238-mm TL, SD: 21-mm TL) reservoir sections. Further, the quantiles (25%, 50%, 70%) of the crappie length distributions in the lower and upper reservoir sections were 235-, 266-, 295-mm, and 206-, 237-, 272-mm, respectively. We found PSD-Q to be much lower in most upper sections (Table 3). Crappie populations in the lower reservoir sections had a PSD-Q 23.6 units (5.2 - 42 units; 95% confidence intervals) greater, on average, than crappie sampled from upper riverine samples ($P < 0.05$, $t = 3.34$, $df = 4.78$). Conversely, we found PSD-P was not significantly different between reservoir sections ($P = 0.19$, $t = 1.44$, $df = 7.13$). Although there were noticeable size structure differences, there was no significant difference in body index between collections in upper and lower sections of reservoirs (Table 4) ($t = 1.92$; $df = 2{,}955$; $P = 0.06$). The random effect of reservoir had a variance of 48.42 (SD = 6.96).

Growth

We found differences in size (i.e., TL) and crappie growth between the upper and lower reservoir sections. We collected longer crappies in the majority of lower, main lake portions of reservoirs compared to upper, riverine samples. Von Bertalanffy growth curves were fit to TL at ages for each reservoir section (Figures 4-7). Our estimates of instantaneous growth rates (i.e., growth coefficient K) for crappies in lower portions ranged from 0.40 to 0.58 (mean: 0.47, SD:

0.07, Appendix A). We estimated a wider range of instantaneous growth rates (0.40 to 0.68) in the upper reservoir populations (mean: 0.48 SD: 0.10, Appendix A).

Estimates of L_{inf} associated with crappie populations in the lower reservoir sections were consistently greater than populations sampled from the upper reservoir sections. L_{inf} associated with crappie from the lower reservoir sections ranged from 319- to 375-mm (mean: 341-mm, SD: 22-mm, Appendix A). We found smaller estimates of L_{inf} associated with upper collections (range: 286- to 337-mm, mean: 310-mm, SD: 19-mm, Appendix A). The time it took crappie to reach the current 229-mm MLL in most lower sections was slightly less than upper sections, but there was overlap in the ranges for all reservoir sections. We found fish collected in lower reservoirs were predicted to reach 229-mm TL at an age range of 1.8 to 3.2 yrs old (mean: 2.4 yrs, SD: 0.5 years, Appendix A). We estimated fish collected in the upper reservoirs had a slightly wider age range (1.8 to 3.4 yrs, mean: 2.9 yrs, SD: 0.7 years, Appendix A). The amount of time it took fish collected in the lower reservoirs to reach 229-mm TL, on average, was not statistically different compared to fish collected from the upper sections ($P = 0.20$; $t = 1.40$; $df = 7.28$).

<u>Mortality</u>

Examination of year class histograms indicated a slight variation in the structure of crappie populations sampled from the upper and lower reservoirs. The frequency of fish at certain year classes peaked in the same year (Figure 8), indicating factors affecting year-class strength at the different sites were similar. We sampled slightly more (i.e., a trend, not statistically more) fish in the lower reservoirs reflecting those strong year classes in 3 of 5 of the lower reservoir sites. In these reservoirs, counts of crappie in upper collections were slightly greater in the 3 years prior to the peak, but most (4 out of 5) lower collections comprised older year-classes (Figure 8). The maximum age collected was older in 3 out of 5 lower sections compared to upper sections (Figures 9-12). In Wheeler (Figure 9) and Eufaula (Figure 12) reservoirs, the maximum age of crappie collected was the same between sections. Our data indicated no instances where the maximum age of crappie was greater in the upper reservoirs compared to the lower reservoirs. In 4 out of 5 reservoirs, the maximum frequency of crappie ages was the same in both sections. In Wheeler Reservoir, the maximum frequency of crappie ages occurred one year later in the lower reservoir compared to the upper reservoir section (Figure 9).

In several reservoirs, we observed a trend of slightly higher mortality estimates and lower survival rates in crappie populations in the upper reservoirs compared to the lower reservoirs; however, there was quite a bit of overlap in these estimates. Total instantaneous mortality of crappie populations from the lower reservoirs ranged from 0.37 to 0.69 yr^{-1}, whereas it ranged from 0.51 to 0.80 yr^{-1} for populations in the upper reservoirs (Figures 9-12; Appendix A). Survival estimates of crappie sampled from the lower reservoirs ranged from 50% to 69%, whereas estimated survival overlapped but was somewhat lower in populations of the upper reservoirs (45% to 60%, Appendix A). Survival estimates were slightly lower in most upper reservoirs compared to lower sections, deviating ≤ 6%, except Martin Reservoir, where survival was 9% lower in the crappie population within the riverine section. In Wheeler Reservoir, however, we estimated survival was slightly higher in crappie populations from the upper section compared to the lower section (Figure 9). Total annual mortality is the inverse of the survival rate, so we saw the inverse trend of slightly higher total annual mortality for most upper section crappies. We found annual mortality was not significantly different in crappie populations in upper reservoir sections, on average, compared to the lower sections ($P = 0.11$; $t = 2.03$; $df = 4$).

We saw no trend in natural mortality estimates between reservoir sections. In 3 out of 5 reservoirs, M varied 0.05 yr^{-1} or less between sections (Appendix A). In Weiss Reservoir, however, the crappie population in the upper section had a 0.15 yr^{-1} lower M compared to the population of the lower section. Contrarily, crappie sampled from the upper section of Wheeler Reservoir had a greater (i.e., 0.10 yr^{-1}) M compared to crappies sampled from the lower section. Conditional natural mortality followed the same trends as observed for natural mortality (Appendix A).

<u>Age-structure models</u>

Results from our age-structured models indicated that a MLL would be more favorable (i.e., small declines of yield and harvest for an increase of memorable sized fish) for crappie populations in lower sections of reservoirs compared to upper sections of reservoirs. In the upper reservoirs, we saw larger decreases in predicted yield with increasing MLLs, when compared to no MLL (Table 6, Figures 12-16). In most upper reservoirs, the predicted number to be harvested decreased at greater magnitudes with MLLs. In Wheeler Reservoir, the predicted change in the number harvested was similar with each increasing MLL (Figure 16). We predicted greater increases in the number of fish over 300-mm TL with each MLL within most upper reservoirs, compared to the lower reservoirs. In Wheeler Reservoir, predicted magnitudes of change in the number of fish over memorable sized were similar between reservoir sections. Although we predicted most upper portions to have greater increases in memorable-sized fish, these upper populations start with less than half the amount of memorable-sized crappies with no MLL compared to lower sections. Further, the highest MLL simulated (279-mm) in most upper sections predicted lower number of memorable-sized crappies than the lower sections with no MLL.

Our models indicate the decrease in predicted crappie yield was greater for populations in the upper reservoirs compared to the lower reservoirs, except for Wheeler Reservoir where results were similar (Table 6, Figures 12-16). Crappie yield was predicted to decrease from 4% to 8% (mean: 5%, SE=1%) in the lower reservoirs under a 229-mm MLL, whereas yield would decrease from 8% to 14% (mean: 11%, SE = 2%) in upper reservoirs. With a 254-mm MLL, yield decreased 12% to 23% (mean: 15%, SE =3%) in the lower sections, and 24% to 38% (mean: 30%, SE = 3%) in upper sections. A 279-mm MLL decreased yield 27% to 44% (mean: 32%, SE = 4%) in the lower sections and 45% to 59% (mean: 54%, SE = 5%) in upper sections.

The predicted number of crappies harvested decreased more in the upper reservoirs compared to the lower reservoirs, except in Wheeler Reservoir where our results were similar (Table 6, Figures 12-16). A 229-mm MLL decreased predicted the number of fish harvested 15% to 25% (mean: 22%, SE = 2%) in lower sections, and 24% to 28% (mean: 26%, SE = 1%) in upper sections. With a 254-mm MLL, harvest decreased 37% to 47% (mean: 42%, SE = 2%) in lower sections, whereas upper sections decreased 47% to 56% (mean: 51%, SE = 2%). A 279-mm MLL largely decreased harvest in both lower (mean: 59%, SE = 3%) and upper (mean: 72%, SE = 2%) sections.

Our models indicated a greater increase in the number of memorable sized crappies in most of the upper reservoirs compared to the lower reservoirs, except in Wheeler Reservoir where our results were similar (Table 6, Figures 12-16). Under a 229-mm MLL, we predicted a 19% - 27% increase (mean: 24%, SE: 2%) in memorable-sized crappies in the lower reservoirs, whereas our model results indicated a 27% - 35% increase (mean: 31%, SE: 2%) in upper sections memorable crappies. With a 254-mm MLL, memorable-sized crappies increased 51% to 73% (mean: 58%, SE = 5%) in lower sections, and 71% to 99% (mean: 85%, SE: 7%) in upper sections. With a 279-mm MLL, memorable sized crappies increased 105% (SE: 10%) and 161% (SE: 12%) on average in lower and upper sections, respectively.

Discussion

Several of the parameters we estimated were similar in the upper and lower reservoir sections but variability within these groupings may have implications for management. The asymptotic end size for fish was different between sections and can be associated with factors that relate to growth (Spier 2002). These factors include density dependence, nutrient availability, ecosystem variables, and prey availability (Spier 2002; Michaletz et al. 2012; Lindmark 2022). Although these factors may be underlying reasons for differences in growth, angler pressure can also influence crappie population dynamics (Isermann et al. 2010a). Anglers may be able to target fish in upper, riverine areas easier due to small amounts of "open areas" to fish in, ultimately removing the larger fish; thus, our estimates indicate lower estimates of asymptotic lengths in the riverine sections. Further, forward-facing sonar may accelerate changes in population dynamics due to increased catch rates (Neely et al. 2022). Growth parameters are typically one of the factors that influence the results of equilibrium yield models (Brousseau and Armstrong 1987; Sammons et al. 2000; Miazga et al. 2022). Lower asymptotic lengths predicted from the von Bertalanffy growth equation influenced our results towards populations in lower, main lake areas being more favorable for MLLs. Our model results indicated different regulations for reservoir sections could be related to higher angler exploitation on harvestable fish in upper reservoirs (i.e., that we did not quantify), leaving fewer large fish for us to sample. Although this is possible, there could also be other underlying factors that may contribute such as environmental factors, density dependence factors, or differences in sampling efficiency.

Differences between the two reservoir sections could be influenced by differences in sampling efficiency. Sampling bias can significantly influence fish population assessments in upper and lower reservoirs due to differences in habitat, water quality, and fish behavior. Upper reservoirs can sometimes be cooler, with faster-flowing water and may support different species compositions or size structures compared to warmer, more lentic lower reservoirs (Miranda et al. 2024). Although temperature may influence spawning behavior (Siefert 1968), the male fish we collected during the spring seasons of both sections displayed spawning colors (i.e., black coloring on the bottom jaw), suggesting these fish spawned near the same time. In our reservoirs, differences between sections in water velocity and shoreline lengths were evident. If standardized sampling methods (e.g., electrofishing) are used without accounting for these environmental and structural differences, certain species or size classes can be underrepresented. Crappie populations, in particular, are vulnerable to sampling bias because their seasonal movements, schooling behavior, and vertical distribution, which can cause them to avoid common gear types during certain times of year (Maceina and Stimpert 1998; Gwinn et al. 2010). For example, crappies may suspend in deeper, open water during summer or winter, making them difficult to detect with shoreline electrofishing or shallow gill nets (Boxrucker and Ploskey 1988; Fischer and Quist 2014). Other behavior differences could include water-depth use or the time of year these fish spawn in different habitats (Phelps et al. 2009). For this reason, we standardized our sampling period to limit this as one possible concern; though changes in the amount of woody debris or water depth could not be controlled. Sampling biases can lead to misrepresentation of abundance estimates, size structure, and recruitment, complicating population assessments and harvest management (Allen and Miranda 1995; Boxrucker and

Ploskey 1988). Unfortunately, sampling large reservoirs is inherently difficult, and the associated sampling bias is difficult to quantify.

Differences in size structure and growth between the two reservoir sections could be due to nutrient availability, fish composition, and angler pressure. Nutrients and fish compositions are different between reservoir sections (Fontes De Oliveira et al. 2005), which could influence growth rates and natural mortality rates of crappies. Upper reservoirs may receive higher sediment and nutrient loads from river inflows, leading to increased phytoplankton productivity and zooplankton abundance, which support early life stages of fish (Thornton et al. 1990). However, excessive nutrients can cause eutrophication, leading to algal blooms, hypoxia, and poor water clarity, which may impair foraging efficiency and reduce growth, especially in visual predators (Rowe and Dean 1998). Although nutrient levels tend to decrease closer to the dam of impoundments, our upper riverine samples often comprise shorter fish compared to lower sections of these reservoirs. Crappie growth is influenced by prey availability, especially zooplankton and small forage fish. Ecosystems can be affected by abundant forage that enhance crappie growth by supporting piscivorous feeding (Michaletz et al. 2012; Galinat and Miller 2024), or hindered due to zooplankton depletion, that can suppress early fish growth and survival (Reed and Davies 1991; DeVries et al. 1998). Interspecific competition may also limit food resources, resulting in density-dependent growth reductions and delayed size-at-age (Boxrucker 2002b; Matthias et al. 2018). Slower growth extends the time crappies spend in vulnerable size classes, increasing natural mortality through predation and starvation. Consequently, high juvenile mortality and reduced recruitment to harvestable sizes lower equilibrium yield, especially in overpopulated or prey-limited systems (Allen and Miranda 1995). In our study, differences in forage and density dependence between reservoir sections were not assessed; thus, we are unsure of the factors that affect differences in crappie population dynamics between sections. Although size structures and some growth parameters were slightly different between the two sections, we did not see significant differences in average Wr between reservoir sections. Similarities in Wr may reflect abundant food availability (Gabelhouse 1991). It may also indicate that the slight differences in length-frequencies are not particularly biologically meaningful (or result from sampling bias, see above). Lastly, there are differences in the bioenergetic demands of fish occupying lotic and lentic ecosystems that could relate to our observed differences. A follow-up creel survey is an important next step to adequately address catch rates and the size distribution of fish kept by anglers in different reservoir sections.

Total annual mortality was similar between populations in each reservoir section, but minor trends in other mortality rates between sections could relate to multiple factors. In the early stages of a crappie's life, they are more susceptible to natural mortality (i.e., predation, starvation). After recruiting to the fishery, the fish also become susceptible to fishing mortality (Allen et al. 1998), which can be a large part of mortality in crappie populations (Isermann et al. 2010a). Fishing mortality rates could vary between reservoir sections for older crappies. Fishing mortality could be greater in upper, riverine areas due to there only being one main channel for these fish to school during spawning (i.e., spring) or feeding (i.e., autumn) periods (Gabelhouse 1991; Mitzner 1991). In our study, survival estimates in most of the lower, main lake portions of the reservoirs were slightly higher than upper, riverine sections. Higher survival could be attributed to fishing mortality, environmental factors, or species interactions (i.e., predator and prey abundance, nutrient availability, temperature variation) (Pauly 1980; Allen et al. 2008; Jorgensen and Holt 2013; Langangen et al. 2023). We hypothesized that crappie samples from upper reservoir sections may be characterized by higher mortality rates compared to lower.

Although we saw slightly higher mortality in upper reservoir sections, it is unclear if the differences between sections were biologically meaningful, especially given the variable nature of crappie populations (Mitzner 1991; Allen and Miranda 1995; Allen and Miranda 2001; Michaletz 2020). The small difference in these data only provides the first step into a more comprehensive look into how new technologies affect mortality between reservoir sections; thus, further experimenting is warranted.

Our equilibrium yield models generated different results between most upper and lower sections of each reservoir due to the growth differences found between sections. Equilibrium-yield model results are most influenced by growth and natural mortality parameters (Brousseau and Armstrong 1987; Sammons et al. 2000; Miazga et al. 2022). Because we held CM constant in our models, upper and lower sections of most reservoirs may benefit from different regulations due to growth differences. Slow-growth reservoirs with higher estimates of natural mortality often benefit most from no length limit, whereas faster growth populations warrant a MLL (Brousseau and Armstrong 1987; Colvin 1991; Allen and Miranda 1995; Maceina et al. 1998; Sammons et al. 2000; Isermann et al. 2002). In our study, the upper sections of most reservoirs were characterized by slower growth; thus, lower population models resulted in more favorable tradeoffs with length limits if management goals are to maximize yield and memorable sized crappies for limited declines in harvest.

Reservoir section differences may be due to a myriad of factors, but enforcing different management regulations within one reservoir could be complex. Naturally occurring factors could affect crappie populations between reservoir sections differently. Underlying factors could include reservoir structure and habitat, nutrient loads, temperature shifts, hydrology factors (i.e., flow, water levels), predator and forage abundance, crappie density dependence, and other factors (Pauly 1980; Buynak et al. 1989; Thornton et al. 1990; Gabelhouse 1991; Fontes De Oliveira et al. 2005; Allen et al. 2008; Jorgensen and Holt 2013; Stewart et al. 2015). Additionally, angler preference in harvest may vary between reservoir sections. Angler attitudes toward different fishing regulations within the same river or reservoir can vary depending on individual fishing goals, species targeted, and perceptions of fairness and effectiveness. Regulations, such as MLLs, may be viewed favorably by conservation-minded or trophy-oriented anglers who prioritize sustainability and quality fishing experiences (e.g., memorable size or trophy catches). However, harvest-oriented anglers, typified by many crappie fishers (Isermann et al 2010a), may perceive these regulations as overly restrictive, particularly if they reduce immediate catch opportunities or create confusion when rules differ across zones or species (Arostegui et al. 2021). Understanding the biological rationale behind regulations can also influence angler compliance and support. For example, anglers who are not informed about the benefits of protecting juvenile fish or spawning aggregations may be less supportive of slot limits or seasonal closures (Arostegui et al. 2021). When different regulations are applied within a single reservoir, anglers may express frustration or noncompliance due to perceived complexity or inequity. Therefore, effective communication, stakeholder engagement, and clear signage are beneficial for gaining angler support and ensuring successful implementation if complex fishing regulations are adopted.

Chapter III Tables

Table 3-1. The number of crappies sampled from each reservoir section (i.e., upper and lower), where we examined differences in population dynamics and how each section would respond to MLLs. Female and male collections are included but may not sum to the total collected in each section due to intermediate fish being collected.

Reservoir	Section	Males	Females	Total
Eufaula	Lower	245	68	313
	Upper	159	146	314
Harris/Wedowee	Lower	140	149	291
	Upper	194	188	403
Martin	Lower	166	154	329
	Upper	134	166	326
Weiss	Lower	189	92	282
	Upper	133	144	300
Wheeler	Lower	119	115	255
	Upper	128	152	284

Table 3-2. Morphometric data of fish collected in lower and upper sections. Data are mean length and weights collected, and standard deviations (SD). The minimum and maximum length and weights collected in each section are also listed.

Reservoir	Reservoir section	Mean length (mm)	SD length (mm)	Mean weight (g)	SD weight (g)	Minimum length (mm)	Maximum length (mm)	Minimum weight (g)	Maximum weight (g)
Eufaula	Lower	255	40	268	139	144	372	47	911
	Upper	232	48	199	124	87	354	6	755
Harris/ Wedowee	Lower	275	40	311	135	169	373	59	810
	Upper	242	41	221	117	118	367	17	735
Martin	Lower	264	44	271	135	83	404	6	929
	Upper	229	38	172	88	69	321	28	498
Weiss	Lower	264	39	295	128	102	379	7	820
	Upper	215	56	171	160	92	410	10	1116
Wheeler	Lower	257	67	328	228	89	385	9	1030
	Upper	271	54	364	200	91	380	9	971

Table 3-3. The proportion of larger-than-stock-size crappies to at-least-stock-size crappies (PSD) in each reservoir section. PSDs were defined by dividing the number of quality (PSD-Q) (≥ 250 mm) and preferred (PSD-P) (≥ 300 mm) size crappies by the number of at least stock (≥ 130 mm) size crappies then multiplying times 100. PSD-Q and PSD-P of crappies collected in each reservoir are distinguished between reservoir sections (lower versus upper).

Reservoir	Lower PSD-Q	Lower PSD-P	Upper PSD-Q	Upper PSD-P
Eufaula	57	10	37	6
Harris	70	30	43	7
Martin	65	23	28	2
Weiss	63	14	27	5
Wheeler	62	31	64	35

Table 3-4. The lower and upper mean Wr of crappie populations collected in each reservoir section. Crappies under 130-mm TL were not included in these analyses as we were not able to identify reproductive organs in most fish under this TL.

Reservoir	Lower Wr	Upper Wr
Eufaula	93	91
Harris	88	91
Martin	86	87
Weiss	94	91
Wheeler	96	98

Table 3-5. Parameters derived from our age and growth analyses between upper and lower portions of each reservoir that were used in our Beverton Holt equilibrium yield models. The youngest age for fish in each reservoir was held constant at 0, and average length at maturity in crappie was also held constant at 175 mm TL for all models. Length weight regressions from each section were used to derive a (i.e., y-intercept) and b (i.e., slope) for each model.

Reservoir	Linf (mm)	K	t0	Max age (years)	a	b
Eufaula Lower	319	0.40	-0.05	10	2.0e-06	3.36
Eufaula Upper	301	0.40	-0.05	10	3.0e-06	3.28
Martin Lower	339	0.45	-0.05	13	6.0e-06	3.15
Martin Upper	286	0.48	-0.05	11	5.0e-06	3.19
Harris/Wedowee Lower	346	0.43	-0.05	11	9.0e-06	3.08
Harris/Wedowee Upper	312	0.41	-0.05	16	2.0e-06	3.33
Weiss Lower	326	0.58	-0.05	14	4.0e-06	3.25
Weiss Upper	313	0.44	-0.05	13	4.0e-06	3.24
Wheeler Lower	375	0.51	-0.05	9	2.0e-06	3.34
Wheeler Upper	337	0.65	-0.05	9	5.0e-06	3.20

Table 3-6. Predicted percent magnitude changes at 40% CM with a 229-, 254-, and 279-mm MLL for crappies in lower and upper sections, when compared to the assumed "no MLL" (200-mm). Metrics include predicted yield ("Yield"), predicted harvest ("Harvest"), and predicted number of crappies at or over memorable sized (300-mm) in the population ("N300").

Reservoir	Metric	MLLs (mm) at 40% CM for lower collections			MLLs (mm) at 40% CM for upper collections		
		229	254	279	229	254	279
Eufaula	Yield	- 8%	- 23%	- 44%	- 14%	- 34%	- 59%
	Harvest	- 23%	- 47%	- 67%	- 28%	- 54%	- 75%
	N300	+ 27%	+ 73%	+ 135%	+ 35%	+ 94%	+ 176%
Harris/ Wedowee	Yield	- 4%	- 12%	- 27%	- 9%	- 26%	- 48%
	Harvest	- 25%	- 41%	- 58%	- 24%	- 49%	- 69%
	N300	+ 24%	+ 54%	+ 96%	+ 28%	+ 77%	+ 146%
Martin	Yield	- 4%	- 13%	- 28%	- 15%	- 38%	- 65%
	Harvest	- 25%	- 42%	- 58%	- 28%	- 56%	- 78%
	N300	+ 25%	+ 55%	+ 99%	+ 35%	+ 99%	+ 186%
Weiss	Yield	- 4%	- 13%	- 28%	- 8%	- 24%	- 45%
	Harvest	- 15%	- 37%	- 54%	- 25%	- 47%	- 67%
	N300	+ 19%	+ 51%	+ 89%	+ 27%	+ 71%	+ 134%
Wheeler	Yield	- 1%	- 4%	- 10%	- 2%	- 9%	- 20%
	Harvest	- 8%	- 24%	- 41%	- 7%	- 23%	- 43%
	N300	+ 10%	+ 33%	+ 60%	+ 9%	+ 31%	+ 62%

Chapter III Figures

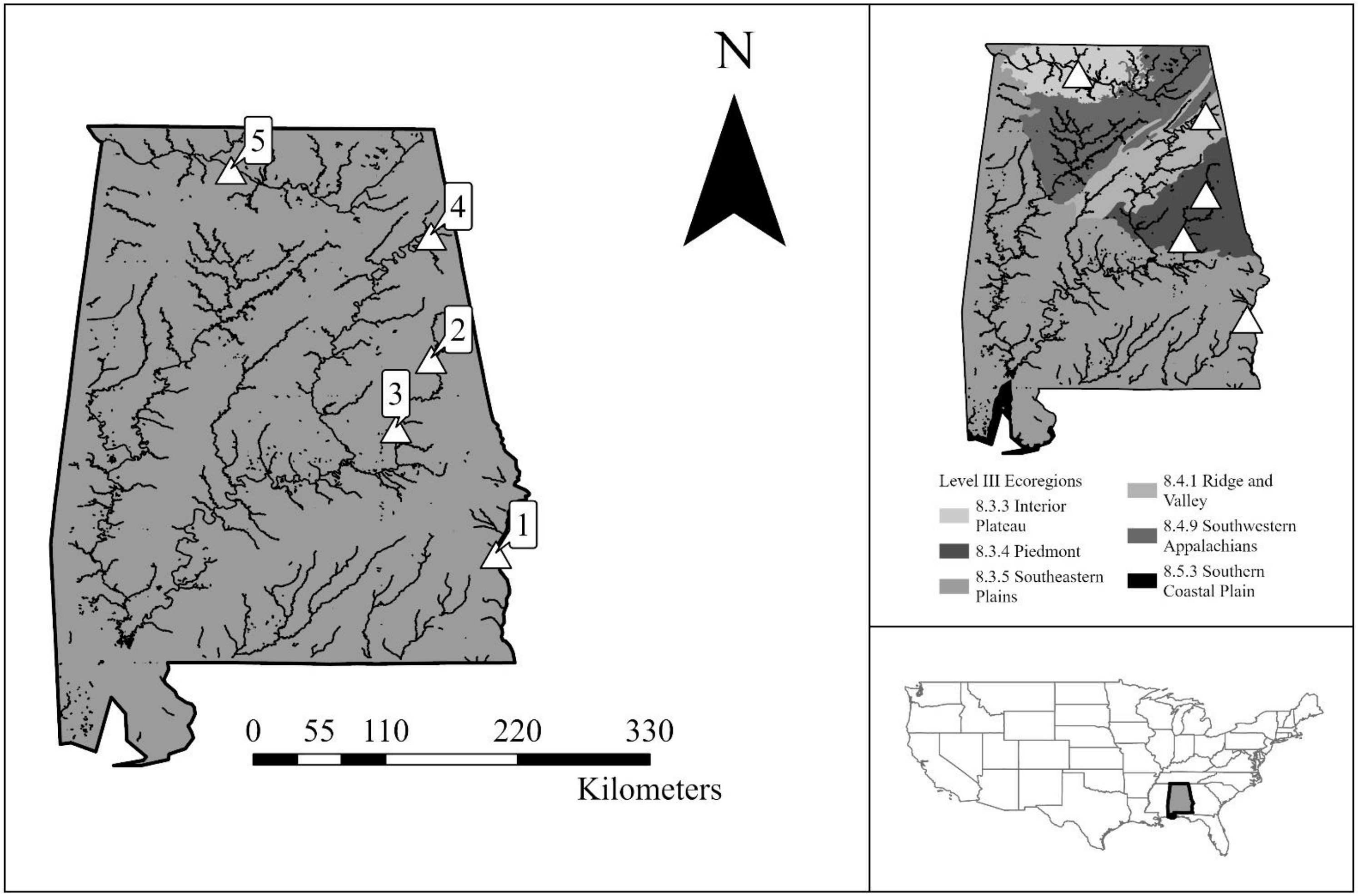

Figure 3-1. Reservoirs sampled from 2022-2024 to examine population differences between upper and lower sections of reservoirs. Reservoirs are 1) Eufaula, 2) Harris/Wedowee, 3) Martin, 4) Weiss, 5) Wheeler reservoirs.

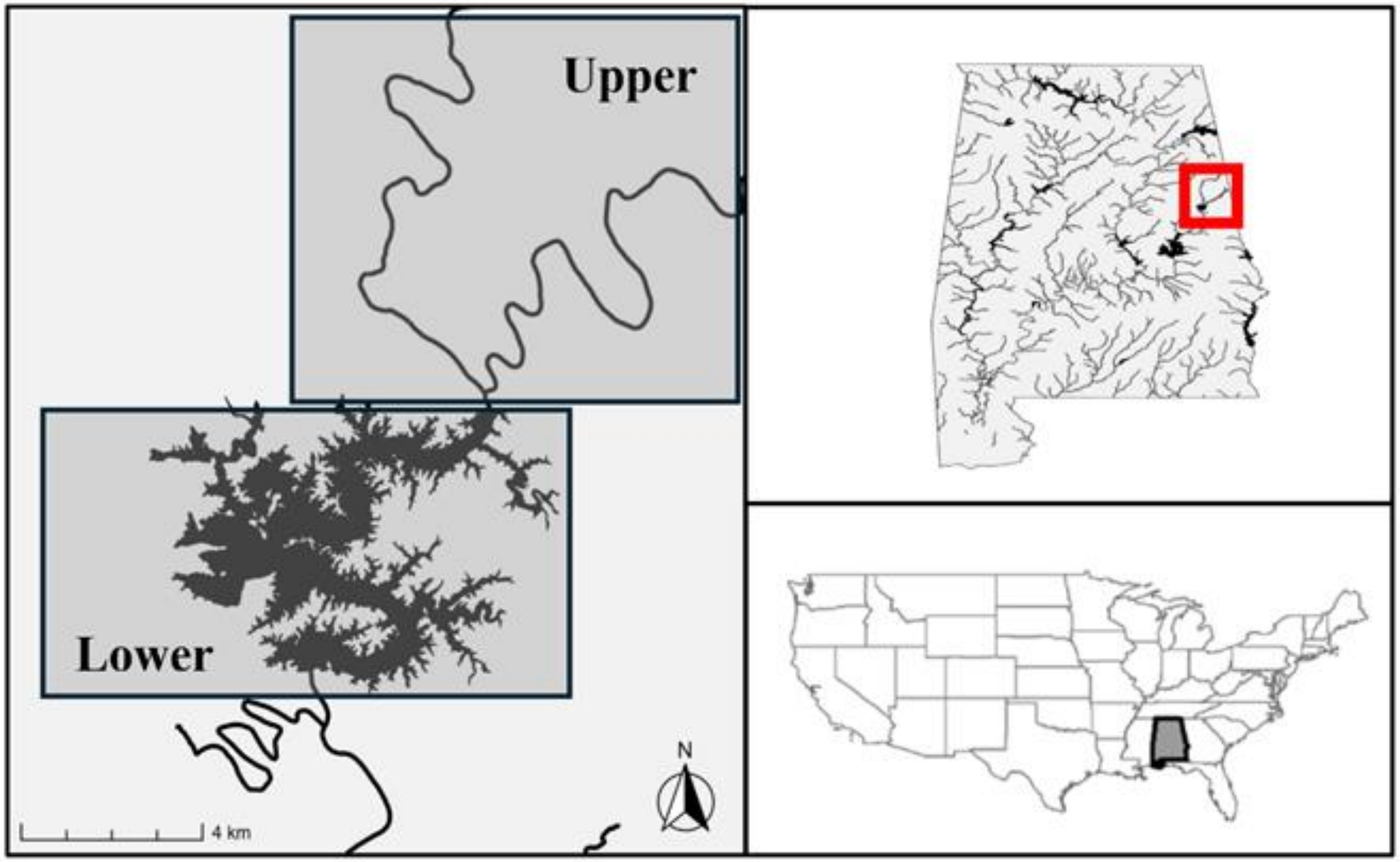

Figure 3-2. Example of “lower” versus “upper” reservoir section classifications using Harris Reservoir in east-central Alabama. All crappies collected in the upper portion of the reservoirs with flow present was given an “upper” designation. All crappies collected in the lower reservoir sections where water was pooled with no perceivable flow was classified was given a “lower” designation.

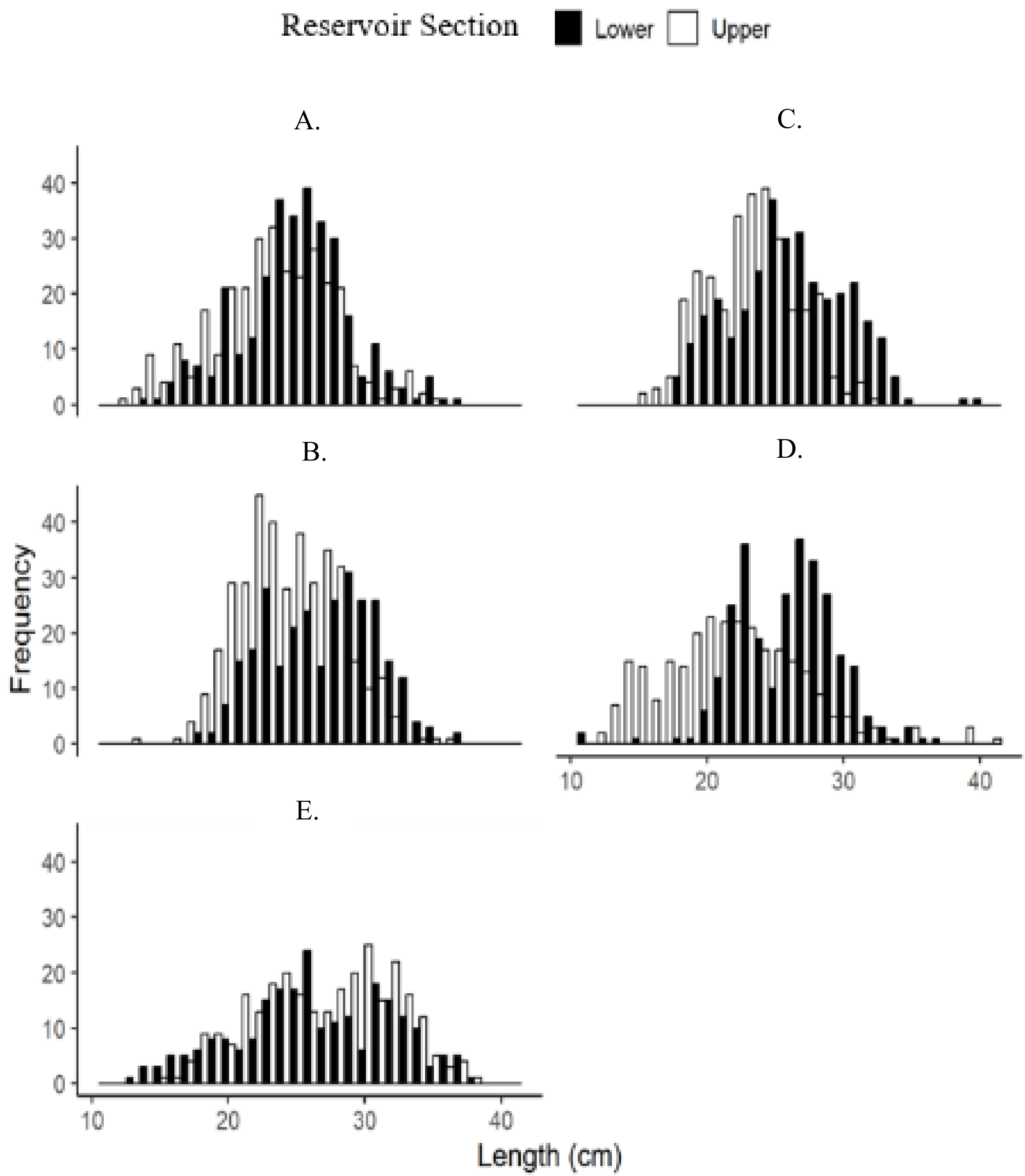

Figure 3-3. Total length (i.e., length on X axes) frequencies of crappies sampled from the upper and lower reservoir sections. All length frequencies start at 10-cm on the X-axis. Reservoirs were A.) Eufaula, B.) Harris/Wedowee, C.) Martin, D.) Weiss, and E.) Wheeler reservoirs.

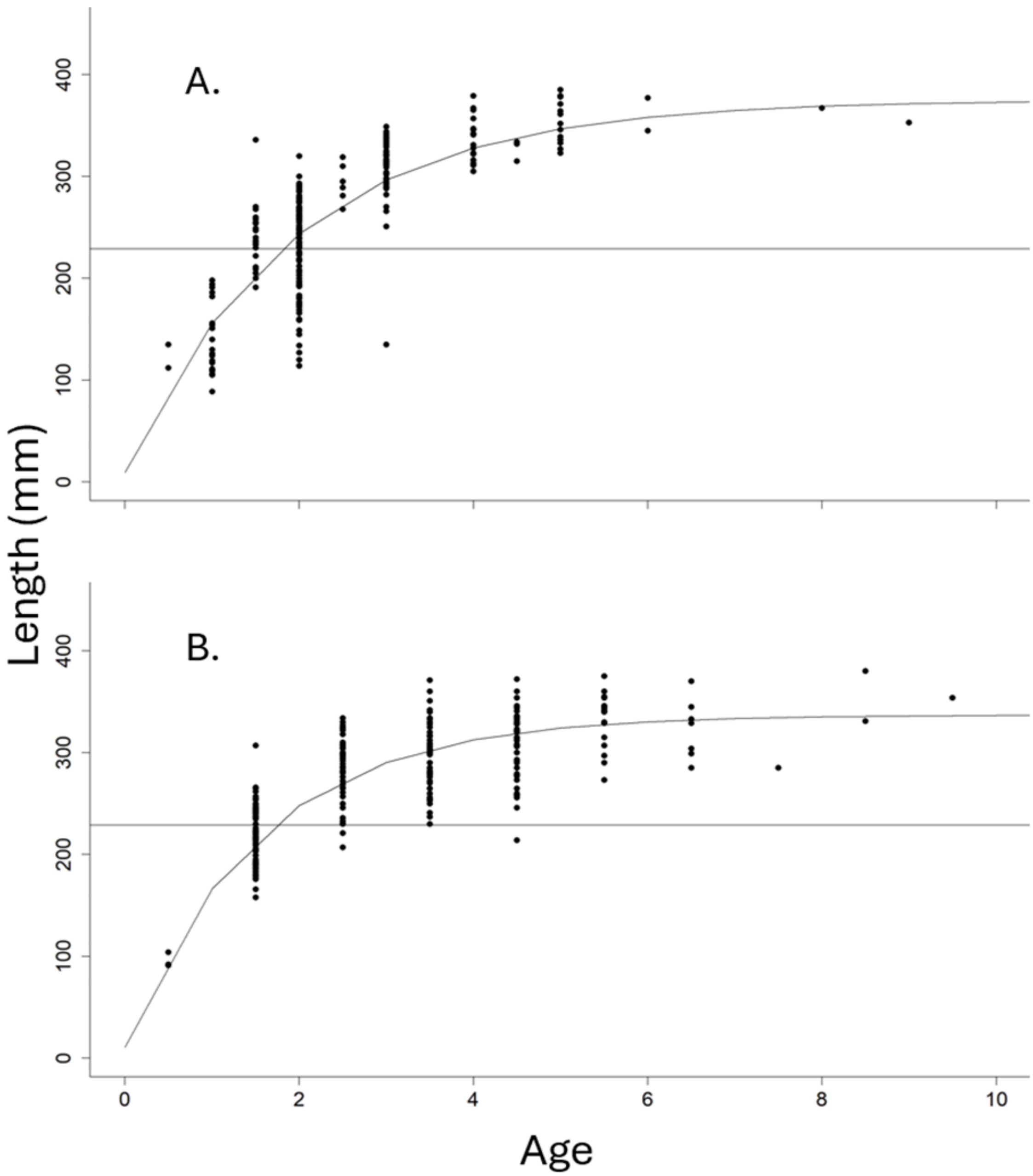

Figure 3-4. Von Bertalanffy growth equation results for crappie populations in A.) lower and B.) upper sections of Wheeler Reservoir within the Interior Plateau ecoregion. The horizontal line within the graphs reflects the current statewide 229-mm minimum length limit. Parameters estimated were K, the growth coefficient; Linf, the estimated length (TL, mm) of the average crappie in each population at the end of its life; and the estimated time it takes for crappies to reach the current statewide minimum length limit (229-mm). Parameters are reported in Appendix A

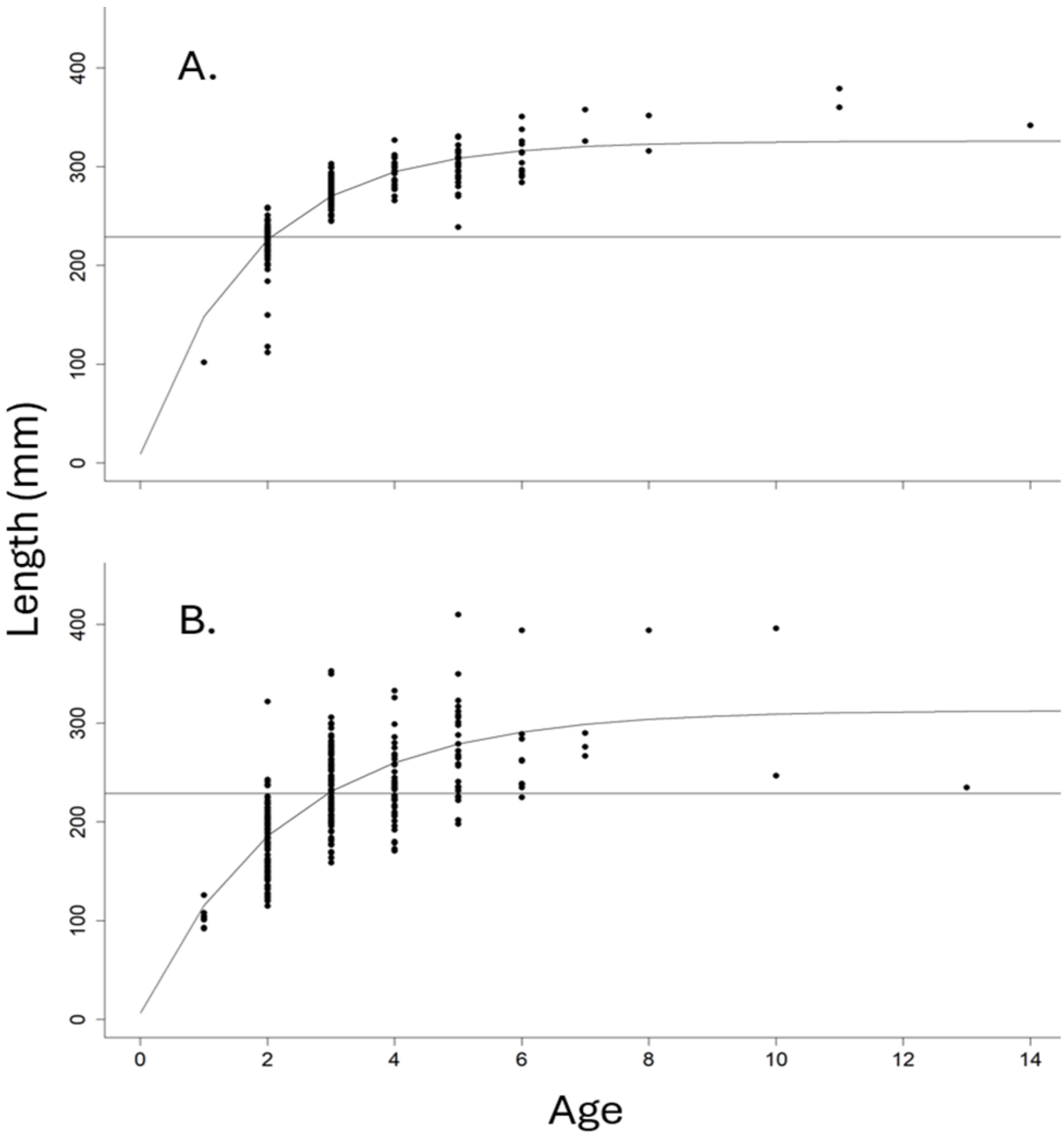

Figure 3-5. Von Bertalanffy growth equation results for crappie populations in A.) lower and B.) upper sections in Weiss Reservoir within the Ridge and Valley ecoregion. The horizontal line within the graphs represents the current statewide 229-mm minimum length limit. Parameters estimated were K, the growth coefficient; Linf, the estimated length (TL, mm) of the average crappie in each population at the end of its life; and the estimated time it takes for crappies to reach the current statewide minimum length limit (229-mm). Parameters are reported in Appendix A.

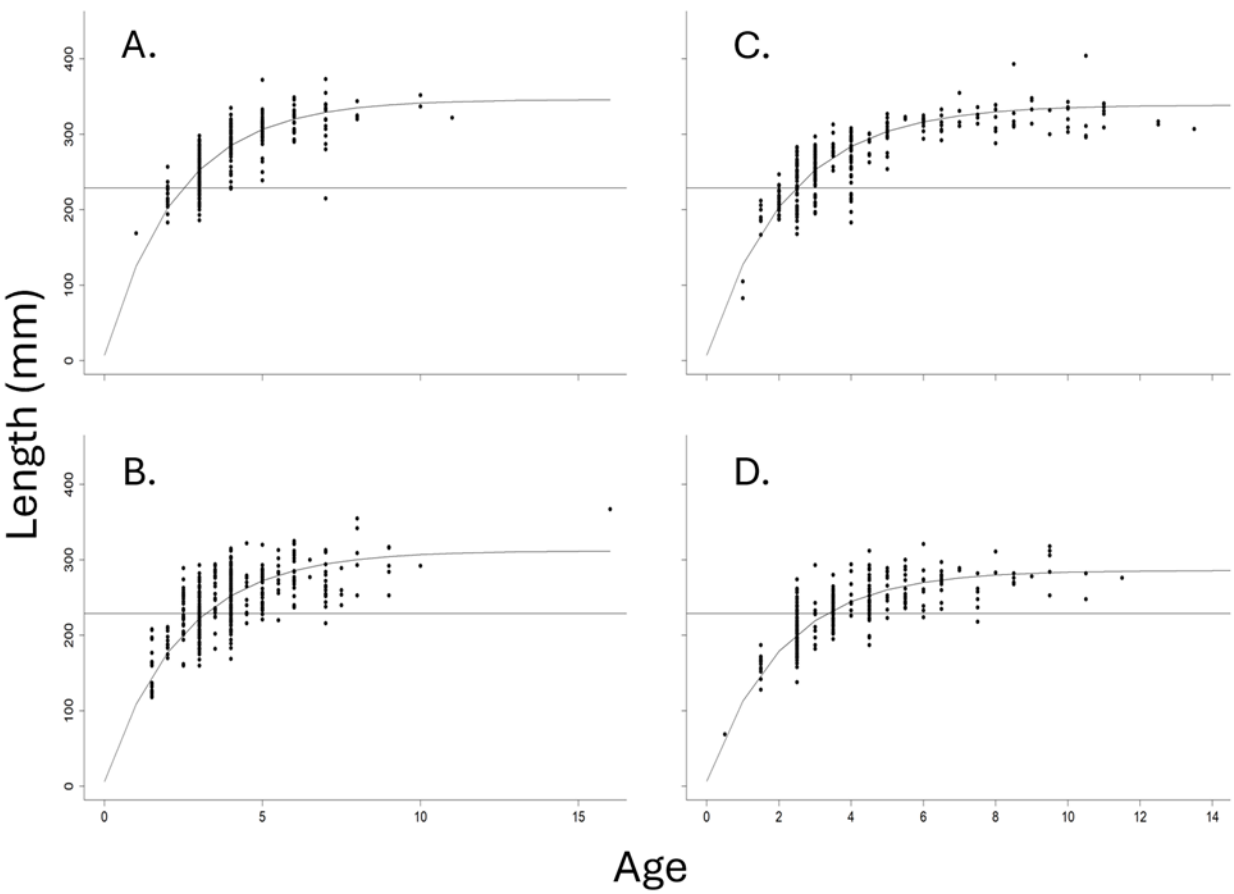

Figure 3-6. Results from Von Bertalanffy growth equations for crappie populations in lower (Top graphs, A. and C.) and upper sections (Bottom graphs, B. & D.) in Harris/Wedowee (Left graphs, A. & B.) and Martin Reservoirs (Right graphs, C. & D.) within the Piedmont ecoregion. The horizontal line within the graphs reflects the current statewide 229-mm minimum length limit. Parameters estimated were K, the growth coefficient; Linf, the estimated length (TL, mm) of the average crappie in each population at the end of its life; and the estimated time it takes for crappies to reach the current statewide minimum length limit (229-mm). Parameters are reported in Appendix A.

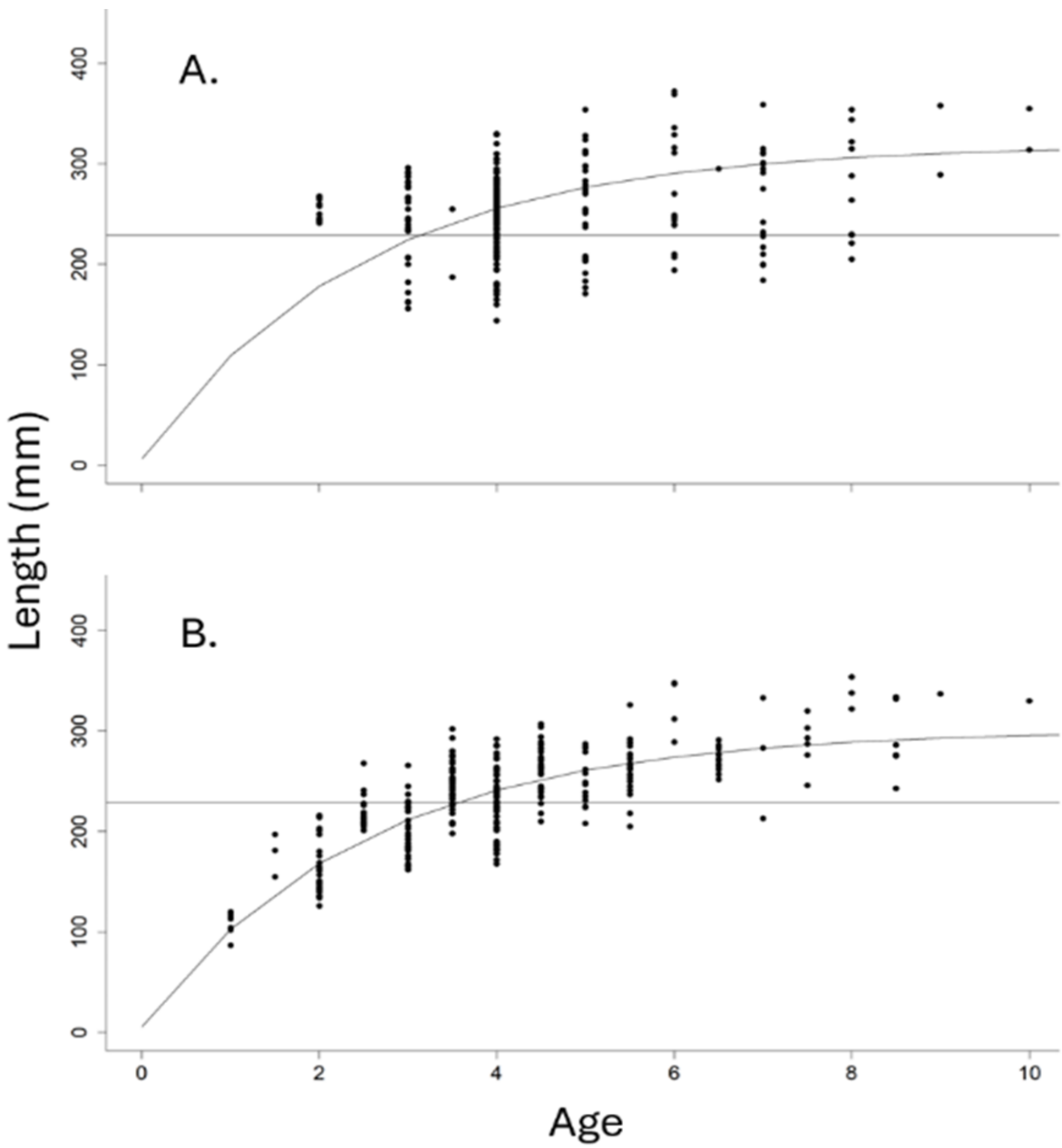

Figure 3-7. Von Bertalanffy growth equation results for crappie populations in A.) lower and B.) upper sections in Eufaula Reservoir within the Southeastern Plains. The horizontal line within the graphs represents the current statewide 229-mm minimum length limit. Parameters estimated were K, the growth coefficient; Linf, the estimated length (TL, mm) of the average crappie in each population at the end of its life; and the estimated time it takes for crappies to reach the current statewide minimum length limit (229-mm). Parameters are reported in Appendix A.

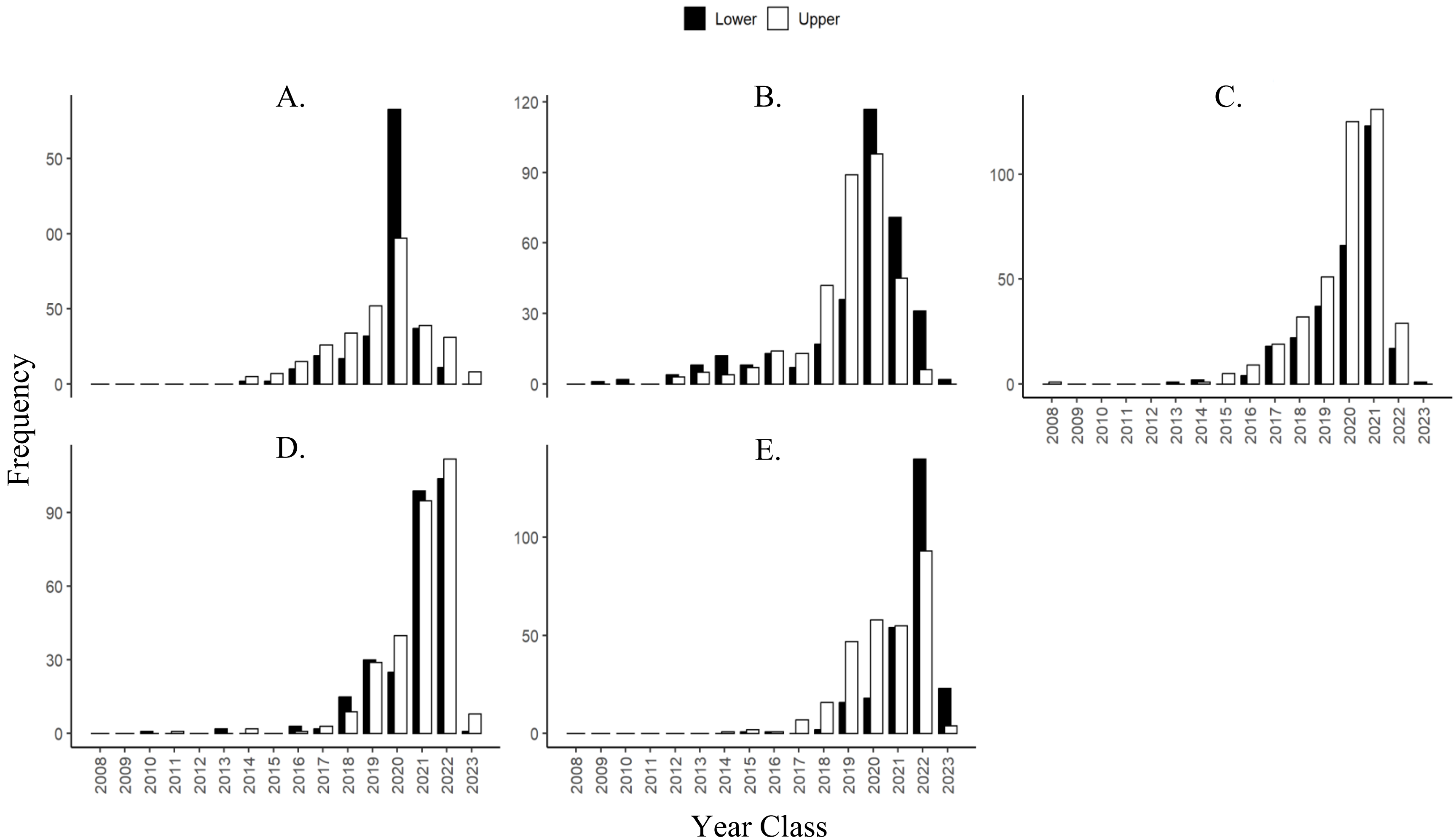

Figure 3-8. Year-class frequency histograms associated with crappies collected from the lower (black bars) and upper (white bars) sections. Sample locations were A.) Eufaula, B.) Martin, C.) Harris/Wedowee, D.) Weiss, and E.) Wheeler reservoirs.

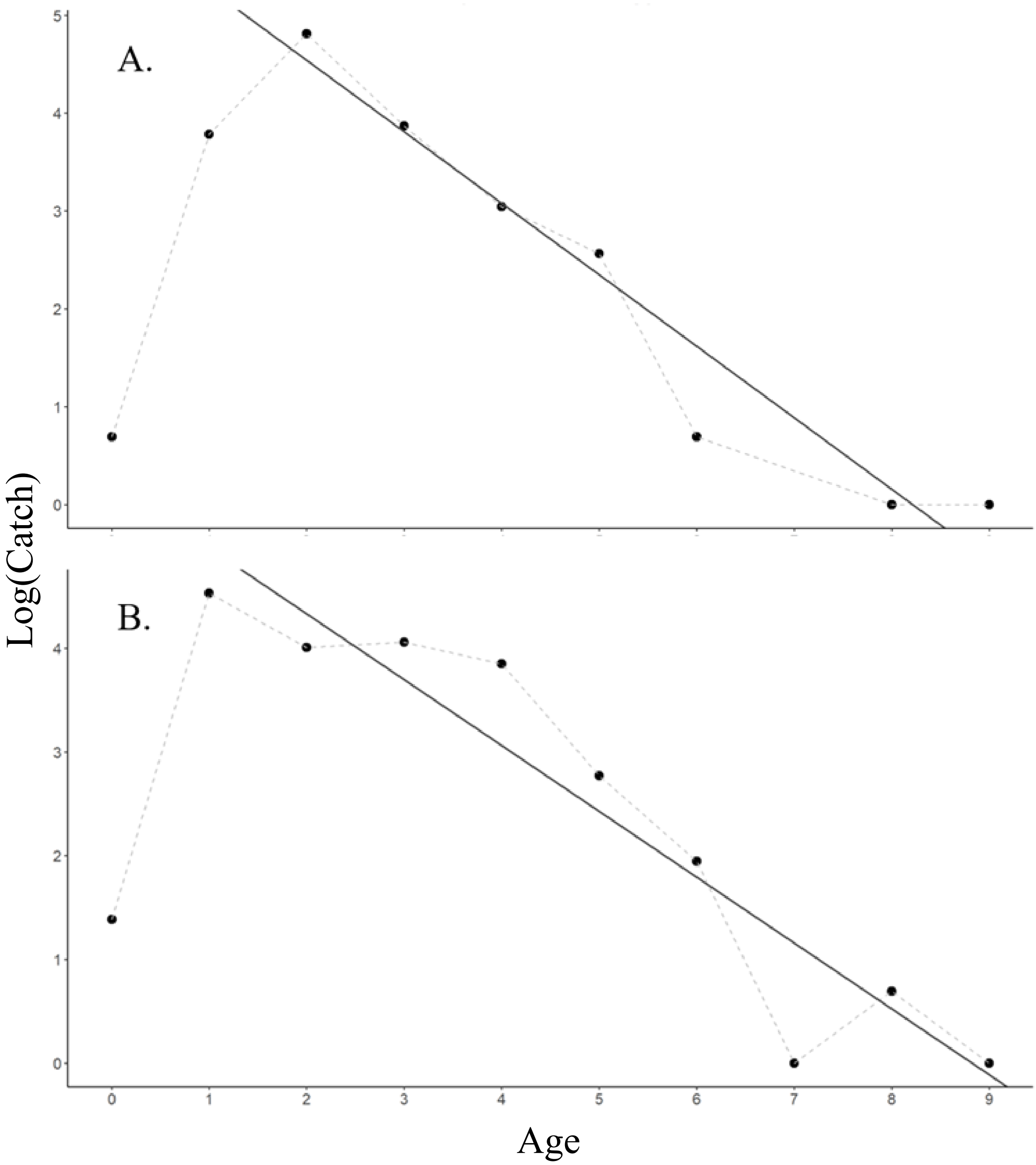

Figure 3-9. Catch-curves associated with crappie in the A.) lower and B.) upper portions of Wheeler Reservoir within the Interior Plateau ecoregion. The solid line shown is the regression line from the descending limb of the catch curve, whereas the dotted line follows the actual numbers collected for each age class.

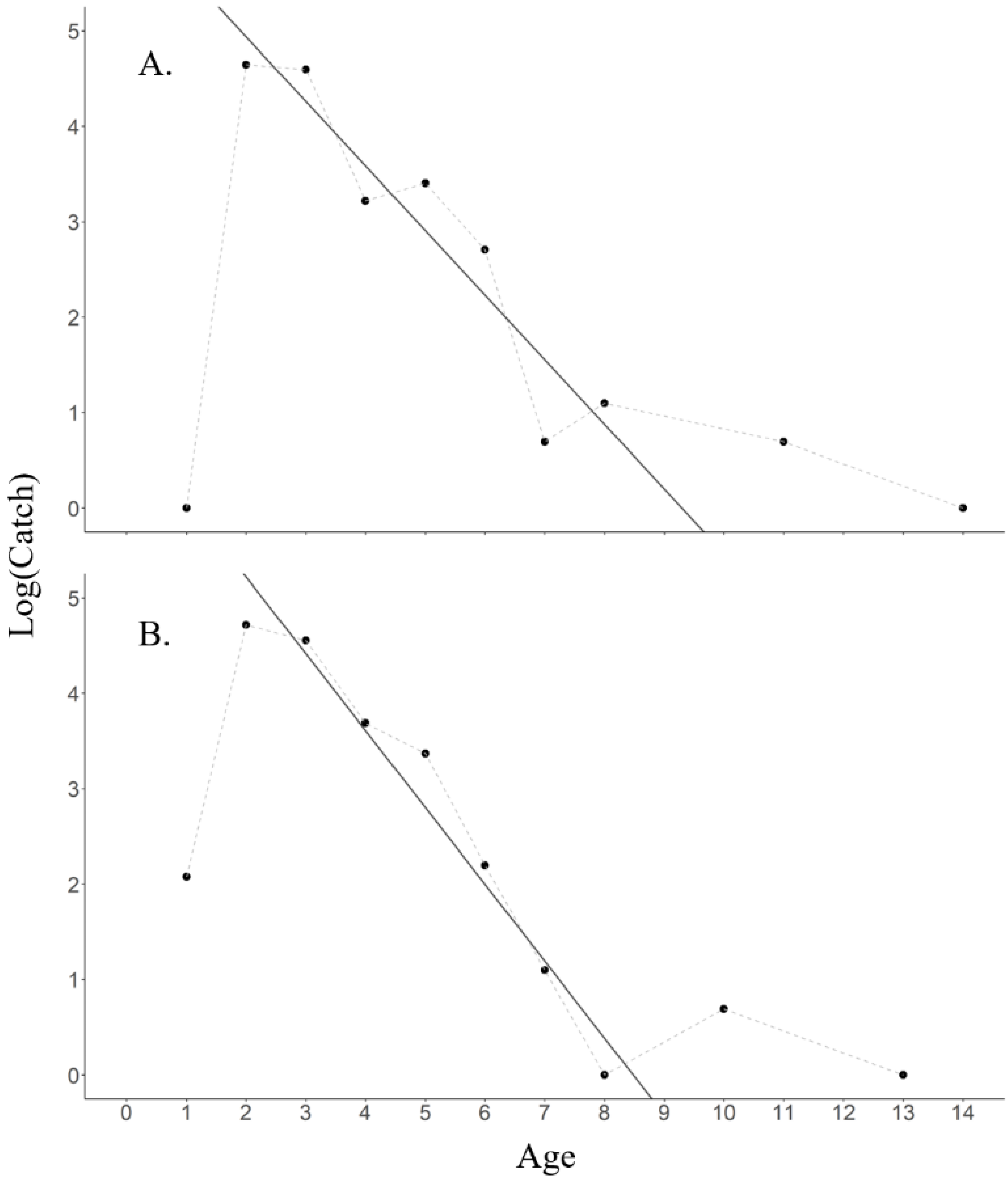

Figure 3-10. Catch-curves associated with crappie in the A.) Lower and B.) Upper collections for the crappie sampled in Weiss Reservoir within the Ridge and Valley ecoregion. The solid line shown is the regression line from the descending limb of the catch curve, whereas the dotted line follows the actual numbers collected for each age class.

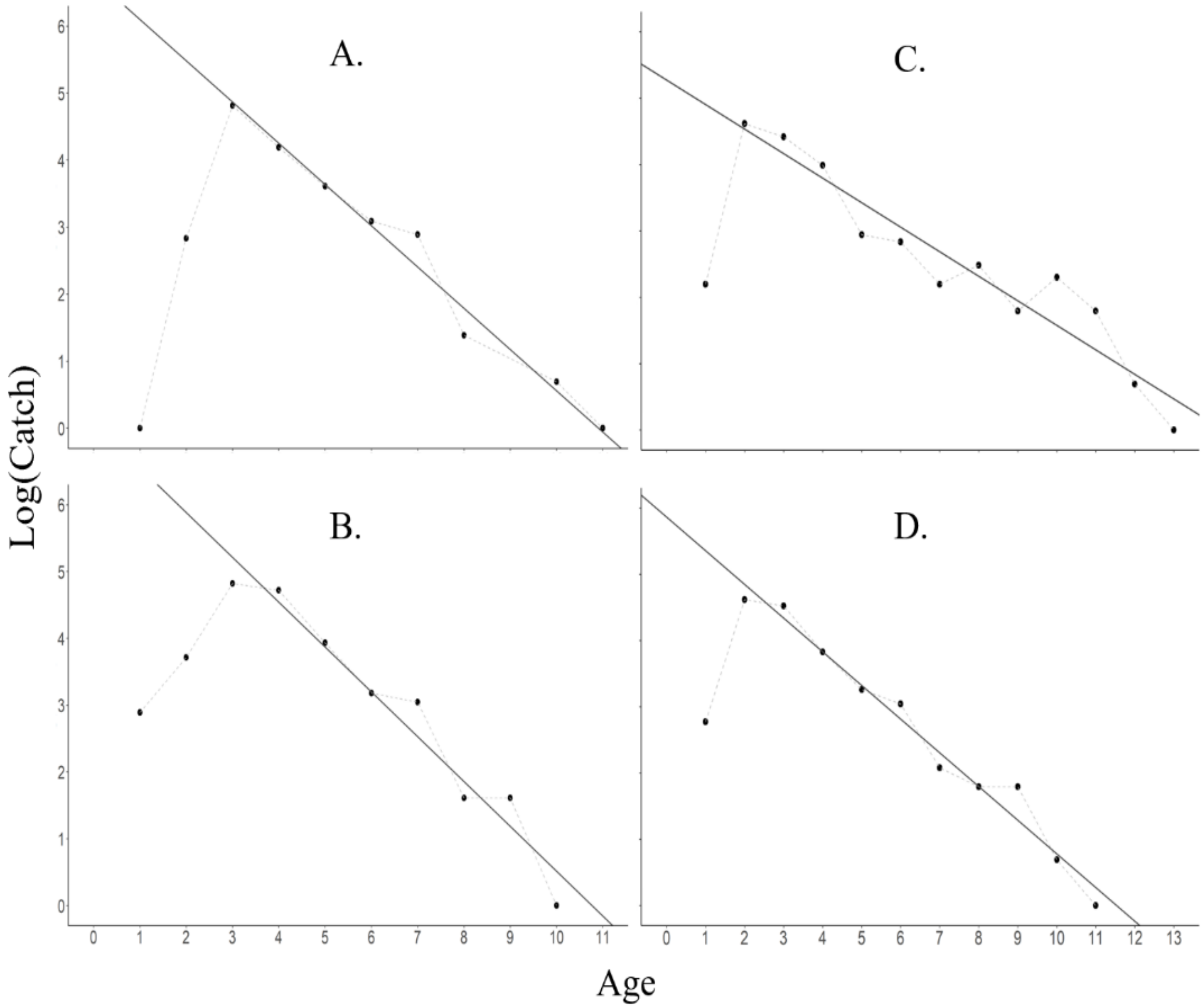

Figure 3-11. Crappie Catch-curves reflecting populations in the lower (Top graphs, A. and C.) and upper sections (Bottom graphs, B. & D.) in Harris/Wedowee (Left graphs, A. & B.) and Martin reservoirs (Right graphs, C. & D.) within the Piedmont ecoregion. The solid line shown is the regression line from the descending limb of the catch curve, whereas the dotted line follows the actual numbers collected for each age class.

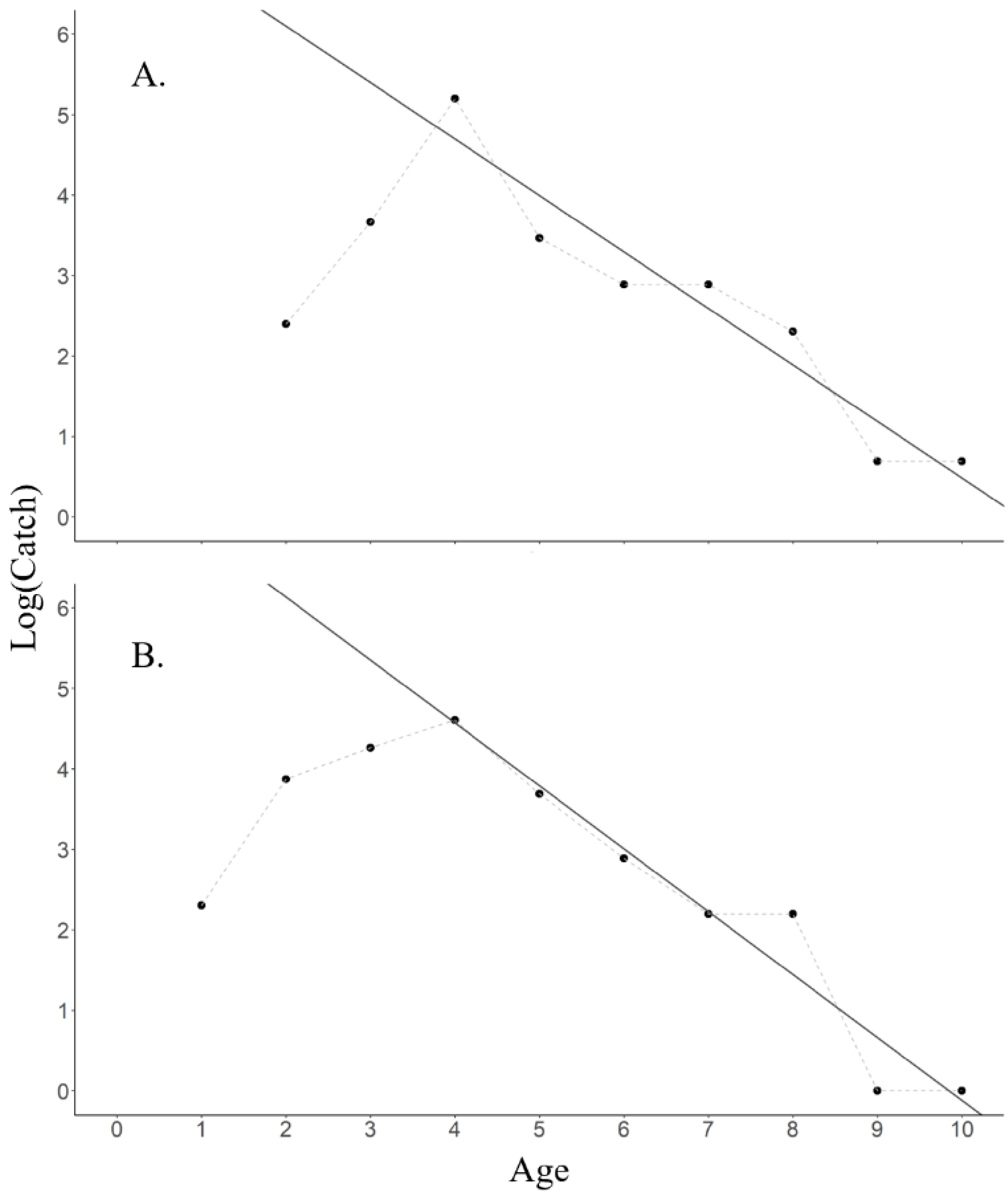

Figure 3-12. Catch-curves associated with crappie in the A.) Lower and B.) Upper collections for the crappie sampled in Eufaula Reservoir within the Southeastern Plains ecoregion. The solid line shown is the regression line from the descending limb of the catch curve, whereas the dotted line follows the actual numbers collected for each age class.

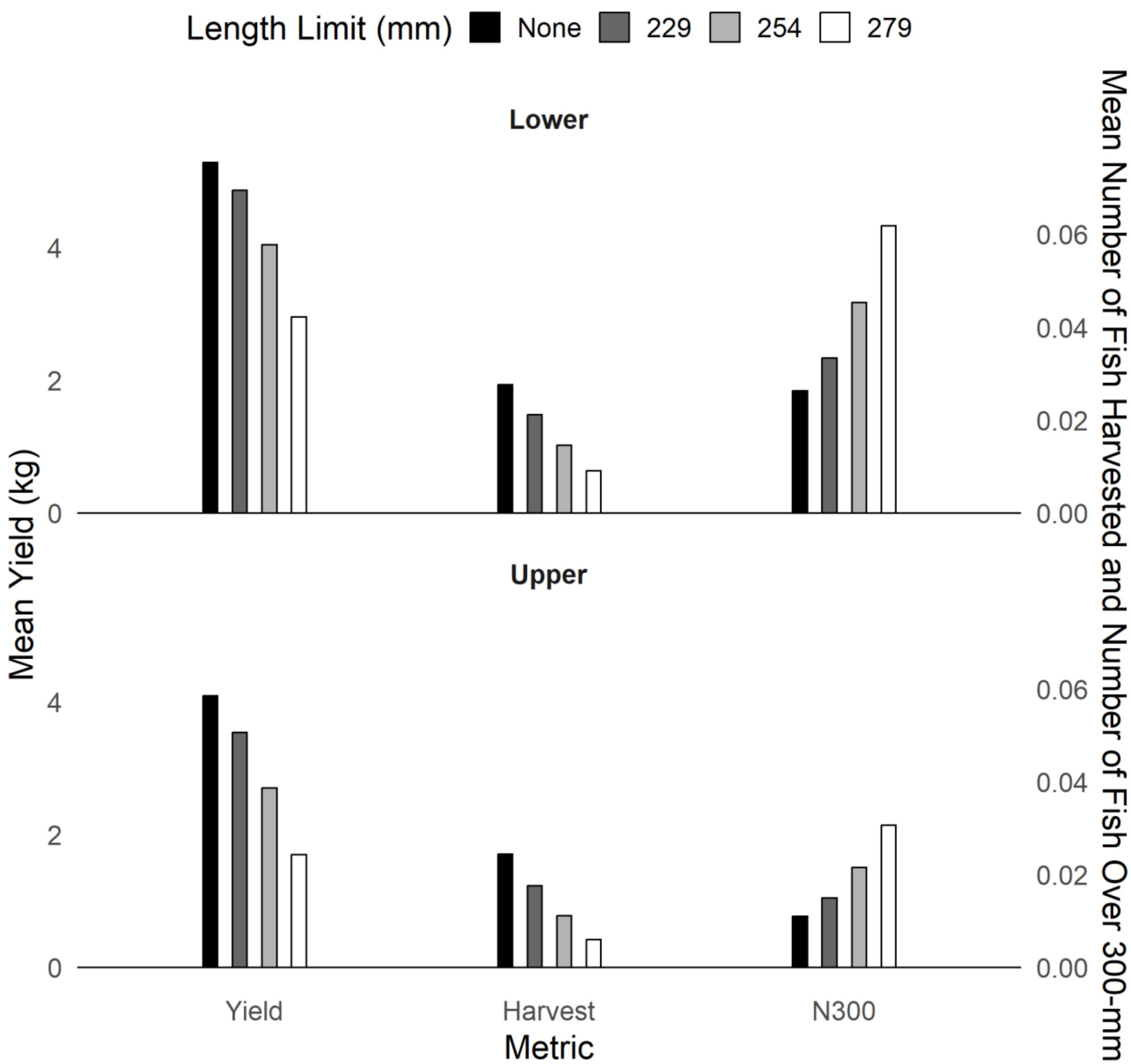

Figure 3-13. Mean yield (kg), mean number of fish harvested (per 1 recruit), and mean number of fish over 300-mm ("N300") in the population at an equilibrium of "1" under four different size restrictions and between reservoir sections in Eufaula Reservoir, Alabama. Data are averaged over exploitation rates from 0.20 to 0.60, using 0.40 for conditional natural mortality for both models.

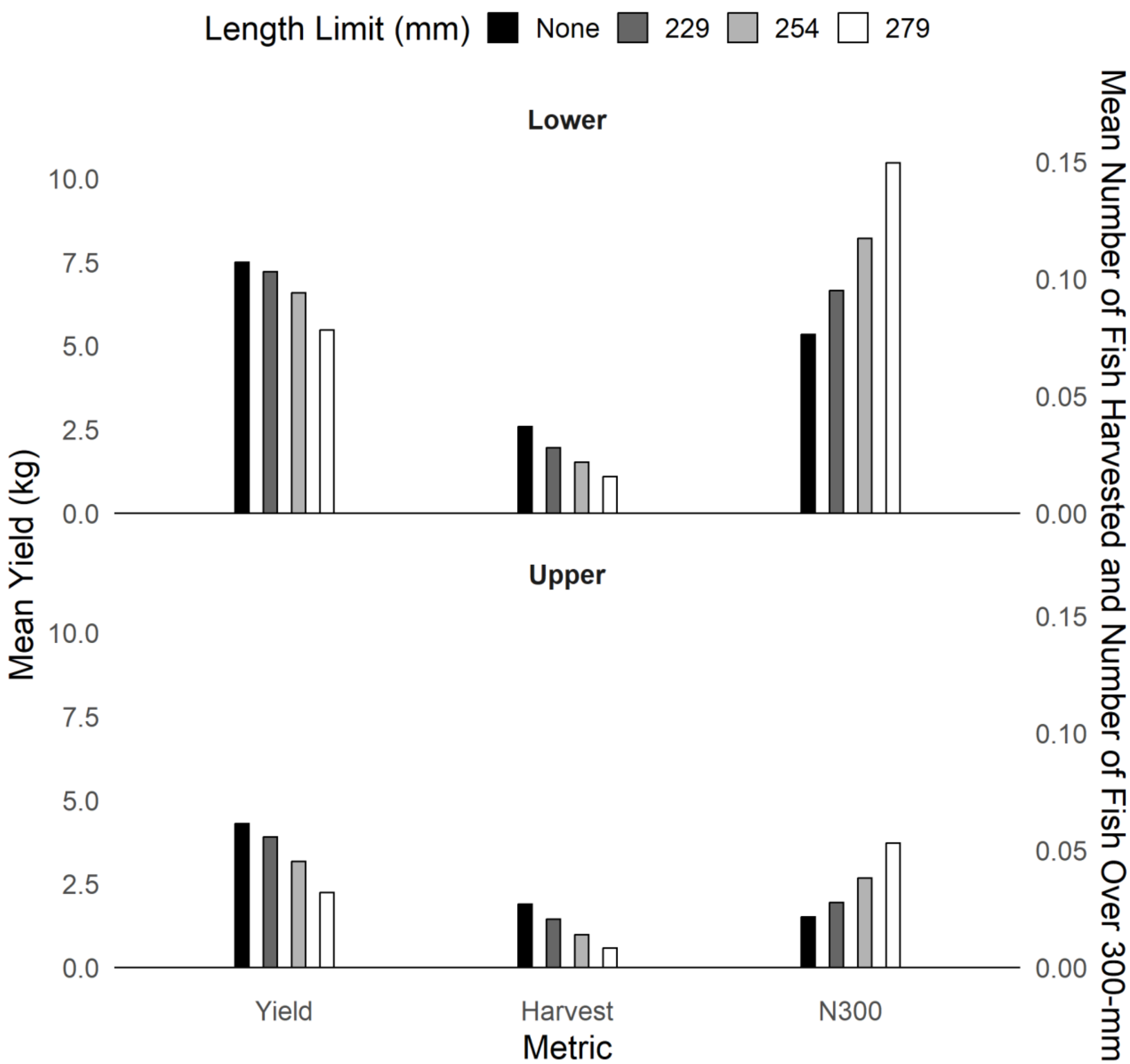

Figure 3-14. Mean yield (kg), mean number of fish harvested (per 1 recruit), and mean number of fish over 300-mm ("N300") in the population at an equilibrium of "1" under four different size restrictions and between reservoir sections in Harris/Wedowee Reservoir, Alabama. Data are averaged over exploitation rates from 0.20 to 0.60, using 0.40 for conditional natural mortality for both models.

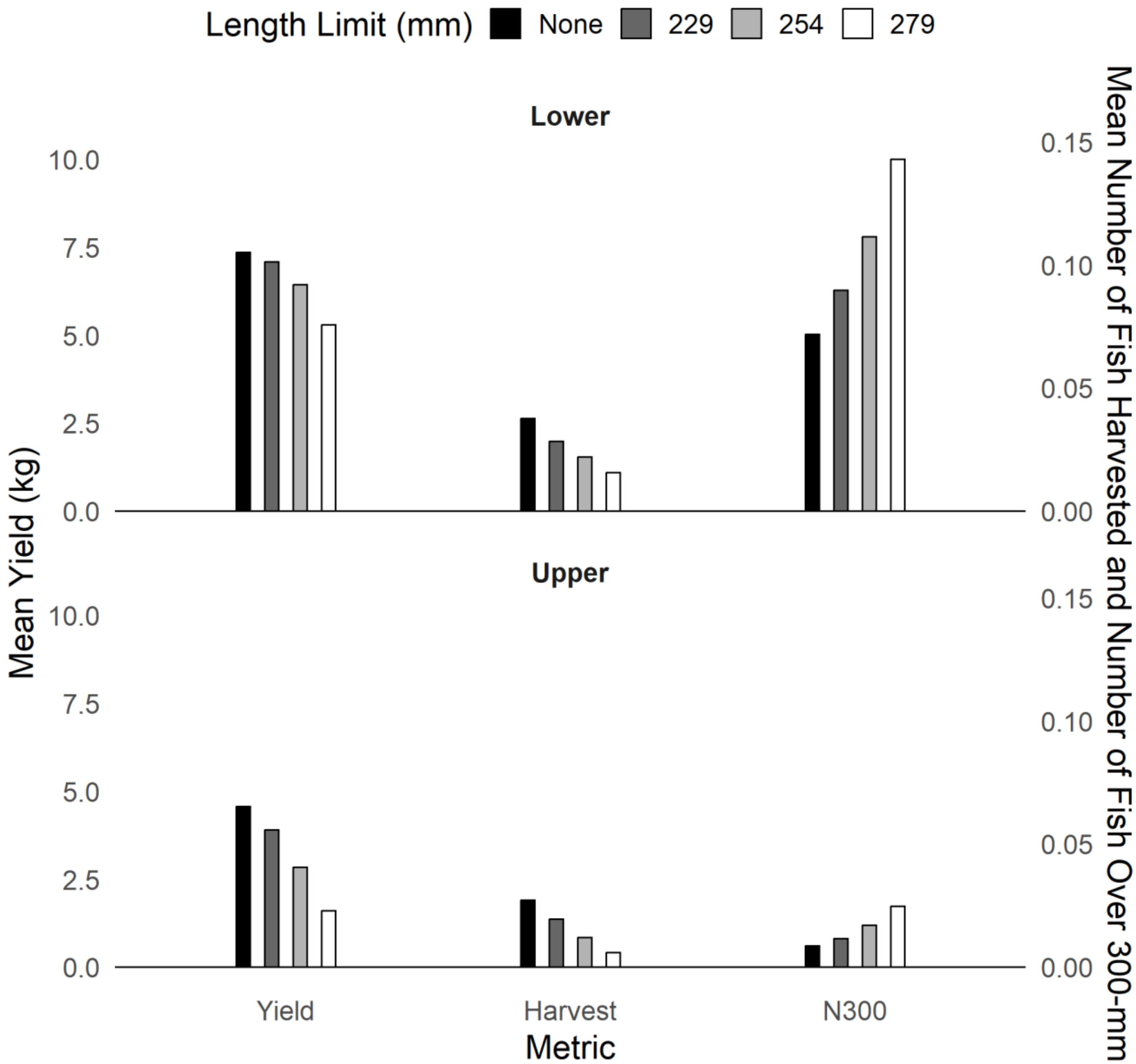

Figure 3-15. Mean yield (kg), mean number of fish harvested (per 1 recruit), and mean number of fish over 300-mm ("N300") in the population at an equilibrium of "1" under four different size restrictions and between reservoir sections in Martin Reservoir, Alabama. Data are averaged over exploitation rates from 0.20 to 0.60, using 0.40 for conditional natural mortality for both models.

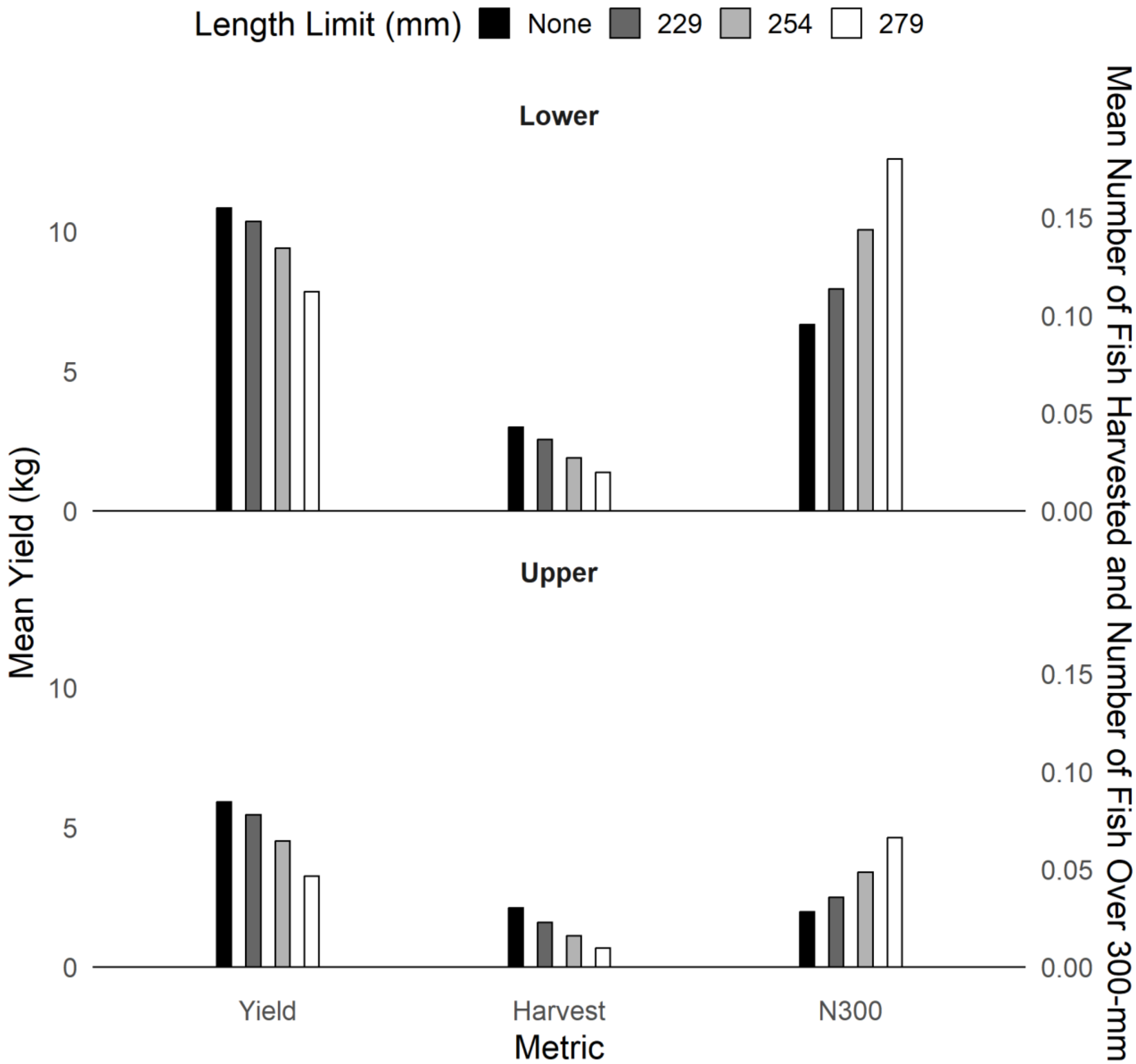

Figure 3-16. Mean yield (kg), mean number of fish harvested (per 1 recruit), and mean number of fish over 300-mm ("N300") in the population at an equilibrium of "1" under four different size restrictions and between reservoir sections in Weiss Reservoir, Alabama. Data are averaged over exploitation rates from 0.20 to 0.60, using 0.40 for conditional natural mortality for both

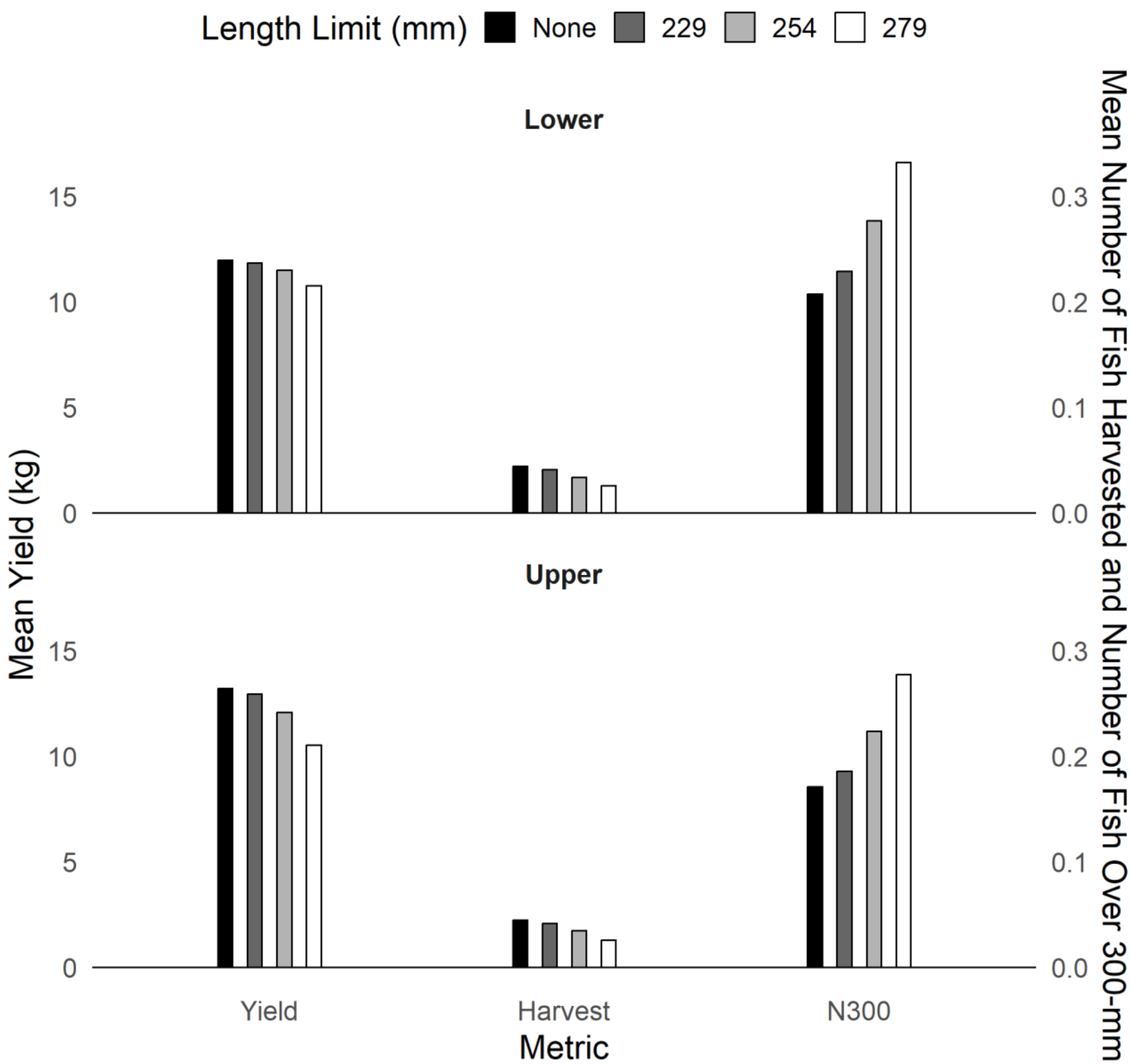

Figure 3-17. Mean yield (kg), mean number of fish harvested (per 1 recruit), and mean number of fish over 300-mm (“N300”) in the population at an equilibrium of “1” under four different size restrictions and between reservoir sections in Wheeler Reservoir, Alabama. Data are averaged over exploitation rates from 0.20 to 0.60, using 0.40 for conditional natural mortality for both models.

Appendices

Appendix A

Table A.1. Von Bertalanffy growth parameters estimated in upper and lower reservoirs. These parameters were used to compare reservoirs sections and were used in Beverton Holt equilibrium equation models. Age at 0-mm TL is described as "t0" and had to be manually constrained to -0.05 for all reservoirs. Parameters estimated were: K, the growth coefficient; and Linf, the estimated length (TL, mm) of the average crappie in each population at the end of its life. The estimated time it takes for crappies to reach the current statewide minimum length limit (229-mm) is also described. The state average is also provided.

Reservoir	Reservoir section	Linf (mm)	K	t0	Time to 229-mm (years)
Eufaula	Lower	319	0.40	-0.05	3.16
	Upper	301	0.40	-0.05	3.56
Martin	Lower	339	0.45	-0.05	2.50
	Upper	286	0.48	-0.05	3.37
Harris/Wedowee	Lower	346	0.43	-0.05	2.55
	Upper	312	0.41	-0.05	3.18
Weiss	Lower	326	0.58	-0.05	2.09
	Upper	313	0.44	-0.05	2.94
Wheeler	Lower	375	0.51	-0.05	1.83
	Upper	337	0.65	-0.05	1.78
Statewide Average	Lower	341	0.47	-0.05	2.43
	Upper	310	0.48	-0.05	2.97

Table A.2. Mortality estimates of crappie populations sampled from the upper and lower reservoirs. These parameters were used to compare reservoir sections and in the Beverton Holt equilibrium yield equation. Parameters estimated were: Z, total instantaneous mortality; A, total annual mortality; S, annual survival; M, instantaneous natural mortality; and CM, conditional natural mortality. The state average is also provided.

Reservoir	Reservoir section	Z (yr^{-1})	S	A	M (yr^{-1})	cm
Eufaula	Lower	0.69	0.50	0.5	0.51	0.40
	Upper	0.78	0.46	0.54	0.51	0.40
Harris/Wedowee	Lower	0.60	0.55	0.45	0.53	0.41
	Upper	0.67	0.51	0.49	0.52	0.41
Martin	Lower	0.37	0.69	0.31	0.52	0.41
	Upper	0.51	0.60	0.40	0.57	0.43
Weiss	Lower	0.67	0.51	0.49	0.66	0.48
	Upper	0.80	0.45	0.55	0.51	0.40
Wheeler	Lower	0.69	0.50	0.5	0.59	0.45
	Upper	0.63	0.53	0.47	0.69	0.50
Statewide Average	Lower	0.61	0.55	0.45	0.56	0.43
	Upper	0.68	0.51	0.49	0.57	0.43

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