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ARTICLE

Evaluation of shoreline rotenone application to control Largemouth Bass recruitment in small impoundments

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Abstract

Objective: Reducing Largemouth Bass *Micropterus salmoides* recruitment and therefore population density could benefit recreational fisheries in small impoundments by improving individual growth rates and increasing the average size and condition of Largemouth Bass. To achieve these effects, methods of controlling Largemouth Bass recruitment should avoid reducing the productivity of their primary prey species, the Bluegill *Lepomis macrochirus*.

Methods: We tested this hypothesis by evaluating the effects of shoreline rotenone application on the density of Bluegill and the density, growth, and survival of age-0 and age-1 Largemouth Bass in 15 Alabama small impoundments.

Result: After treatment, Largemouth Bass age-0 densities declined and mean age-1 length increased, whereas Bluegill populations were not significantly reduced.

Conclusion: Our study indicates that shoreline rotenone application may be a valuable method for reducing Largemouth Bass recruitment and increasing the growth of age-1 Largemouth Bass in small impoundments. However, further research is needed to understand the effects of treatment on nontarget fishes and to better assess the effects of factors such as impoundment surface area and treatment frequency and duration on the ultimate utility of the approach.

KEYWORDS

density-dependent, fisheries management, growth, Largemouth Bass, *Micropterus salmoides*, small impoundment

INTRODUCTION

Small impoundments (water bodies < 200 ha) are ecologically, economically, and aesthetically important in the United States. In 2016, 83% or 24.6 million of all U.S. freshwater anglers fished reservoirs, lakes, and ponds (U.S. Fish and Wildlife Service and U.S. Census Bureau 2018). While there are many uses for small impoundments, including aesthetics, irrigation, livestock watering, aquaculture, geothermal heating, and cooling, among others (Willis and Neal 2012), recreational fishing is the most common use of the nearly 9 million small impoundments in the continental United States (Renwick et al. 2005). Fishing in small impoundments generates significant revenue via pay-to-fish operations (Haley et al. 2012), facilitates the introduction to fishing for many first-time anglers, and provides habitat for an array of animals and plants (Chaney et al. 2012). As such, it is important to develop effective small-impoundment management strategies for attaining fish population characteristics (e.g., density, growth, and body condition) that are desirable for angling.

Largemouth Bass *Micropterus salmoides* and Bluegill *Lepomis macrochirus* represent a common and often-studied (e.g., Swingle and Smith 1942; Guy and Willis 1990; Shoup and Broderius 2018) stocking combination in small impoundments of middle and lower North American latitudes (Smitherman 1975; Novinger and Legler 1978; Brenden and Murphy 2004; Dauwalter and Jackson 2005; Wright and Kraft 2012). Additionally, both Largemouth Bass and Bluegill are widespread and popular sport fishes (Wright and Kraft 2012). The Largemouth Bass is a top-level piscivore that is the most sought-after, economically significant, and heavily managed fish in North America (Allen et al. 2008; Carlson and Isermann 2010; Bonvechio et al. 2014; Claussen 2015), attracting nearly 9.6 million anglers in 2016 (U.S. Fish and Wildlife Service and U.S. Census Bureau 2018).

Along with maintaining habitat, fisheries management of small impoundments involves manipulating population densities to achieve desired growth rates and, ultimately, desired body sizes of both Largemouth Bass and Bluegill. Fish density is typically the object of manipulation because fish populations in these systems often exhibit compensatory density-dependent growth (Swingle and Smith 1942; Gabelhouse 1987; Aday and Graeb 2012) involving intraspecific competition for food and habitat (Heath 1992; Rose et al. 2001). Small-impoundment managers commonly manipulate densities of Largemouth Bass and Bluegill to obtain "balanced" populations that optimize fish size and production to achieve sustainable harvest for both species (Swingle 1950; Geihsler and Holder 1983; Sammons and Maceina 2005). Overharvest of Largemouth Bass was historically one of the most common small-impoundment management problems because it reduced predation on Bluegill and led to excess Bluegill densities or "Bluegill-crowded" conditions. An overabundance of Bluegill can reduce their growth rate and body condition (Willis et al. 2010) and can interfere with Largemouth Bass recruitment via nest destruction (Smith 1976) or consumption of eggs or larvae (Swingle and Smith 1942; Bennett 1970; Swingle 1970; Wright and Kraft 2012). Furthermore, juvenile Bluegill and age-0 Largemouth Bass occupy similar habitats, resulting in the potential for competition between these species (Zweiacker and Summerfelt 1974; Werner 1977; Kelso 1983; Brenden and Murphy 2004).

> **Impact statement**
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> Small impoundment management could benefit from reducing Largemouth Bass recruitment. We found that shoreline rotenone application improved age-1 Largemouth Bass growth rates while Bluegill densities were unaffected. Shoreline rotenone application appears to immediately enhance Largemouth Bass populations in impoundments ≤11 ha.

Over the past 30 years, Largemouth Bass anglers across North America have increasingly adopted catch-and-release fishing, which has led to increased bass densities and caused density-dependent growth reductions of bass in some systems (Quinn 1996; Sammons and Maceina 2005; Wright and Kraft 2012; Bonvechio et al. 2014). Additionally, Largemouth Bass spawn annually at rates of 900–3200 eggs/kg of body weight (Moyle 1976; Laarman and Schneider 2004; Claussen 2015), increasing their vulnerability to overcrowding and density-dependent growth reductions (Aday and Graeb 2012; Wright and Kraft 2012). Methods that are used to maintain balanced populations of Largemouth Bass and Bluegill in small impoundments include aquatic macrophyte control, maintaining consistent fertility, targeted harvest, and recruitment reduction (Swingle and Smith 1942; Davies et al. 1982; Eder 1984; Gabelhouse 1987; McHugh 1990). However, time and financial limitations can constrain the suitability of these management approaches (Haley et al. 2012), catch-and-release fishing can make management via length limits less effective for Largemouth Bass (Gabelhouse 1987; McHugh 1990), and common sampling gears (e.g., hook-and-line gear and electrofishing) are inefficient at capturing age-0 sport fish in some circumstances (Sammons and Bettoli 1999; Dembkowski et al. 2020). Moreover, consistently high annual recruitment of Largemouth Bass can increase density and, therefore, intraspecific competition, preventing most individuals from growing to an adequate size (Swingle 1950; Shelton et al. 1979; Allen and Hightower 2010; Aday and Graeb 2012). Thus, small-impoundment managers across the United States would benefit from the development and enhancement of an improved method for controlling Largemouth Bass recruitment.

One technique that is used to sample or control fish populations in small impoundments is rotenone application (Finlayson et al. 2000; McClay 2000). For example, McHugh (1990) used early summer shoreline rotenone treatments and removal via fall electrofishing to reduce Largemouth Bass densities in two 24–28-ha impoundments, which led to increased Largemouth Bass growth, improved Bluegill size structure, and improved crappie *Pomoxis* spp. recruitment. Juvenile Largemouth Bass recruit in littoral areas of impoundments after dispersing from male-guarded fry schools in late spring (Kramer and Smith 1962; Jackson and Noble 1995), at which time they are highly vulnerable to shoreline rotenone application (McHugh 1990). To date, no studies have evaluated shoreline rotenone treatments targeting Largemouth Bass recruitment in 11-ha or smaller impoundments. As such, our objectives were to (1) assess the effectiveness of shoreline rotenone application in reducing age-0 and age-1 Largemouth Bass densities in small impoundments (≤11 ha), (2) investigate compensatory density-dependent responses of Largemouth Bass growth and survival, and (3) quantify changes in Bluegill density.

METHODS

Study site

We used 15 small impoundments (hereafter, referred to as "impoundments") ranging from 0.7 to 11.0 ha for this study (Table 1). Impoundments were located across central to southern Alabama on private lands or on lands owned by Auburn University (Figure 1). Seven impoundments received shoreline rotenone application; the remaining eight impoundments served as untreated controls. We selected impoundments so that control and treatment systems were similar in littoral vegetation coverage, bank depth, surface area, and Largemouth Bass and Bluegill community structure. Impoundments were chosen to be treated with rotenone or untreated based on private owner and Auburn University requests, such that some people did not want rotenone to be applied in specific areas due to potential effects on the surrounding ecosystem. We sampled impoundments during spring 2017 through spring 2019 for this study by (1) electrofishing each spring and (2) applying rotenone (if selected) and seining in the summers of 2017 and 2018, which we refer to as "treatment periods" (Table 1). We included seven impoundments (i.e., four control and three treatment impoundments) in the first treatment period, with six of those (i.e., three control and three treatment impoundments) being included again in the second treatment period. We added eight more impoundments (four control and four treatment impoundments) for the second treatment period,

TABLE 1 Impoundments sampled, surface area (ha), years of spring electrofishing, and year(s) of shoreline rotenone application, if any ("Control" = no application). Impoundments are located across central to southern Alabama, USA (locations are depicted in Figure 1).

Impoundment	Size (ha)	Years electrofished	Year(s) of treatment
Anderson	2.8	2017, 2018	Control
AE1	1.6	2017, 2018, 2019	Control
Big Pit	11	2017, 2018, 2019	Control
FP3	0.7	2017, 2018, 2019	Control
Drummond 3	8.8	2018, 2019	Control
Meriwether	3.4	2018, 2019	Control
Williams	3.3	2018, 2019	Control
Promise	1.9	2018, 2019	Control
Little Pit	4	2017, 2018, 2019	2017, 2018
S3	4	2017, 2018, 2019	2017, 2018
Horseshoe	1.3	2017, 2018, 2019	2017, 2018
Drummond 1	8.7	2018, 2019	2018
Britton	2.2	2018, 2019	2018
Zachry	5.3	2018, 2019	2018
Dead	2.2	2018, 2019	2018

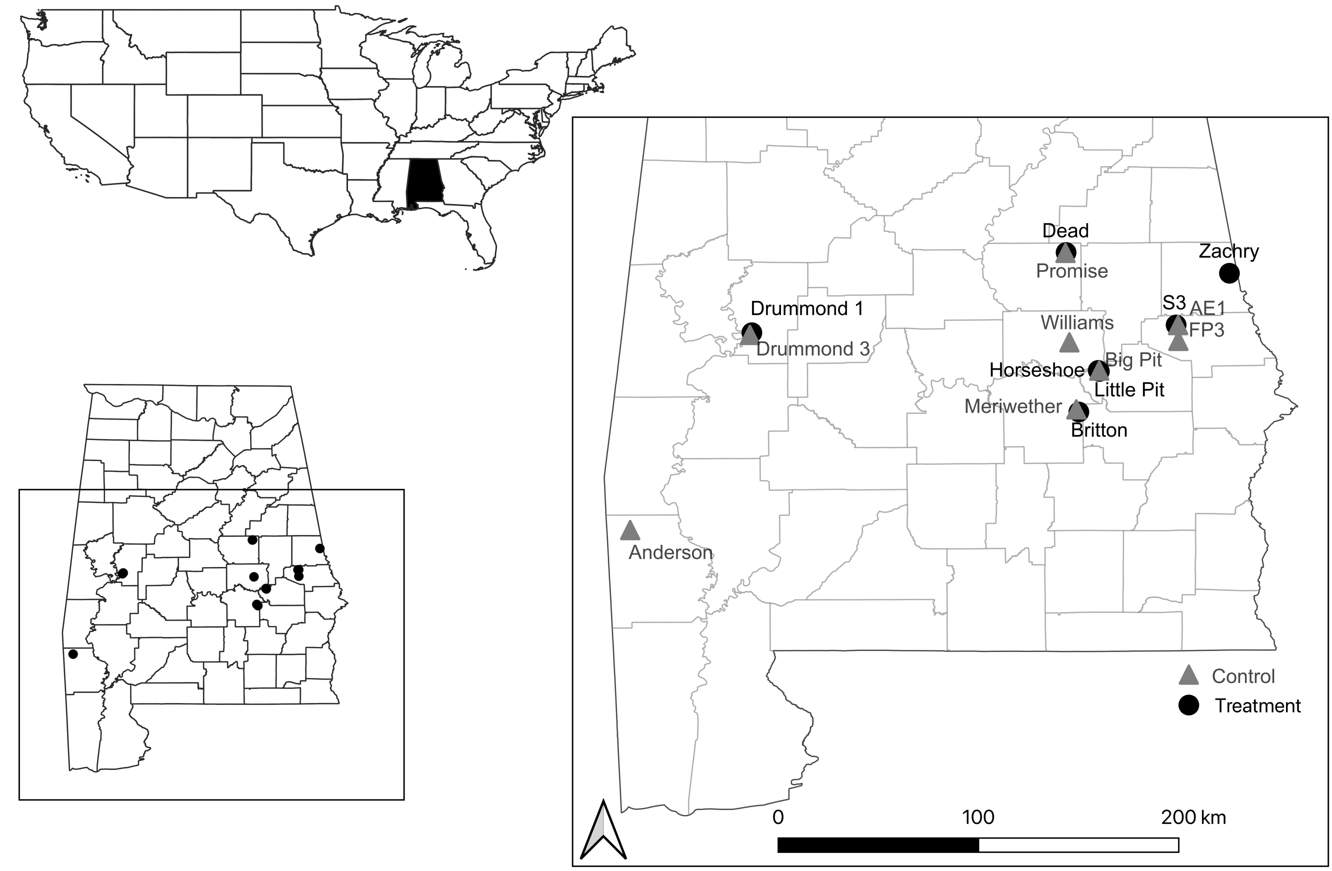

FIGURE 1 Map of small impoundments studied in Alabama, USA. Control (untreated) impoundments are represented by gray triangles; rotenone treatment impoundments are represented by black circles. Horseshoe (treatment), Little Pit (treatment), and Big Pit (control) are all within 50 m of each other, so their symbols almost completely overlap.

resulting in a total of 14 impoundments examined during that period (Table 1).

Summer rotenone application

We used 5% biodegradable liquid rotenone (Prenfish Fish Toxicant) to target age-0 Largemouth Bass. Treatment impoundments received rotenone in summer 2017 only, in summer 2018 only, or in both summers (Table 1). Two applications were used each year (referred to as days 1 and 21); the first application was in May (day 1), with a follow-up application approximately 21 days later to ensure that the progeny of late-spawning fish were not missed. We applied liquid rotenone by using a boat outfitted with an injection system and two 151-L tanks. Applicators wore personal protection equipment as required on the product label (e.g., nitrile gloves, eye protection, respirator, and hazmat suit). We connected one tank to a surface spray wand (21.092 kg/cm^2 [300 psi]) and the other to a multiport subsurface injector composed of a 1.5-m section of chlorinated polyvinyl chloride pipe with five evenly spaced ports (2 mm diameter) fixed to a 3.5-m fiberglass pole. Together, the surface spray wand and subsurface injector created a sediment-to-surface curtain of rotenone along the shoreline. We used injector and spray wand pressure, water volume in the treatment area around the perimeter of the shoreline, and boat application speed to calculate the amount of rotenone–water mixture needed so that each tank would empty after a single pass. We held the subsurface injector 3–5 m off the shoreline and sprayed the surface application simultaneously between the subsurface injector and the shoreline. We made a single pass around the perimeter of each treatment impoundment, applying 0.5 L of Prenfish Fish Toxicant (0.025 L of rotenone) per 90 m of shoreline.

Summer seining

We seined each impoundment using a 4.5- × 1.8-m seine net with 3.2-mm knotless mesh at 15 randomly selected sites within accessible areas of each impoundment. In the summer of 2017 and 2018, we seined each impoundment on five occasions, beginning in May and ending in July. Four of the occasions were immediately before (days 1 and 21) and after (days 2 and 22) rotenone application, and the fifth sample was a midsummer follow-up sampling event (day 42). On days 1 and 21, we seined the treatment impoundments at sunrise (i.e., immediately before rotenone application; see above) and the control impoundments immediately after we treated the treatment impoundments (all on the same day). The day after each rotenone application (days 2 and 22), we seined the treatment and control impoundments at similar times of day as the preapplication samples to minimize time-of-day effects on seine catches. On day 42, one additional seine sample was collected from each impoundment at the same time of day as previously sampled to compare catches over time. The same seine sites were sampled consistently over time. We recorded age-0 Largemouth Bass total lengths and enumerated Bluegill in length bins (0.0–12.5, 12.6–37.5, 37.6–62.5 mm, etc.) before we released all live fish back into the water.

Electrofishing

We sampled all impoundments via electrofishing (Smith-Root 5.0 GPP aluminum boat; 50–60 Hz, 4–5-ms pulse width, 300–400 V) during March before the first rotenone treatment (which occurred in the succeeding May) and again the following March (Table 1). Sampling included two 15-min shoreline electrofishing transects in which we collected all fish larger than 80 mm. We measured (nearest mm) and weighed (nearest g) all captured fish, and we selected a random subsample of 10 Largemouth Bass per 25-mm length interval (for 150–250-mm fish) to take back to the laboratory for aging using sagittal otoliths; all other fish were released. We also used this subsample to determine the appropriate length cutoff of age 1 versus age 2 for fish that were not aged to estimate and compare mean length at age (MLA). We embedded otoliths in epoxy resin and removed a transverse section that included the core using a low-speed, diamond-blade saw (South Bay Technologies Inc). We then mounted the transverse sections on rectangular petrographic slides, ground and polished them to a smooth appearance to expose the otolith core, and aged them under a compound microscope using a drop of immersion oil to increase clarity. Two readers aged the otoliths without prior knowledge of fish length, fish weight, or the other reader's age estimates. When different ages were assigned to individual fish, a third independent reader provided an estimate and a consensus age was reached by discussion.

Age-0 relative abundance and mean length

We used R (R Core Team 2022) for all analyses and figures. Two before–after, control–impact (BACI) analyses were used to test for effects of shoreline rotenone treatment on Bluegill and age-0 Largemouth Bass seine catches (i.e., total catch per impoundment) in the impoundments (Stewart-Oaten et al. 1986). The first analysis compared seine catches immediately before (i.e., days 1 and 21) and after (i.e., days 2 and 22) rotenone application to evaluate the short-term effect of the application. We conducted this analysis by using a generalized linear mixed-effects model with a negative binomial noise distribution. The model included random effects for impoundment × year intercepts and fixed effects of application (first: day 1 versus day 2; second: day 21 versus day 22), treatment (control versus treatment), time period (before versus after treatment), and all interactions. The treatment × time interaction tested whether catches declined significantly more in treatment impoundments than in control impoundments.

The second analysis compared the initial pretreatment (i.e., day-1) seine sample with the midsummer follow-up sample (i.e., day 42) to estimate the cumulative effect of both rotenone applications (compared to natural variation in control impoundments) on Bluegill and age-0 Largemouth Bass populations. We used a generalized linear mixed-effects model with a negative binomial noise distribution, which included random effects for impoundment × year intercepts and the fixed effects of treatment, time period, and their interaction.

We compared Largemouth Bass MLA-0 (i.e., mean length at age 0) in the pretreatment and midsummer follow-up seine samples by using a BACI analysis estimating initial growth differences between control and treatment impoundments. We conducted this analysis using a linear mixed-effects model and $\log_e$ transformed mean total length data for each impoundment in each year to meet the assumption of normality. We included independent random effects of impoundment and year intercepts and fixed effects of treatment, time period, and their interaction.

Age-1 growth, recruitment, survival, and size structure

We estimated the effect of rotenone treatment on Largemouth Bass MLA-1 using a BACI analysis. For this analysis, the effect of rotenone treatment was represented as (1) a control or pretreatment, (2) treated during 1 year, or (3) treated during 2 years. We obtained MLA values from otolith-aged subsamples by taking the average length of each age-class, weighted by the sample size in each size-class (DeVries and Frie 1996). We used a linear mixed-effects model with an independent random effect of impoundment intercepts and a fixed effect of rotenone treatment on the natural logarithm of MLA-1 to meet the assumption of normality; we could not use a random effect of year because our sample size led to a singular fit (e.g., see Table 1).

We evaluated the effect of rotenone treatment on $\log_e$ transformed electrofishing catch per unit effort (CPUE; fish caught per 30 min of electrofishing) for age-1 Largemouth Bass and stock-sized Bluegill (i.e., >80 mm) using a BACI analysis. To meet the assumption of normality, we added a 1 to all age-1 Largemouth Bass CPUE values (due to the presence of zeroes) to allow for log transformation of the data; however, the Bluegill data did not contain zeroes. We analyzed the effects of rotenone application on (1) Largemouth Bass recruitment using age-1 CPUE and (2) nontarget fish (i.e., stock-sized Bluegill) using Bluegill CPUE. For each dependent variable, we fitted a linear mixed-effects model with an independent random effect of impoundment intercepts—with no year effect for the same reason as explained above—and a fixed effect of rotenone treatment (control, 1 year of treatment, or 2 years of treatment) on the natural logarithm of CPUE.

We tested for compensatory age-0 Largemouth Bass survival after rotenone treatment using an index of Largemouth Bass age-0 survival. The survival index was calculated by dividing the age-1 electrofishing catches in March by the age-0 seine catches in the midsummer follow-up (day-42) sample from the previous year, reducing our sample size by almost half from the previous analyses described above. We tested for differences in the survival index as a function of rotenone treatment frequency (i.e., no treatment, 1 year of treatment, or 2 years of treatment) by fitting models on the natural logarithm of the survival index to meet the assumption of normality. We fitted a linear mixed-effects model with an independent random effect of year intercepts and a fixed effect of rotenone treatment.

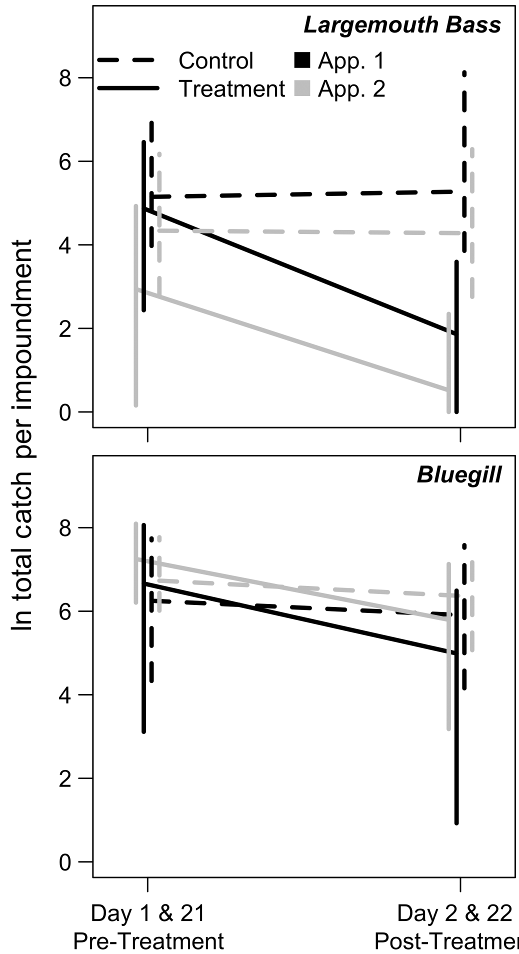

FIGURE 2 Total seine catches ($\log_e$ transformed) of Largemouth Bass (top panel) and Bluegill (bottom panel) immediately before (days 1 and 21) and after (days 2 and 22) the first shoreline rotenone application (App. 1; black lines) and the second application (App. 2; gray lines) in small impoundments located across central to southern Alabama. Solid lines denote treated impoundments, and dashed lines denote controls. Observations were pooled across years (2017 and 2018), and error bars represent the 2.5th and 97.5th percentiles (95% confidence intervals).

RESULTS

Age-0 relative abundance and mean length

The treatment × time period × application (first: day 1 versus day 2; second: day 21 versus day 22) interaction for Largemouth Bass seine catches was not statistically significant; catches between treated versus control impoundments before and after rotenone treatment were similar between the first and second rotenone applications ($F_{1, 57} = 0.38$, $p = 0.57$; Figure 2). In other words, regardless of application (day 1 or day 21), the same immediate treatment effect was observed. Bluegill seine catches were also unrelated to application and its associated interactions ($F_{1, 57} = 0.50$, $p = 0.48$). However, we did find that impoundments treated with rotenone experienced an additional 96% (95% confidence interval [CI] = 89–99%) and 62% (95% CI = 23–81%) reduction in Largemouth Bass and Bluegill seine catches, respectively, on the day after application (i.e., from day 1 to day 2 and from day 21 to day 22) compared to control impoundments ($F_{1, 61} = 44.57$, $p < 0.001$; $F_{1, 61} = 7.48$, $p = 0.0070$; Figure 2).

Pretreatment (i.e., day-1) Largemouth Bass ($F_{1, 19} = 11.22$, $p = 0.56$) and Bluegill ($F_{1, 19} = 5.69$, $p = 0.24$) seine catches were not significantly different initially in treatment and control impoundments (Figure 3). When comparing day-1 seine catches to the midsummer follow-up (i.e., day-42) seine catches of Largemouth Bass, we found that the treatment × time period interaction was statistically significant ($F_{1, 19} = 6.73$, $p = 0.017$) and represented an

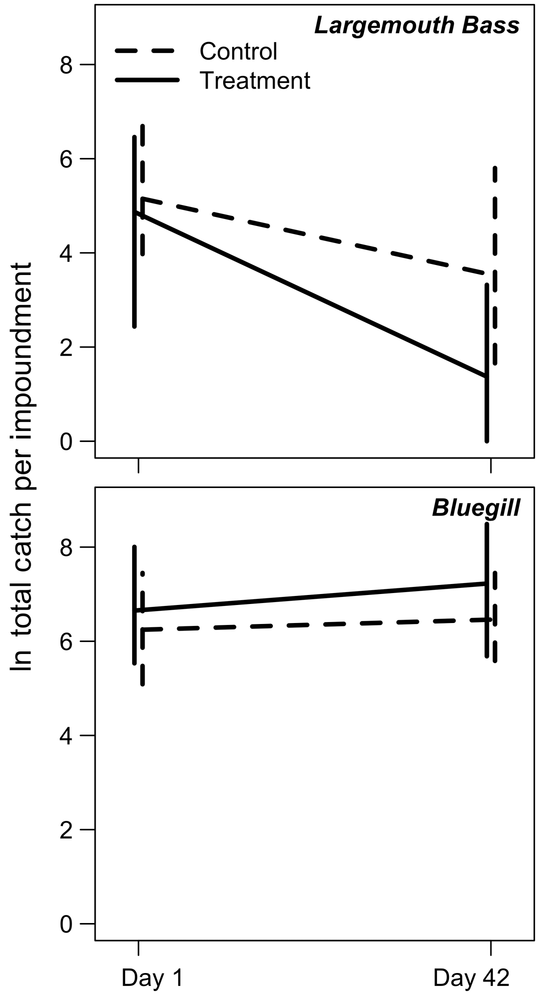

FIGURE 3 Total seine catches ($\log_e$ transformed) of Largemouth Bass (top panel) and Bluegill (bottom panel) in Alabama small impoundments immediately before rotenone application (day 1) and at midsummer after both rotenone applications (day 42). Solid lines denote impoundments that received shoreline rotenone treatments, and dashed lines denote controls. Data were pooled across years (2017 and 2018), and error bars represent 95% confidence intervals.

additional 86% (95% CI = 38–97%) posttreatment decrease in Largemouth Bass catches in treatment impoundments compared to control impoundments (Figure 3). However, for Bluegill seine catches, the treatment × time period interaction was not statistically significant ($F_{1,\ 19}=0.39$, $p=0.55$), presenting no change in catches of Bluegill from day 1 to day 42 in treatment impoundments compared to controls (Figure 3).

In treatment impoundments, we failed to capture age-0 Largemouth Bass in 5 out of 10 midsummer follow-up seine sampling events; however, we captured age-0 Largemouth Bass in all 11 controls. In impoundments from which they were captured, Largemouth Bass MLA-0 in the pretreatment (i.e., day-1) seine catches were similar in the treatment and control impoundments ($F_{1,19}=0.025$, $p=0.94$). The treatment × time period interaction did not indicate any additional age-0 growth from day 1 to day 42 in the treatment impoundments versus the controls ($F_{1,\ 14}=0.024$, $p=0.88$). On day 42, Largemouth Bass MLA-0 was 67 mm (95% CI = 50–87 mm) in the treatment impoundments and 68 mm (95% CI = 35–106 mm) in the control impoundments.

Age-1 growth, recruitment, survival, and size structure

Largemouth Bass MLA-1 in impoundments significantly increased on average by 27% (95% CI = 16–40%) after 1 year of treatment ($F_{1,\ 24}=19.15$, $p<0.001$) and by 31% (95% CI = 16–48%) after two consecutive years of treatment ($F_{1,\ 24}=19.15$, $p<0.001$) compared to MLA-1 in the control impoundments (Figure 4). However, there was no difference between 1 year versus 2 years of treatment ($F_{1,\ 24}=19.15$, $p=0.69$). We found that Largemouth Bass recruitment (i.e., age-1 CPUE) declined 87% (95% CI = 74–93%) and 84% (95% CI = 58–94%) more in the

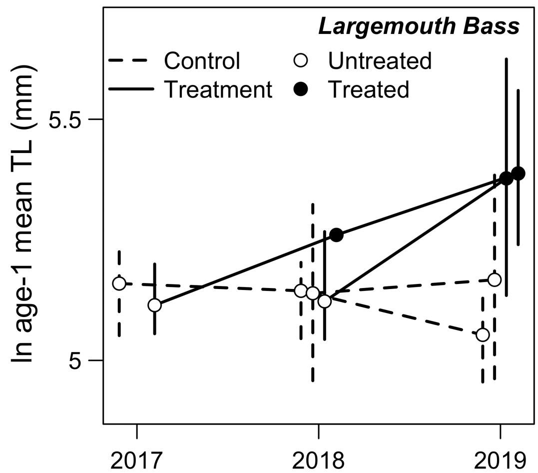

FIGURE 4 Temporal trends in mean length ($\log_e$ transformed) at age 1 for Largemouth Bass in control (dashed lines) and treatment (solid lines) small impoundments located across central to southern Alabama. Open circles denote untreated impoundments, and closed circles denote impoundments that were treated with rotenone. Solid lines leading from a closed circle to another closed circle represent the impoundments that were treated twice (e.g., see Table 1). The number of times treated (untreated control, treatment during 1 year, or treatment during 2 years) was the variable of interest in our model, and this portrays how the model compared those different levels of treatment. The interaction term tested whether the slopes of the solid lines (i.e., 1 year or 2 years of treatment) differed from the slopes of the dashed lines (controls). Error bars represent the 95% confidence intervals of the data when the sample size for that year was greater than two impoundments.

treatment impoundments than in the controls after 1 year ($F_{1,\ 19}=22.21$, $p<0.001$) and 2 years ($F_{1,\ 19}=22.21$, $p<0.001$) of rotenone application, respectively (Figure 5). We detected no difference between 1 year versus 2 years of treatment ($F_{1,\ 19}=22.21$, $p=0.73$). We did not identify any difference in Bluegill CPUE in the control impoundments versus the treatment impoundments after 1 year ($F_{1,\ 19}=2.021$, $p=0.31$) or 2 years ($F_{1,\ 19}=2.021$, $p=0.16$) of treatment, and Bluegill CPUE did not differ between 1 year versus 2 years of treatment ($F_{1,\ 19}=2.021$, $p=0.056$; Figure 5). We failed to detect any change in Largemouth Bass survival rates between the control impoundments versus 1 year of treatment ($F_{1,\ 15}=1.86$, $p=0.47$), between controls versus 2 years of treatment ($F_{1,\ 15}=1.86$, $p=0.071$), and between 1 year versus 2 years of treatment ($F_{1,\ 15}=1.86$, $p=0.25$).

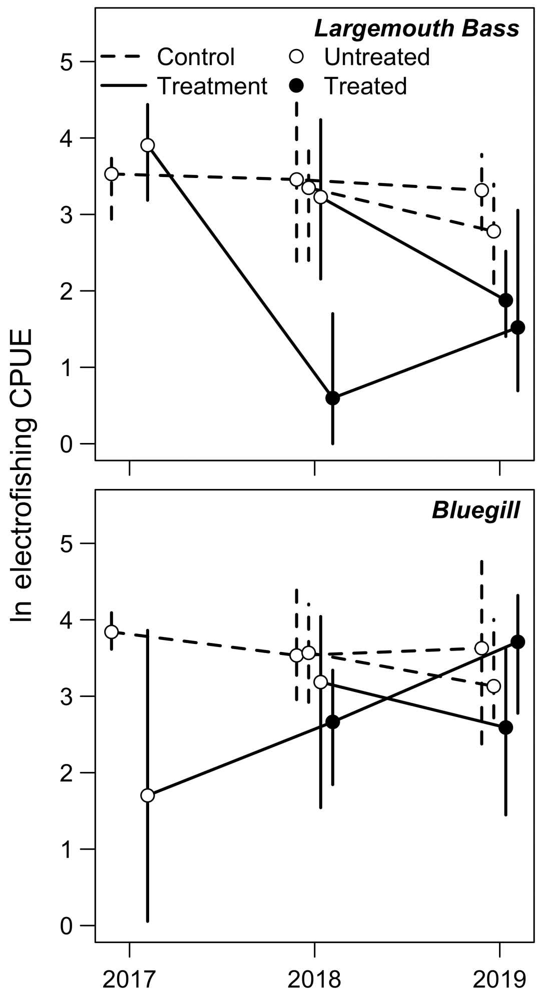

FIGURE 5 Temporal trends in electrofishing catch per unit effort (CPUE; $\log_e$ transformed; fish caught per 30 min of electrofishing) for age-1 Largemouth Bass (top panel) and for Bluegill larger than 80 mm (bottom panel) in control (dashed lines) and treatment (solid lines) small impoundments located across central to southern Alabama. Open circles denote untreated impoundments, and closed circles denote impoundments that were treated with rotenone. Data are presented as in Figure 4.

DISCUSSION

Evaluating the responses of age-0 Largemouth Bass and Bluegill to shoreline rotenone application in small impoundments is critical to determine whether this approach can be used as a management tool for Largemouth Bass and Bluegill small-impoundment recreational fisheries. Long-term population success for both Largemouth Bass and Bluegill is influenced by mechanisms related to individual size and population density during early life stages (Ludsin and DeVries 1997; Rogers and Allen 2009), which are directly affected by reducing recruitment using rotenone applications. In the present study, visual observations after each rotenone treatment indicated that age-0 Largemouth Bass and Bluegill smaller than 80 mm were killed in large numbers. More specifically, our results indicated that seine catches of age-0 Largemouth Bass and Bluegill in treatment impoundments significantly declined 24 h after rotenone applications, whereas catches in control impoundments did not significantly change. These qualitative and quantitative results are similar to observations made by McHugh (1990) after combined rotenone application and targeted removal via electrofishing in two larger Alabama lakes. In our impoundments, age-0 Largemouth Bass seine catches declined in both control and treatment impoundments by day 42, with a significantly greater decline in the treatment impoundments. In addition to rotenone mortality, this numerical decline is likely partially attributable to the reduced vulnerability of larger individual fish to capture with a seine (Jackson and Noble 1995; Willis and Murphy 1996; Reynolds and Kolz 2012). Moreover, the natural mortality of age-0 Largemouth Bass is likely important during the summer (Rogers and Allen 2009), also contributing to reduced seine catches. In contrast, Bluegill seine catches did not change significantly from day 1 to day 42 in control and treatment impoundments. Bluegill catches were likely less affected by temporal changes in gear vulnerability than Largemouth Bass because of their slower growth combined with multiple spawning events (Cargnelli and Neff 2006; Bartlett et al. 2010), which may have offset losses due to natural mortality and rotenone mortality.

We did not detect a rotenone treatment effect on Bluegill CPUE in spring electrofishing samples, perhaps reflecting natural variation in Bluegill reproduction or overwinter survival that could offset or obscure treatment effects. Research shows that Bluegill move from pelagic to littoral habitats as they grow (Werner and Hall 1988). When Bluegill fry move from pelagic to littoral areas, they become more vulnerable to shoreline rotenone application. However, adult Bluegill can spawn multiple times throughout the summer, and the fry transition from pelagic to littoral habitats at different times (Partridge and DeVries 1999). As such, the overall Bluegill population may have had inherently low vulnerability to rotenone treatments in the present study. Alternatively, if Bluegill were affected by rotenone treatment in the previous summer, density dependence could cause overwinter survival of Bluegill to increase, in turn reducing the effect on Bluegill CPUE the following spring.

In our small impoundments, Largemouth Bass recruitment to age 1 was significantly lower in treatment impoundments than in controls—regardless of whether treatment occurred during 1 year or 2 years—similar to findings for age-0 Largemouth Bass in seine catches the previous summer. Therefore, the rotenone treatment was effective at reducing Largemouth Bass recruitment. However, research shows that age-0 Largemouth Bass in the southeastern United States experience a survival bottleneck via high overwinter mortality rates (Aggus and Elliott 1975; Miranda and Hubbard 1994a; Ludsin and DeVries 1997). Low survival may also be caused by cumulative interactions between abiotic and biotic factors (e.g., water temperature, water level, predation, and starvation; Kramer and Smith 1962; Miranda and Hubbard 1994b; Ludsin and DeVries 1997; Garvey et al. 2002). Survival bottlenecks can lead to compensatory density-dependent survival, which could offset density reductions due to rotenone application. Our survival index analysis showed an absence of compensatory density-dependent survival in response to rotenone treatment, indicating that overwinter survival bottlenecks may be weaker in these impoundments than in other systems. Alternatively, the survival index may have been too imprecise to detect compensatory survival given that it was constructed as the quotient of two independent and relatively noisy observations: electrofishing CPUE (Hangsleben et al. 2013; Dembkowski et al. 2020) and seine catches (Jackson and Noble 1995). Thus, it is plausible that sampling variation from spring electrofishing and late-summer seine catches may have confounded detection of changes in Largemouth Bass survival.

Density-dependent growth refers to a negative relationship between growth and population density such that increased population density results in intraspecific competition for prey resources and slower growth (Heath 1992; Rose et al. 2001). Reduced age-0 Largemouth Bass densities after rotenone treatment provided us with an opportunity to test for density-dependent growth. In the present study, we found that rotenone treatment led to increased Largemouth Bass MLA-1 after treatment in small impoundments. McHugh (1990) found similar results from combined rotenone application and targeted electrofishing removal wherein Largemouth Bass MLA-3 before treatment was comparable to MLA-2 after treatment. Similarly, Beckman (1941) concluded that the growth of age-1 Rock Bass *Ambloplites rupestris* increased due to a rotenone application used to target juveniles.

Although Largemouth Bass MLA-1 increased after rotenone treatment, we found no effect on MLA-0 in midsummer seine catches. We speculate that seine sampling was biased against the collection of larger age-0 Largemouth Bass (Jackson and Noble 1995), thereby potentially masking treatment effects. Alternatively, perhaps density-dependent growth responses require more time for cumulative growth differences to emerge. Moreover, no age-0 Largemouth Bass were captured during midsummer seine hauls in 50% of the treatment impoundments, so mean lengths may not have been representative of all impoundments.

Prey availability and size also affect fish growth (Shelton et al. 1979; Allen and Hightower 2010). With reduced intraspecific competition and large numbers of juvenile Bluegill still present after rotenone treatment (i.e., we found no rotenone effect on Bluegill densities in the midsummer seine catches), Largemouth Bass prey availability should be plentiful. Age-1 Largemouth Bass growth increased after rotenone treatment (discussed above); therefore, future studies should assess whether differences exist in stock-size Bluegill and the growth, condition, and diet of age-2 and older (age-2+) Largemouth Bass after rotenone applications. It is important to consider the effects of rotenone application on nontarget species and life stages. For instance, McHugh (1990) reported that small numbers of nontarget fishes (e.g., larger Bluegill, larger Largemouth Bass, and Grass Carp *Ctenopharyngodon idella*) were killed during the shoreline rotenone treatment. In the present study, we observed various numbers of mortality events affecting larger Bluegill and Largemouth Bass (i.e., from none to nearly 200 fish) along the shoreline of our treatment impoundments on the morning after (i.e., nearly 24 h after) rotenone treatment. We did not assess the responses of age-2+ Largemouth Bass to the rotenone treatment; however, effects on older Largemouth Bass age-classes would be of interest in determining the overall value of this approach. Avoiding high rotenone-related mortality of age-2+ Largemouth Bass in efforts to reduce recruitment is desirable given that these fish are catchable and, if harvest is allowed and preferred, are of harvestable size.

Further research to assess differences more definitively in growth responses as a function of impoundment size could improve our understanding of rotenone treatment. We used similarly constructed small impoundments (≤11 ha); however, larger impoundments tend to have more complex littoral habitats (e.g., thick emergent vegetation, overhanging terrestrial vegetation, and shallow backwaters) that may affect the efficiency of the rotenone treatment by providing temporary refuge for young-of-year Largemouth Bass. Ensuring rotenone spray coverage could also be more difficult in complex littoral habitats. Understanding this rotenone application effect on larger impoundments (e.g., >30 ha) would be highly valuable to agencies and managers.

MANAGEMENT IMPLICATIONS

The shoreline rotenone application described above allows applicators traveling at 1.9–2.4 km/h to treat a 4-ha impoundment in about 20 min with as few as two personnel. This shoreline rotenone treatment can be used to reduce recruitment of Largemouth Bass in small impoundments, but the efficacy of this approach needs to be investigated further. We found that shoreline rotenone application improved age-1 Largemouth Bass growth rates without affecting Bluegill densities in our impoundments. This improvement was evident after 1 year of rotenone application, whereas an additional year of rotenone application resulted in no further improvement. Shoreline rotenone application appears to immediately enhance Largemouth Bass populations in 11-ha and smaller impoundments. An important subject for future research could be to assess the effects of this shoreline rotenone application on population parameters for nontarget species (e.g., growth, condition, and diets of age-2+ Largemouth Bass; condition of stock-size Bluegill) and in larger impoundments (30–200 ha). Additionally, McHugh (1990) found that combined shoreline rotenone application and targeted removal via electrofishing affected fish populations for a few years after initial application. As such, our shoreline rotenone application technique may need to be repeated at regular intervals (e.g., 2–4 years), which is another important subject for future research in impoundment management.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data supporting the findings of this study are openly available in GitHub: https://github.com/tscoleman3/rotenone_small_impoundments_target. Please contact T. S. Coleman for data-related questions.

ETHICS STATEMENT

The ethical guidelines of Auburn University, the University of Florida, and the Florida Cooperative Fish and Wildlife Research Unit were used throughout the execution of this research and the development of this manuscript. This study was performed under the auspices of Auburn University Institutional Animal Care and Use Committee Protocol 2017-3088.

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