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Add Abstract here

Introduction

Small impoundments (water bodies <200 hectares [ha]) are ecologically, economically, and aesthetically important in the United States. In 2016, 24.6 million U.S. freshwater anglers (83%) targeted reservoirs, lakes, and ponds (USDOI 2018). Recreational fishing is the most common use of the nearly 9 million small impoundments in the continental United States (Renwick et al. 2005), which generate significant revenue via pay-to-fish operations (Haley et al. 2012) while providing aesthetic values and habitats 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 parameters (e.g., density, growth, body condition) that are desirable for angling.

Largemouth Bass *Micropterus salmoides* and Bluegill *Lepomis macrochirus* represent a common, often studied (e.g., Swingle and Smith 1942; Guy and Willis 1990; Shoup and Broderius 2018) sympatric stocking combination in small impoundments of middle and lower latitudes of North America (Smitherman 1975; Novinger and Legler 1978; Brenden and Murphy 2004; Dauwalter and Jackson 2005; 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 (USDOI 2018). Largemouth Bass and Bluegill are opportunistic feeders that are widespread and highly productive, making them popular sport fish for anglers (Wright and Kraft 2012).

Fisheries management in small impoundments often involves manipulating population densities to achieve desired growth rates. 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 increased Bluegill densities (Funk 1974; Willis et al. 2010). An overabundance of Bluegill can reduce their growth rate and body condition (Willis et al. 2010) and 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, which can increase competition between these species (Zweiacker and Summerfelt 1974; Werner 1977; Kelso 1983; Brenden and Murphy 2004).

Over the last 30 years, Largemouth Bass anglers across North America have increasingly adopted catch-and-release fishing, which has increased bass densities and caused density-dependent growth reductions in some systems (Quinn 1996; Sammons and Maceina 2005; Wright and Kraft 2012; Bonvechio et al. 2014). Largemouth Bass spawn annually at high rates (2000—7000 eggs/lb body weight; Moyle 1976; Laarman and Schneider 2004; Claussen 2015), making them highly vulnerable to overcrowding and density-dependent growth reductions (Aday and Graeb 2012; Wright and Kraft 2012). Methods used to regulate Largemouth Bass density and maintain balanced populations with Bluegill include aquatic macrophyte control, fertilization, length limits, recruitment reduction, and fish removal via poisoning or impoundment draining (Swingle and Smith 1942; 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 length limits less effective for Largemouth Bass (Gabelhouse 1987; McHugh 1990), and common sampling gears (e.g., hook-and-line, electrofishing) are inefficient at capturing age-0 bass to reduce recruitment. Moreover, consistent annual recruitment of Largemouth Bass can increase density and intraspecific competition and prevent 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 methods for controlling Largemouth Bass recruitment.

One technique used to sample or control fish populations in small impoundments is rotenone application (Finlayson et al. 2000; McClay 2000). For instance, McHugh (1990) used shoreline rotenone treatments and electrofishing to reduce Largemouth Bass densities in two 24–28 ha impoundments, which increased Largemouth Bass growth and improved Bluegill size structure and Crappie *Pomoxis* spp. recruitment. To date, no studies have evaluated shoreline rotenone treatments targeting Largemouth Bass recruitment in impoundments ≤10 ha. 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, (2) investigate compensatory density-dependent responses of Largemouth Bass growth and survival, (3) quantify changes in Bluegill density, and (4) evaluate the effect of impoundment surface area on the efficacy of shoreline rotenone application.

<A> Methods

*Study site.—*We used 20 small impoundments ranging from 0.7–48 ha for this study (Table 1). Impoundments were located from central to southern Alabama on private lands or those owned by the Alabama Department of Conservation and Natural Resources (ADCNR) or Auburn University (Figure 1). Ten impoundments received shoreline rotenone application; the remaining ten impoundments were untreated controls. We selected impoundments so that control and treatment systems were similar in littoral vegetation coverage, bank depth, surface area (with one exception), and Largemouth Bass and Bluegill densities. We sampled a total of 20 impoundments sampled over two treatment periods (2017–2018, 2018–2019; Table 1). We sampled twelve impoundments (six controls, six treatments) between March 2017 and March 2018, eight of which were sampled again between March 2018 and March 2019 (four controls, four treatments). We sampled eight additional impoundments between March 2018 and March 2019 for a total of sixteen impoundments in the second period.

*Summer rotenone application.—*We used 5% biodegradable liquid rotenone to target age-0 Largemouth Bass. Juvenile Largemouth Bass recruit to littoral areas of impoundments after dispersing from male-guarded fry schools in May (Kramer and Smith 1960; Jackson and Noble 1995), at which time they are highly vulnerable to shoreline rotenone application (McHugh 1990). Treatment impoundments received rotenone in 2017 only, in 2018 only, or both years (Table 1). The first application was in May, with a follow-up application approximately 21 days later to ensure that progeny of late-spawning fish were not missed. We applied liquid rotenone with a boat, two 151-L tanks, and standard safety gear (e.g., nitrile gloves, eye protection, respirator, hazmat suit). We connected one tank to a surface spray wand (210,920 kg/m2) and the other to a multiport subsurface injector composed of a 1.5-m section of chlorinated polyvinyl chloride 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 held the subsurface injector 3–5 m off the shoreline and sprayed the surface application simultaneously between the subsurface injector and shoreline. We made a single pass around the perimeter of each treatment impoundment, applying 0.5 L rotenone per 90 m of shoreline.

*Summer seining.—*We seined each impoundment using a 4.5 X 1.8-m seine net with 3.2-mm knotless mesh at 15 randomly selected sites. In summer 2017 and 2018, we seined each impoundment on five occasions , beginning in May and ending in July. Four occasions were immediately before/after rotenone application, and the fifth sample was a mid-summer follow-up. On days 1 and 21, we seined treatment impoundments at sunrise (i.e., immediately before rotenone application) and the paired control impoundments immediately after we treated the treatment impoundment. The day after each rotenone application (days 2 and 22), we seined in the treatment and control impoundments at similar times of day as the pre-application samples to minimize time-of-day effects on seine catches. On day 42, an additional seine sample was conducted at each impoundment at the same time of day as before to compare catches over time. We marked seine sites with a Garmin eTrex 20x global positioning system to ensure that the same sites were sampled consistently over time. We recorded age-0 Largemouth Bass total lengths and enumerated Bluegill in length bins (0–12.5mm 12.6–37.5mm, 37.6–62.5mm, etc.).

*Electrofishing.—*We sampled all impoundments via electrofishing (Smith-Root 5.0 GPP aluminum boat) during March before the first treatment and at least once thereafter (Table 1). Sampling included two 15-minute shoreline electrofishing transects in which we collected all fishes >80 mm. We measured (nearest mm) and weighed (nearest g) all fishes captured and collected a subsample of 10 Largemouth Bass per 25-mm length interval (for fish 150–250 mm) for ageing using sagittal otolithsWe also used this subsample to determine the appropriate length cutoff for age-1 vs. age-2 fish and quantify and compare mean length-at-age. We mounted otolith transverse sections on slides using methods of Boehlert (1985) and aged slides using immersion oil for clarity. Two readers aged otoliths without prior knowledge of fish length, weight, or the other reader’s age estimates. When different ages were assigned to individual fish, we recruited a third reader had a group discussion to reach a consensus age.

*Age-0 relative abundance and mean length.—*We used R (R Core Team 2020) to run all analyses. We used two before-after-control-impact (BACI) analyses to test for effects of shoreline rotenone treatment on Bluegill and age-0 Largemouth Bass seine catches in both large-sized and small-sized impoundments (Stewart-Oaten et al. 1986). The first analysis compared seine catches immediately before (i.e., day-1 and -21) and after (i.e., day-2 and -22) rotenone application to evaluate the short-term effect of the application. We conducted this analysis with a generalized linear mixed-effects model with a negative binomial sampling distribution. There were random effects for impoundment x year intercepts and fixed effects of application (i.e., first: day-1 vs. day-2, and second: day-21 vs. day-22), treatment (control/treatment), time period (before/after treatment), and all interactions. The treatment x time interaction tested whether catches declined significantly more in treatments than controls.

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

We compared Largemouth Bass mean length-at-age (MLA)-0 in the pre-treatment and mid-summer follow-up seine samples using a BACI analysis, estimating initial growth differences between controls and treatments for both large-sized and small-sized impoundments. We conducted this analysis using a linear mixed-effects model and natural-log-transformed catch data 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 for both large-sized and small-sized impoundments using a BACI analysis. We obtained MLA 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 via maximum likelihood with independent random effects of impoundment and year intercepts and a fixed effect of rotenone treatment (once or twice) on the natural logarithm of MLA-1.

We evaluated the effect of rotenone treatment on natural-log-transformed electrofishing catch-per-unit-effort (CPUE) of age-1 Largemouth Bass and stock-sized Bluegill (i.e., >80 mm) using a BACI analysis for both large-sized and small-sized impoundments. We analyzed effects of rotenone application on Largemouth Bass recruitment using age-1 CPUE and effects on non-target fish for rotenone application (i.e., Bluegill) using Bluegill CPUE. For each dependent variable, we fit a linear mixed-effects model via maximum likelihood that included independent random effects of impoundment and year intercepts and a fixed effect of rotenone treatment.

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 March age-1 electrofishing catches by the mid-summer follow-up seine (day-42) catches from the previous year. We tested for differences in the survival index as a function of rotenone treatment frequency (i.e., no treatment, one year, two years) for both large-sized and small-sized impoundments using linear models with a fixed effect of rotenone treatment.