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ARTICLE

Bowfishing shoot and release: High short-term mortality of nongame fishes and its management implications

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Abstract

Objective: Although bowfishing is legal in all 50 states in the USA, the practice of releasing shot fish is only legal in 8 states. An argument favoring this practice has been that survival of fish after shoot-and-release fishing is high. Bowfishing mortality trials were conducted in 2021–2022 in Lake Texoma, Oklahoma, to quantify shoot-and-release mortality and characterize the mortality via the location of the wound associated with the release of fish shot by bowfishing.

Methods: A total of 240 nongame fish were shot by experienced bowfishers with conventional bowfishing equipment and held in convalescent pools, with control fish captured by electrofishing to document short-term mortality up to 5 days.

Result: Overall mortality of bowfished fish was 87% versus 0% for control fish. Fish shot in critical areas (head, internal organs, or spine; 78% of total) suffered 96% mortality, whereas fish shot in noncritical areas (dorsal musculature, tail, or fins) experienced 52% mortality. In addition, 13.7% of fish shot were not successfully retrieved. Shot fish were generally older (mean = 19.4 years, range = 3–54) and contained more females (62%) than control fish (mean = 12.5 years, range = 2–39; 37% female), providing evidence that bowfishing can remove individuals of great recruitment value. The shoot-and-release mortality rates in this study, for fish shot in both critical and noncritical areas, exceeded mortality from a wide range of angler catch and release in other studies.

Conclusion: The high mortality rate associated with shoot and release observed in this study and as practiced by recreational bowfisheries renders shoot and release inconsistent with scientifically regulated and sustainable bowfisheries for native nongame species. These results provide evidence that the bow and arrow, when aimed at animals, is a weapon that is intended to kill. Bowfishing should realistically be managed as a 100% consumptive (i.e., kill) pursuit in which shoot and release is prohibited and nonretrieval of shot fish is accounted for.

KEYWORDS
bowfishing, mortality, native nongame

INTRODUCTION

Bowfishing, the practice of using specialized archery equipment (bow and arrow or crossbow) to shoot and retrieve fish, is increasing in popularity among freshwater and saltwater anglers throughout North America (Scarnecchia and Schooley 2020; York et al. 2022). Bowfishing is often legally defined by state fish and wildlife agencies as a distinct and alternative method from the hook-and-line or rod-and-reel angling gear most commonly used for state-designated “game” species. As a result, bowfishing take is typically restricted to fish codified in state statutes and classified by state management agencies as “nongame” species. For example, Oklahoma Statutes (29 O.S. § 2–115) define “game fishes” as a list of 14 species (some of which are hybrids or nonnative to Oklahoma), and any species not on this list is legally considered nongame (29 O.S. § 2–123). Although the catch-all designation “nongame” includes a diversity of fish species across the United States and many of those species would qualify as de facto game fishes (Scarnecchia et al. 2021), the species are hereafter placed into two distinct groups of common regulatory and ecological relevance: native nongame species and nonnative invasive species. Among the freshwater native nongame species often targeted by bowfishing are the buffalofishes (Smallmouth Buffalo *Ictiobus bubalus*, Bigmouth Buffalo *I. cyprinellus*, and Black Buffalo *I. niger*), gars (Longnose Gar *Lepisosteus osseus*, Spotted Gar *L. oculatus*, Shortnose Gar *L. platostomus*, and Alligator Gar *Atractosteus spatula*), Paddlefish *Polyodon spathula*, carpsuckers (River Carpsucker *Carpiodes carpio*, Highfin Carpsucker *C. velifer*, and Quillback *C. cyprinus*), Bowfin *Amia calva*, Freshwater Drum *Aplodinotus grunniens*, redhorses *Moxostoma* spp., bullheads *Ameiurus* spp., and others, depending on the locality (Scarnecchia and Schooley 2020). Among the most common nonnative invasive species taken by bowfishing are Common Carp *Cyprinus carpio*, Grass Carp *Ctenopharyngodon idella*, Bighead Carp *Hypophthalmichthys nobilis*, and Silver Carp *H. molitrix* (Scarnecchia and Schooley 2020).

Recent life history research on many native nongame species and the expansion of bowfishing as a sport has highlighted the need for more conscientious conservation and management of these chronically undervalued species (Lackmann et al. 2021). The native nongame fishes targeted by the sport have greater conservation value (Rypel et al. 2021) and can be more sensitive to overharvest than previously recognized (Scarnecchia and Schooley 2020; Scarnecchia et al. 2021). Many of these ecologically valuable native nongame species are now known to be long lived with irregular or episodic recruitment (Table 1) and therefore are highly vulnerable to unregulated harvest (Scarnecchia and Schooley 2020; Scarnecchia et al. 2021). These research findings and conclusions are counter to more traditional agency and angler views, in which native nongame species have often been considered undesirable and their reduction or elimination beneficial to game fishes (reviewed in Scarnecchia 1992; Rypel et al. 2021; Scarnecchia et al. 2021). In many cases, bowfishers and anglers have believed, or been led to believe, that the removal of native nongame fishes had no negative consequences for waters and that the take and subsequent disposal of these fish was aiding managers, many of whom shared similar views of these species.

Impact statement

Bowfishing is increasing in popularity and is legal in all states in the USA. Based on this short-term study, fish shot with bow and arrow experience high mortality when released. Therefore, bowfishing should be managed as a consumptive pursuit and releasing shot fish should be prohibited.

The need to better conserve and manage desirable fish species, both native game and native nongame, while typically allowing some take, has led managers in many localities to encourage catch and release. Catch-and-release angling, a long-recognized voluntary or regulatory practice that leads to the capture and subsequent release of the fish unharmed, coalesced into a more formal fishing and fisheries management philosophy after the first catch-and-release symposium at Humboldt State University (California) in 1977 (Barnhart and Roelofs 1977). Since then, it has become an increasingly popular approach in recreational fishing for many species of fish (Barnhart and Roelofs 1987; Arlinghaus et al. 2007; Brownscombe et al. 2017). Catch and release can have potential benefits to anglers by enhancing recreational quality, increasing angler catch rates, and improving size structure of desired species (Brownscombe et al. 2017). In theory, it is especially well suited to situations where fishing effort is high, need for consumption of fish is relatively low, rates of natural mortality are low (e.g., Scarnecchia and Stewart 1997), recruitment is sparse, and larger, sometimes trophy-sized individuals can be stockpiled and repeatedly captured (Hunt 1977).

A critical assumption of catch and release for its success as a management tool is that a high fraction of fish survive the catch-and-release experience. However, fishing-related stressors (e.g., hooking, handling, exhaustive physical exercise, air exposure) can elicit physiological distress, substantial physical injuries, and behavioral impairments that may result in immediate or delayed mortality or reduced fitness (Raby et al. 2014). Factors including, but not limited to, fish size, sex, water temperature, hook size and shape, hooking location, handling procedures of harvesters, handling time (both in and out of water), and barotrauma (Bellquist et al. 2019) can contribute to increased mortality (Bartholomew and Bohnsack 2005; Martins et al. 2018; Wegner et al. 2021). Postrelease mortality associated with using hook-and-line fishing, the most common recreational fishing method,

TABLE 1 Summary of select published life history statistics for native nongame fishes often shot by bowfishers. Validated age estimates are indicated by an asterisk.

Species	Maximum age	Age at maturity (sex)	Irregular recruitment	Citations (state)
Alligator Gar	68*			Daugherty et al. (2020) (Texas)
	95*			A. H. Andrews, NOAA Fisheries, personal communication (Mississippi)
		5		DiBenedetto (2009) (Louisiana)
			Yes	Buckmeier et al. (2013, 2017); Smith et al. (2020) (Texas)
Bigmouth Buffalo	26			Paukert and Long (1999) (Oklahoma)
	>100*	10 (female)	Yes	Lackmann et al. (2019); Lackmann et al. (2021); Lackmann et al. (2022) (Minnesota)
Black Buffalo	56			Lackmann et al. (2019) (Michigan)
Blue Sucker	42			Radford et al. (2021) (Indiana, Illinois)
Bowfin	33		Yes	Lackmann et al. (2022) (Minnesota)
Freshwater Drum	58*			Davis-Foust et al. (2009) (Wisconsin)
Longnose Gar	27			McGrath et al. (2016) (Virginia)
	29			This study (Oklahoma)
Paddlefish	29	8 (female)	Yes	Schooley et al. (2014); Scarnecchia and Schooley (2022) (Oklahoma)
	>60	16* (female)	Yes	Scarnecchia et al. (2011); Scarnecchia et al. (2019) (Montana, North Dakota)
Quillback	44	8–9	Yes	Lackmann et al. (2022) (Minnesota)
River Carpsucker	>45			Lackmann et al. (2022) (Minnesota)
Smallmouth Buffalo	62			Snow et al. (2020) (Oklahoma)

has been extensively researched and quantified for common freshwater game fishes such as Largemouth Bass *Micropterus salmoides*, Blue Catfish *Ictalurus furcatus*, Bluegill *Lepomis macrochirus*, Muskellunge *Esox masquinongy*, and Walleye *Sander vitreus* (Bartholomew and Bohnsack 2005; Pollock and Pine 2007; Kerns et al. 2012; Schmitt and Shoup 2013). In a review of 274 hook-and-line catch-and-release mortality estimates from 54 studies, Bartholomew and Bohnsack (2005) reported an average mortality of 18% and a median rate of only 11%; more than three-fourths of the mortality estimates were <30%. These overall low rates have led to catch and release becoming a commonly used approach among both tournament and casual anglers and an increasingly applied regulation tool for game fishes used by agency fisheries managers.

In sharp contrast, research on native nongame catch-and-release mortality from angling is largely lacking in the literature, likely the result of lower social regard for native nongame species (Rypel et al. 2021) and minimal funding allocated to native nongame fishes (Scarnecchia et al. 2021). Only Alligator Gar and Paddlefish, the largest and most charismatic megafauna among the native nongame fishes targeted by anglers, have been studied and are regulated by some states to minimize catch-and-release angling mortality (Scarnecchia and Stewart 1997; Bettoli et al. 2019; Snow and Porta 2021). Furthermore, no mortality studies following fish release have focused on the alternative fishing methods (e.g., bowfishing, spearing, gigging) targeting these undervalued native nongame fishes. These fisheries have historically been regarded as harvest, take, or consumption oriented and not worthy of or justifiable as catch-and-release fisheries. Retention of fish shot by sport bowfishers is mandated in all but eight states as of 2021 (A. Lackmann, University of Minnesota Duluth, personal communication). The mortality and fate of bowfished and released fish in these eight states (i.e., shoot and release) is unknown.

Bowfishing shoot-and-release mortality is hypothesized to exceed that of angling catch-and-release mortality because bowfishing take involves (1) an arrow impaling or passing entirely through the fish, (2) the subsequent struggle of the fish on the arrow, (3) landing the fish by gaff or arrow-hoisting the fish under its own weight, and (4) dislodging the fish from the arrow. Therefore, bowfishing likely results in greater physiological stress and increased incidence of injuries to vital areas, such as internal organs, than traditional hook-and-line angling. However, no one has quantified bowfishing shoot-and-release mortality and the sport is overall understudied (Scarnecchia and Schooley 2020). Therefore, our primary objective in this study was to quantify shoot-and-release mortality and characterize the mortality via the location of wounds associated with the release of native nongame and nonnative invasive fishes shot by bowfishing. Information obtained is designed to aid managers in developing sustainable regulatory frameworks and in understanding realistic and defensible regulatory options for the expanding sport of bowfishing.

METHODS

Bowfishing shoot-and-release mortality trials were conducted in May and September of 2021 and May and August of 2022 in the Red River arm of Lake Texoma, Oklahoma (36,000 ha; 33.8947°N, 96.6745°W), near the University of Oklahoma Biological Station. Beyond the extra ecological data collected for the study, the trials were designed to simulate typical bowfishing outings by experienced bowfishers using typical gear. Fish were shot ad libitum by two to three locally recruited bowfishers from a boat while two Oklahoma Department of Wildlife Conservation (ODWC) observers collected data. Each bowfisher was equally equipped with a compound bow (15.8–25.0-kg draw weight) that held a reel attached to the bow containing 68-kg test line. Each fish was shot with fiberglass arrows, with heads consisting of a single point and two barbs. This bowfishing rig is commonly used in Oklahoma waters. Bowfishing trials occurred during both daytime and nighttime. Water temperature was recorded during each trial.

On the boat during active bowfishing, the ODWC observer recorded the shot success (hit or miss), fish species shot, and fish retrieval time, representing the elapsed time (minutes) between arrow penetration and landing on the boat, where the arrow was removed. Fish shot but not successfully retrieved were recorded but yielded limited data, including an abbreviated retrieval time that ended when the fish freed itself from the arrow. For fish not successfully retrieved, verifiable visual assignment of species was not possible; therefore, species was not recorded for fish not successfully retrieved. Fish successfully retrieved were placed in a 757-L aerated holding tank on the boat that received a constant flow of fresh water directly from Lake Texoma to maintain consistent water quality and temperature. Each fish was tagged with a unique T-bar anchor tag (Floy tag FD-94) in the dorsal musculature between the pterygiophores, measured for total length (TL; mm) and weight (g), and assessed for the anatomical location or locations where the fish was penetrated by the arrow (head, internal organs, spine, dorsal musculature, tail, or fins; Figure 1). Fish that immediately died were placed on ice in a cooler. Anatomical locations of arrow penetration were a priori assumed to be unequal in their impacts on mortality. Therefore, injuries to the head, internal organs, or spine were considered "critical wounds," whereas injuries to the dorsal musculature, tail, or fins were considered lesser "flesh wounds." These categories were used for analyses examining mortality associated with location of arrow penetration.

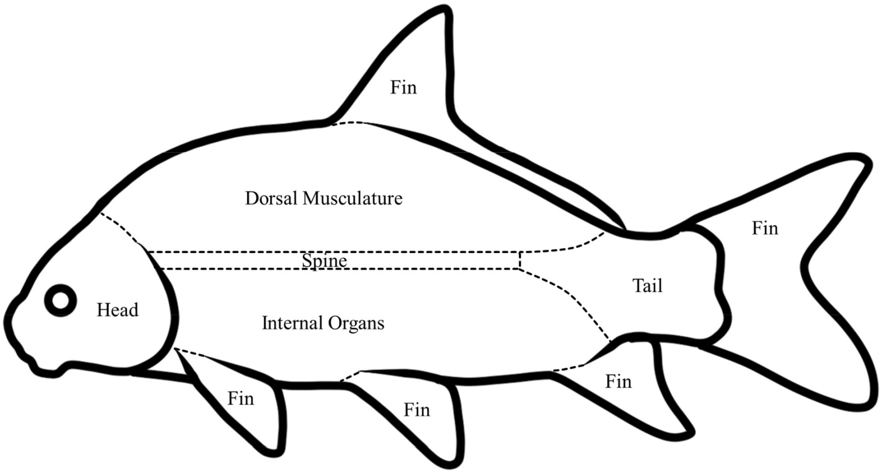

FIGURE 1 Anatomical locations of arrow penetration (head, internal organs, spine, dorsal musculature, tail, and fins) recorded from nongame fish shot with a bow and arrow (Smallmouth Buffalo, illustration courtesy of Henry Hershey).

Live fish were transported to the University of Oklahoma Biological Station and divided randomly between two convalescent holding pools (4.6 m diameter × 1.2 m deep; Intex Recreation) that were positioned under trees to provide shade. Each holding pool served as a flow-through system and was continuously filled with water directly from Lake Texoma using a 1-HP 115-V Utilitech utility pump (Model 148008). An air stone was placed in each pool to increase water circulation and to supplement dissolved oxygen (DO; mg/L) concentrations in both pools. Temperature (°F) and DO concentration were recorded daily with a YSI meter (Model Pro 2030; Yellow Springs Instruments) throughout the pool to ensure that DO levels were maintained at 6 mg/L or greater.

Additional fish were captured from Lake Texoma with boat electrofishing (pulsed direct current; Smith Root 7.0 GPP electrofishing unit) for use as control fish, tagged with a T-bar anchor tag, measured, weighed, and placed in the convalescent holding pools along with, and at the same time as, the shot fish. All fish were monitored, and mortalities were removed every 3 h for the first 12 h, then every 24 h for 4 days (96 h) in trial 1 and for 5 days (120 h) in trials 2–4. After removing dead fish and identifying them by their tag number, a necropsy was performed to confirm shot location and internal injuries caused by the arrow. At the end of the study period, all surviving injured fish were placed in a 1:1 ice-to-water slurry to be euthanized (Blessing et al. 2010), and all fish were later necropsied at the ODWC Oklahoma Fisheries Research Lab. All activities performed on site at University of Oklahoma Biological Station were permitted under University of Oklahoma Institutional Animal Care and Use Committee protocols (permit number R21-014).

Fish were assigned a maturity status (immature or mature). Immature fish were those showing no signs of gonadal development. Ovaries of immature fish were classified as barely distinguishable or clearly distinguishable but not developed. Mature female fish were classified if they had well-developed ovaries that contained yellowish to white-yellow eggs or if their ovaries were spent (i.e., the eggs previously expelled). Mature male fish were classified if their testes were enlarged and white in color. For some analyses, fish were taxonomically grouped by family or into two morphotypes: Teleostei (the deeper-bodied buffalofishes and carps) and Holostei (the elongate-bodied gars).

Otoliths were extracted from each fish and placed into an individually numbered envelope and allowed to dry for 24 h (Secor et al. 1992). Once dried, otoliths were processed. Otolith selection and processing methods varied by species: gars (sagittal; Buckmeier et al. 2018), buffalofishes (lapilli; Love et al. 2019; Snow et al. 2020), River Carpsucker (lapilli; Bartnicki and Snow 2021), Freshwater Drum (sagittal; Davis-Foust et al. 2009), and Common Carp and Grass Carp (lapilli; Stich et al. 2013). The sole Flathead Catfish taken was unable to be aged. After processing, otoliths were viewed using a stereo microscope (capable of 130× magnification) with a fiber optic filament attached to an external light source to illuminate annuli (Buckmeier et al. 2002). Each otolith was estimated in concert by two readers; however, if the readers disagreed on the age of the fish, then that otolith was put aside and later viewed again (Hoff et al. 1997). If an otolith was unreadable, the second otolith's age was estimated; however, if that otolith was also unreadable, the fish was removed from the study. Each otolith was evaluated in random order with no reference of TL, weight, or sex (Hoff et al. 1997).

Analysis

We generated summary statistics for retrieval success and retrieval times and compared fish TLs, weights, sex ratios, and age estimates obtained from shot and control fish. When sample size allowed, we also compared fish TLs, weights, sex ratios, and age estimates obtained from shot and control fish from each family. Comparisons at the family level were used to confirm cross family comparisons by controlling for influence of family level variations in morphology and longevity. We compared fish TLs, weights, and age estimates using a Students *t*-test and sex ratios using a χ^2 test ($\alpha = 0.05$).

A series of hypotheses on shot location and mortality were tested using a χ^2 test ($\alpha = 0.05$) based off of 10,000 Monte Carlo iterations. The strength of association for each hypothesis was determined using Cramér's *V* statistic with thresholds for weak, moderate, and strong associations determined by the minimum number of rows or columns within a table (Cohen 1988). When possible, a 95% CI for Cramér's *V* was also calculated. All analyses were conducted in program R (R Core Team 2023). For analyses involving family, only Catostomidae, Cyprinidae, and Lepisosteidae were included as Ictaluridae and Sciaenidae families were each represented by one fish and no control fish from either family were obtained. The following 10 hypotheses were tested in this manner:

1. Shot location differed between families (Catostomidae, Cyprinidae, and Lepisosteidae) for fish shot in only one location.
2. Shot locations differed between families (Catostomidae, Cyprinidae, and Lepisosteidae) for fish shot in one or more locations.
3. Mortality differed between bowfished and control fish.

4. Mortality differed between bowfished and control fish (Catostomidae only).
5. Mortality differed between bowfished and control fish (Cyprinidae only).
6. Mortality differed between bowfished and control fish (Lepisosteidae only).
7. Mortality differed between fish shot in a single location and fish shot in multiple locations.
8. Mortality varied by shot location (for fish shot in only one location).
9. Mortality varied by shot location (for fish shot in one or more locations).
10. Mortality differed between fish with "critical wounds" and "flesh wounds."

We used a generalized linear model (GLM; McCullagh and Nelder 1989) with a logit link function to determine what factors had the strongest influence on shoot-and-release mortality. The response variable for this GLM was a dummy variable determined based on each individual fish's status at the end of their trial (i.e., survived = 0, died = 1). Predictor variables used in this GLM were water temperature (°F), TL (mm), weight (g), number of times shot, family, sex, estimated age (years), five of the six anatomical shot locations (head, internal organs, spine, dorsal musculature, and tail), and if a shot hit a "critical" location (i.e., head, internal organs, or spine). The fin shot location was excluded from this analysis as only one Smallmouth Buffalo was shot in the fins and that individual was also shot in the internal organs. Likewise, the Freshwater Drum and Flathead Catfish were also removed from this analysis as they were the only observations from each of their respective families. This resulted in a total of 200 usable observations for fitting the GLM once single-observation species and fish with incomplete data (e.g., missing an age estimate) were removed. A Pearson's correlation test was performed to ensure predictive variables were not correlated sufficiently to cause multicollinearity issues. Paired variables were considered moderate to strongly correlated at $r \geq |0.60|$ (Akoglu 2018). Only the internal organ shot location and the critical shot location predictors were moderate to strongly correlated ($r = 0.63$), and the critical shot location predictor was removed prior to analysis as retaining the internal organs shot location allowed us to better compare the effect of each individual shot location on mortality and reduce redundancy in our predictor variables.

A backwards selection process was used to determine the most important predictive variables (James et al. 2013). In this approach, we first fit the GLM using all predictors, removed the least significant predictive variable (i.e., predictor with the highest p-value), then refit the GLM with the remaining predictors. The process of refitting the GLM and removing the least significant predictive variable was repeated until all only significant ($\alpha = 0.05$) predictors remained. Goodness of fit for the final model was determined via a Hosmer–Lemeshow goodness-of-fit test ($\alpha = 0.05$; Hosmer and Lemeshow 2000). To help confirm that our backward selection process (i.e., removal of nonsignificant predictors) did not result in a model with poorer relative fit to the data, we compared our final model from the backwards selection process to the prior two models (i.e., models with one or two nonsignificant predictors) using likelihood-ratio tests ($\alpha = 0.05$).

The predictive accuracy of our GLM was determined using area under the receiver-operating-characteristic curve (AUC; James et al. 2013) estimated from the 40 samples not used for fitting the GLM. The AUC estimates were interpreted as acceptable (AUC = 70–79), excellent (AUC = 80–89), or outstanding (AUC ≥ 90) based on criteria in Hosmer and Lemeshow (2000). Predicted outputs from our binomial model were probabilities between 0 and 1; therefore, a classification breakpoint was used to estimate predictive accuracy. The classification breakpoint represents the threshold at which probability values are assigned to either the mortality (i.e., 1) or survival (i.e., 0) categories (James et al. 2013). The classification breakpoint was selected as the probability value along the predicted curve from the final model where naïve AUC (i.e., AUC estimated from the 200 samples used to fit the model) was maximized (Zentner et al. 2021). We then used the classification breakpoint to predict mortality or survival for the 40 samples not used for fitting the GLM to estimate AUC for the final model.

Discrete shoot-and-release mortality was estimated at 3, 6, 9, 12, 24, 48, 72, and 96 h for all four of our trials and at 120 h using three of our four trials as the first trial was only conducted for 96 h. Finite shoot-and-release mortality was estimated for each individual trial using the following equation:

$$\widehat{M}_{HOFi} = 1 - \left(\frac{\widehat{S}_{HTi}}{\widehat{S}_{CTi}} \right),$$

where $\widehat{M}_{HOFi}$ represents the finite shoot-and-release mortality estimated at time T for the ith trial, $\widehat{S}_{HTi}$ is the finite survival of shoot-and-release fish at time T from the ith trial, and $\widehat{S}_{CTi}$ is the finite survival of control fish at time T from the ith trial (Pollock and Pine 2007).

Once finite shoot-and-release morality estimates were obtained for each of our trials, mean shoot-and-release mortality was estimated as follows:

$$\overline{M}_T = \frac{\sum_{i=1}^{r} \widehat{M}_{HOFi}}{r},$$

where $\overline{M}_T$ represents the mean finite shoot-and-release mortality estimated at time T from all finite shoot-and-release estimates at time T, i indicates the trial number, and r indicates the number of replicate trials (Pollock and Pine 2007).

A 95% CI for finite shoot-and-release mortality at each discrete time interval was estimated via normal approximation from the standard error. Standard errors of the mean finite shoot-and-release mortality estimates at each time interval $\left[SE\left(\overline{M}_T\right)\right]$ were obtained from finite and mean shoot-and-release mortality estimates using the following:

$$SE\left(\overline{M}_T\right)=\sqrt{\frac{\sum_{i=1}^{r}\left(\hat{M}_{HOFi}-\overline{M}_T\right)^2}{r(r-1)}}.$$

When estimating mortality with these equations, we assume no mortality of control fish and that handling mortality is equal between treatment and control fish. Though the assumption of no mortality for control fish is easily verified, equal handling mortality is difficult to verify. With respect to hooking mortality studies, assuming equal handling mortality has generally been a reasonable assumption (Pollock and Pine 2007). Given we are estimating shoot-and-release mortality, the assumption of equal handling mortality may be unnecessary as handling the fish to remove the arrow would be part of the shoot-and-release process.

RESULTS

A total of 281 fish were shot during the four individual bowfishing shooting events (trials), and 240 of those were successfully retrieved (85.4% overall). The proportion retrieved varied across the four trials from 71.6% to 98.0%. Therefore, if our four trials reflected an average bowfishing outing, the predicted retrieval rate was 86.3% (95% CI = 75.7–96.8%).

Retrieval time was observed for 181 shot and successfully landed fish and ranged from 5 to 105 s (mean = 20 s). In some instances, fish were shot multiple times by one or more bowfishers in the process of successful retrieval. Six fish of various species were shot twice with a mean retrieval time of 38 s, one 9-kg Grass Carp was shot three times, requiring 29 s to land, and one 4-kg Smallmouth Buffalo was shot four times, but retrieval time was not recorded. Abbreviated retrieval time for 30 fish shot but not successfully landed ranged from 2 to 68 s (mean = 14 s).

Shot and retrieved fish represented five families: Catostomidae ($n=172$), Lepisosteidae ($n=45$), Cyprinidae ($n=21$), Sciaenidae ($n=1$), and Ictaluridae ($n=1$). Only 21 of the 172 fish were nonnative invasive species, specifically Common Carp ($n=12$) and Grass Carp ($n=9$). Retrieved fish were monitored for short-term mortality (up to 5 days) in the convalescent holding pools. These species, ordered by decreasing abundance, included Smallmouth Buffalo, Black Buffalo, Spotted Gar, Longnose Gar, Common Carp, Grass Carp, River Carpsucker, Shortnose Gar, Freshwater Drum, and Flathead Catfish (Table 2). Control fish species ($n=83$) captured via electrofishing included a subset of shot fish species, representing three families: Catostomidae, Cyprinidae, and Lepisosteidae (Table 2). All fish were weighed and measured except for one Longnose Gar, and the Flathead Catfish was measured but not weighed (Table 2). For species in common between control and bowfished groups, only Smallmouth Buffalo differed significantly in size, with bowfishing selecting for longer ($t=6.34$, df = 155, $p<0.05$) and heavier ($t=5.01$, df = 155, $p<0.05$) individuals (Figure 2).

Among shot fish for which sex was confidently determined, 145 were females (62%) and 90 were males (38%). Among native nongame shot fish with sample sizes >1, sex ratio for Black Buffalo was most heavily skewed towards female (65%), followed by Smallmouth Buffalo (63%), River Carpsucker and Longnose Gar (each 60%), and Spotted Gar (50%). Of the 83 control fish, 2 were characterized as immature (3.9%), 19 as female (37.3%), and 30 as male (58.8%). Shot fish had significantly more females than control fish ($\chi^2=10.44$, df = 1, $p<0.05$), and a similar result was found for Smallmouth Buffalo ($\chi^2=3.97$, df = 1, $p<0.05$). Sex ratios for other species were not statistically compared due to sample size limitations; however, shot Common Carp and River Carpsucker were proportionally more female than control fish.

Estimated ages of native nongame shot fish ranged from 3 to 54 years (mean = 19.4; Table 2). No Black Buffalo were aged at fewer than 13 years, and median age (31.5 years) exceeded the mean age (30.3 years). Although 62% of Smallmouth Buffalo were younger than age 25, 82% of Black Buffalo shot were 25 or older, and the distribution included a gap of no fish between ages 15 and 25 (Figure 3). Estimated ages of nonnative invasive shot fish ranged from 3 to 28 years (mean = 11.2; Table 2). Estimated ages of control fish ranged from 2 to 39 years (mean = 12.5; Table 2). Overall, mean age of shot fish ($n=202$, 18.6 years) was significantly greater ($t=3.259$, df = 251, $p<0.05$) than that of control fish ($n=51$, 12.5 years). Mean age for shot Smallmouth Buffalo was significantly greater than for control Smallmouth Buffalo ($t=2.57$, df = 149, $p<0.05$).

Mortality was observed for 208 (87%) of 240 shot fish monitored (Table 3). Mortality within species ranged from 79% for Spotted Gar to 100% for River Carpsucker and Grass Carp. Although Flathead Catfish, Shortnose Gar, and Freshwater Drum also experienced 100% mortality, each species was represented by only a single individual.

TABLE 2 Summary of length, weight, and age statistics for fish shot with bowfishing equipment and control fish, both taken from Lake Texoma, Oklahoma. One Longnose Gar was not weighed or measured and was therefore omitted from fish shot with bowfishing equipment. Comparisons of mean length, weight, or age by species for control fish versus shot fish indicated by an asterisk were significantly different (Student's *t*-test, α = 0.05). The abbreviation NA indicates that data was not available.

		Total length (mm)		Weight (g)		Age (years)
Species	***n***	**Mean (95% CI)**	**Range**	**Mean (95% CI)**	**Range**	**Max, mean, *n***
Shot and retrieved						
Black Buffalo	34	670 (648–693)	554–804	4828 (4343–5314)	2690–9160	48, 30.3, 22
Common Carp	12	606 (568–644)	521–774	2992 (2348–3635)	1750–5810	28, 9.9, 9
Freshwater Drum	1	453		1050		9, NA, 1
Flathead Catfish	1	630				
Grass Carp	9	884 (839–929)	763–956	8296 (6884–9707)	5125–11,580	21, 12.8, 8
Longnose Gar	15	1057 (975–1139)	687–1230	3277 (2697–3857)	1180–5020	29, 10.2, 12
River Carpsucker	6	430 (377–484)	306–497	1088 (814–1363)	435–1370	13, 9.6, 5
Smallmouth Buffalo	132	562 (549–574)*	341–711	3076 (2861–3291)*	690–9250	54*, 21.3, 117
Shortnose Gar	1	645		1110		
Spotted Gar	28	616 (591–640)	451–742	893 (769–1017)	245–1560	13, 8.2, 27
Control						
Black Buffalo	2	596 (540–651)	567–624	3916 (2515–5316)	3201–4630	26, NA, 1
Common Carp	15	553 (514–592)	420–730	2408 (1892–2924)	1220–5200	13, 10.3, 9
Longnose Gar	8	1118 (992–1244)	902–1450	3355 (2730–3980)	2205–4670	
River Carpsucker	6	425 (394–455)	358–470	1097 (851–1342)	590–1520	5, 4.0, 3
Smallmouth Buffalo	41	484 (457–512)*	279–630	2123 (1797–2450)*	320–4470	39*, 15.2, 34
Spotted Gar	11	615 (593–637)	568–683	860 (739–981)	695–1270	13, 7.8, 4

For families represented by more than one individual, mortality was greatest in Cyprinidae (90%), followed by Catostomidae (88%) and Lepisosteidae (80%). Species grouped as native nongame or nonnative invasive experienced 86% and 90% mortality, respectively. In contrast, all control fish ($n = 83$) survived the convalescent holding period.

Of the shot fish necropsied, 144 fish sustained injuries to internal organs, 128 to the dorsal musculature, 42 to the head, 19 to the spine, 7 to the tail, and 1 to the fins (Table 4). Most fish (61%) sustained injuries to only one location (Table 5), although the remainder (93 fish) sustained injuries to two or more locations, with 86 fish injured in two locations, 6 in three locations, and 1 in four locations (Table 6). By taxonomic morphotype (Teleostei: Catostomidae and Cyprinidae, Holostei: Lepisosteidae; Table 7), Teleostei were shot in the head 20% of the time, whereas Holostei were shot in the head only 7% of the time. In the Holostei, the dorsal musculature was shot at the highest frequency (80%). When examined by family (Catostomidae, Cyprinidae, and Lepisosteidae; Table 7), Cyprinidae were observed to be more often shot in the internal organs and dorsal musculature (81% and 71%, respectively), than were Catostomidae (56% and 44%, respectively).

When comparing fish with "critical wounds" (i.e., injuries to one or more critical areas: head, internal organs, or spine, regardless of other injuries) to fish with "flesh wounds" (i.e., not injured in head, internal organs, or spine), a majority of shot fish (78%) sustained critical wounds (Figures 4–6). Short-term mortality was near total (96%) for fish with critical wounds, whereas mortality was 52% for fish with flesh wounds. Using 10,000 Monte Carlo iterations, shot location was found to significantly differ between families (Catostomidae, Cyprinidae, and Lepisosteidae) for fish shot in only one location, with a moderate association, but shot location did not significantly differ for fish shot in more than one location (Table 8). Mortality was found to significantly differ between bowfished and control fish, and this association was determined to be strong (Table 8). When mortality was compared between bowfished and control fish, but within family, significant differences and strong associations were found for each family (Table 8). Mortality of shot fish was found to vary significantly between fish shot in a single location and fish shot in multiple locations; this association was weak–moderate. Although mortality significantly varied by shot location for both fish shot in only one location and fish shot in one or more locations, this association was stronger

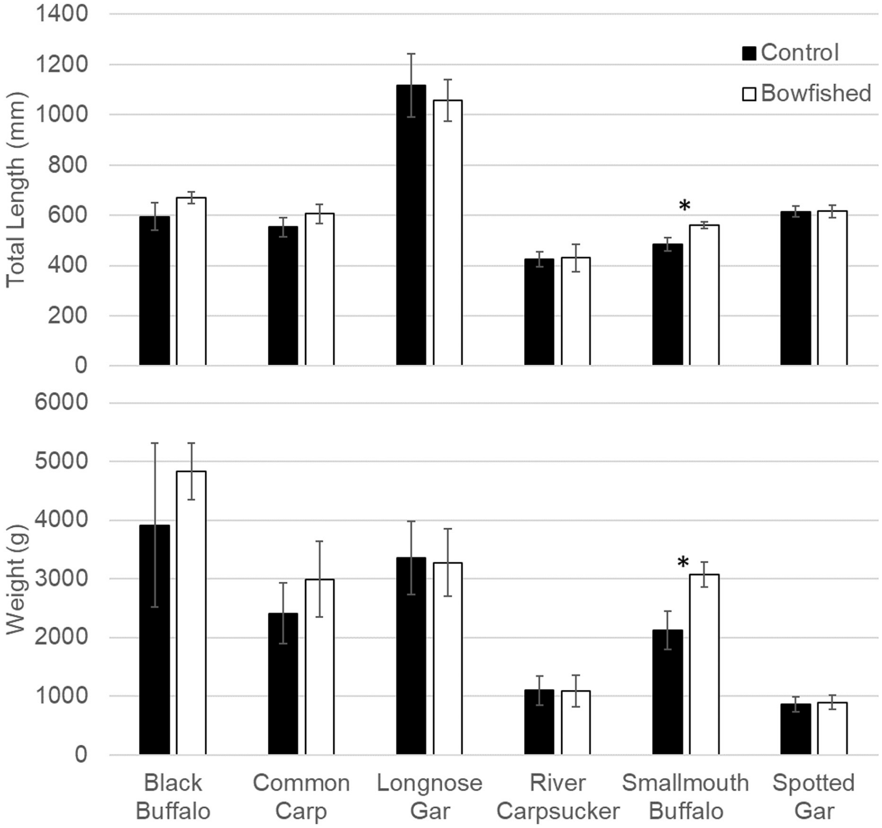

FIGURE 2 Mean total lengths and weights with associated 95% confidence intervals for control and bowfished species demonstrating that bowfishing selected for larger Smallmouth Buffalo than electrofishing for fish taken from Lake Texoma, Oklahoma. Significant differences (Student's *t*-test, $\alpha = 0.05$) between means are noted with an asterisk.

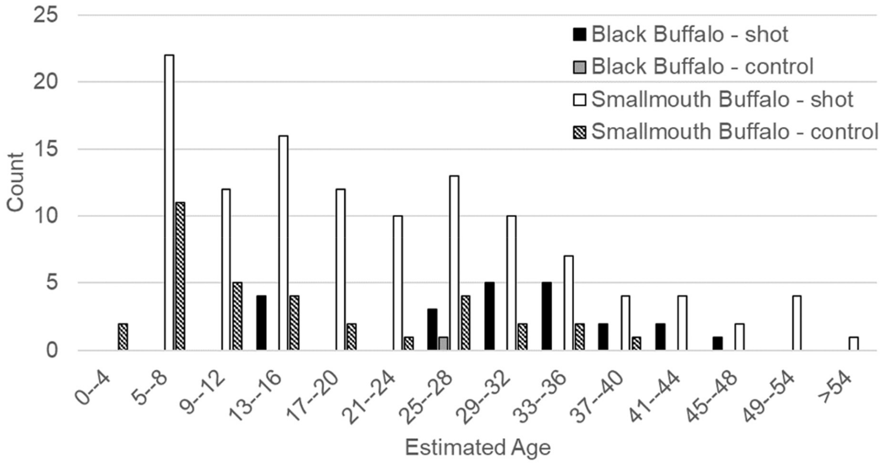

FIGURE 3 Estimated ages of Black Buffalo and Smallmouth Buffalo shot with bowfishing gear or captured using electrofishing (control) in Lake Texoma, Oklahoma.

when considering only one location (Table 8). Mortality was significantly different between fish with critical wounds and fish with flesh wounds; the association was strong (Table 8).

Our backward selection process removed eight variables from the initial model, suggesting that water temperature and being shot in the head or internal organs had the strongest influence on a fish dying from an arrow puncture. Increasing water temperature, being shot in the head, and being shot in the internal organs all increase the probability of mortality for shot-and-released fish (Figure 7). The Hosmer–Lemeshow goodness-of-fit test suggested that

TABLE 3 Observed short-term mortality of fish shot with bowfishing equipment from Lake Texoma, Oklahoma, and held in convalescent pools with control fish for up to 120 h. Control fish placed in the convalescent pools with the shot fish experienced 0% mortality.

Family	Species	*n*	Survived *n*	Survived %	Died *n*	Died %
Catostomidae	Black Buffalo	34	1	3	33	97
	River Carpsucker	6	0	0	6	100
	Smallmouth Buffalo	132	20	15	112	85
Ictaluridae	Flathead Catfish	1	0	0	1	100
Lepisosteidae	Longnose Gar	16	3	19	13	81
	Shortnose Gar	1	0	0	1	100
	Spotted Gar	28	6	21	22	79
Sciaenidae	Freshwater Drum	1	0	0	1	100
Cyprinidae	Common Carp	12	2	17	10	83
	Grass Carp	9	0	0	9	100
All	All	240	32	13	208	87

TABLE 4 Anatomical locations of injuries on nongame fish collected by bowfishing conducted in Lake Texoma, Oklahoma, showing shot locations by species (includes multiple locations impacted by a single shot). Locations include head (H), internal organs (IO), spine (S), dorsal musculature (DM), tail (T), or fins (F).

Species	*n*	H	IO	S	DM	T	F
Black Buffalo	34	11	17	3	10	1	
Common Carp	12	1	10		7	1	
Flathead Catfish	1		1		1		
Freshwater Drum	1	1					
Grass Carp	9	2	7	2	8	1	
Longnose Gar	16	1	10	1	11	1	
River Carpsucker	6	2	3		2		
Smallmouth Buffalo	132	22	77	10	64	2	1
Shortnose Gar	1		1		1		
Spotted Gar	28	2	18	3	24	1	
Total	240	42	144	19	128	7	1

TABLE 5 Anatomical locations of injuries on nongame fish collected by bowfishing conducted in Lake Texoma, Oklahoma, showing a subsample of fish shot where only one anatomical location was impacted. Locations include head (H), internal organs (IO), spine (S), dorsal musculature (DM), tail (T), or fins (F).

Species	*n*	H	IO	S	DM	T	F
Black Buffalo	25	7	13	1	4	1	
Common Carp	5	1	3			1	
Freshwater Drum	1	1					
Grass Carp	1	1					
Longnose Gar	8		3		5		
River Carpsucker	5	2	2		1		
Smallmouth Buffalo	90	11	46	1	31	1	
Spotted Gar	11	1	2		8		
Total	147	24	69	2	49	3	0

TABLE 6 Anatomical locations of injuries on nongame fish collected by bowfishing conducted in Lake Texoma, Oklahoma, showing a subsample of fish shot where more than one anatomical location was impacted. Locations include head (H), internal organs (IO), spine (S), dorsal musculature (DM), tail (T), or fins (F).

Species	*n*	H+IO	H+DM	IO+DM	IO+S	IO+F	S+DM	S+T	H+IO+DM	IO+S+DM	IO+DM+T	S+DM+T	H+IO+S+DM
Black Buffalo	8	2	2	2			2						
Common Carp	7			7									
Flathead Catfish	1			1									
Grass Carp	8			5			1				1		1
Longnose Gar	8	1		6				1					
River Carpsucker	1			1									
Smallmouth Buffalo	42	5	5	21	3	1	5		1			1	
Shortnose Gar	1			1									
Spotted Gar	17	1		12			1			2	1		
Total	93	9	7	56	3	1	9	1	1	2	2	1	1

our final model adequately fit the data ($\chi^2 = 7.16$, df = 8, $p > 0.05$). Likelihood-ratio tests comparing our final model with the prior two iterations from the backward selection processes, specifically models including weight or weight and total length, suggested that removing nonsignificant predictors did not influence the relative fit of the predictive model (χ^2 range = 3.76–5.10, df range = 1–2, all $p > 0.05$). Using the classification breakpoint of 0.75 (based on naïve AUC), our final model correctly predicted mortality and survival with 81.3% and 87.5% accuracy, respectively. This resulted in an AUC estimate of 84.4, suggesting that our final model was an excellent classifier. Further investigation suggested that all survival misclassifications (i.e., fish that were predicted to die but survived) were likely due to fish surviving damage to the head or internal organs. However, mortality misclassifications did not exhibit any clear pattern, though a small proportion could be attributed to spinal damage in fish.

Estimates of discrete shoot-and-release mortality increased at every successive time interval, with discrete shoot-and-release mortality estimates from all four trials increasing rapidly up to 12 h postrelease and estimates increasing at a slower rate up to 96 h (Figure 8). This suggests that additional mortality was still occurring when the first trial was ended. The following three trials were conducted for 120 h, and the estimate of discrete shoot-and-release mortality appeared to still be increasing (Figure 8). Though estimates of discrete shoot-and-release mortality at 120 h from the final three trials are not directly comparable to estimates from 3 to 96 h made with all four trials, reestimation of the discrete mortality curve using only the final three trials showed the same general pattern between 3 to 96 h as estimates with all four trials (Figure 8). Mean discrete shoot-and-release mortality was estimated to be 85.5% at 96 h (95% CI = 77.3–93.6%) from all four trials and 89.9% at 120 h (95% CI = 85.8–94.0%) from the final three trials. Mean discrete shoot-and-release mortality estimates suggested that over half the fish died within 9 h of release, and the 95% CI suggested that over half the fish died within 48 h of release.

DISCUSSION

Short-term mortality: Bowfishing shoot and release versus angling catch and release

Results of this study indicated that mortality rates of shoot and release for native nongame and nonnative invasive fish taken by bowfishing were much higher than mortality rates from all but the most destructive catch-and-release fisheries based on angling. Short-term (up to 120 h)

TABLE 7 Percent of nongame fish injured by bowfishing in Lake Texoma, Oklahoma, for each anatomical location where they were shot. Locations include head (H), internal organs (IO), spine (S), dorsal musculature (DM), tail (T), or fins (F). Species are grouped by taxonomic morphotype, Teleostei (buffalofishes and carps) or Holostei (gars), and by family.

Taxonomic group	*n*	H	IO	S	DM	T	F
Morphotype							
Teleostei	193	0.20	0.60	0.07	0.47	0.03	0.01
Holostei	45	0.07	0.64	0.09	0.80	0.04	0.00
Family							
Catostomidae	172	0.20	0.56	0.08	0.44	0.02	0.01
Cyprinidae	21	0.14	0.81	0.10	0.71	0.10	0.00
Lepisosteidae	45	0.07	0.64	0.09	0.80	0.04	0.00

FIGURE 4 Examples of bowfishing injuries on native nongame fish that survived the 5-day convalescent period. Fish species pictured are (A) Longnose Gar, (B) Spotted Gar, (C)–(D) Smallmouth Buffalo (same fish pictured on each side), and (E)–(F) Black Buffalo (same fish pictured on each side). All fish sustained injuries solely to the dorsal musculature. The internal organs and spine were not injured. In image (F), the individually coded tag is visible and indicated by an arrow.

mortality of various native nongame and nonnative invasive fish shot with bowfishing equipment was 86–90%. In contrast, in a review of 53 freshwater and marine catch-and-release mortality studies of 48 species, Bartholomew and Bohnsack (2005:136) described an overall mean mortality rate of 18%; of 274 total estimates, “46% of estimates [were] below 10% mortality, 23% between 10% and 20% mortality, 9% between 20% and 30%, and 22% of estimates above 30% mortality.” Sixty-nine percent of the catch-and-release studies showed mortality rate estimates of 20% or less, a desirable range for justifying catch and release as providing opportunities for multiple recaptures. No species exceeded 60% mortality.

In addition to the typically low catch-and-release mortality rates for angling in other studies, evidence suggests that mortality rates from snagging native nongame species also are lower than rates for bowfishing shoot and release. Most states with recreational Paddlefish snag fisheries allow catch and release (Mestl et al. 2019), and indirect evidence suggests that catch-and-release snag mortality is minimal in these springtime fisheries that typically occur in cooler water temperatures (Scarnecchia and Stewart 1997; Bettoli et al. 2019). Further, snagging catch-and-release mortality of Paddlefish is often mitigated via regulations designed to reduce the severity of injuries; for example, hook size 2/0 or smaller in South Dakota

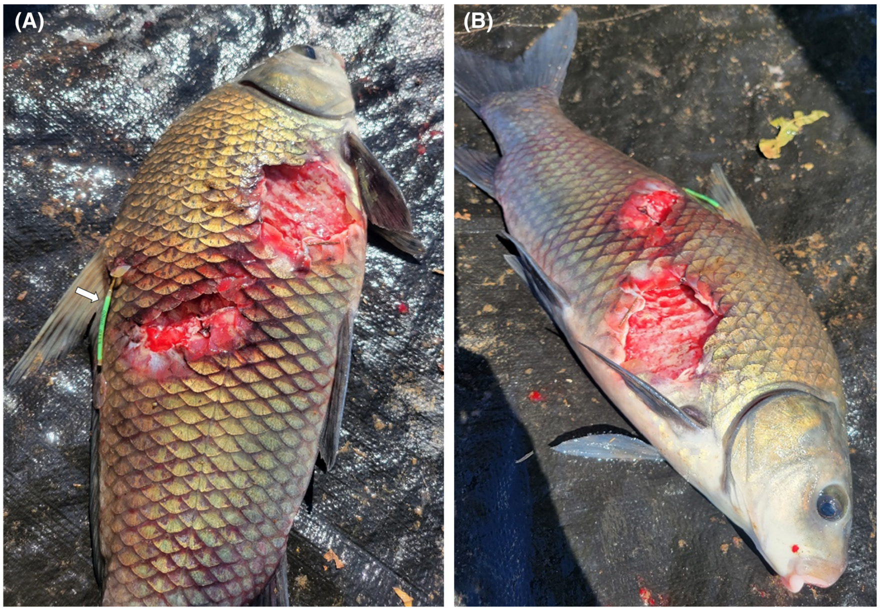

FIGURE 5 Example of bowfishing injuries on a native nongame Smallmouth Buffalo that survived the 5-day convalescent period. (A) The fish was shot at an angle through the dorsal musculature, causing tissue loss; (B) however, the internal organs and spine were not injured. Mechanisms of delayed mortality due to such injuries are unknown. The individually coded tag is indicated by an arrow.

FIGURE 6 Examples of bowfishing injuries on nongame fish shot in Lake Texoma, Oklahoma, that died during the 5-day convalescent period. Fish species pictured are (A) Smallmouth Buffalo, (B) Black Buffalo, and (C) Common Carp. Fish sustained critical injuries to the internal organs and spine (panels A, B) or head (panel C). In image (A), the individually coded tag is visible and indicated by an arrow.

(https://gfp.sd.gov/paddlefish/), barbless hooks only in Oklahoma (https://wildlifedepartment.com/fishing/regs/paddlefish-regulations), and no boat trolling in Montana (https://fwp.mt.gov/fish/regulations/paddlefish).

Moreover, the overall short-term shoot-and-release mortality of 86–90% in this study probably underestimates the mortality that would be experienced by shot fish convalescing in the wild, rather than in our shaded convalescent pools. Recovering fish were subjected to recirculated and aerated water monitored for quality variables, such as temperature and DO. Although no food was provided in the convalescent pools, fish were shielded from predators, scavengers, and potentially other stressors experienced by similarly injured fish in Lake Texoma. All control fish survived in the convalescent pools, which indicated that handling in addition to the convalescent environment did not enhance mortality for the shot fish. It is unknown if the fish that survived the convalescent period (Figure 4) may have developed infections or suffer from other permanent impairment resulting in mortality beyond the 120 h examined in our study (Figure 5). Therefore, given that fish were kept in a relatively ideal environment and our

TABLE 8 Series of comparisons based off 10,000 bootstrap replicates and performed using a chi-square (χ^2 test and Cramér's *V* to determine significance ($\alpha = 0.05$) and strength of association (association result) of several hypotheses (hypotheses tested) examining shot location and mortality of fish shot from bowfishing from Lake Texoma, Oklahoma. Association thresholds have been provided for each test to explain interpretation as the categorical strength of association changes for Cramér's *V* based on table size. The abbreviation NA indicates that data was not available.

		Association threshold				
Hypotheses tested	χ^2 (*p*-value)	**Weak**	**Moderate**	**Strong**	**Cramér‘s *V* (95% CI)**	**Association result**
Shot locations differed between families (for fish shot in only one location)	21.1 ($p < 0.05$)	0.07	0.20	0.35	0.27 (NA)	Moderate
Shot locations differed between families (for fish shot in one or more locations)	13.3 ($p = 0.22$)	0.07	0.20	0.35	0.14 (NA)	Weak
Mortality differed between bowfished and control fish	174.2 ($p < 0.05$)	0.10	0.30	0.50	0.76 (0.69–0.83)	Strong
... for Catostomidae only	111.8 ($p < 0.05$)	0.10	0.30	0.50	0.74 (0.64–0.83)	Strong
... for Cyprinidae only	35.8 ($p < 0.05$)	0.10	0.30	0.50	0.88 (0.71–1.00)	Strong
... for Lepisosteidae only	33.6 ($p < 0.05$)	0.10	0.30	0.50	0.73 (0.59–0.87)	Strong
Mortality differed between fish shot in a single location and fish shot in multiple locations	19.7 ($p < 0.05$)	0.10	0.30	0.50	0.29 (0.21–0.36)	Weak–moderate
Mortality varied by shot location (for fish shot in only one location)	35.8 ($p < 0.05$)	0.10	0.30	0.50	0.49 (NA)	Moderate
Mortality varied by shot location (for fish shot in one or more location)	24.1 ($p < 0.05$)	0.10	0.30	0.50	0.27 (NA)	Weak
Mortality differed between fish with critical wounds and flesh wounds	69.4 ($p < 0.05$)	0.10	0.30	0.50	0.54 (0.40–0.66)	Moderate–strong

discrete mortality estimates continued to increase through the observation period, it is likely that long-term (>120 h) shoot-and-release mortality is greater than the estimates from our study.

A major factor in the mortality of shoot-and-release bowfishing in this study being higher than in the 54 angling catch-and-release studies reviewed by Bartholomew and Bohnsack (2005) is probably the overall higher incidence of contact with critical areas (e.g., vital organs) in shoot-and-release bowfishing than catch-and-release angling. In our study, near total mortality occurred after fish were shot in the head, internal organs, or spine; in addition, most of the fish (78%) shot in our study were wounded in critical areas (Figure 6). Although hook location (noncritical tissue versus critical areas) was also the singular most important factor associated with catch-and-release mortality (Bartholomew and Bohnsack 2005), the incidence of contact of critical areas tends to be much less in most hook-and-line fisheries than in shoot and release. In those unusual situations where penetration of organs is high in catch-and-release fishing, mortality rates can also be high. For example, Snow and Porta (2021) quantified hooking mortality of Alligator Gar in Lake Texoma and found that delayed mortality of Alligator Gar caught by rod and reel was only 6.3%, whereas mortality from juglines was 81.1% (42% of jugline-caught fish died within the first 24 h). In Oklahoma jugline fishing, unlike most hook-and-line fishing, lines are typically unattended and must only be checked once every 24 h, leaving considerable time for a hooked fish to ingest the hook. Great hooking depth (i.e., typically when the hook was ingested with the bait) and the long time lapsed after hooking, rather than fishing method per se, was the ultimate cause of mortality. Injuries to the esophagus and stomach and lacerations or punctures of adjacent internal organs (i.e., heart and liver) were associated with rapid mortality, while swim bladder punctures resulted in more protracted morbidity and delayed mortality (Snow and Porta 2021). An Australian catch-and-release study found higher short-term mortality (44%) for the primarily deep-hooked Golden Perch *Macquaria ambigua* than for the primarily mouth-hooked Freshwater Catfish *Tandanus tandanus* (3% mortality; Hall et al. 2015). Although the authors did not describe the nature of the deep-hooking injuries, damage to internal organs is likely to have contributed to the elevated mortality rate.

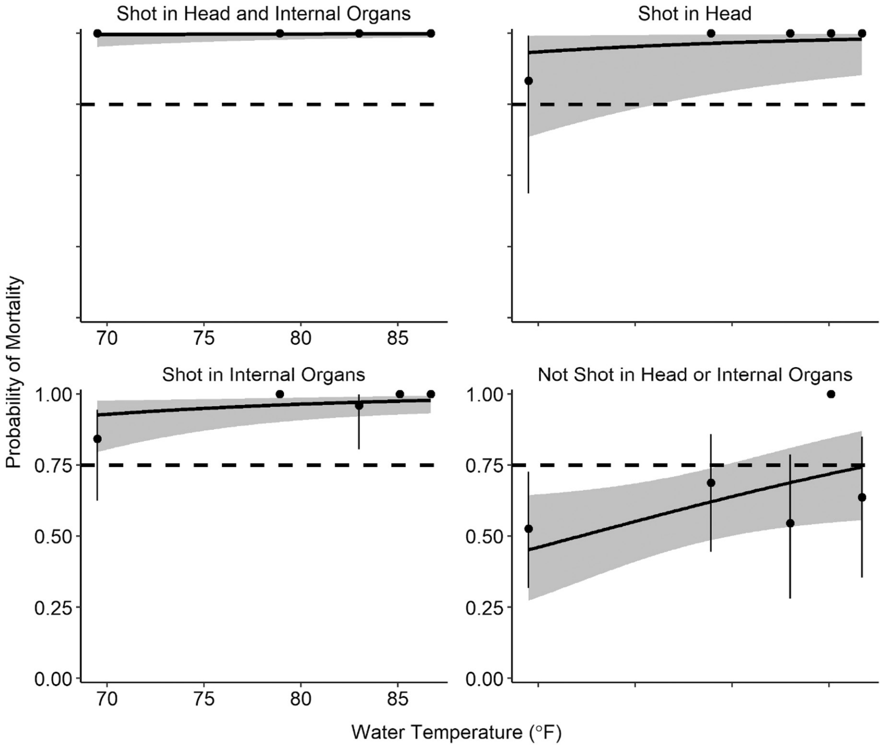

FIGURE 7 Predicted mean (black line) and 95% confidence interval (gray shading) from the backward-selection process estimating the probability of mortality for all fish in the shoot-and-release study conducted on fish shot in Lake Texoma, Oklahoma. Observed binomial mean (black circles) and associated 95% confidence interval estimates for study fish shot in different anatomical locations (or combinations of locations) are included. The horizontal dashed line indicates the classification threshold for a fish being predicted as a mortality (above the line) or a survival (below the line).

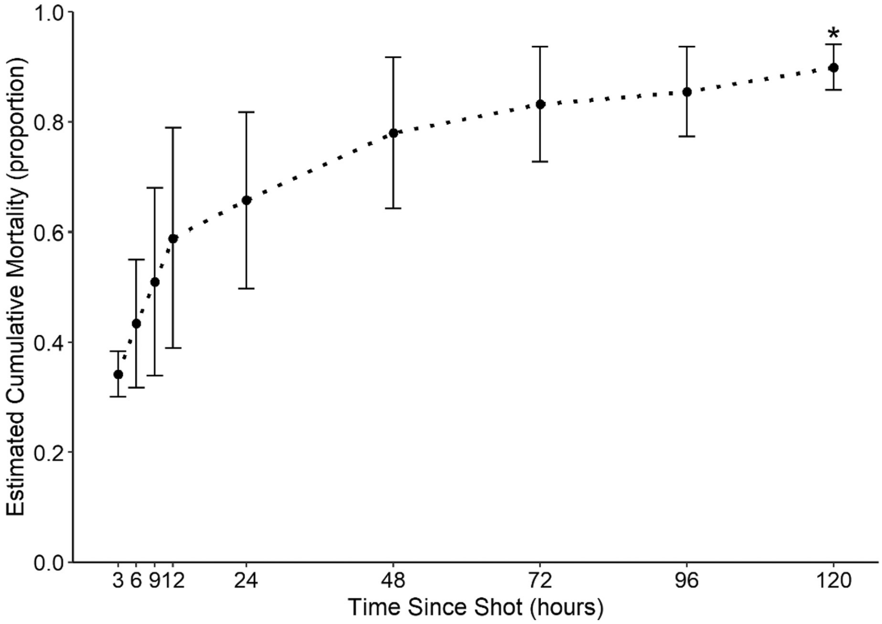

FIGURE 8 Estimated cumulative mortality (with 95% confidence intervals) of 240 fish shot with bowfishing equipment in Lake Texoma, Oklahoma. Mortality at 120 h (noted with an asterisk) was estimated from only three bowfishing trials as the first trial ended at 96 h.

Another striking difference between shoot-and-release bowfishing and catch-and-release angling was the differential mortality rate of fish taken in ways that did *not* involve damage to vital organs. In our study, for fish shot in noncritical areas (e.g., dorsal musculature, fins, or tail), the probability of short-term mortality was still high (>50%), substantially higher than mean mortality rates for all but 3 of 48 species reviewed in Bartholomew and Bohnsack (2005; their Figure 7). Rates for their species, although typically far lower than rates in our study, included fish hooked in both critical and noncritical areas.

The higher shoot-and-release bowfishing mortality rate compared with catch and release likely results from the fundamental difference in the nature of the wounds between shoot and release and most catch and release (i.e., with possible exceptions such as juglines or other unattended longlines). Whereas an angling or snagging hook wound in a fish or other organism will most commonly be a shallow jaw-, mouth-, or esophagus-related puncture or a body puncture (Albin and Karpov 1998; Meka 2004, James et al. 2018; e.g., Paddlefish snagging: Scarnecchia and Stewart 1997), an arrow wound has been described as a deep wound that is both punctured and incised (Bill 1887; Shereen et al. 2018; Sung et al. 2018). Although a hook puncture can be fatal if it penetrates sensitive areas, such as the ventral aorta (e.g., Paddlefish, Scarnecchia and Stewart 1997; Lingcod *Ophiodon elongatus*, Albin and Karpov 1998), and large hooks are more likely to damage organs and other sensitive areas in smaller fish (e.g., Rainbow Trout *Oncorhynchus mykiss*: Meka 2004), these hooking and snagging events are typically less invasive, and less likely to lead to mortality, than being shot with an arrow. Although much is known about the long history and treatment of human wounds from arrows (Karger et al. 2001), including its vital role in surgical advances, the traumatology of fish is largely unexplored. Mortality rates in this study and observations of wounds in a few other studies are all that is available; formal studies of experimentally wounded bowfished species have not been conducted at physiological or cellular levels. The closest studies might be evaluations of healing following wounding in commercial fish farming operations (e.g., mirror carp, a variant of Common Carp *Cyprinus carpio*; Iger and Abraham 1990; Sveen et al. 2020).

Management implications in the sustainable regulation of Bowfishing

Results of this study and the quasinatural, field-realistic experimental design employed in obtaining the shoot-and-release mortality rates provide useful information and insights for evaluating the viability of shoot and release in regulated bowfisheries. Here we highlight some of those implications.

Size, age, and sex of fish shot

The high shoot-and-release mortality of fish in this study, as in localities throughout the United States, consisted of long-lived species with ages up to 54 years and were primarily female. This predominance of larger, older fish, mostly females in certain fisheries, is the prevailing pattern of the selective bowfishing take nationwide because of the evolved life history strategies of bowfished species (Table 1; Scarnecchia and Schooley 2020). One of the Longnose Gar taken by bowfishing in our study was estimated to be 29 years old, 2 years older than the oldest published age estimate for the species (McGrath et al. 2016). Along with these long life spans, native nongame fishes often exhibit delayed onset of sexual maturity (Table 1) and irregular or episodic recruitment (e.g., multidecadal gaps between recruitment cohorts for Bigmouth Buffalo; Lackmann et al. 2021, 2022).

Our results that control fish were generally smaller, younger, and a lower percentage female than shot fish are consistent with the conclusions from previous research that bowfishing selectively targets larger, older individuals of native nongame species (Scarnecchia and Schooley 2020). In this study, the species most commonly shot, Smallmouth Buffalo, were significantly longer, heavier, older, and contained more females than their control conspecifics collected via electrofishing in similar shoreline habitats. Elsewhere, Quinn (2010) found that a high proportion of bowfishing tournament take was larger than the published size at maturity for gars (89–100%), suckers (including Bigmouth Buffalo, Smallmouth Buffalo, and River Carpsucker; 85–97%), and Freshwater Drum (97%). Stein et al. (2019) demonstrated that Longnose Gar and Shortnose Gar taken in bowfishing tournaments were larger than those captured in standardized sampling events on the same water bodies as the tournaments. Kelley (2012) reported that bowfishing shot distance (>9 m) was positively biased towards larger, and predominantly female, Longnose Gar. The selective take of larger, older, sexually mature native nongame fish in bowfishing, which occurs naturally without culling, may be exacerbated in tournaments through the culling of smaller fish and the retention of larger fish to achieve the greatest aggregate weight of a fixed number of shot fish (e.g., “Big 20” format, where only 20 fish are weighed from each team). The selective depletion of large, older, mature females can have negative impacts on the recruitment and reproduction success of native fishes (Scarnecchia and Schooley 2020; Scarnecchia et al. 2021), a global trend now realized with the decline of many freshwater megafauna (He et al. 2019). Managers must consider this pervasive selective take of larger, older, predominantly female fish when developing regulatory frameworks for sustainable bowfisheries.

Native nongame versus nonnative invasive species: Different implications of a high mortality rate

Although mortality rates of native nongame fish (86%; $n = 219$) and nonnative invasive fish (90%; $n = 27$) were both high and not significantly different, the management implications of the high mortality rates may differ greatly. Nonnative invasive species can have negative ecological impacts on native nongame communities. All of the carps are invasive; Bighead and Silver carps are subject to expensive removal and prevention efforts nationwide (Vilizzi et al. 2015; Chapman et al. 2021; Cupp et al. 2021; Ridgway et al. 2021). Where nuisance nonnative invasive species are abundant and harvestable by bowfishing with little native nongame bycatch, nonnative invasive species removal may benefit native nongame species (Scarnecchia and Schooley 2020). In such locations, fisheries managers can actively promote direct harvest power of sport bowfishers towards eradication of nonnative invasive species. Allowing shoot and release in fisheries targeted at nonnative invasive fish is not advised where habitats are shared by nonnative invasive and native nongame species, as native bycatch would be of issue. Fish identification was noted by multiple states as a concern for success in managing bowfishing (Scarnecchia and Schooley 2020), and this challenge is pervasive among other types of fisheries (Schmetterling and Long 1999; Page et al. 2012; Chizinski et al. 2014). According to York et al. (2022) beginner bowfishers reported targeting buffalofishes less often than experienced bowfishers; however, the authors noted that beginners may have greater difficulty distinguishing native nongame buffalofishes from nonnative invasive carps. A quick reaction time is required for bowfishers to identify a fish by species and take aim while compensating for distance, depth, and refraction. The ability to rapidly distinguish between legal versus illegal fishes is a requirement of bowfishing participants, and thus distinguishing native nongame and nonnative invasive fishes in real time is possible and already practiced by many bowfishers. The ability to identify one's target before shooting should be a requirement for beginners, like in other forms of hunting.

Accounting for mortality in shoot-and-release

In an "ideal" bowfishery, where retention of all shot fish was required and all shot fish were also retrievable, mortality (either short term or long term) would be fully accounted for and not a harvest management concern beyond managing native nongame species for a sustainable take. However, less than ideally, several states (including Oklahoma) allow, or fail to prohibit, shoot and release in bowfishing. In a 2021 phone survey of all 50 state fish and wildlife agencies, Lackmann (personal communication) inquired about the legality of shoot and release and rationales for prohibiting or not prohibiting it. Among the eight remaining states in 2023 where shoot and release is legal, Montana has regulated, seasonal bowfisheries, with much of the state closed to shoot and release. In Idaho, New Mexico, and Wyoming, shoot and release is legal but only practiced with Common Carp. The remaining states (Alabama, North Carolina, Oklahoma, and Tennessee) have no restrictions preventing shoot and release and the practice impacts both native nongame fishes and nonnative invasive fishes. Reasons cited by the respective state management agencies that prohibit bowfishing shoot and release included (1) explicitly stated as illegal or bag limits are in effect, (2) violates wanton waste statutes, (3) violates littering statutes, or (4) violates chumming statutes (Lackmann, personal communication). In Oklahoma, shoot and release is not explicitly prohibited in state statutes; however, rules exist on wanton waste and proper disposal of fish remains (https://www.wildlifedepartment.com/fishing/regs).

Arguments justifying shoot and release in these states have chiefly relied on the assertion that mortality of shoot-and-release fish is low. For example, the 2020 ODWC proposal to prohibit shoot and release by mandating retention of all fish shot by bowfishing met resistance from some bowfishers and advocates of shoot and release, who argued that many fish are shot high in the back or in the tail, receiving nonlethal wounds, and many such fish survive. Prior to this study, mortality rates of such fish had not been measured or accounted for.

Bowfishing shoot-and-release mortality is also accompanied by other unaccounted cryptic mortality (i.e., escaping measurement; Bettoli et al. 2019) from fish shot but not retrievable. In our trials with experienced bowfishers, 13.7% of the fish shot were not successfully retrieved; their fate was unknown but most likely the same as landed fish. Failed retrieval most commonly occurs at the boatside or shoreline as bowfishers attempt to land the fish by hoisting it by the arrow or line attached to the arrow. Gaff hooks (where legal) are often used to assist this process, with only limited success. For example, in addition to the 193 Bigmouth Buffalo that were successfully collected by bowfishers in Lackmann et al. (2019), another 33% were not successfully retrieved (Lackmann, personal observation). Failed retrieval is likely elevated for larger species such as the buffalofishes, as larger individuals more easily rip off the arrow (or gaff) under their own weight as they are pulled from the water into air at the boatside or shoreline. Use of handheld landing nets in bowfishing may reduce the rate of failed retrieval and their use warrants additional study. If a typical bowfishing outing includes the unsuccessful retrieval of shot fish, and it usually does, then the total take impact of an individual bowfisher exceeds the number of landed and retained fish. This additional, unaccounted, cryptic mortality must be considered when managers develop bag limits or other bowfishing regulations. Fisheries managers should also include questions on unsuccessful retrieval in creel surveys of bowfishers to better estimate nonretrieval mortality.

Release versus disposal in Bowfishing

Complicating the issue of shoot and release is the sometimes-blurred distinction between "release" and carcass disposal, especially when both can occur in the body of water bowfished. Regulations on carcass disposal vary among states. Some states consider fish carcasses and remains as equivalent to litter, other states as chum (i.e., fish attractant or bait), whereas other states provide guidelines for legal disposal. Oklahoma, for example, requires that fish remains must be buried, burned, or returned to lakes and reservoirs (29 O.S. § 7–403). It is further prohibited to kill wildlife and "abandon the body" without proper disposal, effectively prohibiting wanton waste (29 O.S. § 7–205). The term "fish remains" is defined in Oklahoma Administrative Code as "any fish that has been filleted or has had the entrails removed" (OAC 800:10-3-3); shoot-and-release fish released whole therefore do not qualify as fish remains.

In a statewide bowfishing survey, York et al. (2022) determined that Oklahoma bowfishers were more likely to bury their take or turn it into fertilizer (78%) than to consume it as food (46%). Moreover, approximately 40% of respondents deemed it acceptable to return shot fish to the water, though the survey did not distinguish between disposal of remains and shoot and release. In essence, the legality of shoot and release for bowfishing is based on the lack of specific prohibition of it and a legal loophole through a presumption of high survival upon release. Our study provides evidence that the presumption of high survival is unwarranted.

Shoot and release in a broader bowfishing management context

Few fisheries in the United States are unregulated; however, bowfishing for native nongame species with no bag limits has largely expanded without much attention from managers (Scarnecchia and Schooley 2020). Management and regulatory restrictions on various types of fisheries, both freshwater and marine, are often justified by conservation ethics and the need for sustainability. State fish and wildlife agency missions and philosophies for management are often aligned with the tenets of the North American Model of Fish and Wildlife Conservation, which holds that wildlife has value and should not be killed for frivolous reasons (https://www.fishwildlife.org/landing/north-american-model-wildlife-conservation). Given the extremely high short-term mortality of shot fish observed in this study, unlimited take and legal shoot and release in bowfishing are inconsistent with this model. This reality has already been tacitly recognized in regulation of shoot and release in two of the higher-valued bowfished species, Paddlefish and Alligator Gar. For example, release of shot Paddlefish is specifically prohibited in Oklahoma, South Dakota, and Montana. Various types of harvest protections are afforded to Alligator Gar in most states throughout its range (Smith et al. 2020), including specific mandatory retention of Alligator Gar bowfished in Oklahoma. As practiced, shoot and release in bowfishing essentially amounts to sport killing of fish with no beneficial use. Inasmuch as agency managers have evidence and recognize that native nongame fishes have ecological, conservation, or social value (Rypel et al. 2021), the high mortality associated with shoot and release should warrant its prohibition in regulated, sustainable bowfisheries.

Is shoot and release amenable to mortality mitigation efforts?

Many strategies and technological improvements have been evaluated and implemented in fisheries worldwide to mitigate catch-and-release mortality: safe handling strategies; hook size, type, or shape (including barbless hooks); the use of natural versus artificial baits; timing of fishing seasons by water temperature; barotrauma devices; and others (Bartholomew and Bohnsack 2005; Bellquist et al. 2019). Many hooking-related modifications have reduced the likelihood of superficial hooking (mostly punctures) transitioning into damage to critical areas of the fish caught. Though our results demonstrate that shot location does have a differential impact on mortality, with flesh wounds imparting a lower mortality rate than critical wounds, the nature of bowfishing, with its concurrent puncture and incision trauma, results in substantially higher mortality rates than catch-and-release fisheries, whether a fish is shot in critical areas or not. The bow and arrow, when directed at living organisms, is designed to kill. In the human realm, it has been estimated that the arrow has perhaps killed more people than any other weapon in history; the lethality of the arrow has led to widespread surgical efforts and advances to reduce that lethality (Karger et al. 2001; Shereen et al. 2018). Based on these and our results, there is little reason to be optimistic that regulatory options will do much to mitigate mortality through modifications to gear, technique, or handling. For example, mandating bowfishers to instantaneously aim for and shoot fish in only their noncritical areas is infeasible. Gear modifications, such as arrow tips designed to reduce damage to shot fish, may result in a higher rate of escape and therefore increase cryptic mortality. Bowhunting equipment is accordingly often regulated by state managers to increase kill efficiency and reduce wounding, among other management objectives (Kurzejeski et al. 1999). Such bowhunting gear regulations may include broadhead shape or size in addition to minimum thresholds on draw weight of bows (Mayer et al. 2000). Sung et al. (2018) discussed human arrow wounds in relation to arrowhead tip morphology. Although variations in bowfishing equipment (including arrowhead design and landing equipment such as gaffs) from what was used in this study may influence the nature and severity of injuries and alter short-term mortality, benefits are anticipated to be minor.

The high mortality rate associated with shoot and release observed in this study and as practiced by recreational bowfisheries renders shoot and release inconsistent with scientifically regulated and sustainable bowfisheries for native nongame species. Our study results and available evidence from the nature of arrow trauma indicates that bowfishing should realistically be managed as a 100% consumptive (i.e., kill) pursuit in which shoot and release is prohibited and nonretrieved shot fish are accounted for. Native nongame and nonnative invasive species can then be managed with different take limits to meet management objectives for native nongame conservation, while allowing more liberal take of nonnative invasive species (Scarnecchia and Schooley 2020). In that way, bowfisheries will continue to provide opportunity for take and supply needed comprehensive data on take for fisheries management and thereby function as instruments of sound long-term fish species conservation and public policy.

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CONFLICT OF INTEREST STATEMENT

There is no conflict of interest declared in this article.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ETHICS STATEMENT

Ethical guidelines were followed in this study under The University of Oklahoma's IACUC protocol number R21-014.

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