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Effectiveness of barotrauma mitigation methods in ice-angled bluegill and black crappie

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Abstract

Barotrauma can lead to physical injury and physiological disturbance (elevated stress hormones, and depleted energy stores during post-release struggling) in angled fish. Effectiveness of methods for reducing effects of barotrauma on fish has not been tested on fish subjected to ice-angling. We examined post-release behavior and re-descension of bluegill *Lepomis macrochirus* and black crappie *Pomoxis nigromaculatus*. Barotrauma was mitigated for fish either during capture by slow retrieval or following capture by venting or re-descension with weights, before observation in a behavioral arena or using small acceleration and depth biologgers. Black crappie spent less time in the center of the behavioral arena and were less likely to successfully re-descend than bluegill. Depth increased over time during the post-release monitoring period, with control fish less likely to descend to depth as fish for which barotrauma was mitigated. Our results demonstrate species-specific effects of ice-angling to inform anglers on the effectiveness of barotrauma mitigation strategies to improve welfare of fish after release.

KEYWORDS
accelerometers, catch-and-release, ODBA, post-release mortality, recreational angling, winter

1 | INTRODUCTION

Recreational angling is a highly important economic activity in much of the world (Arlinghaus & Cooke, 2009), so effective management is essential to preserve healthy fish populations (Bolund & Hunhammar, 1999; Eikeset et al., 2013; Sundmark & Gigliotti, 2019). For recreational anglers, management practices may involve the use of catch-and-release angling, whereby fish are released after capture, typically as a result of regulations (i.e., comply with harvest regulations) or as a result of a personal conservation ethic (Cooke & Schramm, 2007). Despite the overall value of catch-and-release as a management tool, circumstances of capture (species, water temperature, depth, etc.), and angler practices (e.g., angling gear used, handling time, and air exposure period, etc.) may lead to injury, physiological disturbance (elevated stress hormones, depleted energy stores during post-release struggling), and delayed mortality, even if the fish is initially able to swim away freely (Bower et al., 2016; Cooke & Suski, 2005; Klefoth et al., 2008). Among these impacts is barotrauma, caused by rapid decompression of gases in the swim bladder, blood vessels, and other organs of the fish as they are retrieved quickly to the surface from depth (Ferter et al., 2015; Rummer & Bennett, 2005). Fish suffering from barotrauma may be unable to re-descend to depth after being released due to the buoyancy provided by expanded gases in the body that render them helpless against predation as they are trapped at the surface (Eberts et al., 2018; Gravel & Cooke, 2008; Schreer et al., 2009). Investigating the effectiveness of mitigation methods to reduce barotrauma effects (i.e., 'venting', using weights to re-descend fish, or attempting to reduce decompression by retrieving fish slowly to the surface) has been a topic of study, with results differing among approaches (Bellquist et al., 2019; Drumhiller et al., 2014; Eberts & Somers, 2017; Pribyl et al., 2012; Roach et al., 2011).

One context in which effects of barotrauma may be highly significant is in winter ice-angling. Ice-angling is a popular form of angling in northern latitudes when temperatures drop to the point where surface water freezes, thereby allowing anglers to travel across ice to vertically angle fish through drilled holes. Most previous research on effects of capture on fish has focused on the warm-water season, while research interest has only recently increased in how cold winter conditions may influence outcomes for captured fish (Lawrence et al., 2022), including studies designed to determine the incidence of barotrauma on ice-angled fish, particularly the severity and persistence of symptoms in relation to capture depth (Althoff et al., 2021; Twardek et al., 2018). For example, some barotrauma symptoms in ice-angled fish captured at relatively shallow depths (<5 m) include bloating and difficulty swimming (Althoff et al., 2021). If these symptoms, especially if fish cannot swim back to depth, persist after release, fish will die if left pinned against the underside of ice by exposure to freezing or predation. Understanding the eventual fate of fish released after ice-angling, particularly those caught from depths that may lead to barotrauma, is important for fisheries conservation. In addition, the effectiveness of methods to mitigate barotrauma (venting, re-descending, slow retrieval) must be understood to determine if such methods enable anglers to capture fish from depth without negatively impacting fish populations.

High-resolution biologgers to monitor post-release fish behavior provide an excellent tool for the study of barotrauma in fish, specifically re-descent after release. Biologgers are small, do not appreciably inhibit fish movement, and provide detailed data on fish movement, depth, and temperature selection. For catch-and-release angling, post-release fish behavior has been quantified using biologgers for a variety of species, including bonefish *Albula vulpes* (Brownscombe et al., 2013), northern pike *Esox lucius* (Bieber et al., 2022; Chhor et al., 2022), and black bass *Micropterus* spp. (LaRochelle et al., 2021; LaRochelle et al., 2022). For ice-angled fish affected by barotrauma, biologgers have been used to determine if released fish can re-descend, to further understanding of how fish persist following ice-angling capture and release.

Our objective was to determine if methods for mitigating barotrauma, including venting, use of weights to re-descend fish, and slowly retrieving fish during capture to avoid rapid de-compression, influenced post-release behavior and re-descension to a depth of two fish species that are commonly targeted by ice anglers. Bluegill *Lepomis macrochirus* and black crappie *Pomoxis nigromaculatus*, two physoclistous species that cannot quickly evacuate gasses from their swim bladders, were chosen as common targets of ice-anglers and previous subjects of research on ice-angling recovery (Louison et al., 2017; Winter et al., 2018), including the incidence of barotrauma (Althoff et al., 2021). We quantified post-release behavior, in particular, the ability to re-descend, in ice-angled freshwater fish. We also subjected a subset of fish to surface-level behavioral assessment to visually observe locomotor activity following barotrauma mitigation. Results of our study would aid in determining if these two highly targeted species in their home ranges are able to return to depth (i.e., not pinned to the ice) upon release, and if strategies to mitigate barotrauma are effective.

2 | METHODS

2.1 | Study site

Fish were sampled by ice-angling during 28–31 December 2021 in water ranging 3–8 m deep at Shadow Lake, a small (~0.18 km^2) freshwater lake in Waupaca, Wisconsin, USA (N 44.358, W 89.085), with a mean depth of 5.18 m and a maximum depth of 10 m. Only fish captured from at least 3 m depth showing some sort of barotrauma impairment were considered further, based on subsequent testing for barotrauma and incidence of barotrauma expected at varying depths for these two species (Althoff et al., 2021). To ensure captured fish were suffering from barotrauma, fish were placed in a 19 L bucket containing lake water immediately after capture, and fish that were unable to orient (i.e., stayed ventral side up) and avoided floating at the surface within 15 s of placement in the bucket (an indicator of gas expansion and barotrauma) were considered to have barotrauma.

2.2 | Angling methodology

Fish were captured via "jigging", one of the most common forms of ice-angling to capture fish, including bluegill and black crappie (Althoff et al., 2021; Louison et al., 2017). Anglers used a variety of jigging setups, but all involved light (0.9–2.7 kg breaking strain) monofilament line spooled on a spinning reel and a short (<1 m) light action fishing rod. Terminal gear was not standardized among anglers, but in all cases consisted of a small (size 10–14) jig in one of several colors (orange, chartreuse, black, blue, pink, white) baited with a live waxworm (*Galleria* spp.). Each angler suspended the jig and bait through a 0.3-m diameter hole in the ice vertically at a depth of 3–6 m and used quick movements of the rod to move it up and down in the water column in an effort to induce a fish to strike. To avoid confounding effects of hooking injury (i.e., bleeding from hooking in the gills or GI tract), only fish that were hooked in the mouth (i.e., not deep-hooked) and could be quickly dehooked were used further. During 28–30 December, angling was assisted by 15–20 members of a high school fishing team, all fishing with similar techniques, and on 31 December, angling was assisted by three local experienced ice-anglers.

To assist in fish capture and measure capture depth, anglers used Vexilar® sonar units (i.e., "fish finders"). These devices helped anglers to determine if fish were not present, thereby allowing anglers to change locations to locate fish. Sonar units also allowed anglers to observe and communicate the depth of the lure at the time of a strike. Upon capture, anglers placed fish in a water-filled bucket (to minimize additional air exposure) for transportation to a central location for measurement of total length (to the nearest 0.5 cm), and subsequently for barotrauma mitigation and behavioral assessment. Anglers were instructed to bring fish up through the hole quickly upon hooking, except for fish designated as slow-retrieve fish (see below).

2.3 | Barotrauma mitigation

Three approaches to mitigate barotrauma were compared with a control group, including vented, slow retrieve, and weighted re-descension. Fish (including controls) included in the study showed signs of barotrauma as evidenced by an inability to swim to the bottom of a holding bucket. Control fish were only assessed for behavior after measurement. Vented fish were pierced along the side just behind the pectoral fin and above the lateral line with an 18-gauge FishLife® venting needle, to allow gases to escape the swim bladder. Slow-retrieve fish were retrieved at a slow speed by volunteer anglers towards the surface (~0.3 m per second), rather than a faster more-typical speed (1–1.5 m per second), with a goal of reducing barotrauma by reducing the decompression rate (Ferter et al., 2015). This method is largely preventative and has been primarily examined in physostomous fish (Ng et al., 2015), so we examined its use on physoclistous fish that appeared to be suffering from barotrauma symptoms to allow for quicker re-descension and recovery. Weighted re-descension fish were returned to the bottom using a FishSaverPro® descender that consisted of an 8-cm long by 3-cm gap-width blunt hook threaded through the fish's mouth and out the opercular opening before release. The hook was attached to an eyelet with two 60-g lead sinkers to pull the device and fish to the bottom. A separate eyelet was tied to a 9-kg breaking-strain braided line spooled to a fishing rod at the surface to release the fish upon reaching the bottom by cleanly pulling the device free with a steady pull on the rod.

2.4 | Assessment of post-release behavior using biologgers

Post-release behavior and success in re-descending of captured fish was assessed using biologgers equipped with a tri-axial accelerometer, pressure, and temperature sensors (Axy 5XS; TechnoSmArt; Guidonia Montecelio, Italy; 20×10×6 mm, 4 g weight in air) (Chhor et al., 2022; LaRochelle et al., 2021, 2022). The biologger was set to record in all three axes at 25 Hz with an 8-bit resolution and 8 G-Scale. The biologger also measured water pressure (1 per second) that was converted to depth to determine re-descension rate and success. The biologger was attached along the fish's side near the lateral line with zip-ties to a 15-cm long × 1-cm wide Velcro elastic band, by stretching the band around the midsection of the body, behind the pectoral fins (Figure 1b,c). The biologger was attached this way, rather than on the ventral surface, based on pilot trials in a separate lake with bluegill and black crappie that showed the biologger failed to remain on the ventral surface due to lateral compression of these species. One end of the elastic band was fitted with a grommet that allowed the apparatus to be clipped to a 9-kg braided line rigged on a separate fishing rod (same setup as for the re-descending device described earlier).

After processing and harnessing, fish were released into a hole in the ice over a depth of 4–5 m. The fish was allowed to swim freely with the harness for 9 min as the operator (MJL for all trials) opened the bale on the fishing reel. After this time the operator closed the bale, confirmed the fish was still harnessed by a brief steady pull, quickly jerked the harness free and retrieved it to the surface, thereby leaving the fish released. We assumed the harness had fallen off the fish for 11 trials where the fish could not be felt on the end of the line after 9 min, which left a final sample size of 43 fish.

Data from each biologger was processed by first removing static acceleration from all individual measurements using the rollmean function in the R package 'zoo' (Zeilis et al., 2005). Overall dynamic body action (ODBA), a measure of a fish's overall locomotor activity (Halsey et al., 2011), was calculated for each measurement by summing absolute values of acceleration in each dimension (X, Y, and Z). While individual ODBA values were collected 25 times per second, for the purpose of data analysis ODBA values were summed within each 15-s bin over the 9-min measurement to allow for meaningful interpretation of results. Depth occupied by each fish was averaged within the same 15-s periods, to provide matching values of ODBA and depth.

2.5 | Post-capture arena behavioral trial

Post-capture behavior of captured fish at the surface was assessed in two identical arenas that consisted of a cylindrical 227-L polyethylene bin (71-cm height, 63.8-cm diameter) filled to a depth of 20 cm with lake water at the same temperature as at the surface (~4°C) (Figure 1b). The bottom of the arena was spray-painted white to allow for easier viewing of the fish, and marked with circular markings at intervals of 10.6 cm in a "bullseye" pattern to define three ringed zones: Zone 1 was a 21.2-cm diameter circle in the center of

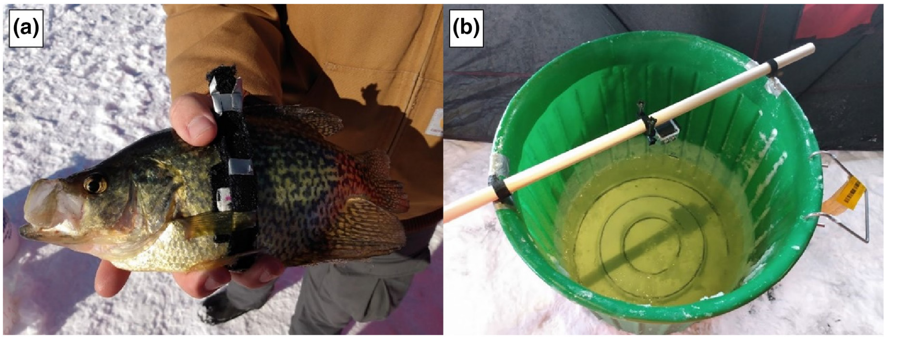


FIGURE 1 A black crappie harnessed with a biologger (a) and a behavioral arena (b) used to evaluate effects of barotrauma mitigation methods on post-release behavior of bluegill and black crappie at Shadow Lake, Wisconsin, USA, during 28–31 December 2021. In the arena, the center circle is Zone 1, the next adjacent ring Zone 2, and the outer ring is Zone 3.

the arena; Zone 2 was a 10.6-cm ring around Zone 1; and Zone 3 was a 10.6-cm ring around Zone 2 to the outside of the arena. This type of arena was used based on other studies that explained behavioral differences (particularly boldness) following disturbance, based on a fish's willingness to swim in the center of a tank, rather than along the edge, to determine if behavior differed among barotrauma mitigation methods (Duteil et al., 2016; Pollack et al., 2021). Video was recorded with an Akaso (r) V50X action camera mounted to a PVC pole positioned across the top of the arena. Arenas were placed within a 10-person Eskimo (r) ice tent with overhead-mounted lighting to avoid disturbance by people or the elements (wind, snow). After capture, fish were held for 3 min in 19-L holding buckets, before transfer to arenas.

Behavioral trials followed a prescribed sequence. After capture and initial processing, each fish was loaded individually into one of the two arenas and allowed to acclimate for one minute before behavioral recording for 5 min. At the conclusion of each trial, fish were released back into the lake. Video files were then returned to the laboratory for scoring. For each fish, behavior was recorded at 5-s intervals throughout the 5-min trial, for a total of 60 behavioral measurements per trial. At each 5-s interval, a single observer scored fish behavior as follows: (a) if the fish was oriented upright or floating on its side; (b) if the fish was moving or holding still, and (c) the zone occupied by the snout of the fish at that point. For orientation*movement combinations, at each measurement point fish were categorized as swimming (upright and moving), still (upright and not moving), struggling (on its side and moving) or floating (on its side and not moving). In addition, the location of the snout was noted at each measurement point, so that at each point a recording of orientation*movement and location within the arena was produced, leading to a total of seven behaviors of interest being extracted for each trial (time spent swimming, time spent still, time spent struggling, time spent floating, and time spent in each of the three zones of the arena).

2.6 | Data analysis

Two-way ANOVA was used to determine if capture depth differed between species or mitigation method, or if a significant interaction between mitigation and capture method was present for fish—This was done separately for biologger and arena-assessed fish. For fish assessed with biologgers, the effect of post-release time (during the monitoring period), species, and barotrauma mitigation approach on ODBA was tested with a linear mixed-effects model using the *lmer* command in the lme4 package (Bates et al., 2015), an approach that has been used for these types of studies previously (Bieber et al., 2022; Chhor et al., 2022; LaRochelle et al., 2021, 2022). Fish length was confounded with species (black crappie were significantly larger than bluegill, *t*-test, $p<0.001$), so was not included in the model. Two-way interactions between post-release time and species, and post-release time and barotrauma mitigation approach, were used to determine if the timeline of ODBA over the course of the monitoring period differed between species and among mitigation approach (the interaction between species and mitigation approach was not included, because no black crappie were tested for re-descension). To account for multiple assessments from the same individuals, Fish ID was included as a random effect in the model. *P*-values for main effects and interactions were from Type-III Wald chi-square tests. For significant effects or interactions, post-hoc differences were tested using the emmeans package in R (Lenth, 2023) with Tukey's method for p-value adjustment. The emmeans command was used to compare groups within significant main effects, and the emtrends command was used to compare slopes of ODBA over time between treatment groups for significant interactions between main effects and post-release time. The same statistical approach was used to evaluate effects of the same fixed effects and their interactions on depth, once again with fish ID as a random effect.

For arena-based trials, Principal Components Analysis (PCA) was used to reduce seven behavioral metrics (time spent swimming, time spent still, time spent floating, time spent struggling, and time spent in each respective zone of the arena) to fewer components, using the package FactoMineR (Lê et al., 2008), after determining that this method was appropriate (Kaiser-Meyer-Olkin test >0.5, Bartlett's test of sphericity $p<0.001$). Varimax-rotated Principal Components (PCs) with eigenvalues ≥1 were retained (Kaiser, 1960), and factors with loadings ≥ ±0.4 were considered primary drivers for that PC (Budaev, 2010). Because species*barotrauma mitigation blocks we were not balanced, existing blocks (bluegill-none, bluegill-vented, bluegill-SR, black crappie-none) were compared with separate Kruskal-Wallis tests for each Principal Component. For significant tests, Dunn's post-hoc tests were used to test pairwise differences. Analysis were conducted in R 4.0.1 (R Core Team, Vienna, Austria).

3 | RESULTS

3.1 | Biologger behavioral assessment

For assessment of post-release activity and re-descent using biologgers, 43 fish were captured (Table 1) from a depth ranging between 3.6 and 7.9 m (mean ± S.E. = 5.23 ± 0.12 m). Capture depth did not differ significantly among mitigation methods (F = 0.49; *df* = 3.36; *p* = 0.68) or between species (F = 1.64; *df* = 1.36; *p* = 0.20). The interaction between species and mitigation method was also not significant (F = 0.40, *df* = 2.36; *p* = 0.67).

Overall dynamic body action (ODBA) declined with post-release time across treatments, and slopes of relationships between post-release time and ODBA differed among barotrauma mitigation methods, as indicated by a significant interaction between time and mitigation method (Table 2, Figure 2). Mitigation method and species were not significant in and of themselves in predicting ODBA (Table 2). While the interaction was significant overall, slopes of relationships between ODBA and post-release time did not differ among

TABLE 1 Number (*N*) and mean length of black crappie and bluegill included in assessments of barotrauma release approaches (vented, slow-retrieve, and weighted), including controls, in Shadow Lake, Wisconsin, USA, during 28–31 December 2021.

Species	Barotrauma mitigation	*N*	Mean length (cm ± S.E.)
Videorecorded Trials			
black crappie	Control	4	24 ± 1.4
	Vented	0	NA
	Slow Retrieve	0	NA
Bluegill	Control	17	18 ± 0.6
	Vented	18	18 ± 0.4
	Slow Retrieve	16	18 ± 0.5
Biologgers			
black crappie	Control	4	23 ± 0.7
	Vented	3	23 ± 0.6
	Slow Retrieve	1	28 ± 0
	Weighted	0	NA
bluegill	Control	11	19 ± 0.8
	Vented	12	19 ± 0.9
	Slow Retrieve	7	19 ± 1.0
	Weighted	5	20 ± 0.4

TABLE 2 Results of linear mixed-effects models (LME) examining effects on post-release time of species (*N* = 8 black crappie, *N* = 35 bluegill), barotrauma mitigation approach (control, vented, slow-retrieve, and weighted), the interaction between post-release time and barotrauma mitigation approach, and the interaction between post-release time and species on overall dynamic body action (ODBA) and depth in Shadow Lake, Wisconsin, USA, during 28–31 December 2021

	Chi-Square	Df	*p*-value
ODBA			
Post-Release Time	109.14	1	**<0.001**
Species	1.45	1	0.22
Barotrauma Mitigation	2.31	3	0.51
Time*Mitigation	9.88	3	**0.01**
Time*Species	0.80	1	0.36
Depth			
Post-Release Time	55.29	1	**<0.001**
Species	10.00	1	**0.001**
Barotrauma Mitigation	2.20	3	0.53
Time*Mitigation	37.86	3	**<0.001**
Time*Species	17.78	1	**<0.001**

Note: Significant effects ($p < 0.05$) are in bold.

barotrauma mitigation methods, based on post-hoc tests ($p > 0.05$ for all pairwise comparisons).

Depth of descent increased with post-release time and differed between species, but not among barotrauma mitigation methods (Table 2, Figure 3). Slopes of relationships between depth and post-release time differed between species and among barotrauma mitigation methods as indicated by a significant interaction (Table 2, Figure 3). Depth increased with post-release time and was bimodal, with 35 of 43 fish reaching depths of at least 3 m within 1 m of release, and 6 of 43 fish failing to return to depth at all and remaining trapped at the surface (Figure 3c). Bluegills descended to significantly greater depths than black crappies (Table 2, Figure 3), a finding driven by the fact that 33 of 35 bluegills descended to at least 3 m depth within 9 min of release, whereas 4 of 8 black crappies failed to descend after release. Slopes of relationships between descent depth and post-release time differed among barotrauma mitigation methods (Table 2; Figure 3b). Specifically, the slope of the relationship between descent depth and post-release time was significantly shallower for weighted fish than for slow-retrieved fish ($t = 5.54$, $df = 1510$, $p < 0.001$), and vented fish ($t = 4.27$, $df = 1510$, $p < 0.001$), but not between weighted and control fish ($t = 2.47$, $df = 1510$, $p = 0.06$). The slope of the relationship between descent depth and post-release time was also significantly shallower for control fish than slow-retrieved fish ($t = -4.23$, $df = 1510$, $p < 0.001$), but not for vented fish ($t = -2.53$, $df = 1510$, $p = 0.054$).

3.2 | Arena behavioral assessment

For the arena behavioral assessment, 55 fish were captured from depths ranging between 3.0 and 7.3 m (mean ± S.E. = 5.5 ± 0.10 m; Table 1). Capture depth did not differ significantly between species ($F = 2.48$; $df = 1, 51$; $p = 0.12$) or among barotrauma mitigation methods ($F = 2.73$, $df = 2.51$; $p = 0.07$). Because the data were not balanced in this suite of fish (i.e. not every species*mitigation method block was accounted for), the interaction between species and mitigation could not be assessed for capture depth.

The first three principal components explained 89.4% of the total variation in seven behavior metrics recorded during arena behavioral trials (Table 3). PC1 (upright score) was positively loaded on by both the amount of time spent swimming and the amount of time spent still, both of which involved the fish being upright rather than on its side (Table 3). Conversely, PC1 was negatively loaded on by the amount of time spent floating on its side. PC2 (center score) was positively loaded on by the amount of time a fish spent in Zone 1 (the center of the arena) and negatively loaded on by the amount of time spent in zone 3 (the perimeter of the arena) (Table 3). PC3 (floating score) was positively loaded by time spent floating and negatively loaded for time spent in Zone 2 and for struggling.

Bluegill controls, bluegill slow-retrieved, bluegill vented, and black crappie controls did not differ significantly in upright scores (Kruskal Wallis test, species*barotrauma mitigation interaction, $\chi^2 = 3.85$, $df = 3$, $p = 0.27$; Figure 4a) or floating scores ($\chi^2 = 3.83$, $df = 3$, $p = 0.28$; Figure 4c), but differed significantly in center scores ($\chi^2 = 7.98$, $df = 3$, $p = 0.04$; Figure 4b). Based on Dunn's Post-hoc tests, center scores differed between control black crappies and slow-retrieved bluegills ($z = 2.8$, $p = 0.01$) and vented bluegills ($z = 2.47$, $p = 0.03$) but not control bluegills ($z = 2.37$, $p = 0.052$). Mean center scores also did not differ between control and slow-retrieved

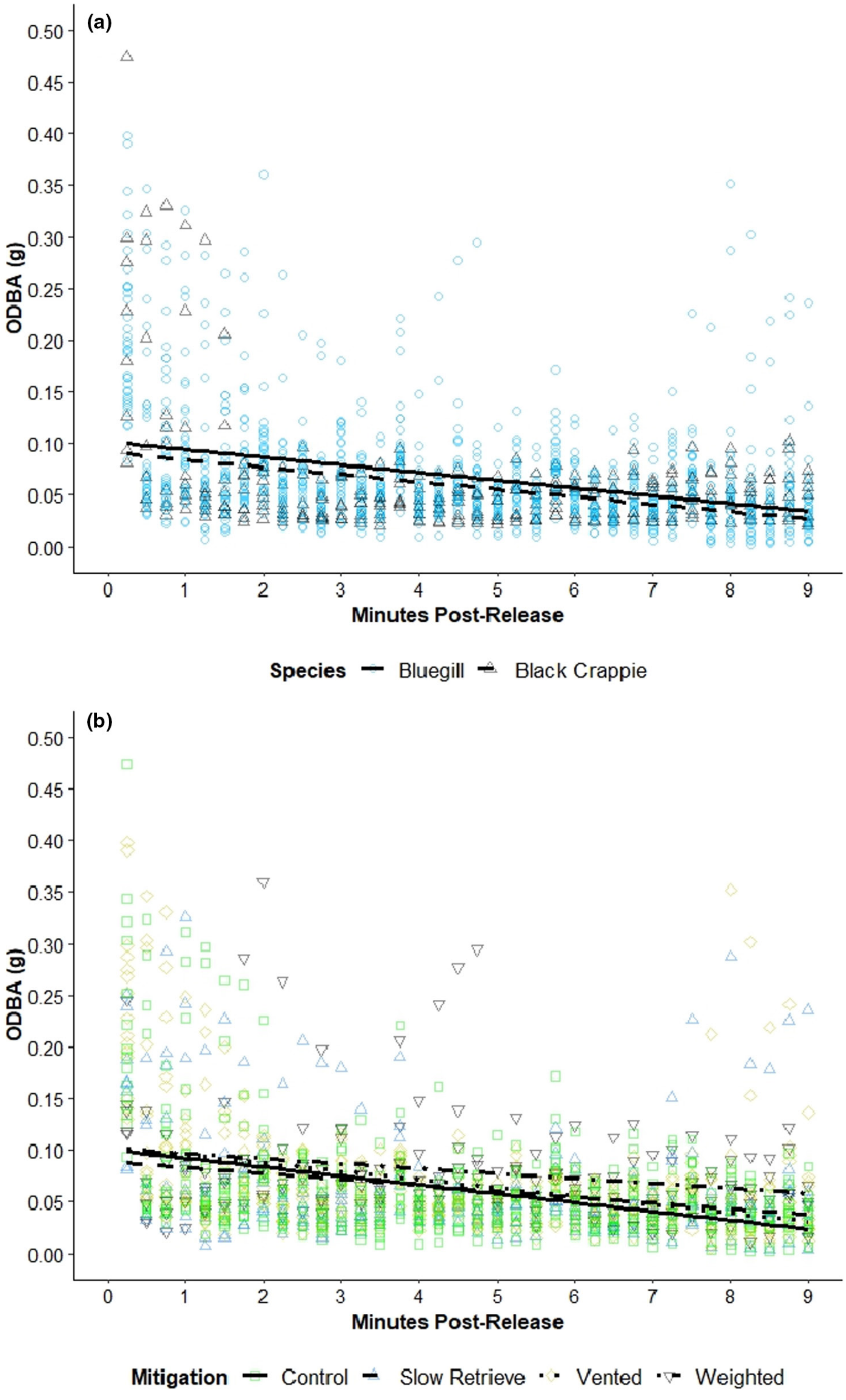


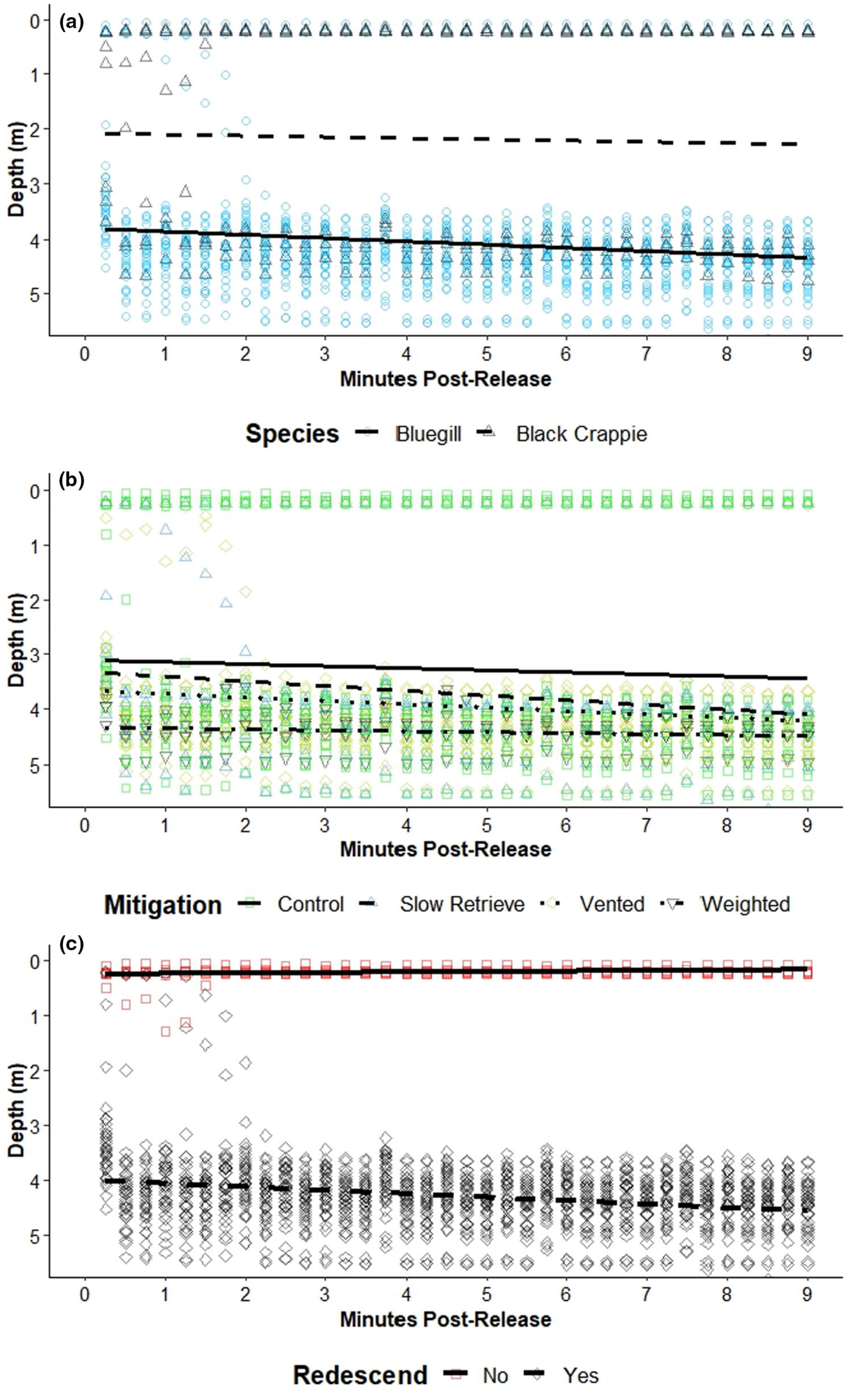
FIGURE 2 Overall dynamic body acceleration (ODBA) in relation to time for bluegill and black crappie assessed for effects of barotrauma mitigation methods on post-release behavior with biologgers at Shadow Lake, Wisconsin, USA, during 28–31 December 2021. Panel A shows ODBA over time by species and Panel B shows ODBA over time by barotrauma mitigation.

bluegills ($z = -0.71$, $p = 0.99$), between control and vented bluegills ($z = -0.14$, $p = 0.99$), or between vented and slow-retrieved bluegill ($z = 0.57$, $p = 0.99$).

4 | DISCUSSION

We found that black crappies were over six times less likely to successfully return to the depth of capture after release as compared to bluegills. This finding was somewhat surprising, given that previous work on these species in the same system that found bluegill were more susceptible to barotrauma symptoms at shallower depths than black crappie (Althoff et al., 2021). Barotrauma is a potential source of mortality for fish that are captured and released (Rummer & Bennett, 2005), including during ice-angling (Althoff et al., 2021; Twardek et al., 2018). Fish that are unable to descend in the water column or are restricted to the surface due to increased buoyancy because of barotrauma are likely to suffer

FIGURE 3 Mean depth (m) (inverted axis) in relation to time for bluegill and black crappie assessed for effects of barotrauma mitigation methods on post-release behavior with biologgers at Shadow Lake, Wisconsin, USA, during 28–31 December 2021. Panel A shows depth over time by species, Panel B shows depth over time by barotrauma mitigation, and Panel C shows depth by whether the fish was able to re-descend to at least 3 m of depth within 9 min.



mortality (Ferter et al., 2015; Pulver, 2017; Schreer et al., 2009), a fate that is more likely to occur during ice-angling when fish are pinned against the ice after release (Lawrence et al., 2022). Bluegill, in our study, were almost always able to swim down to overcome barotrauma-induced buoyancy, especially when a mitigation method was used (both bluegill that failed to descend were control fish), whereas black crappie were often not able to return to capture depth. Problems for black crappie have been documented in previous barotrauma mitigation studies, specifically following venting in warm water (Childress, 1988) or with no mitigation following ice-angling (Althoff et al., 2021). As a result of these findings, we might speculate that crappie have a more difficult time overcoming barotrauma symptoms as compared with bluegill, and that this will lead to higher post-release mortality rates of ice-angled black crappie as a result. This in turn could impact black crappie populations in systems where fishing effort, release rates, and harvest are high. However, our conclusions must be tempered by limitations of the study, specifically the small sample size of black crappie, although

TABLE 3 Loadings, eigenvalues, and % of variance explained by the first three principal components (PC1, PC2, PC3) of video-recorded orientation (swimming, still) and activity (struggling, floating) by bluegill and black crappie in three circular zones within cylindrical 227-L polyethylene tanks at Shadow Lake, Wisconsin, USA, during 28–31 December 2021

Metric	PC1	PC2	PC3
Swimming	0.62		
Still	0.62		
Struggling			−0.70
Floating	−0.46		0.41
Zone 1		0.69	
Zone 2			−0.49
Zone 3		−0.653	
Eigenvalue	2.61	2.29	1.35
% Variance Explained	37.30	32.76	19.37

Note: Loadings exceeding ±0.4 are shown.

we found that black crappie did indeed appear to have difficulty successfully re-descending.

In addition to differences in re-descension, we also found that bluegills and black crappies differed in behavior in arena-based trials at the surface. In our study, control black crappie spent more time in the center of the arena than slow-retrieved and vented bluegill, and tended to spend less time in the center of the arena than control bluegill, a metric that has been previously described as an indicator of stress or a general lack of behavioral boldness (Keiling et al., 2020; Pearish et al., 2019), which means that black crappie behavior in our study could indicate a greater degree of barotrauma-induced disturbance than bluegill. These results somewhat echo previous results in these species, which found differences in reflex-responsiveness between the species in surface trials (Althoff et al., 2021). Our behavioral data should, however, be interpreted with caution given the small number of black crappies sampled overall and the lack of black crappies in treatment blocks that received barotrauma mitigation. Nonetheless, results of behavioral-arena trials are similar to those from biologger trials, and indicate that surface-level assessments of behavior may be predictive of outcomes for fish subjected to barotrauma.

We found no overall effect of barotrauma mitigation methods on depth achieved, although patterns of descent over time differed among methods, with weighted fish returning to depth quickly, and more control fish remaining at the surface (26.6%) than fish treated with a mitigation method (7.1%). Previous studies of barotrauma mitigation effectiveness have confirmed the effectiveness of re-descending devices (Bellquist et al., 2019; Butcher et al., 2012; Drumhiller et al., 2014; Eberts et al., 2018), while venting has been found to be beneficial for red snapper *Pagrus auratus* (Butcher et al., 2012; Drumhiller et al., 2014) and painted comber *Serranus scriba* (Alós, 2008), while having no effect on walleye (Eberts et al., 2018), black crappie (Childress, 1988), or golden perch *Macquaria ambigua* (Hall et al., 2014). It should be noted that

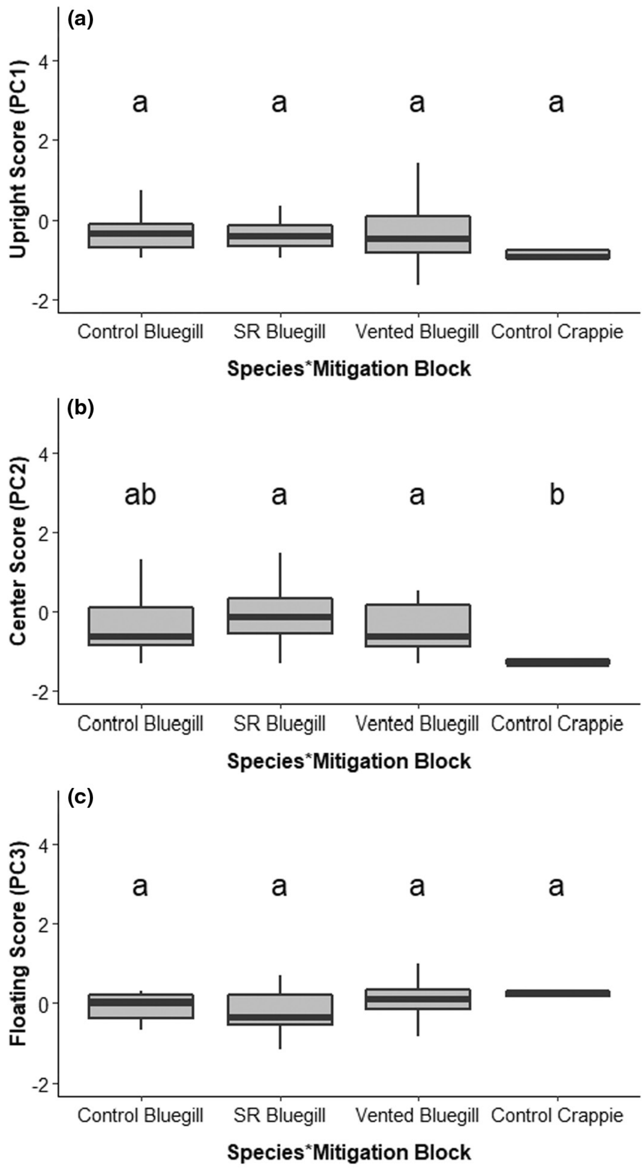


FIGURE 4 Principal components for orientation (Upright Score) and activity (Floating Score) by bluegill and black crappie in three circular zones (Center Score) within cylindrical 227-L polyethylene tanks at Shadow Lake, Wisconsin, USA, during 28–31 December 2021. Shared letters indicate no significant difference among groups (A = Upright Score, B = Center Score, C = Floating Score) based on Kruskal Wallis tests followed by Dunn's post-hoc multiple-comparison tests.

previous work has found that venting is capable of producing a negative effect, possibly due to improper venting leading to injury to vital organs (Wilde, 2009). Overall, our findings suggest that some type of barotrauma mitigation is potentially beneficial for ice-angled bluegill and black crappie captured from <10 m depths, especially for black crappie that appear to need additional mitigation to return to depth. Slow retrieval appeared to aid descent, relative to controls, which introduces a relatively easy method for barotrauma mitigation to ice-anglers (relative to venting or use of re-descending devices), although its effectiveness has not been universally found (Butcher et al., 2012). Therefore, evaluating effects of barotrauma mitigation methods on fish species that are less able to descend will be important for estimating if post-release mortality impacts fish populations.

We found little effect of species or mitigation method on post-release activity (indexed as ODBA) of bluegill and black crappie, both of which showed near-identical patterns of post-release movement, with the highest locomotor activity in the first minute after post-release, followed by reduced activity, as in similar studies (Bieber et al., 2022; LaRochelle et al., 2021, 2022). Biologgers have increasingly been used to assess short-term behavior of stressed animals, particularly for fish after catch-and-release angling (Brownscombe et al., 2013; Chhor et al., 2022; Holder et al., 2020; Landsman et al., 2015). Much of this work focused on effects of air exposure, particularly how air exposure and water temperature interact to affect fish movement and habitat use after release (LaRochelle et al., 2021, 2022). However, while ODBA is often associated with greater movement that may indicate a fish is recovering more effectively, higher ODBA in the context of barotrauma (especially in an ice-angling context) may instead indicate greater disturbance of a fish struggling under the ice surface. We however found that ODBA on average was 6% higher in fish that successfully descended than those that were left trapped under the ice surface. However, a longer period of measurement could potentially quantify activity patterns of fish trapped under the ice surface, and gaining this increased knowledge of behavioral patterns of released fish is indeed important from a fish welfare perspective. Future targeted studies of post-release behavior that focus on time to recovery or death could be used to understand comprehensive effects of barotrauma on ice-angled fish. Similarly, research over a wider range of depths would quantify a gradient of barotrauma symptoms for identifying conditions under which mitigation methods are necessary and effective.

5 | CONCLUSION

Our results demonstrate the widespread nature of barotrauma-related impairment in angled fish, which, in the context of ice-angling, may compound the unique physiological challenges already faced such as reduced metabolic recovery rates and tissue freezing (Card et al., 2022; Winter et al., 2018). Fish in our study were captured from generally shallower depths than in prior studies (Ferter et al., 2015; Pribyl et al., 2012; Rudershausen et al., 2014), but we still found that swimming was impaired by gas expansion in bluegill and black crappie. Despite this impairment, most bluegills successfully descended back to depth. In contrast, black crappie were significantly less likely to descend back to depth, which could lead to mortality as a result of cold surface temperatures or predation. Furthermore, behavioral assays at the surface indicated that black crappie were more behaviorally altered by angling than bluegill. While we did not sample enough black crappies to determine which mitigation method was most effective for this species, we found that slow-retrieved and vented bluegill and black crappie descended more quickly over time than controls, and weighted fish were successfully pulled to depth almost immediately. We therefore recommend that anglers in black crappie fisheries employ some type of mitigation to increase the likelihood of successful descent, such as venting fish, although improper venting can create more problems for fish than it solves by injuring internal organs (Wilde, 2009). We did not employ weighted re-descension for black crappie, although effectiveness of this method on bluegill for returning to depth also likely applies to black crappie, as a low-risk alternative for conservation-minded anglers seeking to release some of their catch. Identifying other species vulnerable to mortality from barotrauma, and effective mitigation methods for angler use, will be important for managers and anglers.

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CONFLICT OF INTEREST

The authors report no conflict of interest in the production of this manuscript.

DATA AVAILABILITY STATEMENT

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

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