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Potential implications of acoustic stimuli as a non-physical barrier to silver carp and bighead carp

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Abstract

The effectiveness of an acoustic barrier to deter the movement of silver carp, *Hypophthalmichthys molitrix* (Valenciennes) and bighead carp, *H. nobilis* (Richardson) was evaluated. A pond (10 m × 5 m × 1.2 m) was divided in half by a concrete-block barrier with a channel (1 m across) allowing fish access to each side. Underwater speakers were placed on each side of the barrier opening, and an outboard motor noise (broadband sound; 0.06–10 kHz) was broadcast to repel carp that approached within 1 m of the channel. Broadband sound was effective at reducing the number of successful crossings in schools of silver carp, bighead carp and a combined school. Repulsion rates were 82.5% (silver carp), 93.7% (bighead carp) and 90.5% (combined). This study demonstrates that broadband sound is effective in deterring carp and could be used as a deterrent in an integrated pest management system.

KEYWORDS
behaviour, *Hypophthalmichthys molitrix*, *Hypophthalmichthys nobilis*, invasive species, management, sound

1 | INTRODUCTION

Silver carp, *Hypothalmichthys molitrix* (Valenciennes) and bighead carp, *H. nobilis* (Richardson; collectively known as bigheaded carps) were originally imported to the southern United States in the 1970s from eastern Asia to control algal growth in sewage treatment and fish farming facilities (Kolar et al., 2007). Their escape into the wild has resulted in detrimental environmental effects. The species' filter feeding ability, fast growth and high fecundity has allowed them to negatively impact adults of native fishes such as paddlefish, *Polyodon spathula* (Walbaum; Schrank, Guy & Fairchild, 2003), gizzard shad, *Dorosoma cepedianum* (Lesueur; Sampson, Chick & Pegg, 2009) and bigmouth buffalo, *Ictiobus cyprinellus* (Valenciennes; Irons, Sass, McClelland & Stafford, 2007) and the early life stages of most fishes. Furthermore, the resulting decline in the density of lower trophic level organisms or community shifts in zooplankton populations with increasing bigheaded carps populations has likely affected additional native aquatic species (Cooke, Hill & Meyer, 2009; Xie & Chen, 2001). There is an urgent need to create barriers and deterrents to prevent further bigheaded carps range expansion and protect the ecosystems in which carp are not present.

Non-physical barriers to deter or control fish movement were originally developed to reduce entrance into hydroelectric dams or power plants. These barriers target fish sensory (auditory, vision, olfactory or lateral line) or locomotion systems to deter passage through a defined area, and can consist of lights, bubbles, acoustic stimuli or electric fields (Noatch & Suski, 2012; Popper & Carlson, 1998). Unlike physical barriers, such as dams, non-physical barriers have minimal impacts on water flow or navigation and have been proposed to combat the movement of invasive fish (Noatch & Suski, 2012). Other than the electric barrier in the Chicago Sanitary and Ship Canal (near Lake Michigan, USA) and a constructed berm in the Eagle Marsh wetland near Fort Wayne, Indiana, USA, solid structure gravity dams (high head dams) are currently the only barriers slowing the upstream expansion of bigheaded carps and their potential colonisation of the Laurentian Great Lakes (Moy, Polls & Dettmers, 2011; Sass et al., 2010). To limit bigheaded carps range expansion, management agencies are evaluating the efficacy of non-physical barriers to deter invasive carp (Kelly,

Engle, Armstrong, Freeze & Mitchell, 2011), with the idea that an integrated pest management system might provide the best approach.

Perhaps the most well-known non-physical barrier is the electric Aquatic Nuisance Species Dispersal Barrier in the Chicago Sanitary and Shipping Canal near Romeoville, Illinois, USA. The barrier was originally installed in 2002 to slow the downstream movement of round gobie, *Neogobius melanostomus* (Pallas), from the Great Lakes into the Illinois River (Moy et al., 2011; Sparks, Barkley, Creque, Dettmers & Stainbrook, 2010), but later improvements to the barrier were made with the goal of blocking the upstream expansion of bigheaded carps into Lake Michigan (Sparks et al., 2010). The electric field targets the neuromuscular junctions, causing temporary paralysis or death and can block fish movement (Lamarque, 1967, 1990). The electric dispersal barrier has been effective in a number of ways, including incapacitating 97%–100% of fish that attempted to pass and has limited the upstream movement of multiple species of fish (Parker et al., 2015; Sparks et al., 2010). However, it also has weaknesses, such as cost, need for continual power, danger to non-target species (including humans), potential ineffectiveness against small fish and disruption by metal-hulled barges (Dettmers, Boisvert, Barkley & Sparks, 2005; Moy et al., 2011; Noatch & Suski, 2012; Parker et al., 2015). During times of power disruption or maintenance, alternative systems are needed to block fish movement (Clarkson, 2004). These shortcomings preclude electric barrier installation in many waterways.

Studies have evaluated other non-physical barriers, such as light (Hamel, Brown & Chipps, 2008), sound (Taylor, Pegg & Chick, 2005; Vetter, Cupp, Fredricks, Gaikowski & Mensinger, 2015) and bubbles (Zielinski et al., 2014), to combat invasive fish species, with the understanding that combinations may be more effective than a single modality (Popper & Carlson, 1998; Welton, Beaumont & Clarke, 2002). For example, Atlantic menhaden, *Brevoortia tyrannus* (Latrobe), spot, *Leiostomus xanthurus* (Lacepède) and white perch, *Morone americana* (Gmelin) demonstrated greater avoidance of strobe lights combined with bubbles compared to either stimulus alone (McIninch & Hocutt, 1987). Patrick, Christie, Sager, Hocutt and Stauffer (1985) found that strobe lighting was more effective in deterring alewife, *Alosa pseudoharengus* (Wilson), smelt, *Osmerus mordax* (Mitchill) and gizzard shad than constant illumination; and a combined strobe light/bubble barrier maximised avoidance behaviour. Finally, bubble curtain barriers that generate 200 Hz sound reduced common carp, *Cyprinus carpio* (Linnaeus) crossing attempts (Zielinski et al., 2014).

In past studies, acoustic stimuli have been used to deter fish from approaching power plants or hydropower dams (Burner & Moore, 1953; Schilt, 2007). Frequencies ranging from 20 to 600 Hz reduced fish approaching a power plant (Maes et al., 2004), and ultrasound deterred (87% repels) alewife from entering a dam intake (Ross et al., 1993). More recently, sound is being examined as a barrier to fish movement (Lovell, Findlay, Moate, Nedwell & Pegg, 2005; Noatch & Suski, 2012; Popper & Carlson, 1998; Vetter et al., 2015).

To use sound as a non-physical barrier, silver carp and bighead carp need to perceive the sound, localise its origin and alter behaviour to avoid the sound. Grass carp, *Ctenopharyngodon idella* (Valenciennes; 600–1000 Hz; Willis, Hoyer, Canfield & Lindberg, 2002) and common carp (400 Hz; Sloan, Cordo & Mensinger, 2013) were classically conditioned to associate sound with feeding, which suggests that close relatives of bigheaded carps can localise sound. Silver carp and bighead carp have demonstrated the ability to detect and alter their behaviour due to sound. Pegg and Chick (2004) found that sound stimuli between 20 and 2000 Hz were more effective at preventing bigheaded carps from crossing an electric and sound barrier compared to frequencies between 20 and 500 Hz. Also, a combination of sound (20–2000 Hz) and bubbles repelled 95% of bighead carp in a shallow, narrow raceway (Taylor et al., 2005). Vetter et al. (2015) showed that complex or broadband sounds (0.06–10 kHz) were more effective than pure tones (500–2000 Hz) in repelling silver carp. Field tests combining sound (500–2000 Hz) with bubbles and strobe lights in a tributary of the Illinois River showed some promise, due to low recapture of bigheaded carps on the opposite side of the barrier, but many of the tagged fish moved out of the area and it is uncertain how many challenged the barrier (Ruebush, Sass, Chick & Stafford, 2012).

For field application, locks represent a key point for management of invasive species moving up or down the Mississippi River and could aid in preventing movement into new habitats. The goal of this study was to examine whether a complex, broadband sound (0.06–10 kHz) could block the movement of silver carp and bighead carp through a barrier, so that the potential for field application, specifically in locks, could be assessed.

2 | MATERIAL AND METHODS

2.1 | Animal husbandry

All experiments were conducted at the U S Geological Survey (USGS) Upper Midwest Environmental Sciences Center (UMESC) in La Crosse, Wisconsin, USA. Silver carp and bighead carp (18–24 cm TL) were maintained in 1500-L flow-through indoor rearing tanks and fed trout starter diet (Skretting, Tooele, UT, USA) at a rate of 0.5% body weight per day. Each experimental fish was tagged with a passive integrated transponder (PIT) tag (Biomark Inc, Boise, ID, USA) at least 1 week prior to experimentation. Prior to tagging, fish were sedated with 100 mg/L AQUI-S® 20E (10 mg/L eugenol, AQUI-S New Zealand Ltd., Lower Hutt, NZ) in the rearing tank. Fish were hand netted and placed in 300 mg/L AQUI-S® 20E (30 mg/L eugenol) until the fish lost equilibrium and did not move in response to a caudal peduncle pinch. A 1% iodine solution was applied to the injection sites, and a passive integrated transponder (PIT) tag was inserted into the abdomen about 2 cm anterior to the vent. Fish were placed in fresh flowing water to recover and segregated from non-tagged fish. To facilitate transport to the outdoor pond, fish were lightly sedated with 50 mg/L AQUI-S® 20E (5 mg/L eugenol) to minimise jumping, stress and potential injury. Food was withheld for 24 hr prior to transport and fish were not fed while in the outdoor pond (<7 days) to avoid food conditioning. Each group (n = 10) was allowed to acclimate in the pond for at least 48 hr prior to the initiation of experiments. This acclimation period allowed the fish to recover from the transport process and sedation. Previous studies suggest that 48 hr is more than enough time

for fish to metabolise eugenol, as the compound was not detected in tissues and normal swimming behaviour resumed in <30 min in fish exposed to greater quantities for longer periods of time (Cupp et al., in press; Hikasa, Takase, Ogasawara & Ogasawara, 1986; Meinertz, Schreier, Porcher, Smerud & Gaikowski, 2014). Two- or three-day trials were conducted from July through August 2014. All fish handling, care and experimental procedures used were reviewed and approved by the UMESC Institutional Animal Care and Use Committee (IACUC Protocol AEH-12-PPT-AC-01).

Experiments were conducted in a 10 m × 5 m × 1.2 m (55 m^3 at 1.1 m water depth) outdoor concrete flow-through pond. Water was pumped into the pond directly from UMESC wells, and the flow rate was adjusted to allow the water temperature to be 17°C ± 4°C. A 2-m wire fence enclosed each pond vertically with anti-bird netting draped across the top. Pond access was restricted via a door that remained locked throughout the experiment. The north side of the pond was partially shaded during the morning hours.

Two walls were constructed out of concrete blocks (0.4 × 2 × 1.2 m) and divided the pond into north and south halves. The concrete blocks extended perpendicular to the long axis of the pond with a 1-m gap in the middle of the barrier to allow passage. Water depth was maintained at 1.1 m, and the height of the barrier was 0.1 m above the water level. The pond was located outdoors, and trials were conducted in July and August to maintain water temperature within 17°C ± 4°C.

2.2 | Sound stimuli

Sound was delivered via one of two pairs of underwater speakers (UW-30, Lubell Labs Inc., Whitehall, OH, USA) that were placed 1 m from each end of the barrier opening, approximately 2 m from the nearest side wall. One HTI-96-MIN (High Tech Inc., Long Beach, MS, USA) hydrophone was placed in the middle of each end of the pond, 2 m from the end wall. The hydrophones monitored the sound stimulus, which was recorded using a PowerLab 4SP data acquisition system and LabChart 7 software (AD Instruments, Colorado Springs, CO, USA). Acoustic stimuli consisted of a 30-s broadband sound recorded underwater using a stationary hydrophone from a moving 6 m aluminium boat equipped with a 100 horsepower 4-stroke outboard motor (Yamaha, Fukuroi City, Japan) in the Illinois River at Havana, IL. The sound file was recorded during the boat's transit past the hydrophone and therefore was amplitude modulated. The broadband sound ranged from 60-10,000 Hz, with maximal energy contained in two broad peaks, the first between 500 and 2,000 Hz and the second peaking at 7,500 Hz (Figure 1).

An UMA-752 amplifier (Peavey Electronics, Meridian, MS, USA) regulated sound intensity, and each speaker pair was controlled manually with a switchbox (MCM Electronics, Centerville, OH, USA). The acoustic properties of the speakers and pond were mapped using the HTI 96-MIN hydrophone at 60 points evenly distributed throughout the experimental pond. Sound recordings for both ambient and the broadband sound broadcast were collected at each site. Sound pressure levels (SPL) were calculated by measuring the root-mean-square (rms) voltage of the ambient and broadband readings, which was then converted into SPL (dB re 1μPa) using Avisoft-SASLab Pro version 5.2.07. The frequency components and power spectrum of the sound were calculated with a 1,024-point fast Fourier transform (Hamming window) and sampling rate of 40 kHz.

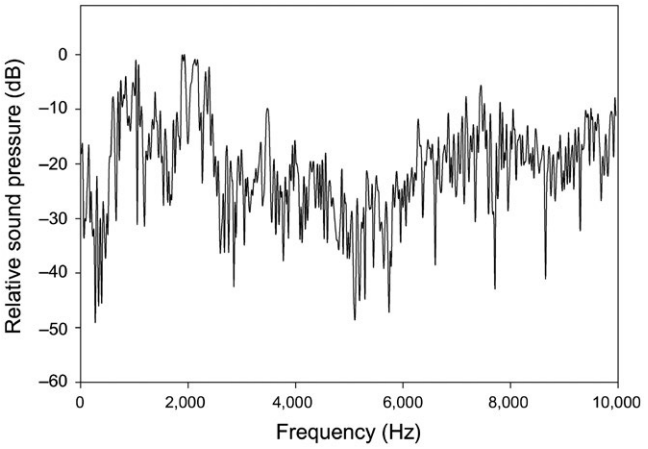

FIGURE 1 The power spectrum in relative dB of the broadband sound stimulus at frequencies of 60-10,000 Hz

2.3 | Behavioural experiments

Behaviour was monitored remotely by an observer who was situated in a shelter approximately 50 m from the test pond using eight overhead SONY bullet 500 TVL video cameras connected to a computer equipped with ProGold software (Security Camera World, Cooper City, FL, USA). The computer viewed four cameras at a time (half of the pond) and could easily be switched to the other four cameras. The cameras continuously monitored the fish and provided full coverage of the pond.

2.4 | Experimental design

One trial consisted of five consecutive periods: (1) pre-sound (120 min); (2) sound playback 1 (30 min); (3) inter-sound (60–270 min); (4) sound playback 2 (30 min) and (5) post-sound (120 min). During the pre-, inter- and post-sound periods, fish were free to swim throughout the pond and the speakers were inactive. All fish remained within 1–2 body lengths of each other in an elliptical-shaped school (diameter ~1 m), in both mono- and hetero-specific groupings; therefore, the fish in each trial were treated as a single unit with position determined as the approximate centre of the school. During the two experimental periods (sound playbacks 1 and 2), the initial location (i.e. north vs south) of fish was randomly chosen, and sound playbacks (i.e. sound stimuli) were not initiated until the school was positioned within the designated end of the pond, opposite the active speakers. Then, the speaker pair on the side of the barrier opposite to the fish was activated whenever at least two fish from the leading edge of the school entered the "reaction zone," or the area within the rectangle formed by the four speakers, which measured approximately 2 m^2 on each side of the barrier (Figure 2). The sound was terminated (within

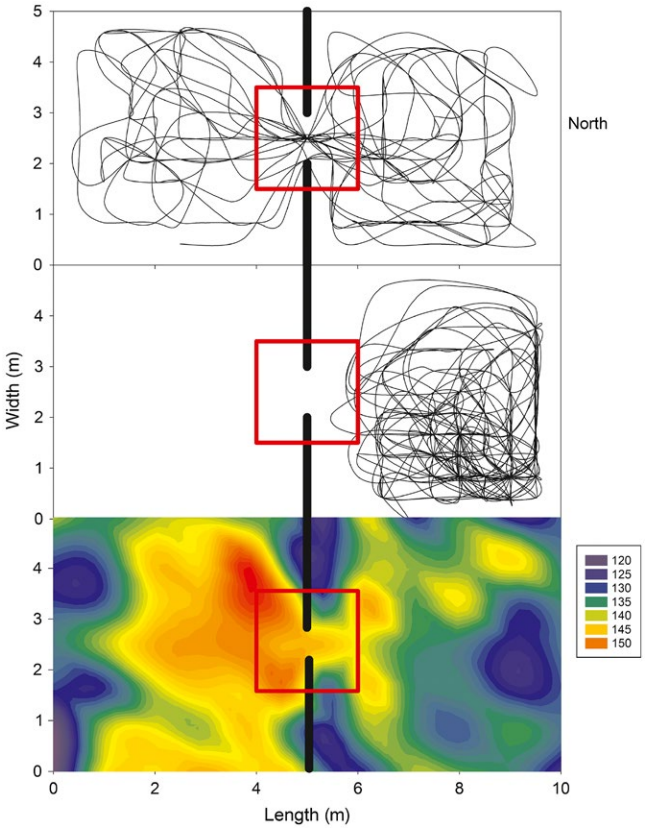

FIGURE 2 Overhead schematic of the experimental pond. The thick black lines indicate the barrier that divided the pond. The length and width of the pond are indicated in metres. The red box indicates the reaction zone with the corners of the box representing speaker locations. The location of the fish school was determined every 5 s and the *x*, *y* coordinates plotted and connected with spline lines. Each trace represents 30 min of swimming for one mixed school with speakers inactive (Top) and speakers activated (Middle). Bottom panel is a sound map of pond with pseudocolour indicating sound intensity level dB re 1μPa @ 1 m during active broadcast of the two underwater speakers on the south side of the barrier. Sound intensity level is indicated by colour panel. [Colour figure can be viewed at wileyonlinelibrary.com]

approximately 20 s of sound initiation) when the fish departed the reaction zone to avoid habituation to sound and fish were not subjected to constant sound during sound playback time periods.

Swimming behaviour was monitored during the pre-sound, inter-sound and post-sound intervals and the 30-min sound playback periods, with fish position recorded every 5 s. The number of attempted and successful crossings and residence time in each side was documented for each trial. The fish position in the reaction zone when sound was first initiated was monitored. Reaction time was defined as the time from sound onset to the point at which the leading edge of the school exited the reaction zone during successful repels.

Silver carp and bighead carp were tested for sound avoidance in both mono-specific and mixed schools. Therefore, three silver carp (n = 10), two bighead carp (n = 10) and two silver carp and bighead carp equally mixed schools (n = 20) were tested. Each school was exposed to between four and six sound playbacks (variation due to weather curtailing playback number) with the overall number of sound playbacks 16, 11 and 10 for silver carp, bighead carp and mixed schools, respectfully.

2.5 | Data analysis

All video and data analysis were performed at the conclusion of the trials. A crossing attempt was defined as at least two fish from the leading edge of the school entering the reaction zone. A successful crossing was scored if the entire school swam through the barrier opening into the other half of the pond. To account for differences in time for the pre-, inter-, post- and sound playback intervals, all attempted or successful crossings were converted to attempted or successful crossings per minute. Conversely, a repulsion was scored if two or more fish entered the reaction zone and did not cross into the other end of the pond following sound initiation. Repulsion rates were calculated by dividing the number of repulsions by the number of times the groups entered the reaction zone. Sound was broadcast from speakers as long as the fish remained in the reaction zone. If the fish breached the barrier despite the sound, they were allowed to cross back to the original side of the pond unimpeded by acoustic stimulus. Two to three trials were conducted for each school, with trials completed over 2–3 days.

Barrier crossings per minute (attempted and successful), percent successful repels, residence time and time to exit the reaction zone were tested for normality using Shapiro–Wilk tests. None of these data sets were normally distributed, and therefore, non-parametric Mann–Whitney rank *t* tests and Kruskal–Wallis ANOVAs with Dunn's post hoc tests were used for analysis. All statistical tests were performed with Sigmaplot, version 12.5. The median and lower and upper quartiles are reported using the following format (median; 1st quartile, 3rd quartile).

3 | RESULTS

The fish swam slowly through the pond in loose schools, 1–2 body lengths apart, and transited readily from the north and south end in the absence of sound (Figure 2: Top), crossing the barrier approximately every 3–5 min. However, when confronted with sound after entering the reaction zone, the majority (255 of 286) of schools turned away and did not cross the barrier (Figure 2: Middle). Fish maintained school formation through sound playbacks, with only one instance of a single fish departing from the school and crossing the barrier without the rest of the school.

Each pair of speakers created a non-uniform sound field throughout the pond, with sound reflected off the barrier, resulting in greater sound pressure level on the same side as the active speakers and reaching a maximum level of 155 dB re 1μPa. The sound stimulus projected through the barrier and reached 146 dB re 1μPa at the barrier midpoint and then attenuated throughout the other half of the pond (Figure 2: Bottom). Sound pressure levels were asymmetrical in each pond half, and fish had a tendency to remain in the area of lowest

sound pressure (i.e. north-eastern edge in Figure 2: Bottom) during sound trials.

For each species, the fish continued to challenge the barrier throughout the trials. Attempted crossings per minute did not differ among the five periods within any of three groups (Figure 3: Kruskal–Wallis: silver carp, $p = .662$, $H = 2.403$, $df = 4$; bighead carp, $p = .062$, $H = 8.980$, $df = 4$; mixed, $p = .106$, $H = 7.644$, $df = 4$).

All groups showed a significant decrease in the number of successful crossing attempts when challenged with sound (Mann–Whitney, $p < .001$). For silver carp, successful crossings decreased significantly (Mann–Whitney, $p < .001$, $U = 36.5$, $df = 1$) from 0.16 (0.10, 0.21) to 0.02 (0.00, 0.07) crossings per minute (Figure 4). Bighead carp showed a significant decline (Mann–Whitney, $p < .001$, $U = 4.5$, $df = 1$) from 0.22 (0.13, 0.42) to 0.00 (0.00, 0.02) crossings per minute. The mixed schools also had a significant reduction in successful crossings (Mann–Whitney, $p < 0.001$, $U = 0.0$, $df = 1$), from 0.32 (0.20, 0.44) to 0.03 (0.00, 0.07) crossings per minute.

Sound playbacks were successful in decreasing fish transiting through the barrier in all three groups, with 82.5%, 93.7% and 90.5% repulsion rates for the combined trials of silver carp, bighead carp and mixed species, respectfully. The initial sound playback for each group of silver carp was the most successful, with sound stopping the fish during all 12 attempts. Success rates dropped during subsequent playbacks before rebounding to 91% during sound playback 5 and then falling to 57% during the final playback (Figure 5). Bighead carp were less likely to cross the sound barrier, with four of the six sound playbacks achieving 100% repulsion and 89 of 95 attempts repelled. The mixed school also displayed sound avoidance behaviour as >90% repulsion rates were observed until the last playback.

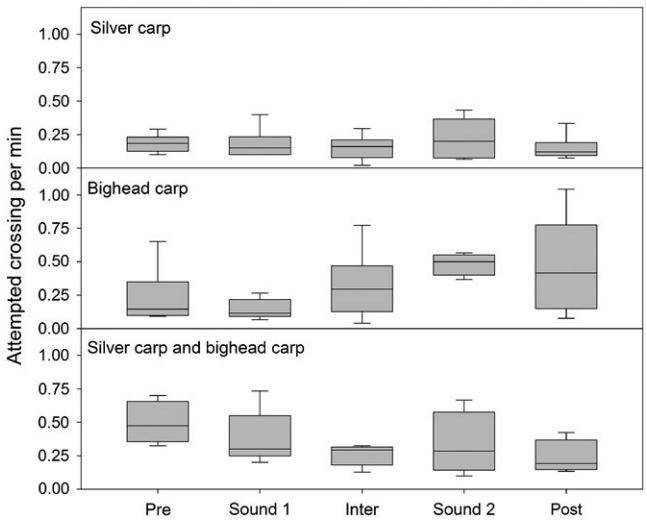

FIGURE 3 Attempted crossings (the number of times fish entered the reaction zone) per minute for silver carp, bighead carp and mixed silver carp and bighead carp schools for the five different intervals (pre—pre-sound; sound 1—sound play back 1; inter—inter-sound interval between the two sound playbacks; sound 2—sound playback 2; post—post-sound interval after playback 2) within a trial. The horizontal line in each box shows the median value, the bottom and top of the box indicate 1st and 3rd quartiles, respectively, and the whiskers are the 10th and 90th percentiles

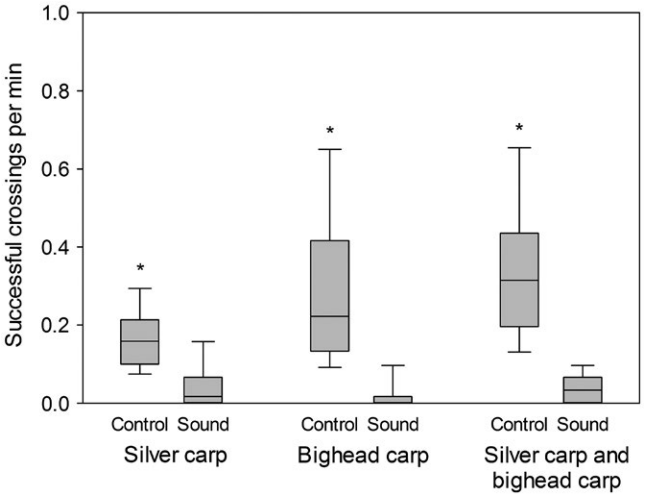

FIGURE 4 Barrier crossings per minute for silver carp, bighead carp and mixed silver carp and bighead carp schools during the control (sound off) and sound activation intervals. The horizontal line in each box shows the median value, the bottom and top of the box indicate 1st and 3rd quartiles, respectively, whiskers are the 10th and 90th percentiles. Asterisks denote significant difference between control and sound interval (Mann–Whitney, $p < .001$) for each species group

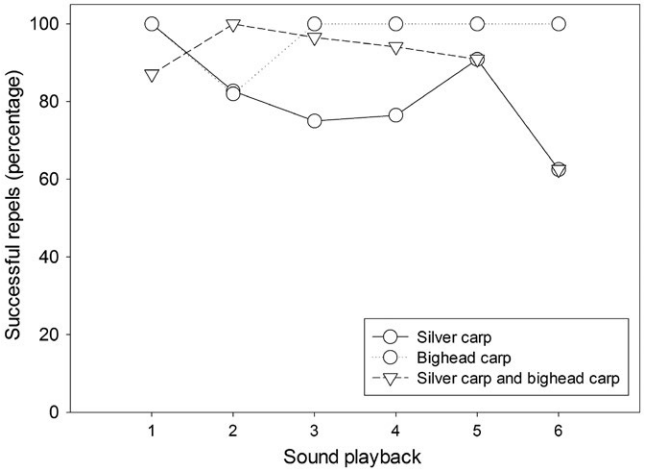

FIGURE 5 The percentage of successful repels (unsuccessful crossing/attempted crossing) for each sound playback for silver carp, bighead carp and mixed silver carp and bighead carp schools. Each data point represents the percentage of all the attempts during successive sound playbacks

The time spent in each half of the pond during the 120-min pre-sound interval was not significantly different for either the silver carp or bighead carp (Figure 6). Silver carp averaged slightly more time in the north end (4,380 s; 3,674 s, 4,869 s) than south (2,796 s; 2,399 s, 3,571 s); however, the results were not significantly different (Mann–Whitney, $p = .12$, $U = 13.0$, $df = 1$). In contrast, bighead carp spent more time in the south (4,483 s; 1,503 s, 5,353 s) than in the north end (2,716 s; 2,104 s, 5,771 s); however, there was no significant difference (Mann–Whitney, $p = .94$, $U = 17.0$, $df = 1$). The mixed schools preferred (Mann–Whitney, $p < .05$, $U = 1.0$, $df = 1$) the north

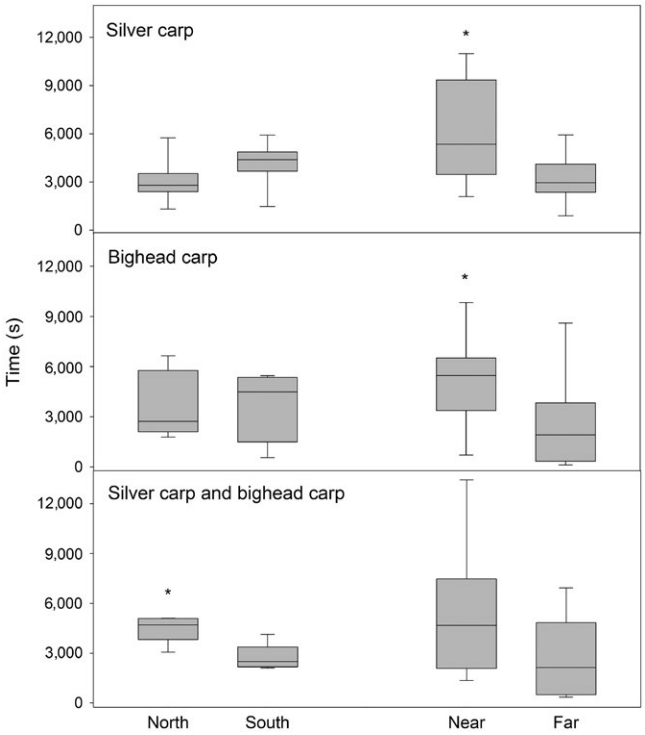

FIGURE 6 Residence times for each side of the pond for the pre-sound interval (north or south) and the inter- and post-sound interval (near or far) for silver carp, bighead carp and mixed silver carp and bighead carp schools. The near side represents the side away from the active speakers of the preceding sound intervals. Each box shows the median value, the bottom and top of the box indicate 1st and 3rd quartiles, respectively, and the whiskers indicate the 10th and 90th percentiles. Asterisks denote significant difference in time intervals (Mann–Whitney, $p < .001$)

end (5,083 s; 3,410 s, 6,858 s) over the south end (2,103 s; 1,269 s, 2,744 s). Following active sound periods, all fish favoured the side furthest from the previously active speakers (i.e. they did not cross the barrier) during the inter- and post-sound intervals. Silver carp resided significantly longer (64%, Mann–Whitney, $p = .014$, $U = 44.0$, $df = 1$) in the near side (5,344 s; 3,467 s, 9,349 s) vs the far side (2,951 s; 2,365 s, 4,107 s). Bighead carp spent significantly more time (74%, Mann–Whitney, $p = .036$, $U = 28.0$, $df = 1$) away from the speakers (5,462 s; 3,367 s, 6,514 s) vs close to the speakers (1,918 s; 344 s, 3,826 s). The mixed school also spent the majority of the time (69%) in the near side (4,671 s; 2,085 s, 7,467 s) compared with the far side (2,145 s; 498 s, 4,831 s) although the difference was not significant (Mann–Whitney, $p = .085$, $U = 27.0$, $df = 1$).

The carp reacted relatively quickly to the sound onset. During repels, silver carp exited the reaction zone in a median time of 5.0 s (3.0 s, 11.3 s), and bighead carp and mixed schools were significantly faster (Kruskal–Wallis, $p < .001$, $H = 24.2$, $df = 2$), with identical median times of 3.0 s (2.0 s, 4.0 s); (Figure 7). Very few schools showed aversive behaviour to the stimulus upon entering the reaction zone with the sound off; therefore, it was not possible to directly compare time to exit the zone with controls. However, in the absence of sound, 75% of the silver carp, 85% of the bighead carp and 75% of the mixed

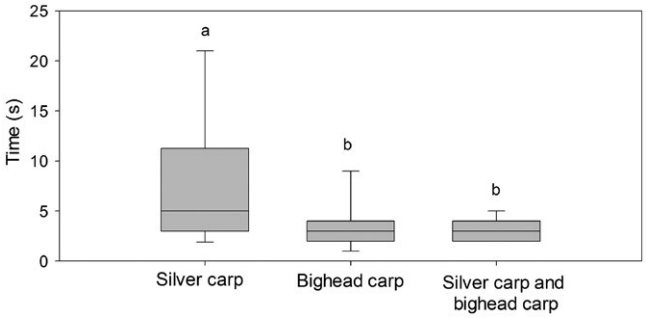

FIGURE 7 Median reaction times following sound onset for fish to exit the reaction zone following successful repels for silver carp, bighead carp and mixed silver carp and bighead carp schools. Each box shows the median value, the bottom and top of the box indicate 1st and 3rd quartiles, respectively, and the whiskers indicate the 10th and 90th percentiles. Letter indicates significantly different means (Mann–Whitney, $p < .001$)

schools continued through the barrier after entering the reaction zone during control intervals.

4 | DISCUSSION

Playback of underwater sound recorded from motorboats was effective at restricting silver carp and bighead carp passage through a 1-m wide channel, suggesting the potential for acoustic stimuli as a non-physical barrier. The sound was most effective during initial trials; however, repulsion levels remained high (>80%) throughout the study. The broadband sound stimulus also influenced bigheaded carps distribution in the pond, with fish residing for longer periods of time in the section opposite the active speakers. The results are encouraging in that the repulsion rate remained high throughout multiple trials over several days.

Silver carp and bighead carp are ostariophysans and have relatively higher hearing sensitivity than non-ostariophysan fish, and previous work has demonstrated that both carp species can detect frequencies up to at least 3 kHz (Lovell, Findlay, Nedwell & Pegg, 2006). Studies have established that silver carp (Vetter et al., 2015) and bighead carp (Vetter et al., in press) had significantly greater movement away from broadband (0.06–10 kHz) sound stimuli compared to pure tones (500–2000 Hz). Therefore, the underwater recording of an outboard motor was used as the deterrent. The sound pressure levels (145–155 dB re 1μPa) were well above the bigheaded carps' reported hearing threshold, 104 dB re 1μPa (Lovell et al., 2006), and the bigheaded carps remained responsive throughout the study, indicating that the sound pressure levels were not impacting hearing sensitivity. Although increased sound intensity may increase success of a barrier, care must be taken not to generate such high noise that hair cells are damaged and acoustic barriers rendered ineffective (Smith, Kane & Popper, 2004).

Acoustic particle motion may be a better parameter to measure than sound pressure levels and could be the force driving the bigheaded carps' response (Zeddies et al., 2012). However, the purpose of these experiments was to determine whether sound can act as a

deterrent to bigheaded carps. It is more important from an integrated pest management approach to first determine whether sound is a deterrent and then to examine what portion of the sound field that is most effective in causing repulsion. Additionally, the practical aspects of deterrents will be deployed in much larger passages where the acoustic environment will be radically different. The future goal is to measure accurately both particle motion and sound pressure under field conditions.

It was predicted that attempted crossings would decline over time because the fish would start to associate the barrier opening with the sound; however, bigheaded carps continuously challenged the barrier during the 7-hr trials. The fish actively swam throughout all five periods and would constantly circle in the near half (side opposite active speakers) of the pond during sound playback periods and invariably challenge the barrier, presumably due to the relatively small swimming area. Their constant movement through the channel during the silent periods indicated that they did not favour one side of the pond over the other and that the sound was restricting movement independent of other variables (e.g. shade). The only exception was the preference for the north side of the pond by the mixed schools during the pre-sound intervals, which had partial shade in the early morning. However, these tests were conducted during warmer days with minimal cloud cover, and the behaviour was consistent with fish preference in shallow water for shaded areas (Gibson & Power, 1975). Sound was only initiated when fish entered the reaction zone and was not on a consistent and predictable time schedule. Bigheaded carps' distribution during sound playback was dependent on sound origination rather than the presence of shady areas, indicating that even when fish favoured a section of the pond, the sound barrier could override this preference. As the fish used were captive in a controlled environment, it is important that an assessment of wild bigheaded carps' behaviour in response to broadband sound is conducted before installing speaker systems in a lock or river setting. This study provides a foundation for conducting such field experiments on wild fish.

Although the pond size provided sufficient opportunity for the bigheaded carps to challenge the barrier, their movements were circuitous and it was not always clear when they would challenge the barrier. To avoid false alarms, a small reaction zone was created close to the barrier opening, based on observations that most schools would cross through this area before entering the channel. However, the small reaction zone only provided a brief period to manually activate the sound before fish would cross the barrier. As fish swim speed fluctuated, the observer needed to visually confirm fish location and manually activate the trigger; therefore, the time needed to activate the speakers was variable. Any observer delay in sound activation could have resulted in further penetration of the carp into the reaction zone before encountering the noise, reducing the distance that the fish needed to swim through the higher sound levels. Therefore, it is likely that the results presented here are a conservative assessment of the efficacy of broadband sound in deterring the experimental fish. Furthermore, the speakers were offset from the opening to reduce any impediment to swimming; therefore, the sound source was never >2 m from the front of the school entering the reaction zone and could be breached in seconds by carp swimming in a direct line. A longer channel would allow a more defined sound gradient and would discourage fish from swimming towards increasing sound pressure levels. Also, an automated detector could provide a more consistent sound trigger.

In the current study, silver carp responded to the sound in approximately 5 s and bighead carp and mixed groups responded in 3 s. Sharp, quick movements indicative of a startle response were rare, suggesting that the fish were not "startled" by the noise onset, but would change their swimming patterns to avoid it. Additionally, the pond had minimal water circulation or directional flow. Under field conditions, downstream flow could slow upstream swimming speeds (Jones, 1963), resulting in greater exposure time to the sound barrier, which could result in higher repulsion rates.

The results demonstrated consistent sound aversion; but, longer observation periods could further refine the behaviour and address potential hearing damage or habituation to the acoustic stimuli. Variability was observed with the silver carp and mixed schools during later trials, but, weather curtailed several day three trials, resulting in lower sample numbers. Future trials will examine fish reactions over a prolonged period to determine when and if habituation to sound will transpire, and it is imperative that this be determined prior to field implementation.

To avoid acoustic interference from concurrent trials, a single concrete pond was used, which reduced the sample size. Temperature has been observed to affect swimming behaviour in fish (Brett, 1967; Brett & Glass, 1973; Jones, Jong & Ellerby, 2008); so, the trials were limited to the period when ambient temperature was sufficient to maintain the outdoor pond above 13°C. Silver carp were tested first and a cold front combined with heavy rainfall resulted in lower water temperatures at the start of these trials (13°C), which could have elicited lower responses to the sound than were observed in succeeding groups. Water temperature was warmer for the bighead carp and mixed trials, and these schools exhibited higher repulsion percentages. Further research is required to fully understand the impact of water temperature on sound aversion behaviour.

The pond was selected as its modest size allowed fish to frequently pass through the channel while providing a small area to swim away from the sound source. Considering the limitations of the small, shallow pond, the results are encouraging for the use of acoustic deterrents as part of an integrated pest management system. In the small concrete pond, echoes were produced from interactions of the sound with the pond's bottom and side, end and barrier walls in addition to the water surface, creating a difficult environment for the fish to localise the sound source. These acoustic challenges would not be as pronounced in a riverine system or even a lock chamber. Also, the experimental fish were constrained to a 25 m^2 area, whereas wild fish would have the opportunity to leave the area in response to a sound stimulus. However, field settings will likely have their own acoustical challenges (e.g. bathymetry, background noise) that will require further analysis for each site before an acoustical deterrent could be deployed.

State and federal agencies are currently developing an integrated pest management approach for bigheaded carps. To create an effective approach, multiple ecological (e.g. risk of invader, prioritising

resources) and biological concepts (e.g. life history, response to stimuli) must be combined into one harmonious management plan (Hobbs & Humphries, 1995). Monitoring movements and habitat selection along with control methods like containment and potential deterrents are also considered to develop the best management techniques for bigheaded carps.

The most effective deterrent locations may be at dams with sound used to remove fish from a lock chamber or deter fish from entering the locks with vessel traffic. The pond mimicked the configuration and construction materials of a lock chamber and, despite the study's limitations, the broadband sound elicited consistent and sustained repulsion of the bigheaded carps. Furthermore, the observer was able to monitor fish position in real time and manually operate the stimulus as opposed to broadcasting the sound for continual periods and risking the fish acclimating to the sound. While manually operating the stimulus might not be applicable to a field setting, these results provide support for a deterrent that is not broadcasting constant sound. For example, sound could be initiated prior to opening lock gates as a means to remove fish from the area and prevent ingress. Then, to prevent passage as the lock gates are open, sound could be remain on until the vessel is in the lock with the gates shut. Field studies in a lock chamber are necessary to determine the impact of broadband sound on wild fish.

Sound barriers present advantages over other non-physical barriers. The speakers are relatively inexpensive and require a modest power supply compared to electrical barriers. Small backup generators or batteries could be used to power the speakers in the event of a power failure, and the low cost could allow two independent speaker arrays to be installed providing redundancy in the case of damage to one array. Sound barriers using higher frequencies provide minimal impact on fish that do not possess Weberian ossicles, using acoustic stimuli above their hearing range (Lovell et al., 2006), but their effects on other species with similar hearing ranges remain to be determined.

The current experiments deployed only sound to mediate bigheaded carps behaviour and achieved relatively high success rates compared to multi-stimuli combination studies such as a bubble and sound barrier (Zielinski et al., 2014), a sound and electric barrier (Pegg & Chick, 2004) and a strobe light and bubble barrier (McInnch & Hocutt, 1987). Further work is warranted to evaluate broadband sound combined with other deterrent methods to increase the effectiveness of the deterrent. Also, the high repulsion rates noted in this study may be sufficient to reduce passage of bigheaded carps at locks such that commercial fishermen could substantially decrease local populations. It also remains unclear what specific subset of this acoustical stimulus causes repulsion and further refinement of the broadband sound may lead to greater repulsion rates.

The results suggest that an acoustic deterrent could be an effective means to slow upstream migration of both bighead carp and silver carp. While physical and electric barriers are expensive and not always practical, an acoustic deterrent has a wide range of applications. For instance, speakers playing a broadband sound stimulus could be used to move bighead carp and silver carp towards a net or shore, clear fish out of a lock, as a part of a bubble or strobe light barrier in a river channel or as backup system at in an electric barrier, especially during routine maintenance. This study indicates that because bighead carp and silver carp are responsive to broadband sound, acoustic stimuli may be an important management tool that could be effective either on its own or integrated with other deterrent technology.

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