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MANAGEMENT BRIEF

Bubble Curtain Deflection Screen Diverts the Movement of both Asian and Common Carp

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Abstract
Bubble curtains are a relatively simple type of behavioral deterrent that produces acoustic and hydrodynamic fields that could serve as a management tool to reduce movement of Asian carp species in many locations. In a proof-of-concept laboratory study, we tested whether two Asian carp species, the Silver Carp *Hypopthalmichthys molitrix* and the Bighead Carp *H. nobilis*, will avoid bubble curtains, and to the same extent as the Common Carp *Cyprinus carpio*, which has a similarly specialized hearing system. We explored the theory and application of a bubble curtain deflection screen using a split-passage experimental channel equipped with angled bubble curtains while mapping both pressure and particle motion (sound) fields. The bubble curtain reduced passage of all three species through the experimental channel by 73–80% while producing sound between 100 and 1000 Hz at 145 dB, well within the hearing range of all three carp. While Common Carp were diverted to an unblocked channel, the Asian carp species reduced overall swimming activity, suggesting a slightly greater overall sensitivity. These results suggest bubble curtains could serve as viable and inexpensive deterrent systems to inhibit the movement of both Asian carp and Common Carp into shallow waters while having minimal impacts on other fish.

Since their introduction in the 1970s, two species of Asian carp species, the Silver Carp *Hypopthalmicthys molitrix* and the Bighead Carp *H. nobilis*, have become established in the Mississippi River as far north as Pool 18 near Burlington, Iowa, (USFWS 2014) and in the Illinois River as far north as Dresden Island Pool near Morris, Illinois. If left unchecked, these fish could invade farther upstream and adversely impact aquatic food webs, native populations, recreational opportunities, and consequently, commercial and recreational fisheries (Schrank et al. 2003; Irons et al. 2007; Sampson et al. 2009; Sass et al. 2014). The National Asian Carp Management Plan has identified a need to develop technologies to control the expansion of carp (ACRCC 2014). Tens of millions of dollars have already been spent in the Chicago Area Waterway System (which is part of the Illinois Waterway System) to install and operate the Electric Dispersal Barrier with the goal of blocking all aquatic life from entering or exiting the Great Lakes (Moy et al. 2011). This barrier is located in the Chicago Sanitary and Ship Canal, which is a relatively narrow passage (~50 m wide) that was built to divert flow from the Chicago River. Native fish are not a concern at this industrialized site, making an electrical barrier a reasonable option. In contrast, electrical barriers are not a viable option in the upper Mississippi River and its large network of tributaries because of high costs, the risk they can pose to human safety, and their potential to block valuable native fish (Noatch and Suski 2012). Behavioral deterrents that use nonphysical stimuli to influence fish movement are thus being considered as an alternative since they are generally easier and less expensive to deploy, are navigable, and can be taxon-specific (Popper and Carlson 1998; Coutant 2001; FishPro Consulting Engineers and Scientists 2004; Noatch and Suski 2012; Barr Engineering 2013). Acoustic deterrents appear to have particular promise because they are safe and Asian carp, as well as the Common Carp *Cyprinus carpio*, have specialized hearing abilities (Popper 1972; Lovell et al. 2006). Sound has already been successfully field tested for Common Carp (Zielinski and Sorensen 2015).

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Among the sound production technologies available are underwater speakers (Pegg and Chick 2004; Taylor et al. 2005; Ruebush et al. 2012; Vetter et al. 2015), water-guns (Romine et al. 2015), and bubble curtains, which use pressurized air-bubbles to create both acoustic and hydrodynamic stimuli. Bubble curtains have special promise by themselves to serve as a practical control for Asian carp in small tributaries and channels (e.g., lock chambers). This is so because bubble curtains are inexpensive to install and maintain (they can be easily laid on the river bottom unlike speakers), are safe, and produce a broad spectrum of sound (Zielinski et al. 2014). We have already shown that bubble curtains alone are an effective deterrent for Common Carp (Zielinski et al. 2014; Zielinski and Sorensen 2015). In particular, we found that when air flow and bubble size are optimized for sound production, bubble curtains can reduce passage of juvenile Common Carp by 75–80% in the laboratory and block up to 60% of downstream swimming juveniles in the field, when used in a cross-stream configuration (i.e., full width barrier placed perpendicular to flow) (Zielinski et al. 2014; Zielinski and Sorensen 2015). In some situations, this level of deterrence will likely be useful for management, especially given its low cost (about US$1,250/m of bubble curtain [see Zielinski and Sorensen 2015]). Our laboratory studies suggest that the sound produced by bubble plumes is primarily responsible for deterring Common Carp passage because the sound produced overlaps the range of sounds this species hears and bubble curtain efficacy is not hindered by low levels of ambient light (Zielinski et al. 2014).

Although all fish detect the particle motion component of sound via their inner ear, Ostariphysians (including the Asian carp species and Common Carp) possess a Weberian apparatus. This anatomical link between the swim bladder and inner ear allows them to detect sound across a wider frequency bandwidth and at lower sound pressures than other fish lacking this specialization (Popper and Fay 2011). Previous studies of Bighead and Silver carp responses to systems that use underwater speakers to project sounds into low volume bubble curtain systems have shown these systems to function as deterrents (Pegg and Chick 2004; Taylor et al. 2005; Ruebush et al. 2012). However, whether optimized bubble curtains alone, which are simpler and less expensive than speaker driven systems, might be equally effective has not yet been tested. Further, although Asian carp and Common Carp have very similar hearing abilities (Popper 1972; Lovell et al. 2006; Ladich and Fay 2013), suggesting that they may be similarly affected by acoustic deterrents, this possibility has yet to be ascertained. This is an important question because only Common Carp are available for in situ tests in the upper Mississippi River, where Asian carp are still uncommon. Sound is of special interest because the hearing capabilities of fish vary (Popper and Fay 2011) suggesting that sound systems could be relatively taxon-specific. Studies of both Walleye *Sander viterus* and Muskellunge *Esox masquinongy*, fish without hearing specializations, show they are minimally deterred by bubble curtains systems alone or combined with other technologies (Flammang et al. 2014; Stewart et al. 2014).

We tested the hypothesis that Silver Carp, Bighead Carp, and Common Carp avoid a bubble-curtain deterrent system in the laboratory as a proof-of-concept study to guide future field tests and application. A split-passage experimental channel was used to test the effectiveness of a bubble-curtain system as a deflection behavioral deterrent. These results were then compared with cross-stream designs tested by Zielinski et al. (2014) and Zielinski and Sorensen (2015) for the Common Carp. Our study appears to represent the first attempt to quantify avoidance behavior of Asian carp to a deterrent system comprised solely of an air-bubble curtain. Both sound pressure and acoustic particle motion fields produced by the bubble curtain were measured to permit future study and improvement. Potential field applications are addressed.

METHODS

Experimental animals.—Juvenile Silver Carp (mean mass = 120 g, SD = 41; mean = 237 mm TL, SD = 35) and Bighead Carp (mean = 215 g, SD = 103; mean = 280 mm TL, SD = 44) were obtained from the Columbia Environmental Research Center (U. S. Geological Survey, Columbia, Missouri) and held in circular 100-L tanks. Silver and Bighead carp were fed a planktonic diet consisting primarily of spirulina and chlorella algae (see Hansen et al. 2014) once a day between 1000 and 1400 hours. Common Carp (mean = 416 g, SD = 113; mean = 298 mm TL, SD = 25) were caught in Casey Lake, Minnesota by pulsed DC electrofishing in July 2012 and transported to the laboratory, where they were maintained in tanks (1.5-m diameter, 50 cm deep). Common Carp were fed pellets (Silver Cup, Utah) once a day between 1000 and 1400 hours and matured while in captivity; the Asian carp did not. We attempted to match fish size irrespective of maturity, which is not known to influence responsiveness to sound. All holding and experimental tanks were supplied with flow-through 20°C well water.

Passive integrated transponder (PIT) tags (12.0 × 2.12 mm, half-duplex, OregonRFID, Oregon) were implanted into seven Common Carp, seven Silver Carp, and three Bighead Carp. Before tagging, all carp were anesthetized in a 0.05% solution of buffered tricaine methanesulfonate (MS-222, Western Chemicals, Utah), and a 1.4-mm diameter syringe fitted with a 12-gauge hypodermic needle was used to inject a PIT tag into each carp's body cavity between their pelvic and pectoral fins. Punctures were allowed to heal for 4 weeks (Acolas et al. 2007) prior to the start of experiments. Tagging resulted in no mortality. The remaining 14 Common Carp, 14 Silver Carp, and 6 Bighead Carp were left untreated and used with marked carp. All experimental procedures were approved by the University of Minnesota Institutional Animal Care and Use Committee (Protocol: 1201A08922), and all necessary federal

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and state permits for shipping and holding prohibited species were obtained.

Experimental set-up.—Experiments were performed in a cylindrical tank (3-m diameter) with an insert (1-m diameter) and wall (2 × 0.5 m) which created a split-passage circular channel with a nominal width of 0.5 m and water depth of 25 cm (Figure 1). Water was supplied to the tank through a submerged pipe located in the single channel portion of the tank and produced a 5 cm/s current. Two bubble curtains were placed in the tank and each was positioned diagonally across the openings of the outside channel while the inner channel was left as control to test for diversion. Fish were tested in groups of three (two untagged, one tagged) to allow them to form shoals because these carp are social and behave more naturally when tested as groups (Sisler and Sorensen 2008; Huntingford et al. 2010; Sloan et al. 2013; R. Ghosal and P. W. Sorensen, University of Minnesota, unpublished results). Only one PIT-tagged fish was used at a time because the PIT antennas could only detect one tag at a time, and Zielinski et al. (2014) found that the movement of a single Common Carp reliably describes that of the entire shoal. Passage data were reported for the tagged fish only.

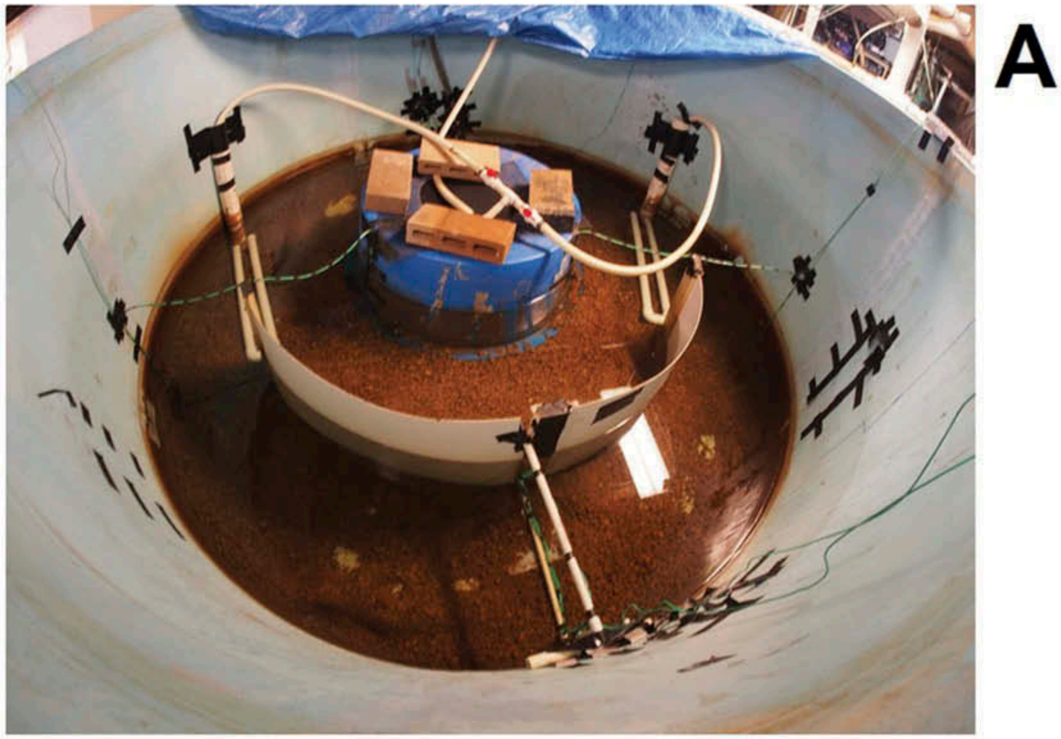
Fish movement was tracked using a PIT antenna array using the Oregon RFID Multi-Antenna HDX reader with four antennas tuned to an inductance of about 60–80 μH. The system was configured for a 10-Hz sampling frequency at each antenna. Each time a tagged fish passed through an antenna, the time of passage, PIT identification number, antenna number, and time between detections were logged onto a memory card for analysis. Antennas were positioned to differentiate between movement through the inside and outside channels, as well as overall activity (Figure 1). Antenna numbers 1, 2, and 4 were placed in the single channel portion of the tank, while antenna 3 was placed midchannel of the outside channel. Antenna 3 was manually tested using PIT tags that were pulsed through at various speeds prior to each trial to ensure that only tagged fish in the outside channel were detected. Manual testing indicated a detection probability at each antenna of >99%.

The bubble curtain was created with a 3.8-cm diameter PVC pipe built in a U-shape configuration with a 15-cm spacing between each leg and 3-mm diameter holes spaced every 5 cm. The same design was used in cross-stream field tests (Zielinski et al. 2014). To create the bubble curtain, a S41 regenerative air-blower (Pentair Aquatic Ecosystems, Florida) was used at 5 kPa to supply 12 L/s of air thorough 1 m of water. This air flow was one-ninth of what our previous studies found to be necessary to drive the highest levels of deterrence in Common Carp in the laboratory (Zielinski et al. 2014). We wanted to test lower airflows both to compare efficacies and because air production can be a challenge in deep water (Noatch and Suski 2012). The blower was operated using an automated switch that was programmed to turn the blowers on or off after a designated period.

Trials were conducted between 2000 and 0600 hours with all lights off in our testing facility and a black tarp covering the experimental tanks so that no light was visible, minimizing the role of any visual stimulus. For each trial, carp were placed into the circular channel and allowed to acclimate for 10 min before the trial began. Each 7 h trial began with a 3.5 h control period, in which the bubble curtain was in place but no bubbles were produced and carp were able to swim through both channels. This control period was followed by a 3.5 h test period when the bubble curtains in front of the outside channel were turned on (irrespective of where carp were located). Seven replicates were performed for Common Carp and Silver Carp and three for Bigheaded Carp because we had few of these in the same size range.

Swimming behavior near the bubble curtain (<20 cm) was also monitored using an underwater camera with infrared LEDs in three additional trials to help us understand the specific role of sound fields, which were also mapped (see below). The camera was located on the tank bottom and positioned to capture movement near antenna 1 to document behavior in the outside channel. Qualitative descriptions of swimming behaviors including channel location, position within channel, turning behavior, freezing, and direction of movement were used to compare how each species reacted with the bubble curtain. The closest distance each carp came to the bubble curtain without crossing it was also recorded.

Bubble curtain sound field.—Sound pressure levels (SPL) and acoustic particle acceleration was mapped at a depth of 12.5 cm below the water surface at 10-cm intervals in the quadrant of the bubble curtains and at 25-cm intervals in the remaining space. This appears to be the first time acoustic particle motion measurements have been taken around a bubble curtain system. Acoustic measurements were made using a PVC probe similar to that used by Zeddies et al. (2012), which contained a hydrophone and triaxial accelerometer. Pressure measurements were obtained using a C55 hydrophone (Cetacean Research, Washington) with integral power amplifier, which has a usable frequency range of 0.008–100 kHz and a sensitivity of approximately –163.5 dB referenced at (ref) 1 V/μPa. The signal was sampled at 44.1 kHz and fed through a TASCAM US-122mkII (TASCAM, California) audio interface, digitized, and stored on a Windows-based computer. Acoustic particle acceleration measurements were also obtained using a PCB model W356A12 triaxial accelerometer (PCB Piezoelectronics, New York), which was made neutrally buoyant by embedding it in a foam enclosure. The accelerometer had a usable frequency of 0.5–5,000 Hz and sensitivity of approximately 100 mV/ms^{-2}. The signal was conditioned using a PCB 482C05 conditioner and fed through a USB-1208FS-Plus data acquisition board (Measurement Computing, Massachusetts) sampling each channel at 16 kHz. At each location a 5 s sample was split into 10 signal ensembles and averaged to improve the signal-to-noise ratio. Data acquisition hardware was controlled by a



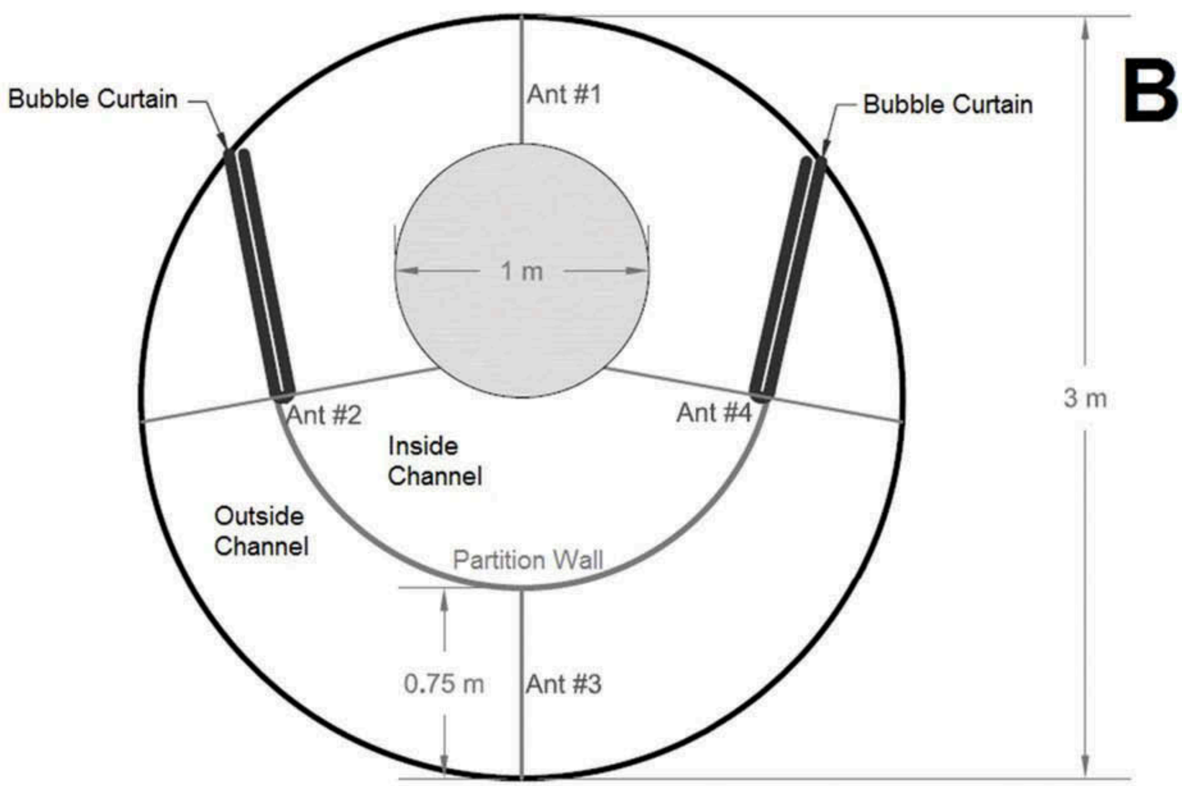


FIGURE 1. **(A)** Top view of the experimental bubble curtain tank. Bubble curtains (90 cm long white PVC pipes) are located at the end of the 50-cm-high partition wall. Water depth was 25 cm. **(B)** Overhead schematic of split-path circular channel showing position of bubble curtains and PIT antennas. Antenna number 3 was tuned and positioned to only detect movement through the outside channel.

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custom graphical user interface operating in Matlab (Mathworks, Massachusetts), which also was used to analyze and transform the pressure and particle acceleration waveforms into the frequency domain.

Statistical analysis.—Movement data were analyzed in several ways. First, a nonparametric chi-square (χ^2) test was used to evaluate deflection, i.e. whether the relative number of tagged carp passing through the inside and outside channels changed when the bubble curtain was turned on. The total number of passages through each channel during the control period was used as the expected count. We did not monitor differences in direction of carp passage because there was little flow (the bubble curtain produced water velocities >15 cm/s, a value that greatly exceeded the 5-cm/s background flow during the control periods). Second, any change in passage through the outside channel as a result of bubble curtain operation was calculated:

$$\%\text{Reduction} = \left(\frac{N_{\exp ected} - N_{observed}}{N_{\exp ected}}\right) \cdot 100\%,$$

where $N_{\exp ected}$ is the mean number of passages through the outside channel during controls and $N_{observed}$ is the mean number of passages through the outside channel during treatments. Third, the total activity of each species before and during bubble curtain operation were quantified by summing the number of times tagged carp passed between any two antennas (i.e., antenna 3 to 4 or antenna 1 to 2) during the control and experimental periods. A Kruskal–Wallis H-test with Mann–Whitney pairwise comparisons was then used to determine whether the activity level of each species changed. To evaluate the video data, a Kruskal–Wallis H-test was also used to compare the closest distance each species reached without crossing the bubble curtain. All statistical analyses used a significance level of $\alpha = 0.05$.

RESULTS

Bubble Curtain Deflection Tests

All three species of carp swam through the outside channel twice as often as the inside channel during control periods (no bubbles) (Figure 2) while exhibiting a similar level of activity (Figure 3). The mean ± SE number of passages through the inside and outside channel during controls was 38 ± 6 and 80 ± 14 for Common Carp, 28 ± 5 and 94 ± 10 for Silver Carp, and 20 ± 2 and 110 ± 23 for Bighead Carp (Figure 2). The bubble curtain reduced Common Carp passage through the outside channel by 73% (χ^2 = 316.4, P < 0.05). Similarly, Silver Carp passage through the outside channel was reduced by 80% (χ^2 = 128.5, P < 0.05) and Bighead Carp passage was reduced by 83% (χ^2 = 107.4, P < 0.05). However, while Common Carp swam through the inside control channel twice as often when the bubble curtain was on (P < 0.05), the passage rates of the Silver and Bighead carp through the

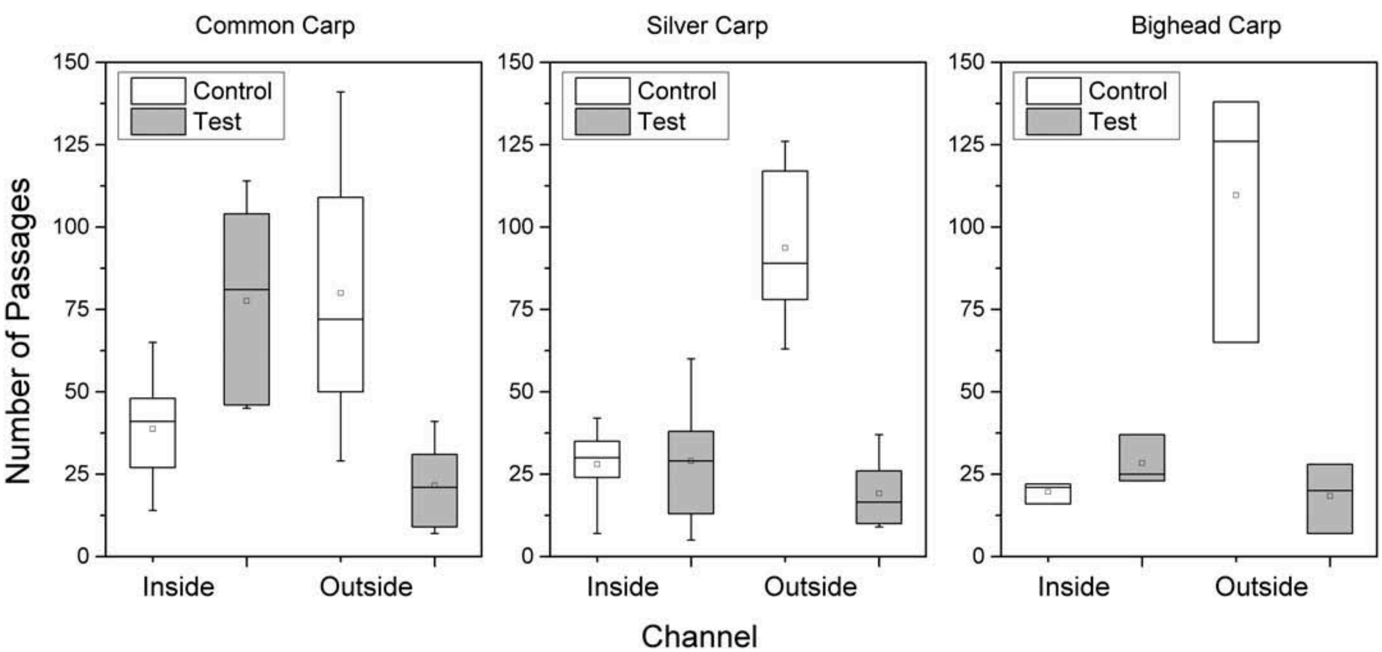

FIGURE 2. Box plots of the number of passages through the inside and outside channel by Common Carp (number tested, N = 7), Silver Carp (N = 7), and Bighead Carp (N = 3), where box = upper and lower quartiles, square = mean, horizontal line = median, and whiskers = 1% and 99% values. Chi-square tests indicated that the reduction in passages through the outside channel was significant for all carp species (P < 0.05). The outside channel was blocked by the bubble curtain during test periods.

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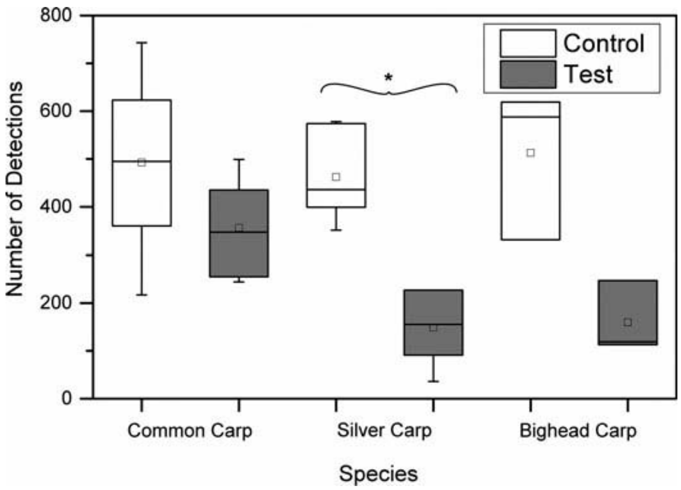

FIGURE 3. Box plots of the number of detections at consecutive antenna as a metric of total activity for three carp species during control and test periods with bubble curtains; see Figure 2 for box plot explanation and sample sizes. Pairs with significant difference are denoted by an asterisk (Kruskal–Wallis with Mann–Whitney pairwise comparisons at α = 0.05.).

inside channel did not change. This change in activity by the Asian carp species was seen in measures of overall activity. Thus, while the total swimming activity of all three carps was the same during control periods (Kruskal–Wallis: $P > 0.05$; Figure 3), total Common Carp activity was unaffected by the bubble curtain (Mann–Whitney: $P > 0.05$); however, Silver Carp activity decreased from 497 ± 126 to 165 ± 81 (Mann–Whitney: $P < 0.01$) and Bighead Carp also decreased from 512 ± 91 to 160 ± 44 (Mann–Whitney: $P > 0.05$, but $N = 3$).

Swimming Behavior Near the Bubble Curtain

All three species typically swam in loose groups along the outside wall of the tank during control periods. Once the bubble curtain was activated, carp swam parallel to the bubble curtain and entered the inside channel rather than cross the bubble curtain. Carp rarely crossed the bubble curtain. The closest distance ± SE to the bubble curtain that individuals of all three species reached before turning around (or occasionally proceeding forward) was 9 cm ± 1 for Common Carp, 10 cm ± 1 for Silver Carp, and 9 cm ± 1 for Bighead Carp (Kruskall–Wallis: $P > 0.5$).

Characteristics of Bubble Curtain Sound Field

The bubble curtain produced a broad spectrum sound with peak frequencies between 100 and 300 Hz and 1,000 Hz (Figure 4A). The frequency range of the bubble curtain sounds overlapped the hearing range of Common Carp (Popper 1972) as well as Silver and Bighead carp (Lovell et al. 2006). Contour plots of the sound pressure field showed the maximum SPLs to be 145 dB ref 1 μPa at 200 Hz and 125 dB ref 1 μPa at 1,000 Hz (Figure 5). The area of peak SPL was located directly above the bubble curtain, acting as an extension of the partition wall. The pressure gradient was oriented perpendicular to the opening between channels. Within 25-cm from the bubble curtain, the SPL decreased to about 15 dB ref 1 μPa above background with 115 dB ref 1 μPa at 200 Hz and 95 dB ref 1 μPa at 1,000 Hz.

The particle acceleration power spectrum peaked in all directions between 100 and 300 Hz (Figure 4B). The contour plot of particle acceleration resembled the SPL contours with a peak of 10 dB ref 1 cm/s^2 above the bubble curtain (Figure 5C). Particle acceleration decreased rapidly away

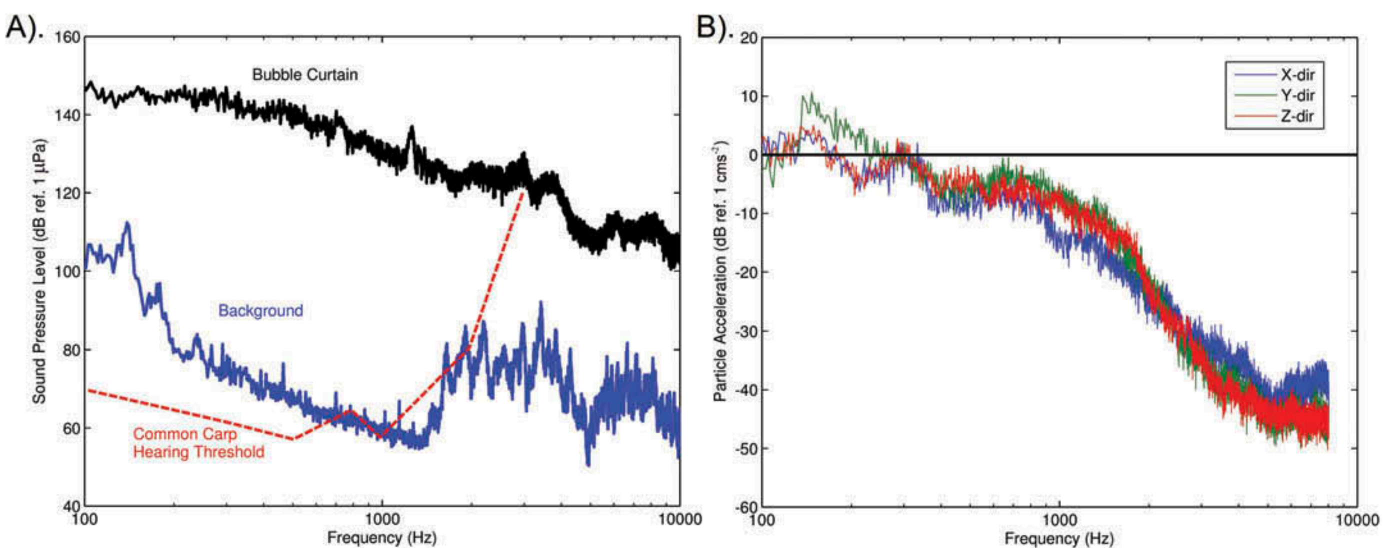

FIGURE 4. **(A)** Sound pressure level power spectrum of the bubble curtain (solid black line), background (solid gray line), and Common Carp hearing threshold (dashed red line; Popper 1972). **(B)** Particle acceleration in each direction: perpendicular (X-dir), parallel (Z-dir), and vertical (Y-dir) to the bubble curtain. Sound measurements were obtained 5 cm away from the bubble curtain in the center of the channel and 12.5 cm from the tank bottom.

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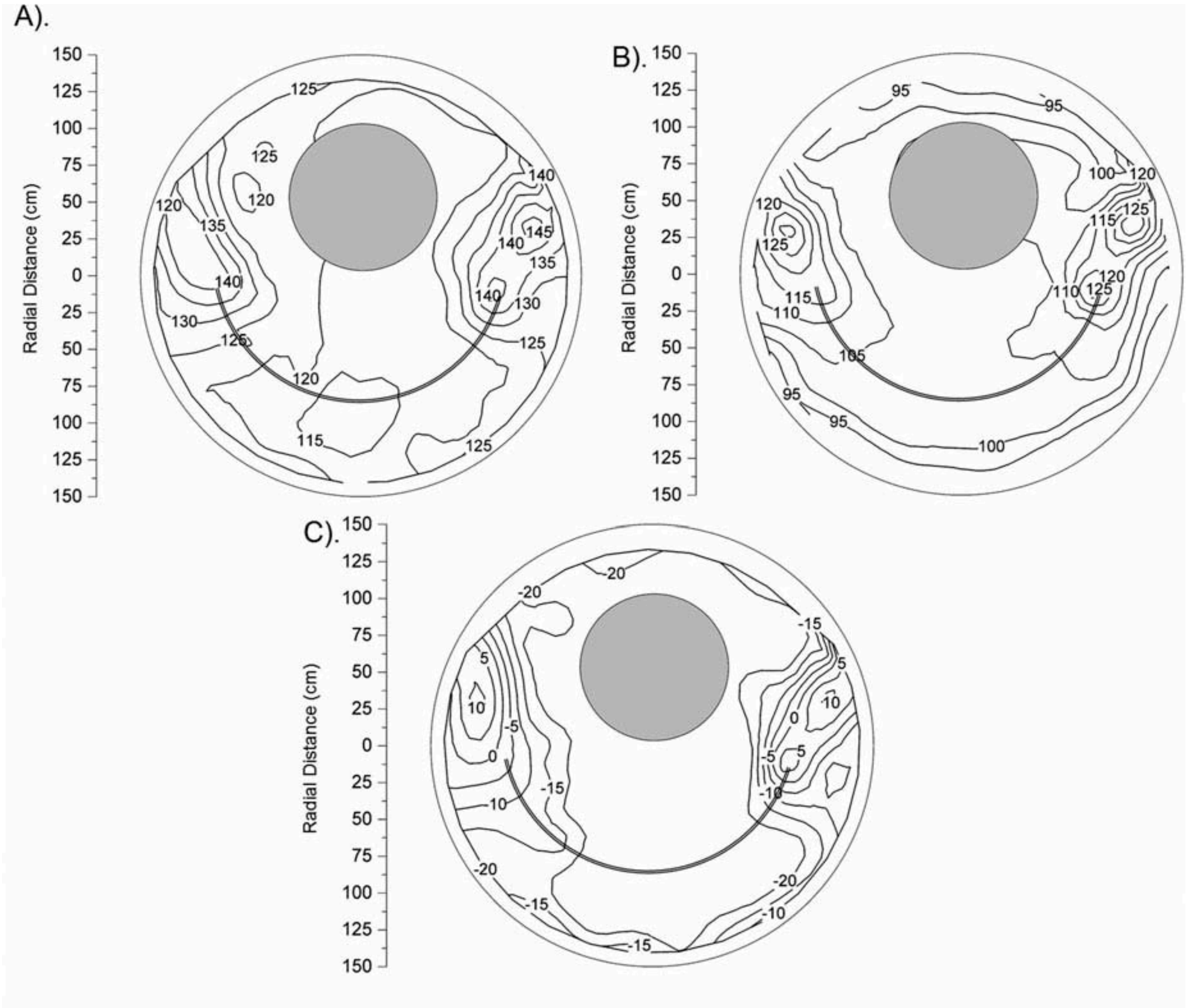

FIGURE 5. Plan view of the sound pressure field in decibels (ref 1μPa) in the experimental tank at a depth of 12.5 cm at **(A)** 200 Hz, **(B)** 1,000 Hz, and **(C)** acoustic particle acceleration in dB (ref 1 cm/s^2). The bubble curtains extended tangentially from the ends of the partition wall (curved line). The background sound pressure level at 200 Hz and 1,000 Hz was 80 and 60 dB ref 1μPa, respectively.

from the bubble curtain, reaching accelerations less than –20 dB ref 1 cm/s^2 at a distance of about 25 cm from the bubble curtain.

DISCUSSION

This study demonstrated that Common Carp, Silver Carp, and Bighead Carp avoid bubble curtains in the laboratory and to similar extents. Functioning as a deflection screen, the bubble curtain diverted passage of all three carp species by 73–83% away from their preferred route in a split passage experimental channel. The remarkably similar effects that the bubble curtain had on all three carp species suggests that the Common Carp is a suitable model to investigate how other carps are deterred by sound and could serve as a reasonable surrogate of Asian carp species when testing the effects of acoustic deterrents in the upper Mississippi where the latter are not yet abundant. These similarities are not surprising given the similar abilities of these three carp species to hear, although their different life history attributes suggest that field tests will eventually be required, especially in shallow tributaries of the upper Mississippi River and its lock chambers. Caution should also be exercised in scaling laboratory data to field scale because the acoustic and hydrodynamic fields produced by bubble curtains will behave differently (Zielinski and Sorensen 2015).

The observed avoidance behaviors of Silver and Bighead carp are in close agreement with previous laboratory and field experiments. Not only have similar rates of deterrence been noted to bubble curtains by Common Carp (Zielinski et al. 2014; Zielinski and Sorensen 2015), but bubble curtains supplemented with underwater speakers have been shown to inhibit the movement of Silver and Bighead carp in hatchery

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pools and streams (Pegg and Chick 2004; Taylor et al. 2005; Ruebush et al. 2012). The bubble curtain tested here produced sound pressure levels roughly 30–40 dB ref 1 μPa above background levels and the hearing thresholds of all three carp species in their most sensitive range (100–2,000 Hz). Although carp avoided this bubble curtain, fish without hearing specializations (e.g., Walleye, Muskellunge, Ruffe *Gymnocephalus cernuus*, White Perch *Morone americana*, and Atlantic Salmon *Salmo salar* [smolts]) have been shown to be largely undeterred by these systems (Sager et al. 1987; Welton et al. 1997; Dawson et al. 2006; Flammang et al. 2014; Stewart et al. 2014). These taxon-specific responses support the possibility that bubble curtains can serve as taxon-specific acoustic deterrent for invasive carps, whose hearing specializations make them disproportionately susceptible to noise-induced stress and movement control than species without such specializations (Maes et al. 2004; Smith et al. 2004).

Bubble curtain deflection systems could ultimately be used to guide carp away from critical habitat or passageways either towards traps (Johnson et al. 2014) or toward areas where carp could be harvested more efficiently. Specifically in the upper Mississippi River system bubble curtains could be used at relatively low cost to limit Asian carp access to low-velocity waters, such as tributaries and oxbow lakes, where large numbers of Asian carp in the lower reaches of the Mississippi River have been observed (Varble et al. 2007; Kolar et al. 2007; Wilson 2014). Juvenile Asian carp have reached nearly 60 km upstream into shallow tributaries of the Missouri River (i.e., Louter River, Cedar River, and Silver Creek; D. Chapman, U.S. Geological Survery, personal communication). The Mississippi River lock chambers offer unique opportunities to deploy bubble curtains because they have a well-defined channel, shallow and slow moving water, and already have much of the infrastructure necessary to operate bubble curtains. Even modestly effective systems might be useful when no alternatives are possible and reducing propagule pressure is a goal.

The fundamental difference between the bubble curtain system we tested and commercially available bubble-speaker-strobe light deterrent systems (Taylor et al. 2005; Ruebush et al. 2012) is cost and simplicity because the release of bubbles into the water column can serve as the sole source of sound, at least if designed in the manner we described. In certain situations underwater speakers could be used to supplement or even replace the sound generated by the bubble curtain, but their use may not be straightforward. While Vetter et al. (2015) demonstrated speakers playing complex sounds (derived from boat motors) have greater impact on modulating Silver Carp swimming behaviors than pure tones, Zielinski et al. (2014) showed Common Carp passage was reduced more by a bubble curtain alone than an array of underwater speakers alone playing a recording of the bubble curtain. Furthermore, a deterrent consisting of just an air-source and bubble diffuser has the benefit that it could be constructed, installed, and maintained at relatively low cost and readily repositioned or removed as needed.

In this study we also characterized the acoustic near field of the bubble curtain (i.e., sound source distance less than the signal wavelength/2π) where acoustic particle motion dominates the sound field (Kalmijn 1988) and show that it probably explains deterrence. In particular, the acoustic particle acceleration produced by the bubble curtain we tested exceeded the 0 dB ref 1 cm/s^2 threshold for acoustic particle acceleration that elicits avoidance behaviors (Knudsen et al. 1992) within 25 cm of the bubble curtain; that is approximately the distance where we noted carp to be deflected and where acceleration reached a maximum of 10 dB ref 1 cm/s^2 at frequencies <300 Hz. In contrast, regions of elevated Reynolds shear stress, a hydrodynamic force implicated in disorienting fish (Silva et al. 2012), extended 50–100 cm away from a similarly sized bubble curtain (Zielinski et al. 2014). Although correlative, the extremely limited range of the sound field stimuli (especially particle acceleration) compared with the wider range of hydrodynamic stresses and the close proximity that carp swam to the bubble curtain (10 cm) seems to confirm that sound and particle motion in particular, has a prominent role in detection and avoidance of bubble curtains by carp. This opens the possibility for further research to study enhancing sound fields to direct fish movement.

Although a direct comparison between the bubble curtain deflection screen tested here and the cross-stream bubble curtains tested by Zielinski et al. (2014) is not straightforward because the latter study used a single channel design, our results provide evidence that behavioral deterrents function best as deflection screens. It may be easier to deflect a fish than to block one. This finding is in agreement with the routine use of behavioral deterrents as deflection screens in fish protection systems at hydropower facilities (Coutant 2001; Welton et al. 2002) or directing migrating fish away from a high-mortality passage route at the divergence of two rivers (Perry et al. 2014). The deflection bubble screen used only 12 L/s of air per meter of water to reduce passage of Common Carp by 73%, while a cross-stream bubble curtain needed 108 L/s to reduce passage by a similar rate (Zielinski et al. 2014). In the field, reduced demand of air should translate to a significant reduction in the cost of continuously running compressors. Additionally, a deflection configuration might also facilitate trapping and removal.

Finally, our study suggests that the Common Carp could serve as a potential surrogate for studies of how other carp species are influenced by sound. Although the sample size for Bighead Carp we used was small, our findings are consistent with Taylor et al. (2005), who found Bighead Carp passage in a concrete-lined channel was effectively reduced by a bubble curtain paired with speakers. In fact, the reduction in total activity exhibited by Silver and Bighead carp suggests they may be slightly more sensitive to acoustic deterrents than

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Common Carp. Using a bubble curtain paired with speakers and strobe light in an Illinois creek, Ruebush et al. (2012) similarly noted a disproportionate upstream passage of Common Carp compared with Asian carp.

In conclusion, our study provides new insight into the theory and application of acoustic deterrents for two Asian carp species and Common Carp. Our findings indicate bubble curtain deflection screens could provide a simple and safe, yet effective means to reduce passage of carp in many locations where other systems are not practical. It also shows that Common Carp could potentially serve as a surrogate for other Asian carp species. We recommend that future applications of bubble curtains be focused on deflecting fish movement rather than outright blockage and that field tests be initiated.

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