Research Article

Evaluation of a broadband sound projected from the gates of a navigation lock in the Mississippi River shows it to be a weak deterrent for common carp and unable to block passage

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Abstract

There is an urgent need to block the passage of carp and other invasive fishes through navigational locks in large rivers. Although the broadband sound of an outboard motor has been shown to strongly repel three species of carp in laboratory flumes and to a lesser extent inside of a lock chamber, it has not yet been tested to determineif it can stop carp from entering a lock. To test this possibility, we attached speakers to lock gates and played the sound of an outboard motor while measuring its efficacy by tracking free-ranging transplanted tagged common carp in its vicinity. Eight groups of 20 carp were tested while the sound system was turned on and off for 2 week periods. When the sound system was on, these carp spent approximately one-third less time in front of the lock gates than when it was off; however, when analyzed by a GLMM this effect was shown to be no greater than the effects of river discharge or temperature. Additionally, lock entrance rates were lower, albeit non-significantly, when the sound was off. A number of factors may have contributed to the limited efficacy of this deterrent system including the sound itself.

Key words: deterrent, invasive species, behavior, lock and dam, bigheaded carp

Introduction

A prevalent theme in ecosystem management is reducing the spread of invasive species. This is especially the case for fishes including the silver carp (*Hypophthalmichthys molitrix*), bighead carp (*H. nobilis*), and common carp (*Cyprinus carpio*). Silver carp and bighead carp (together known as bigheaded carp) are filter-feeding fish from Asia that invaded the Mississippi River from ponds in the 1970s and compete with its native planktivorous fishes (Irons et al. 2007; Sampson et al. 2009; Schrank et al. 2011; Wang et al. 2018). Common carp (*Cyprinus carpio*) are a bottom feeding fish from Eurasia that was introduced from Europe in the 1800s (Sorensen and Bajer 2011), which is also commonly targeted for control because it damages benthic communities (Bajer and Sorensen 2015). Reducing the dispersion of these invasive carps is a highly desired objective by many managers across the globe.

Preventing the upstream movement of invasive carps through gated navigation dams is a particular goal of North American invasive species managers in rivers (ACRCC 2021). Recently, the possibility of achieving this goal by projecting sound into navigational locks has emerged as a promising option for several reasons. Chief amongst these is the fact that carps have a well-developed sense of hearing that is more sensitive than that of many other fishes, especially to frequencies above 1000 Hz (Putland and Mensinger 2019). Indeed, the broadband sound (i.e., a sound with a broad range of frequencies) of an outboard motor has been shown to strongly repel bighead, silver and common carps (with common carp perhaps being slightly less sensitive) in laboratory flumes (Dennis et al. 2019; Murchy et al. 2016, 2017; Vetter et al. 2015, 2017, 2018; Zielinski and Sorensen 2017). Additionally, while a recent field test in a shallow (1–2 m) culvert system with silver carp did not show much promise (Wamboldt et al. 2019), tests with common carp in a deep lock chamber (~3–4 m) did show strong repulsion, although responses appeared to habituate rapidly (Dennis and Sorensen 2020a). However, habituation in the lock chamber may have been exacerbated by the fact that carp were confined to the chamber and could not escape the sound (Dennis and Sorensen 2020a). If true, sound might be more effective if broadcast downstream of locks where free-ranging carp could move downstream to escape. The overarching goal of the present study was to test the possibility of using a relatively simple and inexpensive sound system to deter common carp from approaching and entering a navigational lock in the Mississippi River.

Materials and methods

Study site

Our study took place at Lock and Dam 8 (LD8) in the Mississippi River at Genoa, Wisconsin, USA (43°34′12″N 91°13′54″W). LD8 is approximately 250 km north of the leading edge of bigheaded carp reproduction (Larson et al. 2017; Figure 1A). It stretches the 370 m width of the river and has 15 spillway gates as well as a lock chamber (Figure 1B). LD8's lock chamber is 33.5 m wide and 183 m long, typical of most LDs on the river. During normal operation (June–November), its downstream lock chamber gates open an average of 12.7 times (SD = 7.6) per day. LD8 is operated by the US Army Corps of Engineers (USACE). Neither silver or bighead carp are common at LD8, but common carp are abundant, so they were used in this study.

Experimental design

We designed, constructed, and mounted a sound system on the downstream lock chamber gates of LD8. This system was configured to play a variant of the outboard motor sound previously used by both Zielinski and Sorensen (2017) in the lab and then Dennis and Sorensen (2020a) in a lock chamber.

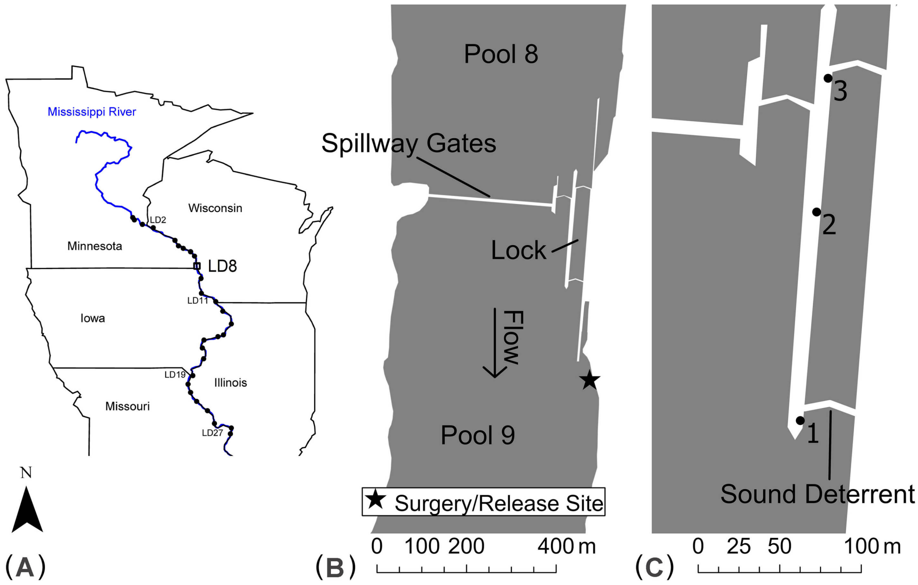

Figure 1. (A) The location of Mississippi River Lock and Dam 8 (LD8), Genoa, Wisconsin, USA. (B) Schematic of LD8 including the spillway gates, navigation lock chamber, and location of the surgery/release site (*). (C) Enlargement of the LD8 lock chamber showing the locations of the acoustic archival tag receivers (1–3) and sound deterrent system.

To reduce the possibility of habituation, the system was designed to project sound only when the gates were open (i.e., when carp could pass). A magnetic reed switch mounted to the gate railing was used to turn the sound on and off. To test the responses of carp to this system, groups of adult common carp were captured upstream of LD8 at regular intervals (~ 2 weeks), tagged with acoustic tags, and released downstream of the LD where their presence was monitored using archival receivers. When transplanted in this manner, common carp have shown a strong tendency to swim upstream (Finger et al. 2020). This procedure was repeated using 6 groups of 20 carp between June–October of 2017 and an additional 2 groups of 20 carp in 2018 (N = 8). Trials alternated between sound-off and sound-on and lasted 13 days. Environmental data including river discharge (m^3/s) and water temperature (°C) were collected at LD8 during the course of each 13-day trial.

The sound deterrent system

Five underwater speakers (LL-1424HP, Lubell Labs, OH, USA) were mechanically mounted on the downstream lock gates at a depth of 1.5–3 m (i.e., slightly deeper than mid-water) (Figure 2). They were connected to a bridge transformer (AC1424HP, Lubell Labs, OH, USA) and power amplifier (CDi2000, Crown Audio, IN, USA) with a custom built Arduino (Arduino, IT) based micro-processor control unit programed to play the sound of a 40 hp outboard motor stimulus used by Zielinski and Sorensen (2017) although its frequency range was attenuated below 500 Hz and above 1500 Hz to prevent speaker damage at high volume per manufacturer specifications. This frequency range included the most sensitive portion of carp hearing

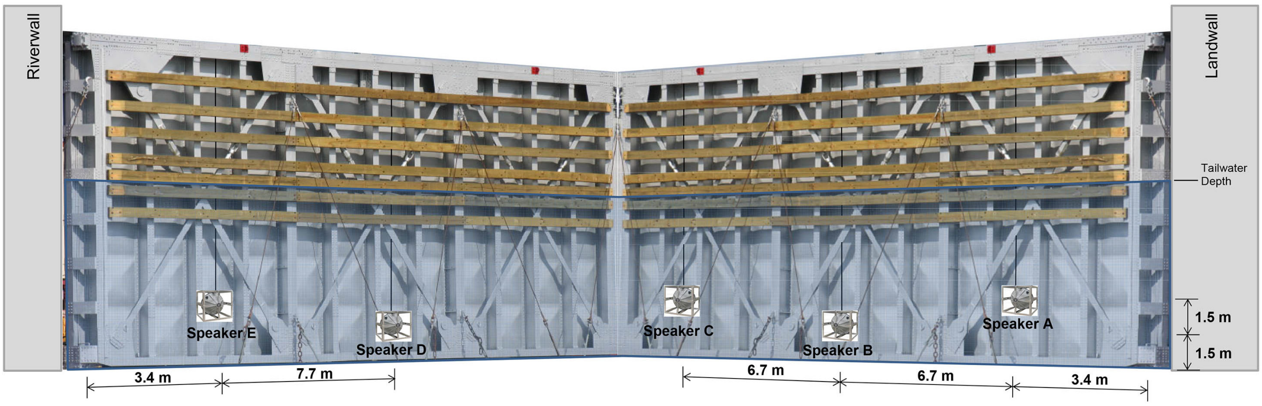

Figure 2. Rendering of the underwater sound deterrent system installed on the face of the downstream lock gates, mounted 1.5–3 m from the river bottom.

(Vetter et al. 2018). The source sound pressure level was set to 140 dB ref. 1µPa, which was similar to the volume used by Dennis and Sorensen (2020a), and a level that was barely perceptible at the water surface and could not interfere with lock communications during commercial barge passage. The entire system cost less than $100,000 (USD) and was installed in a day on existing infrastructure.

The sound field was measured using established protocols (Dennis and Sorensen 2020a). Sound pressure measurements were obtained via a CR1 hydrophone (sensitivity: -197.5 dB; frequency range: 2–48,000 Hz; Cetacean Research Technology, Seattle, WA), sampled at 44.100 Hz and digitized using a TASCAM US-122mkII (TEAC, Montebello, CA) USB audio interface. With the sound on (i.e., the lock gates open), the hydrophone was placed at a depth of 3 m (mid-depth) and measurements were taken at 8.25 m intervals across the width of the lock chamber, and at distances of 0, 5, 10, 17, 24, 30, and 60 m downstream of the gates. Background measurements (i.e., sound-off) were taken at mid-depth, 3, 5, 17, 30 and 60 m downstream of the closed lock gates at the channel width midpoint. The playback signal was recorded for 5-s at each location and then split into ten 0.5-s signal batches and averaged. A custom Matlab (Mathworks, MA) graphical user interface used by Zielinski and Sorensen (2017) was used to analyze and transform the pressure waveforms into the frequency domain. The sound field was characterized by its peak sound pressure level (peak SPL), and root mean squared sound pressure level (SPL_{RMS}) measured between 500 and 1500 Hz.

Carp capture, tagging, and release

Adult common carp (65.5 ± 6.5 cm TL; mean ± SD) were captured by boat electrofishing (5–12 A, 150–250 V, 25–30% duty cycle, and 60 pulse frequency) in Pool 8, approximately 13 km upstream of LD8. Fish were then transported in a 400 L holding tank with recirculating water to a surgery site in Pool 9, located 250 m downstream of LD8 (Figure 1B) for acoustic transmitter insertion. At the surgery site, fish were moved from the holding tank to a net pen in the river to await transmitter insertion which occurred within 2 h. For insertion, carp were anesthetized in a 1:7000 solution of eugenol following established procedures (Hajek et al. 2006; Finger et al. 2020). A 1.5 cm incision was then made below their dorsal fin and a 1 cm-long acoustic transmitter was inserted into the muscle tissue. Once a transmitter had been inserted, the incision was closed using 1 to 2 interrupted absorbable sutures (2-0, Ethicon PDS II), and the fish were then placed back into the river net pen until fully recovered (approximately 20 min) before being released 250 m downstream of the lock. We used individually coded SS300 acoustic transmitters (Advanced Telemetry Systems, Isanti, MN, USA) with a 10-s pulse rate interval at 416.7 kHz and a battery life of roughly 68 days. Fish capture and tagging protocols were approved by the University of Minnesota Institutional Animal Care and Use Committee (Protocol: 1605-33753A). No health problems or mortalities were noted with the tagged carp.

Fish detection

Fish presence and entrances were monitored using an array of three submersible SR3000 acoustic receivers (Advanced Telemetry Systems, Isanti, MN, US; continuous scan). Receivers were deployed in 3 ladder wells on the eastern face of the western lock wall (Figure 1C). Receiver #1 was installed outside of the lock chamber, approximately 12 m downstream of the downstream lock gates so it could monitor the approach channel area immediately downstream of the lock. Receivers #2 and #3 were installed inside the lock chamber, approximately 100 m and 180 m upstream of the downstream lock gates, respectively. Range tests in the lock chamber showed that the acoustic transmitters could be consistently detected (at least once every min) up to a distance of 150 m, meaning if a carp was detected by receiver #3, it was inside the lock chamber and upstream of the downstream lock gates.

Analysis of fish response

Receiver data was downloaded and analyzed after each trial. Data were then filtered to remove uncertain detections (i.e., individual detections that were not immediately followed by at least one other at 10.0-s interval(s) within a 1-min segment; see Finger et al. 2020). We estimated the ability of the sound to deter carp from approaching the lock gates by scoring the presence (or absence) of fish at receiver #1, immediately outside the lock chamber and downstream of the lock gates. The number of 15-min intervals each carp was detected was summed by trial to derive an estimate of the time each fish spent near the lock when the sound source was on and off. The ability of sound to block passage was then evaluated by examining lock entrances. Lock entrances were calculated as the number of times that individual carp were sequentially detected at all three receivers (i.e., #1, #2 and then #3). Time spent near the lock gates and lock entrances were calculated during the 13-day trial period in which they were released (i.e., carp remaining at large during subsequent trials were not evaluated). Data were initially described by trial to determine how many carp approached the lock overall, as well as to produce estimates of total time that carp were near the lock and the number of times they entered it. Because the vast majority of carp were found to approach the lock, the data were next evaluated using data for individual carp as this provided greater power. This approach was especially reasonable because common carp behave in an individualistic manner (Ghosal et al. 2016).

The time that individual carp spent near (i.e., the number of 15-min intervals when detected by receiver #1) the downstream lock chamber gates and the number of lock entrances were analyzed using Generalized Linear Mixed Models (GLMM). The time spent near the lock entrance was analyzed using mean river discharge and mean water temperature across each trial and sound (on/off) as fixed effects and carp identity (ID) as a random effect. To meet the assumption of normality, the count of 15-min intervals that each carp spent near the lock entrance was root transformed. To determine which model was most appropriate, an information theoretic approach was performed using Akaike's information criterion (AIC), where the model with the lowest AIC value was the best model. The best model was validated using the similar measures as Silva et al. (2015) by examining histograms of the normalized residuals, plotting the normalized residuals against fitted values, and by examining residual lag-plots to assess autocorrelation. Lock entrance rates were analyzed using the same GLMM models except they included time spent near the lock entrance as an additional fixed effect and were modeled as logistic regressions with a binomial response variable. Data were analyzed using the fitglme function in Matlab (Mathworks, MA, USA).

Results

The sound deterrent system

The speaker system output had a peak SPL of 177 dB ref. 1 μPa and a maximum SPL_{RMS} of 139 dB ref. 1 μPa at 654 Hz (Figures 3 and 4), similar to the levels used by Dennis and Sorensen (2020a). The distribution of peak SPL showed an attenuation of nearly 30 dB ref. 1 μPa within 60 m downstream of the lock gates (Figure 4A). SPL_{RMS} in the lock approach channel also showed a gradual reduction in pressure level from approximately 140 to 100 dB ref. 1 μPa (Figure 4B, Supplementary material Figure S1). Background sound was measured as being between 95–105 dB ref. 1 μPa between 100–10000 Hz near the gates (Figure 3).

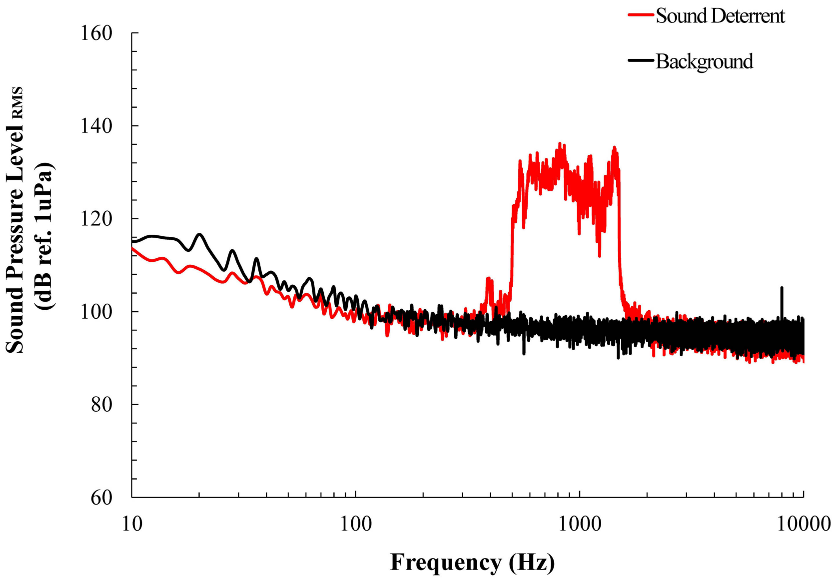

Figure 3. Root mean squared sound pressure level (SPL_{RMS}) power spectrum of the outboard motor sound measured 1 m from the speakers. Background noise is presented as a reference (black line). Sound pressure level measurements are provided at a 2 Hz bandwidth.

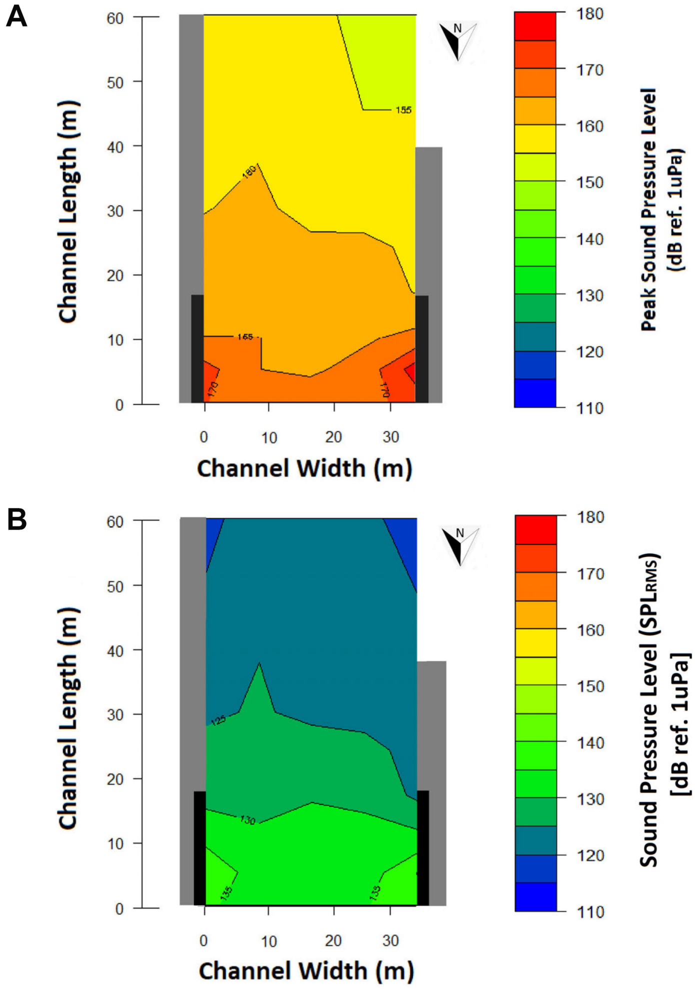

Figure 4. Contour map of the (A) peak sound pressure levels (peak SPL; dB ref. 1 µPa) and (B) root mean squared sound pressure levels at 654 Hz (maximum SPL_{RMS}; dB ref. 1µPa) of the sound deterrent when the lock gates were in the open position. The gray rectangles represent the lock guide walls while the black rectangles represent the lock gates in the open position (sound on). The opening of the lock is at the bottom of each figure.

Table 1. The start date, mean river discharge (m^3/s) and water temperature (°C), tagging statistics of each trial, and sound treatment (on/off). A total of 20 carp were released prior to each trial.

Trial No.	Start date	Discharge	Water temp.	No. detected	Sound
1	07/12/2017	1447	25.3	18	Off
2	07/25/2017	969	25.1	18	On
3	08/09/2017	1016	23.1	19	Off
4	08/29/2017	1531	20.6	20	On
5	09/20/2017	1010	21.1	19	Off
6	10/03/2017	1970	16.7	19	On
7	07/17/2018	2174	25.3	15	Off
8	07/31/2018	1371	24.8	15	On

Table 2. Trials with and without sound, total number of 15-min intervals when carp were detected at the lock gate, and the total number of entrances into the lock. The underline denotes a group of trials and is followed by summary statistics for that group.

Sound	Trial#	Intervals Present	Number of Entrances
Off	1	281	2
Off	3	710	3
Off	5	725	0
Off	7	397	5
Mean ± SD		*528 ± 224*	*2.5 ± 2.1*
On	2	294	3
On	4	403	4
On	6	410	0
On	8	296	1
Mean ± SD		*351 ± 64*	*2.0 ± 1.8*

Fish responses

Of the 160 adult common carp tested, 143 (89%) were detected at least once by receiver #1 in front of the gates suggesting a motivation to move upstream and challenge the lock and dam (Table 1). Both river discharge and water temperature varied during the course of all 8 trials with the peak mean discharge and temperature occurring during trial 7 (Table 1). Initial descriptions of carp presence by trial (mean number of 15-min intervals) near the lock gates showed carp to approach on average about 33% less often when the sound was on than off (351 ± 64 vs. 528 ± 224 mean intervals/trial ± SD), while the mean number of entrances per trial were similar (2.0 ± 1.8 vs 2.5 ± 2.1) (Table 2). Statistical analysis of individual carp next confirmed that individuals spent more time near the gates when the sound was off (26 intervals ± 24 [mean ± SD]) than when it was on (18 intervals ± 14; a 33% reduction). When the frequency of detections was evaluated by its frequency of occurrence, it was noted that while 6 individual carp approached the gates more than 50 times when the sound was off, none did when it was on (Figure 5). Further evaluation of this phenomenon suggested this was because carp tended to re-approach the gates less often days 2-4 after initially doing so when the sound was on (Figure S2). Finally, the best GLMM model to explain time spent near the lock gates contained discharge, temperature, and sound as covariates and fish ID as a random factor (Table 3, Table S1). Specifically, this model showed that individual carp spent less time near the lock entrance with increasing discharge,

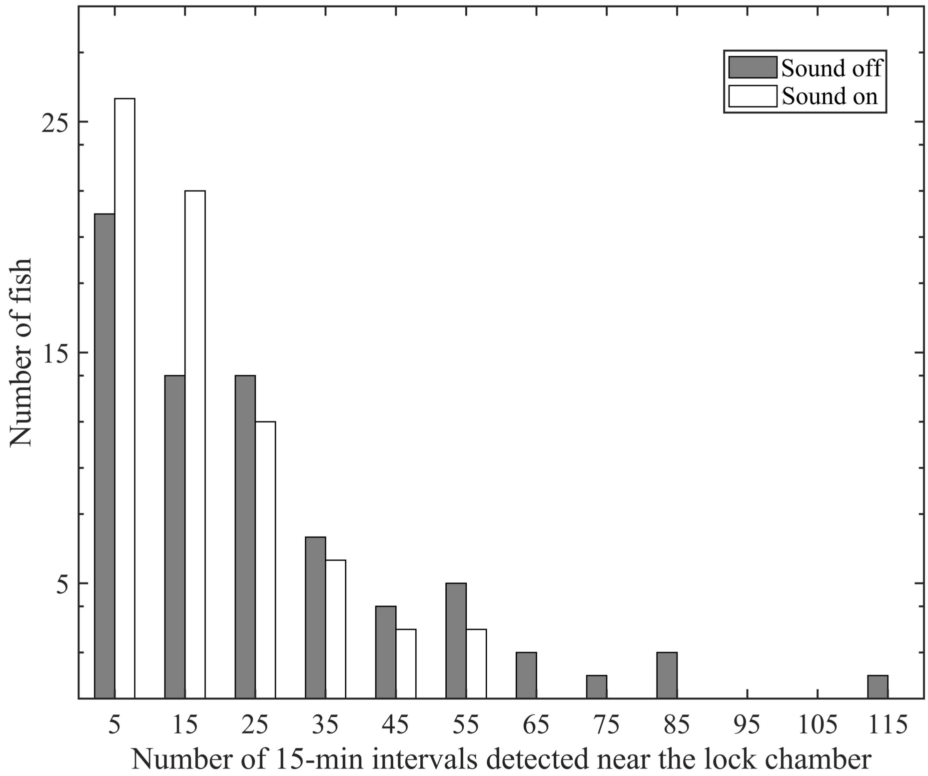

Figure 5. Histogram of the frequencies with which tagged carp were detected (i.e., total number of 15-min intervals) near the lock gates (i.e., by receiver #1) when the sound was either off (grey bars) or on (white bars). Data from all 8 trials were summed.

Table 3. Fixed effects from the best GLMMs which explained time spent near the lock gates and number lock entrances.

Response	Model term	Coefficient	SE	df	t	P value
Time spent near lock gates	Intercept	11.08	1.57	137	7.06	< 0.001
	Discharge	−0.001	0.0004	139	−3.31	0.001
	Water temp	−2.04	0.06	139	−3.58	< 0.001
	Sound	−0.97	0.32	139	−3.00	0.003
Lock entrances	Intercept	−2.37	0.41	141	−5.76	< 0.001
	Time spent near gates	0.01	0.012	141	0.79	0.43

increasing temperature, and when the sound system was on, with all being of approximately equal significance.

Similarly weak trends were seen for lock entrances as for time spent near the gates, although in this case overall values were low (carp only entered the lock 18 times overall) and there was no measurable effect of sound. In particular, while the top model for lock entrances (Table S2) included time spent near the lock entrance and fish ID as a random factor, the effect of time spent near the lock entrance was not significant (Table 3). Entrances could not be explained by any environmental variable or sound (Table S2).

Discussion

Our study appears to be the first to test the ability of a sound deterrent system mounted on the gates of a lock chamber to block upstream swimming carp from entering it. Although we tested an outboard motor sound whose characteristics (spectrum and amplitude) closely resembled that found to be highly effective in the laboratory (Zielinski and Sorensen 2017; Dennis et al. 2019), only small (~33%) reductions in the time spent near the lock gates were noted with no apparent effect on entrances. Further, reductions in time spent near the lock gates could not be solely attributed to the sound system, as the best fit GLMM also identified discharge and temperature as significant covariates. Although disappointing, this result was consistent with results seen inside of a lock chamber where common carp habituated after a single playing of this sound (Dennis and Sorensen 2020a), and field tests in shallow culverts (Wamboldt et al. 2019) with silver carp. The low levels of deterrence we described are unlikely to be useful to the management of upstream swimming carps.

We have confidence in our findings for several reasons. First, our findings are consistent with all other known field results (Dennis and Sorensen 2020a; Wamboldt et al. 2019), as well as ongoing studies (Whitty et al. 2022). Second, our sample size was robust (160 carp) and tests extended over two field seasons. Third, most of our tagged carp swam upstream to the lock gates, as we have seen at another lock and dam (Finger et al. 2020), suggesting we were evaluating a robust challenge to the sound system. Lastly, the sensory physiology of fish hearing and the acoustics of lock chambers both suggest that the type of broadband sound pressure gradients produced may not have been conducive to eliciting strong, oriented and consistent aversion (Dennis and Sorensen 2020a; see below). In any case, our failure to measure strong responses to an outboard motor sound projected from the gates of a lock chamber is important because it suggests that this sound signal, which has received a great deal of attention (Zielinski and Sorensen 2017; Dennis et al. 2019; Vetter et al. 2018), may not be well-suited for use on free-ranging carps in an operational lock chamber using projectors mounted on lock miter gates.

Many reasons may have contributed to lack of a strong response by free-ranging adult common carp to an outboard motor sound played from navigational lock gates. It is possible that the sound was not particularly effective because motorized boats are relatively common in this area of the river (both upstream and downstream of LD8) and fish would be familiar with it and may have already habituated (see: Dennis and Sorensen 2020a). A possible role for habitation is indicated by the decline in effectiveness with time and the fact that this decline decreased after 4–5 days of the sound being played (Figure S2). Notably, the intermittent sound projection strategy we used may have helped reduce possible habituation. Background noise, which was in the range of ~ 100 dB may also have contributed especially because it also was broadband and would have been even higher when motorized ships were present (Putland et al. 2021). The fact that we played a sound whose frequency range attenuated at 500 Hz and 1500 Hz, a slightly narrower range than used in the laboratory (we had to attenuate the frequency to accommodate the speakers), may also have had a role although the sound we used included the most sensitive portion of carp hearing (Vetter et al. 2018). While the amplitude of the sound was considerably less than the maximum range of the speakers (~ 197 dB ref. 1 μPa), it was actually greater than that tested in a closed lock chamber (both rms and peak) and previously found effective (Dennis and Sorensen 2020a), although the nature of the latter's gradient was somewhat sharper. Notably, Wamboldt et al. (2019) tested a very similar sound at a louder amplitude in a shallow culvert without measurable effect. We would not expect bigheaded carps to respond in a fundamentally different manner than common carp as they have not been seen to do so in previous laboratory studies (Murchy et al. 2016; Zielinski and Sorensen 2017), but that possibility might still warrant attention in a field environment.

Finally, acoustic particle motion generated by lock-mounted speakers, which could not be measured in the field, may have also contributed to the limited response in carp. In the lab, carp avoidance responses have been shown to follow the orientation of the local particle motion field (Zielinski and Sorensen 2017). However, mounting speakers to large reflective surfaces (i.e., steel gates) and projecting the sound across the channel at other speakers likely created a complex acoustic particle motion field, likely limiting the ability for carp to respond with directional avoidance.

In sum, the sound system we tested did appear to have a limited role in reducing the time that common carp spent near the lock gates but this did not appear to translate to a decrease in the rate with which common carp entered the lock chamber. However, lock entrance rates were naturally low (less than 10% of available carp entered), similar to those observed by others (Tripp et al. 2014; Finger et al. 2020; Fritts et al. 2020). Presumably, lock passage correlates with entrance rates but that has not yet been shown for common carp. In any case, the low rate with which carp naturally enter locks suggests that human activities in/ near them may make locks naturally aversive, meaning that to be highly effective, deterrent systems will have to be distinctive (i.e., distinguishable) and not just an enhancement of existing background noise. The possibility of pairing sound with other non-acoustic stimuli (e.g., bubbles, strobing lights; Dennis et al. 2019; Dennis and Sorensen 2020b) and positioning them further out in the lock channel in ways that also reduce habituation thus warrant study; such systems would be distinctive and provide multi-modal sensory information that fish could use to orient away from effectively.

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Authors' contribution

ATR contributed to sample design and methodology, data collection, data analysis and interpretation, and writing. JSF contributed to research conceptualization, sample design and methodology, data collection, data analysis and interpretation, and writing. DPZ contributed to research conceptualization (sound deterrent system design, installation, and sound properties), data analysis and interpretation, as well as review and editing. CED contributed to sound data collection, analysis, and interpretation. JW helped with tag data analysis, interpretation, and editing. PWS was responsible for research conceptualization as well as funding and then assisted with sample design and methodology, data analysis and interpretation, ethics approval and writing this manuscript.

Ethics and permits

All procedures were approved by the University of Minnesota Institutional Animal Care and Use Committee (Protocol: 1605-33753A).

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Supplementary material

The following supplementary material is available for this article:

Table S1. Model scores for time carp spent near the lock gates.
Table S2. Model scores for lock entrances.
Figure S1. Root mean squared sound pressure levels produced by the sound deterrent.
Figure S2. Time intervals during which time carp were detected at the lock gate by day.

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