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Research Article

Management implications of broadband sound in modulating wild silver carp (*Hypophthalmichthys molitrix*) behavior

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Editor's note:
This study was first presented at the 19th International Conference on Aquatic Invasive Species held in Winnipeg, Canada, April 10–14, 2016 (http://www.icais.org/html/previous19.html). This conference has provided a venue for the exchange of information on various aspects of aquatic invasive species since its inception in 1990. The conference continues to provide an opportunity for dialog between academia, industry and environmental regulators.

Abstract

Invasive silver carp (*Hypophthalmichthys molitrix*) dominate large regions of the Mississippi River drainage, outcompete native species, and are notorious for their prolific and unusual jumping behavior. High densities of juvenile and adult (~25 kg) carp are known to jump up to 3 m above the water surface in response to moving watercraft. Broadband sound recorded from an outboard motor (100 hp at 32 km/hr) can modulate their behavior in captivity; however, the response of wild silver carp to broadband sound has yet to be determined. In this experiment, broadband sound (0.06–10 kHz) elicited jumping behavior from silver carp in the Spoon River near Havana, IL independent of boat movement, indicating acoustic stimulus alone is sufficient to induce jumping. Furthermore, the number of jumping fish decreased with subsequent sound exposures. Understanding silver carp jumping is not only important from a behavioral standpoint, it is also critical to determine effective techniques for controlling this harmful species, such as herding fish into a net for removal.

Key words: bioacoustics, jumping, herding fish

Introduction

Since their accidental introduction to the southern region of the United States in the 1970's, silver carp (*Hypophthalmichthys molitrix* Valenciennes, 1844) have colonized much of the Mississippi River drainage and now threaten the Laurentian Great Lakes through the Chicago Ship and Sanitary Canal on Lake Michigan. These fish are out competing native species such as gizzard shad (*Dorosoma cepedianum* Lesueur, 1818; Sampson et al. 2009) and bigmouth buffalo (*Ictiobus cyprinellus* Valenciennes, 1844; Irons et al. 2007) because of their prolific spawning and rapid growth rates. They also opportunistically feed on both phytoplankton and zooplankton, impacting other fish populations within this trophic level (Kolar et al. 2007; Sass et al. 2014). In addition to these negative ecological impacts, silver carp also affect humans' recreational activities on affected waterways because they jump in response to motorized watercraft and this presents a hazard, as airborne fish could injure boaters (Kolar et al. 2007).

This jumping behavior also appears to be detrimental to the fish, as they often collide with boat hulls or partially submerged logs and branches. Despite extensive coverage in news and social media outlets, the trigger for and functional significance of

Figure 1. Location of each site on the Spoon River. The Illinois River and the highway bridge on the upstream end of Site 5 are also visible.

jumping remains unknown. When reacting to moving boats (16–40 km/hr), silver carp primarily jumped behind the boat with the pattern of jumping influenced by the boat wake (Vetter et al. 2017). It is also possible that jumping is related to the sound emitted by the outboard motor. Captive silver carp demonstrated consistent negative phonotaxis to a broadband (0.06–10 kHz) outboard motor recording (100 hp at 32 km/hr) and this sound was also >90% effective in deterring silver carp from crossing a narrow (2 m) channel (Vetter et al. 2015; Murchy et al. 2017). However these studies were conducted on captive fish in an artificial environment and the behavioral response of wild silver carp to broadband sound needs to be assessed.

Physical barriers are not always a practical option to prevent aquatic species range expansion, as they can impact shipping and interfere with native species migration and spawning. Therefore broadband sound has been proposed for use as an acoustic deterrent. For instance, broadband sound could be implemented in a lock chamber to manage fish prior to boat passage. However, it is imperative that the behavioral response of silver carp to broadband sound be evaluated in the field. A better understanding of silver carp's jumping behavior, which is likely energetically costly and potentially detrimental to the fish, is also needed. To examine the relationship between broadband sound and silver carp jumping behavior, a field study exposing wild silver carp to broadband sound was conducted on the Spoon River near Havana, IL. Furthermore, this experiment assessed the impact of multiple sound exposures on silver carp behavior with implications for management.

Methods

Study site

The Spoon River is a 237 km tributary of the Illinois River, originating south of Kewanee, IL and meeting the main channel near Havana, IL. Approximately 3.25 km from its terminus, a collapsed bridge had blocked upstream access. Five sites (Figure 1) were selected downstream from the barrier to assess silver carp behavior in response to broadband sound. Sites were chosen because they were far enough apart so the sound stimulus in one site could not influence any of the others (verified with a hydrophone; SoundTrap 202, Ocean Instruments, Auckland, NZ; Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government). Site 1 (100 m long) was located at the mouth of the river and had an average depth of 2.5 m. The second site was approximately 300 m upstream (all distances from river mouth) was 100 m long and an average of 1.8 m deep. Site 3 was located at a large bend approximately 650 m upstream. It was 140 m in length and had an average depth of 2.5 m, except for a deep hole (~ 4.5 m) located half way through the site at the apex of the river bend. The fourth site was 1.1 km upstream, had a length of 100 m, and an average depth of 1.5 m. The final site was 1.5 km upstream and 100 m long with an average depth of 2.3 m. All sites had an approximate water surface area (estimated using Google Earth) of 4,500 m^2 except for Site 3 (6,300 m^2) and turbidity readings ranged between 28 and 90 FTU (USGS 2016).

Sound stimulus

The broadband sound stimulus was recorded in the Illinois River from a 6 m aluminium boat, equipped with a 100 hp motor (4-stroke; Yamaha, Kennesaw, GA), traveling 32 km/hr by a hydrophone (HTI-96-MIN High Tech, Inc., Long Beach, MS) positioned 10 m from the boat's path at a depth of 1 m. In this study, a 30 second clip of this recording was repeatedly broadcast from two underwater speakers (LL916C-025; Lubell Labs, Columbus, OH; frequency response: 200 Hz–23 kHz). Both speakers were housed in cages and the top of each cage was attached to 3 m aluminum poles, which were mounted 1 m apart on the bow railing of a 6 m aluminum boat also equipped with a 100 hp motor. The speakers were submerged such that the tops were approximately 0.15 m under the surface and oriented to project the sound along the longitudinal axis of the boat. A SoundTrap 202 hydrophone (Ocean Instruments, Auckland, NZ) was used to characterize the frequency output of the broadband sound stimulus and measure the sound pressure levels. Acoustic recordings were made in 20 m increments away from the bow of the boat in a direct line from the front of the speakers to 100 m. These measurements were taken after the field experiment in a straight section of the river and at each recording site; the hydrophone was positioned 1.5 m below the water surface and at the midline between the two speakers.

Behavioral observations

Silver carp jumping behavior was recorded using four cameras (GoPro Hero3; San Mateo, CA) during underwater playback of broadband sound in the Spoon River near Havana, IL. One camera was mounted to the bow, port, stern, and starboard sides of the boat and positioned to prevent overlap between each camera's field of view (recording quality: 1080 pixels; 30 frames/second). At each site, the boat moved downstream through the site before making a slow 180° turn and returning to the origin. This was referred to as a "run". The transits favored the starboard side riverbank, so the complete circuit resembled an elongated ellipse, rather than a straight line bisecting the middle of the channel. Each trial consisted of three complete runs with the sound (experimental) and one complete run without sound (control). The order of control and experimental runs was randomized for each trial. In experimental runs, sound was broadcast during the entire transit, with boat speed maintained between 3–6 km/hr. A 10 minute recovery period was allowed between each run, which were 4–6 minutes in duration. An entire trial took 45–50 minutes, and was conducted once at each site on September 15, 2015.

Data analysis

The sound pressure at the source and up to 100 m from the speakers was analyzed using MatLab (R2016b) and the frequency components and power spectrum of both the sound emitted at the speakers and the original outboard motor stimulus (100 hp motor traveling 32 km/hr on the Illinois River) were assessed using Audacity (version 2.0.5).

Prior to video analysis, the distortion from the GoPro fisheye lens was removed using GoPro Studio software (version 2.5.4, San Mateo, CA). The number of jumping in fish each run was quantified by viewing each frame of video (30 frames per second) using Adobe Photoshop CS6 (version 13; San Jose, CA). To ensure a jumping fish was counted once, only jumps that were initiated in a camera's field of view were quantified. The proportion of jumping fish in each run to the total number of jumping fish in a trial (site) was then determined. Runs 1, 2, and 3 and the control at each site were compared against each other using a parametric ANOVA (Shapiro-Wilk test for normality: P = 0.672) with a Holm-Sidack pairwise comparison procedure in SigmaPlot (version 10). Number of jumping fish is reported as mean ± SD.

The fish from Site 3 were further examined using the same method as Vetter et al. (2017) to map the jumping pattern. First, the angle of the jump origin (the point at which the fish broke the water's surface) in relation to the boat's position (bow = 0°; starboard = 90°; stern = 180°; port = 270°) was determined. Next, to estimate the jumping distance from the boat, 2 m PVC pipes marked in 0.25 m increments, were mounted beneath each camera. The number of pixels in each 0.25 m segment was determined in Adobe Photoshop and a linear regression formula for each camera was used to extrapolate jumping distance from the boat.

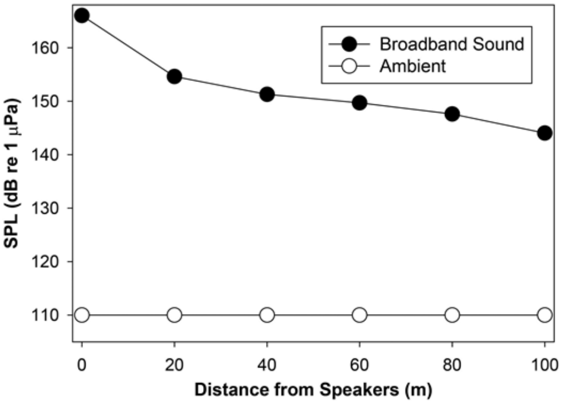

Figure 2. Sound pressure from the stimulus origin and up to 100 m from the speakers.

Results

Sound stimulus

The sound pressure ranged from 166 dB re 1 μPa at the source to 144 dB re 1 μPa 100 m from the speakers while the ambient sound was 110 dB re 1 μPa in this region (Figure 2). The frequency range of the sound emitted from the motorboat was 60 Hz–10 kHz (Figure 3A) while the sound broadcast from the

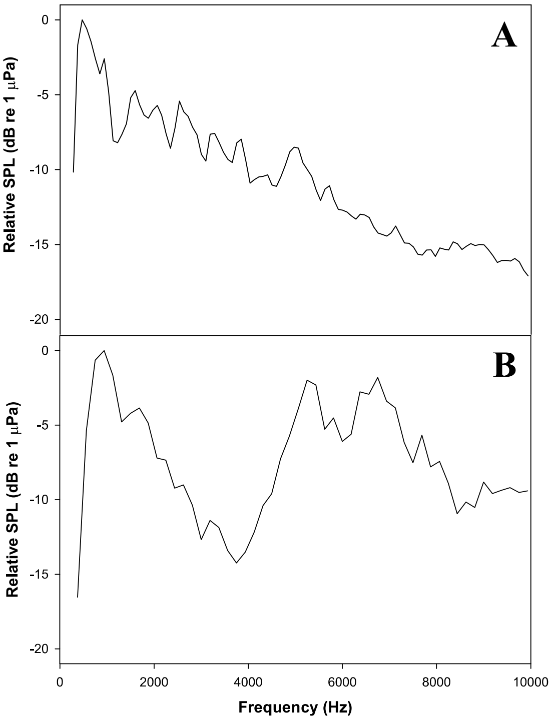

Figure 3. Power spectrum for the (**A**) original outboard motor recording (100 hp motor at 32 km/hr) recorded in the Illinois River and the (**B**) sound stimulus played back to the silver carp on the Spoon River.

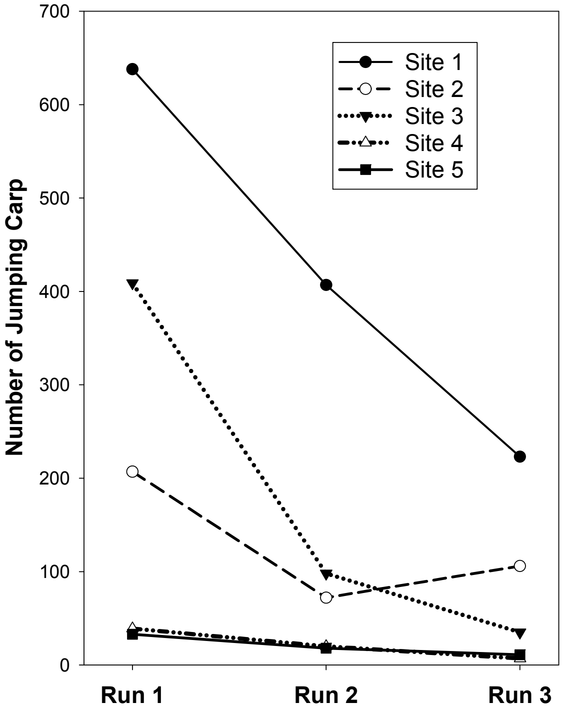

Figure 4. Total number of jumping fish during each run at all five sites.

LL916 speakers ranged from 200 Hz–10 kHz but had two broad peaks between 200 Hz–2 kHz and 6–10 kHz (Figure 3B).

Jumping behavior

The number of jumping carp varied greatly among the three sites, however, the initial run stimulated the most fish at all five sites (Figure 4). Site 1 had the highest total jumping fish (n = 1268), with 638, 407, and 223 jumping during the respective runs (Figure 4). The fewest carp jumped in Sites 4 (n = 66) and 5 (n = 62) (Figure 4). For all five sites, the highest proportion (0.572 ± 0.076) of the total jumps (Figure 5) occurred during the first run (P <0.05) The second runs had the second highest proportion of jumps (0.253 ± 0.071; P <0.05) while the third runs had the lowest proportion of jumping fish of the sound treatments (0.159 ± 0.082; P <0.05). Only control runs in Sites 1 (n = 4) and 3 (n = 46) elicited jumping from the carp and the control runs had the lowest proportion of jumping fish (0.016 ± 0.035; P <0.05). Fish jumped all around the boat during each pass at Site 3 (Figure 6) and a similar pattern was observed at the other sites.

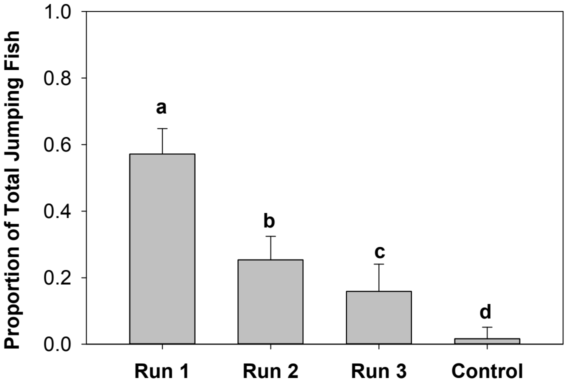

Figure 5. For each run, the mean proportion of total jumping fish is shown. Letters indicate significantly different groups (P < 0.05). Error bars represent ± 1 SD.

Discussion

Silver carp jumped in all runs during which broadband sound was played, while only two of the control runs elicited jumping. These results indicate that broadband sound can trigger the jumping response from silver carp. In all trials, there was a decrease in the number of jumping fish from the first to the third run. Finally, fish jumped all around the boat and did not favor the region astern, as has been observed in fish responding to moving boats (Vetter et al. 2017).

Silver carp are ostariophysans and possess a bony connection (Weberian ossicles) between the swim bladder and their inner ear, which allows them to detect higher frequencies than many non-ostariophysans (Fay and Popper 1999). Lovell et al. (2006) reported sensitivity up to 3 kHz for silver carp, however, since the researchers did not test past this frequency, silver carp may be able to hear beyond 3 kHz, as observed in other ostariophysans (see Ladich and Fay 2013 for a review). Therefore, the carp should have been able to detect at least part of the broadband sound stimulus (0.2–10 kHz).

Silver carp have been observed jumping in the wake created by a moving boat (16–40 km/hr; Vetter et al. 2017), however, in this study it appears that sound was the primary stimulus to elicit jumping, as the boat generated little wake and minimal jumping was observed during boat movement with the speakers inactive. Furthermore, the fish reacting to the sound stimulus jumped 360° around the boat, compared with mostly stern concentrated wake jumping in response to fast moving boats. It is still unclear whether or not the fish were responding to the sound pressure or particle motion from the broadband stimulus, therefore both the sound pressure and particle motion fields for the speaker configuration used in this experiment need to be fully characterized to further correlate jumping and broadband sound.

The decline in fish jumping with subsequent trials could have been attributed to fatigue, habituation, or moving out of the area. Jumping is energetically costly (Rome 1998) and the carp could have remained but become exhausted, which could explain the decrease in jumping during the second and third runs. Alternatively, the carp might have habituated to the sound stimulus. However, broadband sound was effective in directing captive silver carp movement with little evidence of habituation during 2–3 day testing periods (Vetter et al. 2015; Murchy et al. 2017). The negative phonotaxis exhibited by captive carp to broadband sound suggests that this stimulus may have caused the fish in the present study to swim away from the site, however, underwater swimming behavior cannot be inferred from the results of the present study. Therefore, it is imperative that long-term sound exposure experiments on both captive and wild silver carp are conducted to better understand the potential for habituation or exhaustion. An additional field study using a sonar system to monitor fish presence and behavior underwater would aid in determining whether or not fish were exiting the area.

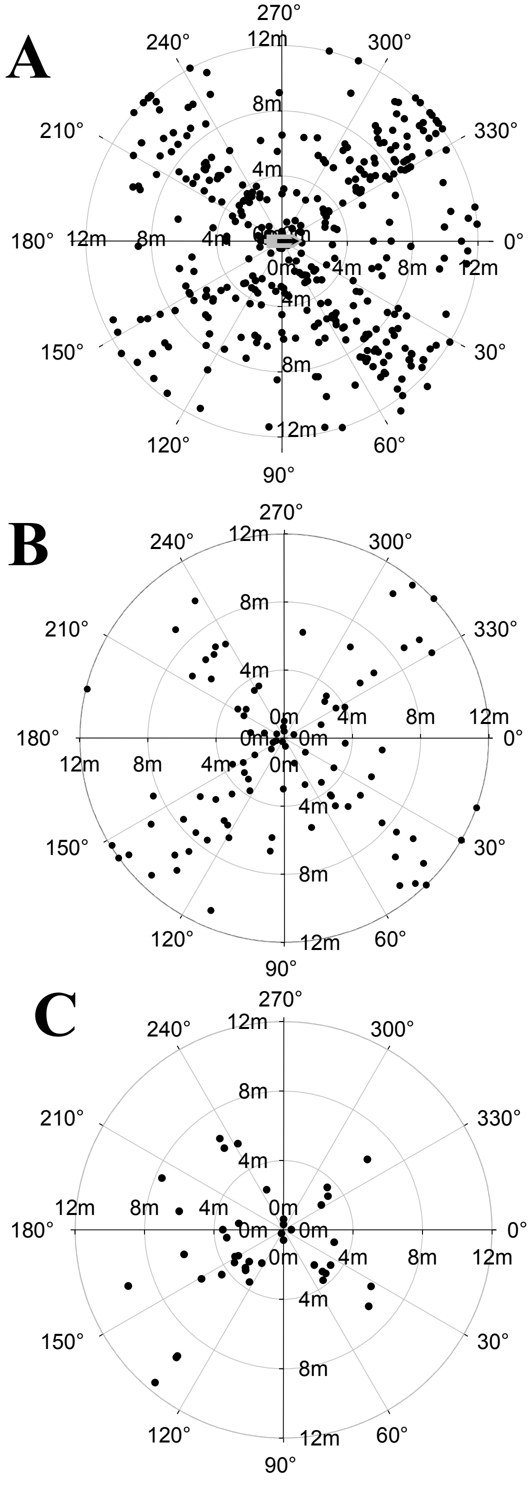

Figure 6. Summary of jump origin angles for airborne fish from an example trial (Site 3) during the (**A**) first, (**B**) second, and (**C**) third runs. Each black circle indicates one fish and 0° represents the boat bow and direction of movement (boat position schematic in (**A**) is not to scale).

The variation in fish jumping between sites may be related to the presence of woody detritus, as areas with partially submerged logs or branches, appeared to have higher densities of jumping fish. Whether fish naturally congregate in submerged structures or retreated to these areas to escape the sound needs further examination. The relationship between presence of partially submerged woody debris and silver carp jumping should be further explored using a sonar system that would allow for accurate census of submerged fish in the regions with and without debris present.

Researchers are currently evaluating the efficacy of acoustical deterrents to prevent further range expansion of silver carp. This study not only implies that sound is capable of eliciting jumping behavior from carp; it also supports the use of broadband sound as a management tool. The decrease in jumping fish with subsequent sound exposures suggests fish could be exhausted or driven from an area using broadband sound however; underwater behavior cannot be determined from the current findings. Therefore, it is imperative that field trials using sonar be conducted to further evaluate fish behavior in response to broadband sound.

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References

Fay RR, Popper AN (1999) The auditory periphery in fishes. In: Fay RR, Popper AN (eds), Comparative Hearing: Fish and Amphibians. Springer Verlag, New York, pp 43–100, https://doi.org/10.1007/978-1-4612-0533-3

Irons KS, Sass GG, McClelland MA, Stafford JD (2007) Reduced condition factor of two native fish species coincident with invasion of non-native Asian carps in the Illinois River, USA - Is this evidence for competition and reduced fitness? *Journal of Fish Biology* 71: 258–273, https://doi.org/10.1111/j.1095-8649.2007.01670.x

Kolar KS, Chapman DC, Courtenay WR, Housel CM, Williams JD, Jennings DP (2007) Bigheaded carps: a biological synopsis and environmental risk assessment. American Fisheries Society Special Publication 33. Bethesda, 204 pp

Ladich F, Fay RF (2013) Auditory evoked potential audiometry in fish. *Reviews in Fish Biology and Fisheries* 23: 317–364, https://doi.org/10.1007/s11160-012-9297-z

Lovell JM, Findlay MM, Nedwell JR, Pegg MA (2006) The hearing abilities of the silver carp (*Hypopthalmichthys molitrix*) and bighead carp (*Hypopthalmichthys nobilis*). *Comparative Biochemistry and Physiology Part A: Molecular & Integrative Physiology* 143: 286–291, https://doi.org/10.1016/j.cbpa.2005.11.015

Murchy KA, Cupp AR, Amberg JJ, Vetter BJ, Fredriks KT, Gaikowski MG, Mensinger AF (2017) Potential implications of acoustic stimuli as a non-physical barrier to silver carp and bighead carp. *Fisheries Management and Ecology* 24: 208–216, https://doi.org/10.1111/fme.12220

Rome LC (1998) Some advances in integrative muscle physiology. *Comparative Biochemistry and Physiology Part B: Biochemistry and Molecular Biology* 120: 51–72, https://doi.org/10.1016/S0305-0491(98)00023-6

Sampson SJ, Chick JH, Pegg MA (2009) Diet overlap among two Asian carp and three native fishes in backwater lakes on the Illinois and Mississippi Rivers. *Biological Invasions* 11: 483–496, https://doi.org/10.1007/s10530-008-9265-7

Sass GG, Hinz C, Erikson AC, McCelland NN, McCelland MA, Epifanio JM (2014) Invasive bighead and silver carp effects on zooplankton communities in the Illinois River, Illinois, USA. *Journal of Great Lakes Research* 40: 911–921, https://doi.org/10.1016/j.jglr.2014.08.010

Vetter BJ, Cupp AR, Fredriks KT, Gaikowski MG, Mensinger AF (2015) Acoustical deterrence of silver carp (*Hypophthalmichthys molitrix*). *Biological Invasions* 17: 3383–3392, https://doi.org/10.1007/s10530-015-0964-6

Vetter BJ, Casper AF, Mensinger AF (2017) Characterization and management implications of silver carp (*Hypophthalmichthys molitrix*) jumping behavior in response to motorized watercraft. *Management of Biological Invasions* 8: 113–124, https://doi.org/10.3391/mbi.2017.8.1.11