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Research Article

In-situ tests of sound-bubble-strobe light barrier technologies to prevent range expansions of Asian carp

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Editor's note:
This special issue of *Aquatic Invasions* includes papers from the 17th International Conference on Aquatic Invasive Species held in San Diego, California, USA, on August 29 to September 2, 2010. 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 within North America and from abroad.

Abstract

Bighead (*Hypophthalmichthys nobilis* [Richardson, 1845]) and silver (*H. molitrix* [Valenciennes, 1844]) carps (collectively, Asian carp) have invaded the Mississippi River Basin and successfully established populations in the Illinois River, where they have negatively influenced native fishes and now pose an imminent threat to invading Lake Michigan through the Chicago Sanitary and Ship Canal. Sound-bubble-strobe light barrier (SBSLB) technologies may have the potential to slow Asian carp range expansions; for example, a sound-bubble barrier was 95% effective at deterring bighead carp passage in a hatchery raceway experiment. In 2009-2010, we tested the effectiveness of a SBSLB at repelling Asian and non-Asian carp species (all other fishes tested) within Quiver Creek, a tributary to the Illinois River. To test barrier effectiveness, Asian carp and non-Asian carp species were removed from upstream of the barrier, marked, and released downstream of the SBSLB. Asian carp were also collected from the mainstem Illinois River and transplanted downstream of the barrier. Trials were conducted with the SBSLB ON and OFF to determine upstream passage rates. Short-term and extended trials were also conducted to test for differences in upstream passage rates using sound, bubbles, and strobe lights (flashing and not flashing) versus sound and bubbles only. Barrier effectiveness was evaluated by upstream recaptures. Two of 575 marked silver carp and 85 of 2,937 marked individuals of other fish species breached the barrier and were recaptured. No marked bighead carp (n=101) made upstream passage. Our results suggest that SBSLB technologies could be used as a deterrent system to repel Asian carp, but should not be used as an absolute barrier to prevent range expansions. Potential negative influences of this technology on non-target fishes must also be evaluated prior to implementation as a management tool.

Key words: *Hypophthalmichthys nobilis, Hypophthalmichthys molitrix,* Illinois River, invasive species, management

Introduction

Bighead (*Hypophthalmichthys nobilis* [Richardson, 1845]) and silver (*H. molitrix* [Valenciennes, 1844]) carps (collectively, Asian carp) are non-native fishes that have invaded the Mississippi River Basin. Both species were intentionally introduced to the United States in the early 1970's for aquacultural purposes (Kolar et al. 2007), but were also introduced for polyculture studies (i.e., raising multiple fishes in a single pond) to process animal waste, improve water quality, and for commercial harvest (Buck et al. 1978). Shortly after their introduction, Asian carp escaped aquacultural confinement and expanded their distribution throughout waterways of the central United States. Asian carp are now present in the Illinois, Mississippi, Missouri, Ohio, and Wabash rivers and their tributaries. Wild populations of Asian carp have expanded their range upstream in the Illinois River and have increased in abundance exponentially in the La Grange Reach (Illinois River Mile 80–157) (Chick and Pegg 2001; Irons et al. 2007; Sass et al. 2010). Sass et al. (2010) estimated over 2,500 adult and sub-adult silver carp per river km in the La Grange Reach, Illinois River in 2007–2008.

The establishment of Asian carp could negatively influence native fishes through competition for habitat and food. Schrank et al. (2003) found that age-0 bighead carp negatively influenced relative growth of age-0 paddlefish (*Polyodon spathula* [Walbaum, 1792]) in a mesocosm experiment. High dietary overlap was observed among Asian carp and two native planktivores, gizzard shad (*Dorosoma cepedianum* [Lesueur, 1818]) and bigmouth buffalo (*Ictiobus cyprinellus* [Valenciennes, 1844]) in backwater lakes of the Illinois and Mississippi rivers (Sampson et al. 2009). Irons et al. (2007) found significant declines in body condition of gizzard shad and bigmouth buffalo after Asian carp established in the La Grange Reach, Illinois River. Asian carp are also a nuisance to recreational and commercial river users and commercial fishermen. Silver carp are known to jump out of the water when disturbed, causing personal injury and property damage for boaters (Perea 2002).

Because a single bighead carp was physically collected upstream of the Aquatic Nuisance Species Dispersal Barrier (ANSDB) in the Chicago Sanitary and Ship Canal (CSSC), and because the Asian carp population in the Illinois River is growing, these invasive species pose an imminent threat to the Laurentian Great Lakes. Researchers have also detected Asian carp environmental DNA (eDNA) in water samples collected upstream of the ANSDB (Jerde et al. 2011). Environmental DNA may detect the presence of Asian carp without capturing an actual specimen, and is particularly acute at detecting Asian carp when they are at low abundances (Jerde et al. 2011). Resource managers and stakeholders are concerned that Asian carp will further contribute to the increased negative ecological effects observed in the Great Lakes due to already established aquatic invasive species (e.g., round goby *Neogobius melanostomus* [Pallas, 1814]).

Sound Projector Array Bio-Acoustic Fish Fence (i.e., sound-bubble barrier; SBB) technologies have been tested to determine their effectiveness as a potential deterrent system that may slow the range expansions of Asian carp. Previous research reported that this technology is effective at altering movements and deterring fishes (Lambert et al. 1997; Welton et al. 2002; Maes et al. 2004; Taylor et al. 2003). SBB technologies were 95% effective at deterring bighead carp (638±38 mm SE) passage in hatchery raceways (Taylor et al. 2005). This type of system was tested because Asian carp are sensitive to sound frequencies ranging from 750-1500 Hz (Lovell et al. 2006). Asian carp and all cyprinids possess a series of small bones that connect the inner ear to the gas bladder, known as a Weberian apparatus (Helfman et al. 1997). This connection allows cyprinids and other ostariophysan fishes to detect higher sound frequencies than non-ostariophysan fishes (Popper and Carlson 1998; Fay and Popper 1999; Lovell et al. 2006). Given the evidence that this technology was effective at deterring bighead carp passage in a mesocosm setting, we conducted *in-situ* tests of a sound-bubble-strobe light barrier (SBSLB) across a range of available bighead and silver carp lengths to test its effectiveness in a scenario more applicable to management and implementation. We hypothesized that SBSLB technologies would deter Asian carp passage because of their hearing capabilities and the results from previous mesocosm studies (Taylor et al. 2005; Lovell et al. 2006). As a byproduct of our experimental design, we also tested SBSLB effectiveness in deterring passage of other fish species. We hypothesized that SBSLB technologies would not deter passage of most other fish species.

Methods

Study site

We tested the effectiveness of a SBSLB in Quiver Creek, Mason County, Havana, Illinois near the Illinois Natural History Survey’s Forbes Biological Station (FBS) (40°21′12.47″N 90°01′17.04″W) (Figure 1). This portion of Quiver Creek was part of the United States Fish and Wildlife Service Chautaqua Refuge. Quiver Creek is a tributary to the Illinois River. Site selection was based on three factors: 1) the portion of Quiver Creek above the SBSLB was blocked by an upstream low head dam that acted as a barrier to prevent emigration upstream; 2) Asian carps were present in Quiver Creek and abundant in the La Grange Reach, Illinois River, and; 3) the FBS provided a power source and housing for electrical components and

Figure 1. Location of the sound-bubble-strobe light barrier in Quiver Creek near the Forbes Biological Station, Havana, Illinois, USA: 1) Illinois River; 2) Quiver Creek; and 3) Sound-Bubble-Strobe Light Barrier.

equipment. During SBSLB testing, Quiver Creek was 16 m wide, maintained about a one meter thalweg (center of the channel) depth, and had flow velocities ranging from 0.4–0.8 m/s.

Sound-Bubble-Strobe Light Barrier components

We deployed a 16 m SBSLB, designed by Fish Guidance Systems, Ltd., United Kingdom and OVIVO USA, Austin, Texas, USA in Quiver Creek in July 2009. System components were fixed on two, eight meter long frames that were situated perpendicular to the flow of Quiver Creek, submerged, and anchored to the substrate (Figure 2). We connected the two frames in the center of Quiver Creek to form the 16 m SBSLB system. System components included 16 evenly-spaced underwater speakers and light-emitting diode (L.E.D.) strobe lights (Figure 3). A 16 m air curtain hose was also attached to the system and was positioned perpendicular to the flow of Quiver Creek (Figure 4). Air and electrical components were housed in a nearby building on the south bank of Quiver Creek. Air was routed through a 5.1 cm PVC pipe down the bank. The electrical supply was also routed down the bank, and connected to the SBSLB.

Components used to operate the SBSLB included two ten horsepower rotary screw air compressors, pneumatic controls, a speaker control box and amplifier, and a strobe light control box. Once operational, the system was only shut down for maintenance or experimental purposes. Unintentional shut downs did occur due to power outages and damage to the air components. In the event of an unintentional shut down, the current experimental test was terminated. The underwater speakers emitted sound frequencies that cycled between 500 and 2000 Hz. The L.E.D. lights either flashed intermittently or remained on as dictated by our experimental design. Air pressure was regulated by the pneumatic control and maintained at 25 psi, the pressure required to open the pores in the air curtain hose.

Experimental design

To estimate our sampling efficiency, we conducted a two-pass depletion estimate on

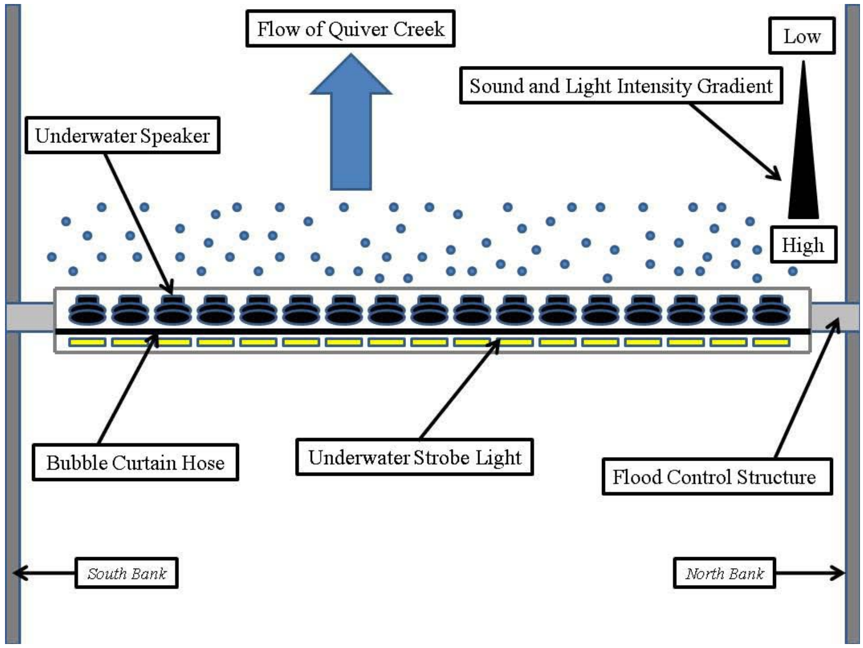

Figure 2. Schematic illustration of the sound-bubble-strobe light barrier in Quiver Creek near the Forbes Biological Station, Havana, Illinois, USA.

Figure 3. Image of the 8 m sound-bubble-strobe light barrier frames prior to deployment in Quiver Creek, Havana, Illinois, USA. Photograph by Blake Ruebush.

Table 1. Experimental design for sound-bubble-strobe light barrier testing of passage rates of fishes in Quiver Creek, Havana, Illinois, USA. (SLF – Strobe Lights Flashing, SLNF – Strobe Lights No Flashing, NSL – No Strobe Lights, BEF – Boat Electrofishing, BPEF – Backpack Electrofishing, HN – Hoop Netting, BS – Beach Seining, AN - Angling).

Year	Dates	Trial	ON/OFF	Sound	Bubbles	SLF	SLNF	NSL	BEF	BPEF	HN	BS	AN
2009	9/14-10/7	1	ON	x	x	x				x	x	x	x
2010	8/27-8/29	2	OFF					x		x	x		x
-	8/29-8/31	3	ON	x	x		x			x	x		x
-	9/3-9/5	4	ON	x	x		x			x	x		x
-	9/5-9/7	5	OFF					x		x	x		x
-	9/9-9/11	6	ON	x	x			x		x	x		x
-	9/11-9/13	7	OFF					x		x	x		x
-	9/15-9/17	8	OFF					x		x	x		x
-	9/28-9/30	9	ON	x	x			x		x	x		x
-	9/27-10/8	10	ON	x	x			x		x	x		x
-	10/12-10/25	11	ON	x	x			x	x		x		x
-	10/25-10/27	12	OFF					x	x				

Figure 4. Image of the sound-bubble-strobe light barrier operating in Quiver Creek, Havana, Illinois, USA. Photograph by Blake Ruebush.

8/24/10 to determine the population size and recapture probability of marked fish upstream of the SBLSB. We computed our population estimate according to Seber and Le Cren (1967):

$$p = \frac{C_1 - C_2}{C_1}$$

$$N = \frac{C_1^2}{(C_1 - C_2)}$$

$$\text{Standard error of } N = \sqrt{\frac{C_1^2 C_2^2 (C_1 + C_2)}{(C_1 - C_2)^4}}$$

where C_1 = the number of fish removed in the first sample, C_2 = the number of fish removed in the second sample, N = the population estimate, and p = the probability of recapture. We used a Smith-Root LR-24 backpack electrofisher to collect fish for the depletion estimate between the SBSLB and the upstream low-head dam during two, one hour backpack electrofishing runs. The SBSLB was not operating during the 24 hours prior to the depletion estimate. We installed a temporary block net immediately upstream of the SBSLB to prevent fishes from escaping downstream during electrofishing and collected all stunned fishes during each run. Captured fishes were held in a well-oxygenated tank, identified to species, measured for length (mm), and released downstream of the SBSLB and temporary block net. After completing the first one hour electrofishing run, we conducted a second run using the same methods. During electrofishing run #1 and #2, we collected 659 and 352 fishes, respectively. Our probability of recapturing a marked fish in the 200 m stretch of Quiver Creek between the SBSLB and upstream low-head dam using backpack electrofishing was 47%. Our population estimate was 1,414 fish (lower 95% confidence interval = 1,258; upper 95% confidence interval = 1,572).

We collected Asian carp and non-Asian carp species between the SBSLB and the upstream low-head dam using backpack electrofishing, hoop netting, angling, beach seining, and boat electrofishing. We also transplanted bighead and silver carp from the main-stem of the Illinois River to Quiver Creek, releasing them downstream of the SBSLB. All captured fishes were identified to species, measured for length (mm) and weight (g), and marked with a unique floy-tag and fin clip, and released immediately downstream of the SBSLB. We collected water quality information from Quiver Creek following fish collections on each sampling occasion. Specifically, Secchi disc transparency (cm), dissolved oxygen (mg/L), turbidity (NTU), conductivity (uS), water temperature (°C), water velocity (m/s), and the stage of the Illinois River at Havana, Illinois. In all experiments, we assumed that Asian carp released downstream of the SBSLB would attempt to make upstream movements and challenge the barrier because they frequently move upstream (DeGrandchamp et al. 2008). Further, we observed silver carp jumping away from the SBSLB shortly after being released downstream of the barrier during preliminary testing in August 2009. We also assumed that non-Asian carp species would challenge the barrier because they were collected upstream of the barrier. Our primary metric for evaluating barrier effectiveness was the number of recaptures. We could not account for fishes that did not attempt to challenge the barrier following downstream release, and our probability of recapturing marked fishes was not 100%. Therefore, we considered the number of fish recaptured upstream of the barrier as the best metric of effectiveness, given environmental conditions within Quiver Creek, the fish species tested, and the operating parameters of the barrier.

Upstream passage testing: Sound-Bubble-Strobe Light Barrier ON vs. Sound-Bubble Barrier ON vs. Sound-Bubble-Strobe Light Barrier OFF

We tested fish passage rates in 2009 and 2010 during a series of trials with the SBSLB ON and OFF (Table 1). The SBSLB was fully operational in Quiver Creek on 8/24/09 and ran continuously until 10/7/09. During this testing period, 1,096 (45–797 mm) non-Asian carp individuals were collected from upstream of the SBSLB, marked, and transplanted downstream of the SBSLB. Thirty-three non-Asian carp species from nine families (Amiidae, Catostomidae, Centrarchidae, Clupeidae, Cyprinidae, Ictaluridae, Moronidae, Percidae, Sciaenidae) were captured upstream of the SBSLB in 2009. Additionally, we transplanted 144 silver carp (141–665 mm) downstream of the SBSLB. Bighead carp were not tested in 2009. Trials resumed on 8/27/10 and continued through 10/27/10, wherein we conducted eleven barrier effectiveness trials (Table 1). We marked 2,756 non-Asian carp individuals (45–890 mm) from 10 families (Amiidae, Catostomidae, Centrarchidae, Clupeidae, Cyprinidae, Ictaluridae, Lepisosteidae, Moronidae, Percidae, and Sciaenidae) in 2010. Individuals tested in trials with the SBSLB ON and OFF totaled 1,841 (45–890 mm) and 915 (91–842 mm), respectively. We released and evaluated movements of 431 silver and 101 bighead carp (367–970 mm) with the SBSLB ON, and one bighead and 125 silver carp (346–686 mm) with the SBSLB OFF in 2010. We used linear regression to test for a relationship between the number of fish marked by species (independent variable) and the number of recaptures (dependent variable) at the α=0.05 level.

Extended trials

We conducted two extended trials from 8/26–10/7/09 and 9/27–10/8/10 to evaluate differences in passage rates based on the operating parameters of the SBSLB. In 2009, all three components (sound, bubbles, and flashing strobe lights) were operational. In 2010, only sound and bubbles were operational. The number, species, and families of marked fishes tested in the 2009 extended trial can be found above. In 2010, 170 non-Asian carp individuals (100–577mm) were collected, marked, and released downstream of the sound-bubble barrier (SBB). We also marked and transplanted 177 silver carp (367–771mm) and 47 bighead carp (661–945mm) from the main-stem Illinois River downstream of the SBB. Seventeen species and an unidentified *Lepomis* spp. from seven fish families (Catostomidae, Centrarchidae, Clupeidae, Cyprinidae, Ictaluridae, Moronidae, Percidae) were included in the 2010 trial.

Short-term trials

In 2010, we conducted four short-term trials (8/29–8/31, 9/3–9/5, 9/9–9/11, 9/28–9/30) to test upstream passage rates of silver carp and non-Asian carp (Table 1). Each trial required three days to complete with fishes collected and marked on day one. We determined upstream passage rates on day two, and on day three we concluded the trial by sampling to recapture marked fish from the current trial. We compared results from two trials using a combination of sound, bubbles, and light (not flashing) (SBLB) and two trials using sound and bubbles only (SBB). Testing of the SBLB and the SBB combinations included 64 (375–635 mm) and 73 (367–675 mm) silver carp, respectively. Additionally, 581 (83–612 mm) and 289 (100–577 mm) non-Asian carp individuals were tested in the SBLB and SBB trials, respectively.

Results

Upstream passage testing: Sound-Bubble-Strobe Light Barrier ON vs. Sound-Bubble Barrier ON vs. Sound-Bubble-Strobe Light Barrier OFF

In 2009, during testing with the SBSLB ON, 32 of 1,096 marked non-Asian carp individuals (82-346 mm) made upstream passage. None of the 144 marked silver carp were recaptured upstream of the barrier. In 2010, 53 of 1,841 marked non-Asian carp individuals (102–766 mm) were recaptured upstream of the SBB. Two of 431 marked silver carp (443–470 mm) made upstream passage when the SBB was ON. In total, 55 of 2,373 marked individuals were recaptured upstream of the SBSLB while it was operating in 2010 (Figure 3). We subsequently recaptured thirty-eight of 915 marked non-Asian carp individuals (116–808 mm) and one of 126 marked Asian carp (446 mm) upstream of the

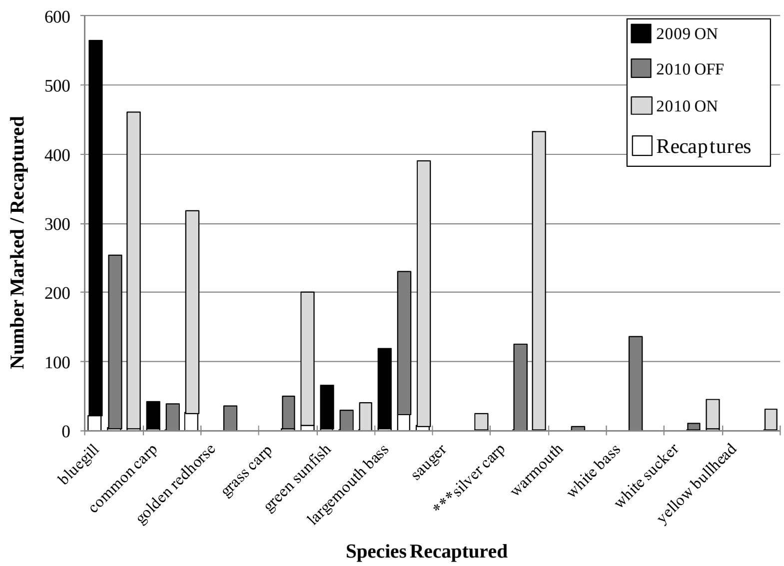

Figure 5. Proportion of fishes marked and recaptured by species during ON and OFF sound-bubble-strobe light barrier trials in Quiver Creek, Havana, Illinois, USA, 2009-2010. Please note that no bighead carp were recaptured.

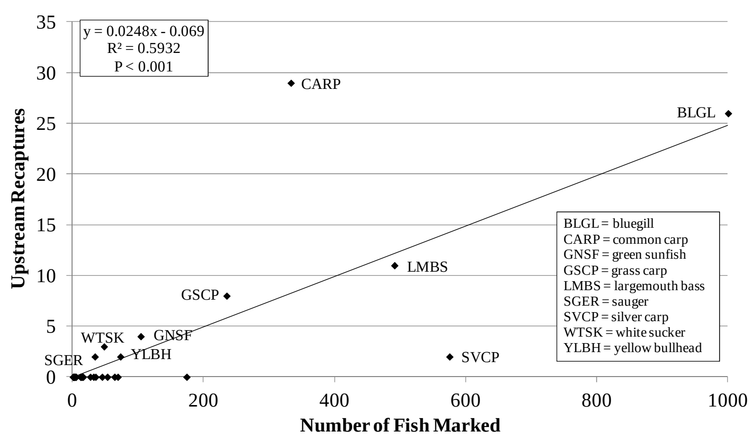

Figure 6. The number of fish recaptured versus the number marked by species for all ON trials testing sound-bubble-strobe light barrier technology in Quiver Creek, Havana, Illinois, USA, 2009–2010. Please note that only recaptured species are labeled.

barrier during testing with the barrier OFF. Bluegill *Lepomis macrochirus* (Rafinesque, 1819) (n=250), largemouth bass *Micropterus salmoides* (Lacepède, 1802) (n=207), and white bass *Morone chrysops* (Rafinesque, 1820) (n=136) were the most commonly marked fishes and bluegill (n=4) and largemouth bass (n=24) were recaptured most often. A significant positive correlation was observed between the number of marked fish by species and the number recaptured ($p < 0.001$) (Figure 4). The number of fish marked by species explained 59% of the variability in the number of recaptures.

Extended trials

Only two fish families made upstream passage when testing the SBSLB and SBB. In the SBSLB trial, 29 of the marked centrarchids (n=775) and three of the marked cyprinids (n=227) made upstream passage. Centrarchids and cyprinids were the most frequently marked families. No fishes from any other families were recaptured upstream of the SBSLB, however, besides ictalurids (n=123) and moronids (n=59), sample sizes for other families were low (n≤21). No silver carp were recaptured upstream of the

Table 2. List of fishes tested in sound-bubble-strobe light barrier effectiveness trials in Quiver Creek, Havana, Illinois, USA, 2009–2010.

Family/Species name	Total Marked	Length Marked (mm)	Total Recaptured	Length Recaptured (mm)	% Recaptured
A - ostariophysan fishes					
Catostomidae	185	106-565	3	293-497	1.6%
Ictiobus cyprinellus (Valenciennes, 1844) - bigmouth buffalo	5	267-565			0.0%
Ictiobus niger (Rafinesque, 1819) – black buffalo	1	484			0.0%
Moxostoma erythrurum (Rafinesque, 1818) – golden redhorse	64	150-485			0.0%
Hypentelium nigricans (Lesueur, 1817) – northern hogsucker	2	352-362			0.0%
Carpiodes cyprinus (Lesueur, 1817) – quillback	13	329-410			0.0%
Carpiodes carpio (Rafinesque, 1820) – river carpsucker	12	204-397			0.0%
Moxostoma macrolepidotum (Lesueur, 1817) – shorthead redhorse	32	106-394			0.0%
Moxostoma anisurum (Rafinesque, 1820) – silver redhorse	3	327-352			0.0%
Ictiobus bubalus (Rafinesque, 1818) – smallmouth buffalo	5	194-468			0.0%
Catostomus commersonii (Lacepède, 1803) – white sucker	48	245-437	3	293-437	6.3%
Cyprinidae	1247	102-970	39	216-766	3.1%
Hypophthalmichthys nobilis (Richardson, 1845) – bighead carp	101	465-970			0.0%
Cyprinus carpio (Linnaeus, 1758) – common carp	333	182-740	29	216-634	8.7%
Notemigonus crysoleucas (Mitchill, 1814) – golden shiner	1	102			0.0%
Carassius auratus (Linnaeus, 1758) - goldfish	2	143-274			0.0%
Ctenopharyngodon idella (Valenciennes, 1844) – grass carp	235	225-890	8	440-766	3.4%
Hypophthalmichthys molitrix (Valenciennes, 1844) – silver carp	575	141-795	2	443-470	0.3%
Ictaluridae	181	83-655	2	160-250	1.1%
Ameirus melas (Rafinesque, 1820) – black bullhead	3	146-250			0.0%
Ameirus nebulosus (Lesueur, 1819) – brown bullhead	35	168-332			0.0%
Ictalurus punctatus (Rafinesque, 1818) – channel catfish	69	110-655			0.0%
Noturus gyrinus (Mitchill, 1817) – tadpole madtom	1	83			0.0%
Ameiurus natalis (Lesueur, 1819) – yellow bullhead	73	107-289	2	160-250	2.7%
Hearing: Ostariophysan	1613	83-970	44	160-766	2.7%
B - non-ostariophysan fishes					
Amiidae	15	280-797	0		0.0%
Amia calva (Linnaeus, 1766) - bowfin	15	280-797			0.0%
Centrarchidae	1674	45-457	42	82-325	2.5%
Pomoxis nigromaculatus (Lesueur, 1829) – black crappie	45	126-325			0.0%
Lepomis macrochirus (Rafinesque, 1819) – bluegill	1000	45-204	26	82-175	2.6%
Lepomis cyanellus (Rafinesque, 1819) – green sunfish	104	75-173	4	135-160	3.8%
Micropterus salmoides (Lacepède, 1802) – largemouth bass	491	45-457	11	112-325	2.2%
Lepomis spp. – *Lepomis* species	14	70-177			0.0%
Lepomis megalotis (Rafinesque, 1820) – longear sunfish	5	107-147			0.0%
Amblopites rupestris (Rafinesque, 1817) – rock bass	1	204			0.0%
Micropterus dolomieu (Lacepède, 1802) – smallmouth bass	2	237-277			0.0%
Lepomis gulosus (Cuvier, 1829) – warmouth	12	112-213			0.0%
Clupeidae	53	101-360	0		0.0%
Dorosoma cepedianum (Lesueur, 1818) – gizzard shad	53	101-360			0.0%
Lepisosteidae	2	489-612	0		0.0%
Lepisosteus osseus (Linnaeus, 1758) – longnose gar	1	612			0.0%
Lepisosteus platostomus (Rafinesque, 1820) – shortnose gar	1	489			0.0%
Moronidae	179	128-835	0		0.0%
Morone saxatilis x chrysops – striped bass x white bass hybrid	1	475			0.0%
Morone chrysops (Rafinesque, 1820) – white bass	174	149-835			0.0%
Morone mississippiensis (Jordan and Eigenmann, 1887) – yellow bass	4	128-224			0.0%
Percidae	50	195-472	2	247-359	4.0%
Sander canadensis (Griffith and Smith, 1834) – sauger	34	195-377	2	247-359	5.9%
Sander vitreus (Mitchill, 1818) – walleye	16	216-472			0.0%
Sciaenidae	27	158-530	0		0.0%
Aplodinotus grunniens (Rafinesque, 1819) – freshwater drum	27	158-530			0.0%
Hearing: Non-Ostariophysan	2000	45-835	44	82-359	2.2%

SBSLB in 2009. During the SBB trial we recaptured two of the marked centrarchids (n=125) and one cyprinid (n=229). Sample sizes for other families tested were low (n≤17). One (470 mm) of 177 (367–771 mm) marked silver carp was recaptured during the SBB trial. During the SBSLB trial, three of 230 ostariophysan (i.e., possessing the Weberian apparatus) individuals were recaptured, whereas 29 of 869 marked non-ostariophysan individuals were recaptured. Results were similar during SBB trials, where one of 247 marked ostariophysan and two of 147 marked non-ostariophysan individuals were recaptured.

Short-term trials

Upstream passage was only observed during one of four short-term trials. During the first SBLB trial, three species were recaptured: three, one, and four of the marked bluegill (n=107), green sunfish (n=23), and largemouth bass (n=90), respectively. Sound-bubble-light barrier testing resulted in zero ostariophysan and eight non-ostariophysan fishes making upstream passage. No ostariophysan or non-ostariophysan fishes were recaptured during the SBB trials.

Discussion

Sound-bubble barrier technology has been shown to deter bighead carp in hatchery raceways (Taylor et al. 2005) and other fishes in various applications (Lambert et al. 1997; Welton et al. 2002; Maes et al. 2004; Taylor et al. 2003). Our study supported previous research that SBSLB and SBB technologies deter fishes; however, the addition of strobe lights did not appear to make an appreciable difference in deterring the fish assemblage we evaluated in Quiver Creek. Although the primary focus of our study was to test the effectiveness of the SBSLB technology in preventing upstream passage of the invasive, and federally injurious, Asian carps, particularly silver carp, we tested other fishes commonly collected at our study site. This secondary evaluation was a novel and important aspect of the study given that the utility of SBSLB technologies may increase if non-target species are able to pass undeterred. For example, many fishes undertake upstream spawning migrations to complete their life histories (Eschmeyer 1950; Carmichael et al. 1998; Ickes et al. 1999). When upstream passage of fishes was tested with the SBSLB turned OFF, we observed higher passage rates for several species, suggesting that at least some *portion* of our marked fish population *was* challenging and breaching the barrier location (Figure 5). Thus, we have focused the remainder of the discussion on tests of barrier effectiveness when it was ON. We found little difference in passage rates between trials when the barrier was ON (with or without strobe lights). Therefore, we collectively discuss results from all trials when sound and bubbles were operational and report the number of recaptures versus the number marked for Asian carp and non-Asian carp species.

Based on our experimental design, recapture probability, and assumptions, the SBSLB appeared to be effective at deterring Asian carp from making upstream passage in Quiver Creek. Despite changes in the operating parameters, Asian carp upstream passage remained minimal when only sound and bubbles were functional. Only two of 575 marked silver carp were recaptured upstream of the barrier during the entire study (Table 2). In 2010, no marked bighead carp (n=101) were recaptured upstream of the barrier (Table 2). Our results were similar to those of Taylor et al. (2005), who observed that 95% of the bighead carp (638 ± 38 mm (SE)) tested were repelled by a SBB in a hatchery raceway. Our results suggested that SBSLB technologies were also effective at repelling larger bighead carp (465–970 mm, mean 810 ± 7 (SE)). Because of the Taylor et al. (2005) study, we specifically put more effort into evaluating barrier effectiveness for silver carp. Marked silver carp ranged in size from 141–795 mm (mean 471±5 (SE)) (Table 2). Low recapture rates of Asian carp precluded our ability to evaluate a potential relationship between fish length and recapture rate. However, because recapture rate for silver carp was low compared to the number marked, silver carp either did not challenge the barrier as much, or the barrier was more effective at deterring them from making upstream passage compared to the other fishes tested (Figure 6). Our observations of silver carp jumping away from the SBSLB immediately after downstream transplant provide further, albeit circumstantial, evidence that silver carp did challenge and were repelled by the technology. Our results suggested that sound frequencies ranging from 500 to 2000 Hz were appropriate for deterring Asian carp. Our results supported the findings of Lovell et al. (2006), who reported that Asian carp were most sensitive to frequencies in the 750–1500 Hz range. We conclude that the collective weight of evidence from previous trials and our experiment indicate SBB technologies may have utility for deterring Asian carp in other aquatic systems.

Our results also suggested that SBSLB technology was effective at deterring most of the non-Asian carp species tested. We marked 39 fish species and hybrids representing ten families. In 2009, 32 non-Asian carp individuals were recaptured upstream of the SBSLB, suggesting that at least some of these fishes were deterred or did not challenge the barrier. We transplanted one common carp *Cyprinus carpio* (Linnaeus, 1758) downstream of the SBSLB twice and recaptured it upstream twice in 2009. Our results from 2010 showed that the SBB deterred all but three non-Asian carp species. Low samples sizes of recaptured non-Asian carp disallowed us from testing for a relationship between length and recapture rate. Negligible differences in passage rates were observed between ostariophysan and non-ostariophysan fishes. If SBSLB technology is used to prevent range expansions of Asian carp, it may also reduce passage rates of other non-native species such as common carp, grass carp *Ctenopharyngodon idella* (Valenciennes, 1844), and goldfish *Carassius auratus* (Linnaeus, 1758). We recaptured 29 of the marked common carp (n=333) and eight of the marked grass carp (n=235). No goldfish (n=2) were recaptured. Thus it appears that common carp were deterred, but were recaptured at a greater proportion than other marked species (Figure 6). Our SBSLB was specifically cycled at sound frequencies that Asian carp are most sensitive to, which may have allowed common carp to breach the barrier. Bell (2005) showed behavioral syndromes, such as boldness and aggression, in threespine stickleback (*Gasterosteus aculeatus*). Behavioral syndromes of individual fish may also explain why some fishes made upstream passage, even though disturbed by the SBSLB. Our SBSLB also deterred native fishes from making upstream passage, which may have negatively affected their typical behaviors (e.g., spawning migrations, the ability to find refuge and foraging habitat). For example, bluegill (n=1000) and largemouth bass (n=491) were the most frequently marked non-Asian carp species, but only 26 and 11 made upstream passage, respectively. A positive correlation was observed between the number of fish marked and the number recaptured upstream of the barrier, for most recaptured species (Figure 6). White bass (n=174) were captured by angling below the low-head dam, yet none were recaptured. Moronids are known to make upstream migrations for spawning and foraging (Carmichael et al. 1998). We suggest that the SBSLB may have altered the preferred behavior of bluegill, largemouth bass, and white bass in Quiver Creek. Therefore, the use of SBSLB technologies to prevent range expansions of fishes should take into consideration the target and non-target species that may be affected. Overall, sound frequencies used to potentially deter certain fish species should be tailored to the hearing capabilities of the target organism. Densities of the target organism must also be considered because our results suggest that the number of recaptures was dependent upon the number of individuals marked below the barrier.

Several factors in our mark-recapture study could have reduced recapture rates and/or our estimation of barrier effectiveness. First, it is possible that marked fish moved downstream and did not challenge the barrier. We attempted to install block nets downstream (e.g., beach seine, chicken wire, 10.2 cm^2 woven wire), but the flow, volume of water, and debris in Quiver Creek quickly rendered these temporary barriers ineffective. We also acknowledge that we did not have the capability to detect all fishes making upstream passage. We estimated the probability of recapturing marked fish using backpack electrofishing was 47%. According to Seber and Le Cren (1967), a p = 47% is considered unbiased. We used other methods of sampling in addition to backpack electrofishing to improve our recapture potential. Our additional sampling suggested that our depletion estimate using only backpack electrofishing was conservative and we likely had a higher probability of capturing marked fishes. Our study was novel in that it was conducted in a natural and dynamic environment, which is a more appropriate scale to draw inferences applicable to management and implementation. While experiments at a micro- or mesocosm scale have the benefit of increased control and replication (Pace and Groffman 1998), ecosystem and *in-situ* experiments are necessary before implementation because the risk of barrier ineffectiveness may lead to range expansions of non-desirable species. In future *in-situ* studies testing SBSLB effectiveness, we suggest that passive integrated transponder (PIT) tags and an automated receiver be used to detect and quantify fish passage. Funding limitations prevented us from incorporating PIT technology in our study. If incorporated, an automated receiver would provide 100% detection rates of upstream passage and/or traverses of the barrier in either direction.

Conclusion

Because Asian carp pose an imminent threat to the Great Lakes and other un-invaded water bodies, there is great need for alternative and safer management tools to prevent range expansions of these aquatic invasive species. SBSLB technology appears to be a potential tool for reducing propagule pressure to areas where Asian carp are not present or are in low abundances. Reducing propagule pressure may lower the probability of Asian carp successfully establishing in the Great Lakes and will reduce invasive species removal and/or control costs in the future. This system could also be used to "herd" Asian carp into areas, which would allow them to be more easily removed. Commercial fishermen herd Asian carp into their trammel nets by motoring in a zig-zag fashion to create noise. Asian carp are deterred by this noise, move away from the boat, and towards the nets. Asian carp are found in high densities below locks and dams, so this technology could be installed to deflect Asian carp from lock chambers and allow commercial harvest within these concentrations. Our results provided evidence that this technology has the ability to deter Asian carp and other fishes. Nevertheless, we do not recommend that this technology be used as an absolute barrier for preventing all upstream movements of Asian carp or other invasive fishes. Finally, negative influences on non-target fishes must be considered and evaluated before implementation as a deterrent system. In the context of range expansion to Lake Michigan, SBSLB technologies could be used as a redundant barrier in association with the current electric aquatic nuisance species dispersal barriers in the Chicago Sanitary and Ship Canal to prevent the establishment of Asian carp. A SBSLB could be used as a tool to deflect Asian carp from making upstream passage through the Lockport lock and dam, which would then reduce propagule pressure on the upstream electric barriers.

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References

Bell AM (2005) Behavioural differences between individuals and two populations of stickleback (*Gasterosteus aculeatus*). *Journal of Evolutionary Biology* 18: 464–473, http://dx.doi.org/10.1111/j.1420-9101.2004.00817.x

Buck DH, Baur R J, Rose C R (1978) Utilization of swine manure in a polyculture of Asian and North American fishes. *Transactions of the American Fisheries Society* 107: 216–222, http://dx.doi.org/10.1577/1548-8659(1978)107<216:UOSMIA>2.0.CO;2

Carmichael JT, Haeseker SL, Hightower JE (1998) Spawning migration of telemetered striped bass in the Roanoke River, North Carolina. *Transactions of the American Fisheries Society* 127: 286–297, http://dx.doi.org/10.1577/1548-8659(1998)127<0286:SMOTSB>2.0.CO;2

Chick JH, Pegg MA (2001) Invasive carp in the Mississippi River basin. *Science* 292: 2250–2251, http://dx.doi.org/10.1126/science.292.5525.2250

DeGrandchamp KL, Garvey JE, Colombo RE (2008) Movement and habitat selection by invasive Asian carps in a large river. *Transactions of the American Fisheries Society* 137: 45–56, http://dx.doi.org/10.1577/T06-116.1

Eschmeyer PH (1950) The life history of the walleye *Stizostedion vitreum vitreum* (Mitchill), in Michigan. *Bulletin of the Michigan Institute of Fisheries Research* 3: 1–99

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, http://dx.doi.org/10.1007/978-1-4612-0533-3

Helfman GS, Collette BB, Fancy DE (1997) The diversity of fishes. Blackwell Science, Inc. Malden, Massachusetts, 528 pp

Ickes BS, Stevens AG, Pereira DL (1999) Seasonal distribution, habitat use, and spawning locations of walleye *Stizostedion vitreum* and sauger *S. canadense* in Pool 4 of the Upper Mississippi River, with special emphasis on winter distribution related to a thermally altered environment. Minnesota Department of Natural Resources, Investigational Report 481, 30 pp

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, U.S.A. Is this evidence for competition and reduced fitness? *Journal of Fish Biology* (Special Supplement D) 71: 258–273, http://dx.doi.org/10.1111/j.1095-8649.2007.01670.x

Jerde CL, Mahon AR, Chadderton WL, Lodge DM (2011) “Sight-unseen” detection of rare aquatic species using environmental DNA. *Conservation Letters* 4: 150–157, http://dx.doi.org/10.1111/j.1755-263X.2010.00158.x

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

Lambert DR, Turnpenny AWH, Nedwell JR (1997) The use of acoustic fish deflection systems at hydro stations. *Hydropower and Dams* 1: 54–56

Lovell JM, Findlay MM, Nedwell JR, Pegg MA (2006) The hearing abilities of the silver carp *(Hypophthalmicthys molitrix)* and bighead carp *(Aristichthys nobilis). Comparative Biochemistry and Physiology* 143: 28–291, http://dx.doi.org/10.1016/j.cbpa.2005.11.015

Maes J, Turnpenny AWH, Lambert DR, Nedwell JR, Parmintier A, Ollevier F (2004) Field evaluation of a sound system to reduce estuarine fish intake rates at a power plant cooling water inlet. *Journal of Fish Biology* 64: 938–946, http://dx.doi.org/10.1111/j.1095-8649.2004.00360.x

Pace ML, Groffman PM (1998) Successes, Limitations, and Frontiers in Ecosystem Science. Springer-Verlag New York, Inc. New York, New York, 499 pp, http://dx.doi.org/10.1007/978-1-4612-1724-4

Perea JP (2002) Asian carp invasion: fish farm escapees threaten native river fish communities and boaters as well. *Outdoor Illinois* 10(5): 8

Popper AN, Carlson TJ (1998) Application of sound and other stimuli to control fish behavior. *Transactions of the American Fisheries Society* 127: 673–707, http://dx.doi.org/10.1577/1548-8659(1998)127<0673:AOSAOS>2.0.CO;2

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, http://dx.doi.org/10.1007/s10530-008-9265-7

Sass GG, Cook TR, Irons KS, McClelland MA, Michaels NN, O’Hara TM, Stroub MR (2010) A mark-recapture population estimate for invasive silver carp (*Hypophthalmichthys molitrix*) in the La Grange Reach, Illinois River. *Biological Invasions* 12: 433–436, http://dx.doi.org/10.1007/s10530-009-9462-z

Schrank SJ, Guy CS, Fairchild JF (2003) Competitive Interactions between Age-0 Bighead Carp and Paddlefish. *Transactions of the American Fisheries Society* 132: 1222–1228, http://dx.doi.org/10.1577/T02-071

Seber GA, Le Cren ED (1967) Estimating population parameters from catches large relative to the population*. Journal of Animal Ecology* 36: 631–643, http://dx.doi.org/10.2307/2818

Taylor RM, Pegg MA, Chick JH (2003) Some observations on the effectiveness of two behavioral fish guidance systems for preventing the spread of bighead carp to the Great Lakes. *Aquatic Invaders* 14: 1–5

Taylor RM, Pegg MA, Chick JH (2005) Response of bighead carp to a bioacoustic behavioral fish guidance system. *Fisheries Management and Ecology* 12: 283–286, http://dx.doi.org/10.1111/j.1365-2400.2005.00446.x

Welton JS, Beaumont WRC, Ladle M (2002) The efficacy of acoustic bubble screens in deflecting Atlantic salmon (*Salmo salar L.)* smolts in the River From, U.K. *Fisheries Management and Ecology* 9: 11–18, http://dx.doi.org/10.1046/j.1365-2400.2002.00252.x