IN-SITU TESTS OF SOUND-BUBBLE-STROBE LIGHT BARRIER TECHNOLOGIES TO PREVENT THE RANGE EXPANSIONS OF ASIAN CARP

BY

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THESIS

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ABSTRACT

Bighead *(Hypophthalmichthys nobilis)* and silver *(H. molitrix)* carp (collectively, Asian carp) have invaded the Mississippi River Basin and have successfully established populations in the Illinois River. Correlative studies have suggested that Asian carp in the Illinois River have negatively influenced native planktivorous fishes and they 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. A sound-bubble barrier was 95% effective at deterring adult bighead carp passage in a hatchery raceway experiment. In 2009-2010, I tested the effectiveness of a SBSLB at repelling Asian and non-Asian carp (all other fishes tested) within Quiver Creek, a tributary to the Illinois River. To test barrier effectiveness, Asian carp and non-Asian carp were removed from upstream of the barrier, marked, and released downstream of the SBSLB. Asian carp were also collected from the main-stem Illinois River and transplanted downstream of the barrier. Trials were conducted with the SBSLB ON and OFF to test 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 non-Asian carp breached the barrier and were recaptured. No marked bighead carp (n=101) were recaptured. My 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 considered prior to implementation as a management tool.

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I am dedicating this thesis to my parents, Brian and Angie, and sister, Ashlyn. My family has been supportive throughout my collegiate career and entire life. Dad introduced me to hunting and fishing at a young age. Mom constantly read to me as a child and was always pursuing new ideas of how to teach Ashlyn and I to become better students. I could not ask for better parents. Thanks, Mom and Dad. I love you and I appreciate everything you have done for me. Ashlyn, thanks for being my best friend. Whether we are just hanging out at home, going out on the town, or taking trips together, we always have fun and I'm glad that we are so close. I cherish the relationship I have with you, Mom, and Dad.

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CHAPTER 1: INTRODUCTION

Invasive species are one of the leading causes of declining biodiversity (Ricciardi 2004). Species are usually introduced for human benefit or to serve as a biological control. For example, the American bullfrog (*Rana catesbeiana*) has been introduced worldwide for human use; however, it is now considered one of the most detrimental invasive species because it competes with and preys upon native amphibians (Kats and Ferrer 2003). Bighead *(Hypophthalmichthys nobilis)* (Figure 1) and silver carp *(H. molitrix)* (Figure 2) (Cyprinidae) (Nelson 2006), collectively Asian carp, are two non-native fishes that were intentionally introduced to the United States in the early 1970's for use in aquaculture to improve water quality (Kolar et al. 2007) and for polyculture (raising multiple fishes in a single pond). Like bullfrogs, Asian carp were introduced to benefit humans, but are now disrupting aquatic ecosystems in the Mississippi River Basin.

In 1975, Illinois Natural History Survey scientists found that silver carp, bighead carp, grass carp *(Ctenopharyngodon idella)*, common carp *(Cyprinus carpio)*, and native fishes such as largemouth bass *(Micropterus salmoides)*, channel catfish *(Ictalurus punctatus)*, and hybrids of bigmouth and black buffalo *(Ictiobus cyprinellus x niger)* could be used for animal waste management and water quality control (Buck et al. 1978). Additionally, these fishes were commercially harvested for protein. Overall, silver and bighead carp (collectively, Asian carp) have been introduced to 88 and 74 countries throughout the world, respectively (Kolar et al. 2007). Bighead carp are native to large rivers and floodplain lakes of eastern China, eastern Siberia, and North Korea (Kolar et al. 2007; Yi et al. 1988). Silver carp are commonly found in large rivers, ponds, lakes, and backwater lakes connected to rivers (Berg 1964; Kaul and Rishi 1993) in southern Asia, eastern China, and eastern Russia (Kamilov and Komrakova 1999).

Following their introduction, Asian carp escaped aquacultural confinement and expanded their distribution throughout waterways in the central United States. Asian carp distributions (Figures 3 and 4) now include several large rivers such as the Illinois, Mississippi, Missouri, Ohio, and Wabash along with their tributaries. Wild populations of Asian carp have expanded their range upstream in the Illinois River and have increased exponentially in abundance in the La Grange Reach (Chick and Pegg 2001; Irons et al. 2007; Sass et al. 2010). In a 2007-2008 mark-recapture study, Sass et al. (2010) estimated an average of 2,544 adult and sub-adult silver carp per river km in the La Grange reach, Illinois River. The invasion of Asian carp in the Illinois River, and other ecosystems, has the potential to negatively influence native fish populations by competing for habitat and food resources. For example, Schrank et al. (2003) found that age-0 bighead carp negatively influenced relative growth (i.e., [final weight-initial weight]/initial weight) of age-0 paddlefish (*Polyodon spathula*) in a mesocosm setting. Sampson et al. (2009) conducted a study testing for dietary overlap among Asian carp and three native filter feeders. Results from this study showed the greatest dietary overlap among Asian carp and gizzard shad (*Dorosoma cepedianum*) and bigmouth buffalo. Sampson et al. (2009) found little dietary overlap between Asian carp and paddlefish. Irons et al. (2007) showed significant declines in body condition of gizzard shad and bigmouth buffalo from 2000-2006 in the La Grange Reach of the Illinois River after Asian carp establishment. Declines in body condition of gizzard shad and bigmouth buffalo were -7% and -5%, respectively, after Asian carp established in 2000. Asian carp are also a nuisance to recreational and commercial boaters 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 Asian carp was physically collected in Calumet Lake upstream of the Aquatic Nuisance Species Dispersal Barrier in the Chicago Sanitary and Ship Canal (CSSC), and the Asian carp population in the Illinois River is increasing, these invasive species pose an imminent threat to the Laurentian Great Lakes. Asian carp DNA has been detected in several water samples taken upstream of the Aquatic Nuisance Species Dispersal Barrier. Fishes release DNA into the water via secretions, feces, and urine. This DNA is collected in a water sample, filtered, and DNA is then extracted and amplified. This test has been labeled environmental DNA (eDNA) and was first used in France to test for the presence or absence of bullfrogs (*Rana catesbeiana*) at high and low densities (Ficetola et al. 2008). Sampling for eDNA helps to detect the presence of Asian carp without capturing an actual specimen, and is particularly acute at detecting Asian carp when they are present at low abundances. However, it cannot be determined how recently an organism was in the sample area because DNA can persist in water (Ficetola et al. 2008). Recent samples have provided positive eDNA detections of Asian carp at Wilmette Pumping Station and in Calumet Harbor, Lake Michigan (Jerde et al. 2011). While it is not known if Asian carp were present at the time the samples were taken, the samples do provide evidence that Asian carp were recently, if not presently, at the sample location. 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 aquatic invasive species introductions.

In the context of invasive species ecology, Asian carp are interesting to study because they have not yet invaded Lake Michigan to our knowledge. Most other invasive species studies focus on the negative effects of invasive species or ways to eradicate or manage them after they have established, rather than taking a precautionary approach to prevent invasions (Finnoff et al.

2007). For example, after alewife (*Alosa pseudoharengus*) invaded Lake Michigan, great effort was directed towards evaluating the potential negative effects of alewife on native fish and plankton communities (Wells 1970; Madenjian et al. 2008). The invasion of the sea lamprey (*Petromyzon marinus*) was followed by efforts to reduce propagule pressure into the Great Lakes (Wagner et al. 2006). The current distribution of Asian carp is not far from the Great Lakes, thus management efforts are focused on preventing Asian carp from entering Lake Michigan to reduce the probability of these fishes negatively affecting native fishes and the aquatic ecosystem.

Rapid upstream movements of Asian carp have been observed in at least two studies in the Illinois River. Greater movement rates were associated with flood events (Peters et al. 2006; DeGrandchamp et al. 2008). According to Peters et al. (2006), bighead carp traveled an average of 1.7 km/day, and up to 14 km/day in the Illinois River. DeGrandchamp et al. (2008) documented mean movements of bighead carp to be 6.8 km/day. Silver carp mean movement rates were slightly higher at 10.6 km/day (DeGrandchamp et al. 2008).

As Asian carp expand their distributions, they may negatively influence native ecosystems. Asian carp feed at low trophic levels, are highly fecund, and have rapid growth rates. Bighead and silver carp are planktivorous and have the ability to filter miniscule particles of detritus, phytoplankton, and zooplankton from the water column. Bighead carp feed on phytoplankton and zooplankton, but are shifted towards larger zooplankton, while silver carp typically consume small zooplankton and phytoplankton (Cremer and Smitherman 1980). Bighead and silver carp have specialized gill rakers that allow them to filter particles as small as 50 and 3.2 μm, respectively (Cremer and Smitherman 1980; Spataru et al. 1983; Opuszynski and Shireman 1991). The Great Lakes are primarily oligotrophic and Asian carp could potentially compete with Great Lakes fishes for phyto and zooplankton. A microcosm study by Cooke et al. (2009) tested bighead carp (5.0 ± 0.3 g) consumption of *Daphnia magna*, calanoid copepods, and rotifers in high and low density zooplankton treatments. Bighead carp decreased in weight by 2.8% when plankton was limited (27 macrozooplankters L^{-1}) and increased in weight by 2.3% when plankton concentrations were high (68 macrozooplankters L^{-1}), concluding the likelihood of Asian carp establishing in the Great Lakes was low (Cooke et al. 2009). Cooke et al. (2009) reported low densities of rotifers in the treatments, which may be attributed to sampling with a 48-µm mesh net. Additionally, a 153-µm mesh net was used to collect zooplankton to add to the low and high density treatments, suggesting that rotifers were likely absent or in very low numbers. Chick et al. (2010) showed that rotifer densities are commonly under-represented when zooplankton samples are filtered with mesh sizes > 35-µm. Therefore, previous estimates of plankton availability should consider all plankton in the environment, and even then, may not be a sound basis for assessing the risk of Asian carp establishing in the Great Lakes. Zebra mussel (*Dreissena polymorpha)* veligers are abundant in Lake Michigan and are a potential food source for Asian carp. Zebra mussel veligers (planktonic larval stage) have been observed in the stomachs of Asian carp in Lake Batalon, Hungary (D. Chapman, United States Geological Survey, Columbia Environmental Research Center, Missouri, personal communication, 2010). Tributaries of the Great Lakes could also provide food resources and spawning habitat for Asian carp.

In addition to potentially competing with native filter-feeding fishes and altering the zooplankton communities, Asian carp are highly fecund. Schrank and Guy (2002) found that fecundities of bighead carp in the lower Missouri River ranged from 12,000 – 770,000 eggs per female in a single spawn. Silver carp may have higher fecundities ranging from 57,000 – 4.3

million eggs per female (Singh 1989; Williamson and Garvey 2005). Asian carp were also observed to spawn up to three times in the La Grange Reach of the Illinois River in 2007 (G. Sass, Illinois Natural History Survey, Havana, IL, personal communication, 2010).

There is contradicting evidence that Asian carp will successfully spawn and survive in the Great Lakes. Although Lake Michigan proper may not be suitable habitat for Asian carp spawning, several tributaries in the United States and Canada have been identified as maintaining suitable spawning habitat conditions (Kolar et al. 2007; Mandrak and Cudmore 2004). Water hardness may influence silver carp egg incubation and cause eggs to prematurely burst (Gonzal et al. 1987). Gonzal et al. (1987) found that the optimal water hardness for successful silver carp egg hatching was high (300-500 mg/L as $CaCO_3$). However, Rach et al. (2009) found contradicting evidence that silver carp eggs showed the highest hatching rates in soft water (50 mg $CaCO_3$/L). Chapman and Deters (2009) also found that bighead carp eggs will successfully hatch in water hardness levels between 29-259 mg $CaCO_3$/L. Water hardness in the Great Lakes ranges from 121-180 mg $CaCO_3$/L (Briggs and Ficke 1977). Osmotic gradient, rather than water hardness, may cause Asian carp eggs to burst (Whittier and Aitkin 2008). These recent studies suggest that water hardness may not be a water quality parameter that limits Asian carp hatching success in the Great Lakes and its tributaries. While Asian carp are lentic fishes, they do require lotic systems for spawning (Jennings 1988; Robinson and Buchanan 1988; Opuszynski and Shireman 1995). Thus, pelagic areas of the Great Lakes may not be ideal for successful reproduction, but connecting tributaries might provide suitable spawning habitat.

Asian carp exhibit rapid growth rates. Nuevo et al. (2004) showed that bighead carp in the Mississippi River reach 1 kg by age 2. In the La Grange Reach of the Illinois River, young-of-year Asian carp reached 330mm in total length in the first summer of growth in 2000

(LTRMP unpublished data). In a 2003 study by Williamson and Garvey (2005), age one and older silver carp were 230 mm or greater in the Middle Mississippi River. Rapid growth rates of Asian carp allow these species to quickly outgrow predation by native fishes in the Mississippi River Basin. However, as Asian carp density increases, individual growth rates may decrease due to intra and inter-specific competition for food resources.

Because Asian carp have been detected with eDNA and a bighead carp was physically captured near Lake Michigan, there is a much greater risk of Asian carp establishing viable populations in the Great Lakes. If Asian carp successfully invade and/or establish in the Great Lakes, great uncertainty exists in predicting the potential ecological threat to current food webs. The Aquatic Nuisance Species Dispersal Barriers in the CSSC are the only barriers that may prevent aquatic organisms from making upstream passage from the Illinois River to Lake Michigan. Preventing invasive species range expansion is more effective than trying to eradicate newly established invasive organisms (Hulme 2006). Although only one male and one female would be required to start a population in a suitable environment, reducing propagule pressure from the Illinois River will be important for reducing the risk of Asian carp establishment in the Great Lakes. Because Asian carp generally move upstream to spawn, there is great concern that Asian carp will continue moving upstream in the Illinois River, which may provide a consistent founding population to Lake Michigan without further management actions. Asian carp upstream movements have been relatively slow. Density-dependent factors such as competition for food and habitat might trigger more upstream movement of Asian carp as the densities increase in the upper reaches of the Illinois River. Because Asian carp are specifically sensitive to high sound frequencies, SBSLB technology could be used as a redundant measure to prevent upstream passage of these invasive fishes. Sound-bubble-strobe light barrier (SBSLB) technologies could be used in concert with the Aquatic Nuisance Species Dispersal Barrier to reduce propagule pressure into Lake Michigan. This technology could also be used to prevent colonization of Asian carp into tributaries of the Great Lakes where they have not yet invaded. Additionally, SBSLB technologies could be used below locks and dams to corral Asian carp into a confined area to easily harvest them. Sound-bubble barriers have been shown to be 95% effective at repelling adult bighead carp in hatchery raceways (Taylor et al. 2005). The goal of my thesis research was to conduct *in-situ* tests of SBSLB technologies to determine its effectiveness at repelling bighead, silver, and available species of non-Asian carp in order to draw inferences about its use for managing Asian carp.

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FIGURES

Figure 1. Photograph of a bighead carp *(Hypophthalmichthys nobilis)* collected from the La Grange Reach, Illinois River. (Photo Credit: Blake Bushman)

Figure 2. Photograph of a silver carp *(H. molitrix)* collected from the La Grange Reach, Illinois River. (Photo Credit: Blake Bushman)

Figure 3. Distribution of bighead carp *(H. nobilis)* in the United States.

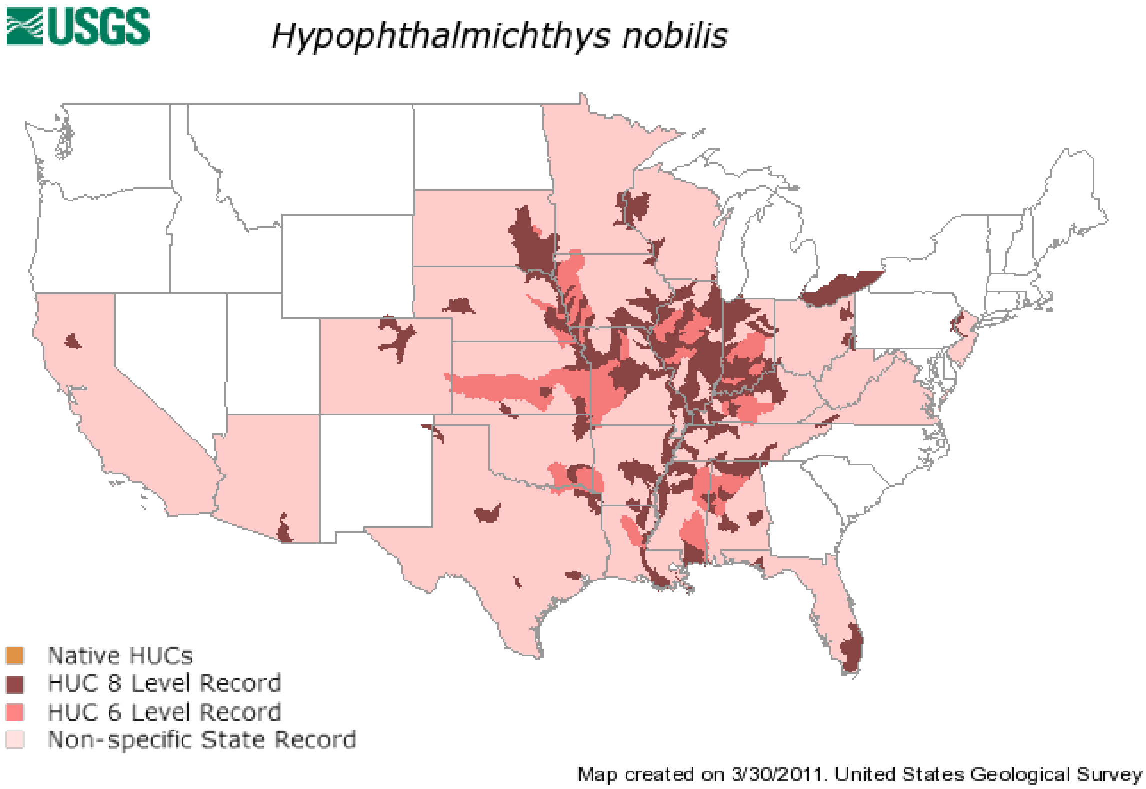
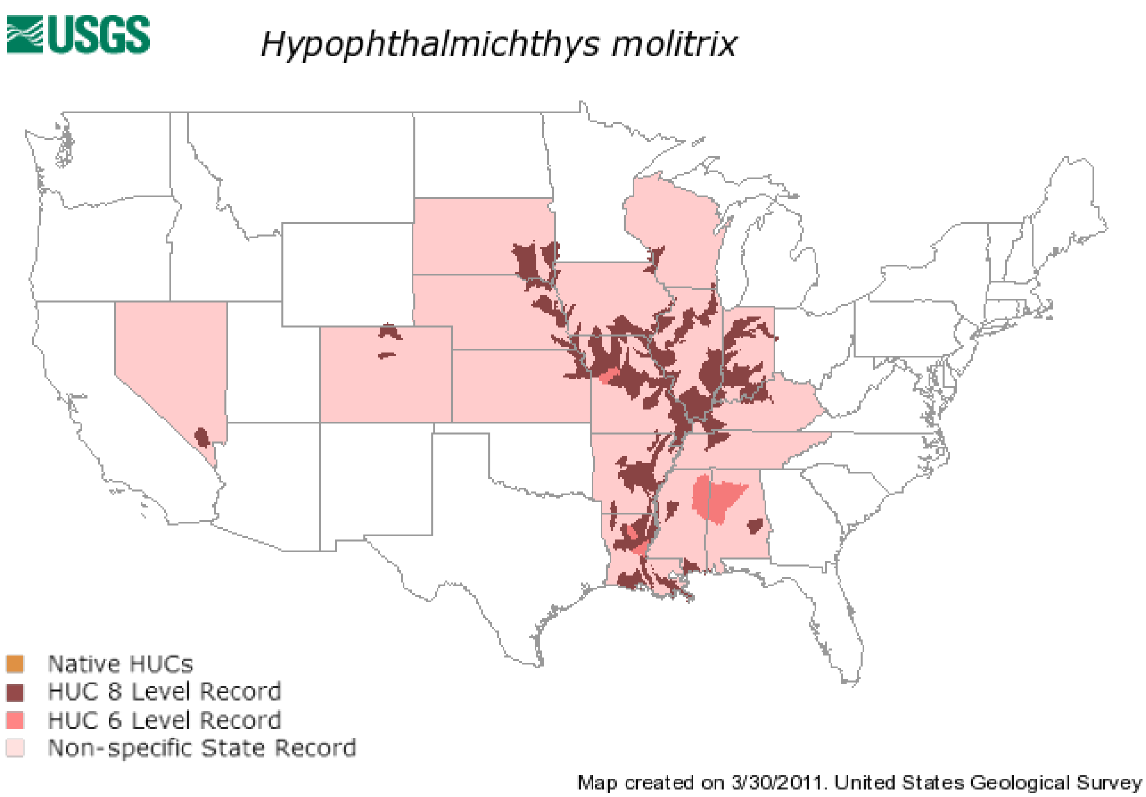


Figure 4. Distribution of silver carp *(H. molitrix)* in the United States.



CHAPTER 2: *IN-SITU* TESTS OF SOUND-BUBBLE-STROBE LIGHT BARRIER TECHNOLOGIES TO PREVENT THE RANGE EXPANSIONS OF ASIAN CARP

INTRODUCTION

Biodiversity loss may be caused by habitat degradation and the influence of invasive species (Didham et al. 2007). The establishment of invasive species has shown to cause declines in native fish assemblages (Hermoso et al. 2011). Complete eradication of invasive species is nearly impossible to achieve; however, long-term management has proven effective for controlling some invasive organisms (Mack et al. 2000). For example, predicting spawning dates and locations of rainbow smelt *(Osmerus modax)* makes harvest programs more effective at reducing the density of this invasive species (Lischka and Magnuson 2006). Preventing the spread of invasive species, using precautionary management, is the best approach to reduce the risk of invasions (Finnoff et al. 2007). Currently, the Laurentian Great Lakes are threatened by the invasion of bighead *(Hypophthamichthys nobilis)* and silver carp *(H. molitrix),* collectively Asian carp.

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 increasing, these invasive species pose an imminent threat to the Great Lakes. Asian carp environmental DNA (eDNA) has also been detected in water samples collected upstream of the ANSDB (Jerde et al. 2011). Environmental DNA detects the presence or absence of organisms without capturing an actual specimen (Ficetola et al. 2008), 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,* zebra mussel *Dreissina polymorpha*).

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). Sound-bubble barrier 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, I conducted *in-situ* tests of a sound-bubble-strobe light barrier (SBSLB) across a range of available bighead and silver carp sizes to test its effectiveness in a scenario more applicable to management and implementation. I hypothesized that SBSLB technologies would deter Asian carp passage because of their hearing capabilities and the results from a previous mesocosm study (Taylor et al. 2005; Lovell et al. 2006). As a byproduct of my experimental design, I also tested SBSLB effectiveness in deterring passage of non-Asian carp. Scholik and Yan (2002) showed the bluegill (*Lepomis macrochirus*), a “hearing generalist”, were not sensitive to sound frequencies between 300-2000 Hz. I hypothesized that SBSLB technologies would not deter passage of most “hearing generalist” species tested.

METHODS

Study site

I 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 5). This portion of Quiver Creek was part of the United States Fish and Wildlife Service Chautaqua Refuge. Quiver Creek is a tributary to the La Grange Reach, 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 upstream fish movements; 2) Asian carp 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 equipment. During SBSLB testing, Quiver Creek was 16 m wide, maintained about a one m thalweg depth, and had flow velocities ranging from 0.4-0.8 m/s.

Sound-Bubble-Strobe Light Barrier Components

I 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 m long frames that were situated perpendicular to the flow of Quiver Creek, submerged, and anchored to the substrate. I connected the two frames in the center of Quiver Creek to form a 16 m SBSLB system. System components included 16 evenly-spaced underwater speakers and light-emitting diode (L.E.D.) strobe lights. A 16 m air curtain hose was also attached to the system and was positioned perpendicular to the flow of Quiver Creek (Figure 6). 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 my 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.

Depletion Estimate

I 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 hr backpack electrofishing runs. The SBSLB was not operating during the 24 hours prior to the depletion estimate. I 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 hr electrofishing run, I conducted a second run using the same methods. I computed the population estimate according to Seber and Le Cren (1967).

Sampling and Data Collection

I collected Asian carp and non-Asian carp between the SBSLB and the upstream low-head dam using backpack electrofishing, hoop netting, angling, beach seining, and boat electrofishing. I 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), marked with a unique floy-tag and fin clip, and released immediately downstream of the SBSLB. I collected water quality information from Quiver Creek following fish collections on each sampling occasion. Specifically, I measured 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, I 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, I observed silver carp jumping away from the SBSLB shortly after being released downstream of the barrier during preliminary testing in August 2009 suggesting upstream passage attempts. I also assumed that non-Asian carp would challenge the barrier because they were collected upstream of the barrier. My primary metric for evaluating barrier effectiveness was the number of recaptures versus the number marked for each fish species. I could not account for fishes that did not attempt to challenge the barrier following downstream release and my probability of recapturing marked fishes was not 100%. However, my 47% recapture efficiency was likely conservative as multiple recapture gears were used in addition to backpack electrofishing. Therefore, I considered the number of fish recaptured as the best metric of effectiveness, given environmental conditions within Quiver Creek, the fish species tested, and the operating parameters of the barrier.

Experimental Design

<u>Upstream Passage Testing: SBSLB ON vs. SBSLB OFF</u>

I 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 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, I 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 I conducted eleven barrier effectiveness trials (Table 1). I marked 2,756 non-Asian carp (45-890 mm) from 10 families (Amiidae, Catostomidae, Centrarchidae, Clupeidae, Cyprinidae, Ictaluridae, Lepisosteidae, Moronidae, Percidae, and Sciaenidae) in 2010. Fishes tested in trials with the SBSLB ON and OFF totaled 1,841 (45-890 mm) and 915 (91-842 mm), respectively. I 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. I used linear regression to test for a relationship between the number of fish marked by species (independent variable) and the number of fish recaptured by species (dependent variable) at the α=0.05 level.

Extended trials

I 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 (100-577mm) were collected, marked, and released downstream of the sound-bubble barrier (SBB). I also marked and transplanted 177 silver (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, I 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. I determined upstream passage rates on day two, and on day three I concluded the trial by sampling to recapture marked fish from the current trial. I 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 were tested in the SBLB and SBB trials, respectively.

RESULTS

Depletion Estimate

To estimate sampling efficiency, a two-pass depletion estimate was conducted on 8/24/10 to determine the population size and recapture probability of marked fish upstream of the SBLSB. During electrofishing run #1 and #2, 659 and 352 fishes were collected, respectively. The 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%. According to Seber and Le Cren (1967), the probability of recapture is unbiased when $p \geq 0.80$ and unreliable when $p \leq 0.20$. Therefore, the recapture probability for this study ($p=0.47$) was acceptable. The population estimate was 1,414 fish (lower 95% confidence interval = 1,258; upper 95% confidence interval = 1,572).

Upstream Passage Testing: SBSLB ON vs. SBSLB OFF

Passage rates of non-Asian and Asian carp were low in most trials testing the effectiveness of the SBSLB in 2009 and 2010. In 2009, 32 of 1,096 marked non-Asian carp (82-346 mm) made upstream passage during testing with the SBSLB ON. None of the 144 marked silver carp were recaptured upstream of the SBSLB while it was ON. In 2010, 53 of 1,841 marked non-Asian carp (102-766 mm) were recaptured upstream of the SBB while ON. Two of 431 marked silver carp (443-470 mm) made upstream passage when the SBB was ON. In total, 55 of 2,373 marked fish were recaptured upstream of the SBSLB while it was operating in 2010 (Figure 3). Thirty-eight of 915 marked non-Asian carp (116-808 mm) and one of 126 marked Asian carp (446 mm) were recaptured during testing with the barrier OFF. Bluegill *Lepomis macrochirus* (n=250), largemouth bass *Micropterus salmoides* (n=207), and white bass *Morone* *chrysops* (n=136) were the most frequently marked fishes. Bluegill (n=4) and largemouth bass (n=24) were recaptured most often. A significant relationship was observed between the number of marked fish by species and the number recaptured by species (n=40, df=39, f=55.4, $p < 0.001$, r^2=.59) (Figure 8). The number of fish marked by species explained 59% of the variability in the number recaptured by species.

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. Sample sizes for other families were low (n≤21), except for ictalurids (n=123) and moronids (n=59). No silver carp were recaptured upstream of the SBSLB in 2009. During the SBB trial two of the marked centrarchids (n=125) and one marked cyprinid (n=229) were recaptured. Sample sizes for other families tested were low (n≤17). One of 177 (367-771 mm) marked silver carp were recaptured (470 mm) during the SBB trial. During the SBSLB trial, three of 230 ostariophysan (i.e., possessing the Weberian apparatus) fishes were recaptured, whereas 29 of 869 marked non-ostariophysan fishes were recaptured. Results were similar during SBB trials where one of 247 marked ostariophysan and two of 147 marked non-ostariophysan fishes 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 *Lepomis cyanellus* (n=23), and largemouth bass (n=90), respectively. SBLB testing resulted in no 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). My 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 I tested in Quiver Creek. Although the primary focus of my study was to test the effectiveness of the SBSLB technology in preventing upstream passage of the invasive and federally injurious Asian carp, particularly silver carp, I tested other fishes commonly collected at my 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 native 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, I observed greater passage rates for several species, suggesting that at least some proportion of my marked fish population was challenging and breaching the barrier (Figure 7). Thus, I have focused the remainder of the discussion on tests of barrier effectiveness when it was ON. I found little difference in passage rates between trials when the barrier was ON (with or without strobe lights). Therefore, I 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.

Based on my 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). My 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. My 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, I specifically allocated more effort into evaluating barrier effectiveness against 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 my ability to test for a relationship between fish length and recapture rate. Because recapture rates for silver carp were 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 8). My 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 this technology. My results suggested that sound frequencies ranging from 500 to 2000 Hz were appropriate for deterring Asian carp. My 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. I conclude that the lines of evidence from previous trials, and my experiment, indicate SBB technologies may have utility for deterring Asian carp in other aquatic systems.

My results also suggested that SBSLB technology was effective at deterring most of the non-Asian carp species tested. I marked 39 fish species and hybrids representing ten families. In 2009, 32 non-Asian carp were recaptured upstream of the SBSLB, suggesting that at least some of these fishes were deterred or did not challenge the barrier. I transplanted one common carp *Cyprinus carpio* downstream of the SBSLB twice and recaptured it upstream twice in 2009. My results from 2010 showed that the SBB deterred all but three non-Asian carp. Low samples sizes of recaptured non-Asian carp disallowed me from testing for a relationship between length and recapture rate. There were no biologically significant differences in passage rates 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*, and goldfish *Carassius auratus*. I 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 8). Bell (2005) showed behavioral syndromes, such as boldness and aggression, in threespined stickleback (*Gasterosteus aculeatus*). Behavioral syndromes might explain why some fishes made upstream passage, even though disturbed by the SBSLB. My SBSLB also deterred native fishes from making upstream passage, which may have negatively affected their normal 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 by species and the number recaptured upstream of the barrier, for most species (Figure 8). It could be that species that were more frequently marked were recaptured upstream more frequently simply because more were marked and there is a higher probability of recapturing the species. An increase in propagule pressure below the SBSLB could also explain why some species made upstream passage. 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). My results 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.

Several factors in my mark-recapture study could have reduced recapture rates and/or my estimation of barrier effectiveness. First, it is possible that marked fish moved downstream and did not challenge the barrier. I 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. I also acknowledge that I did not have the capability to detect all fishes making upstream passage. I 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. I used other methods of sampling in addition to backpack electrofishing to improve my recapture potential. My additional sampling suggested that my depletion estimate using only backpack electrofishing was conservative and I likely had a higher probability of capturing marked fishes. My study was novel in that it was conducted in a natural and dynamic environment, which is at 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, I suggest that passive integrated transponder (PIT) tags and an automated receiver be used to detect and quantify fish passage, which funding limitations prevented in my 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. Sound-bubble-strobe light barrier technology appears to be a potential tool for reducing propagule pressure to areas where Asian carp are not present or are in low abundances. This system could also be used to "herd" Asian carp into areas, which would allow them to be more easily removed. My results provided evidence that this technology has the ability to deter Asian carp and other fishes. Nevertheless, I 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 ANSDB in the CSSC to prevent the establishment of Asian carp.

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TABLES AND FIGURES

Table 1. Experimental design for sound-bubble-strobe light barrier testing of passage rates of fishes in Quiver Creek, Havana, Illinois, USA.

Year	Dates	Trial	ON/OFF	Sound	Bubbles	Strobe Lights Flashing	Strobe Lights (No Flashing)	No Strobe Lights	Boat Electrofishing	Backpack Electrofishing	Hoop Netting	Beach Seine	Angling
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				

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

Family / Common Name / Scientific Name		Total Marked	Length Marked (mm)	Total Recaptured	Length Recaptured (mm)
Family Catostomidae		**185**	**106-565**	**3**	**293-437**
bigmouth buffalo	*Ictiobus cyprinellus*	5	267-565		
black buffalo	*Ictiobus niger*	1	484		
golden redhorse	*Moxostoma erythrurum*	64	150-485		
northern hogsucker	*Hypentelium nigricans*	2	352-362		
quillback	*Carpiodes cyprinus*	13	329-410		
river carpsucker	*Carpiodes carpio*	12	204-397		
shorthead redhorse	*Moxostoma macrolepidotum*	32	106-394		
silver redhorse	*Moxostoma anisurum*	3	327-352		
smallmouth buffalo	*Ictiobus bubalus*	5	194-468		
white sucker	*Catostomus commersoni*	48	245-437	3	293-437
Family Cyprinidae		**1247**	**102-970**	**39**	**216-766**
bighead carp	*Hypophthalmichthys nobilis*	101	465-970		
common carp	*Cyprinus carpio*	333	182-740	29	216-634
golden shiner	*Notemigonus crysoleucas*	1	102		
goldfish	*Carassius auratus*	2	143-274		
grass carp	*Ctenopharyngodon idella*	235	225-890	8	440-766
silver carp	*Hypophthalmichthys molitrix*	575	141-795	2	443-470
Family Ictaluridae		**181**	**83-655**	**2**	**160-250**
black bullhead	*Ameiurus melas*	3	146-250		
brown bullhead	*Ameiurus nebulosus*	35	168-332		
channel catfish	*Ictalurus punctatus*	69	110-655		
tadpole madtom	*Noturus gyrinus*	1	83		
yellow bullhead	*Ameiurus natalis*	73	107-289	2	160-250
Hearing: Ostariophysan		**1613**	**83-970**	**44**	**160-766**

Table 3. All non-ostariophysan fishes tested in sound-bubble-strobe light barrier effectiveness trials in Quiver Creek, Havana, Illinois, USA, 2009-2010.

Family / Common Name / Scientific Name		Total Marked	Length Marked (mm)	Total Recaptured	Length Recaptured (mm)
Family Amiidae		**15**	**280-797**	**0**	
bowfin	*Amia calva*	15	280-797		
Family Centrarchidae		**1674**	**45-457**	**42**	**82-325**
black crappie	*Pomoxis nigromaculatus*	45	126-325		
bluegill	*Lepomis macrochirus*	1000	45-204	26	82-175
green sunfish	*Lepomis cyanellus*	104	75-173	4	135-160
largemouth bass	*Micropterus salmoides*	491	45-457	11	112-325
Lepomis species	*Lepomis spp.*	14	70-177		
longear sunfish	*Lepomis megalotis*	5	107-147		
rock bass	*Amblopites rupestris*	1	204		
smallmouth bass	*Micropterus dolomieu*	2	237-277		
warmouth	*Lepomis gulosus*	12	112-213		
Family Clupeidae		**53**	**101-360**	**0**	
gizzard shad	*Dorosoma cepedianum*	53	101-360		
Family Lepisosteidae		**2**	**489-612**	**0**	
longnose gar	*Lepisosteus osseus*	1	612		
shortnose gar	*Lepisosteus platostomus*	1	489		
FamilyMoronidae		**179**	**128-835**	**0**	
striped bass x white bass hybrid	*Morone saxatilis x chrysops*	2	475-835		
white bass	*Morone chrysops*	173	149-431		
yellow bass	*Morone mississippiensis*	4	128-224		
Family Percidae		**50**	**195-472**	**2**	**247-359**
sauger	*Sander canadensis*	34	195-377	2	247-359
walleye	*Sander vitreus*	16	216-472		
Family Sciaenidae		**27**	**158-530**	**0**	
freshwater drum	*Aplodinotus grunniens*	27	158-530		
Hearing: Non-Ostariophysan		**2000**	**45-835**	**44**	**82-359**

Figure 5. Location of the sound-bubble-strobe light barrier in Quiver Creek near the Forbes Biological Station, Havana, Illinois, USA.

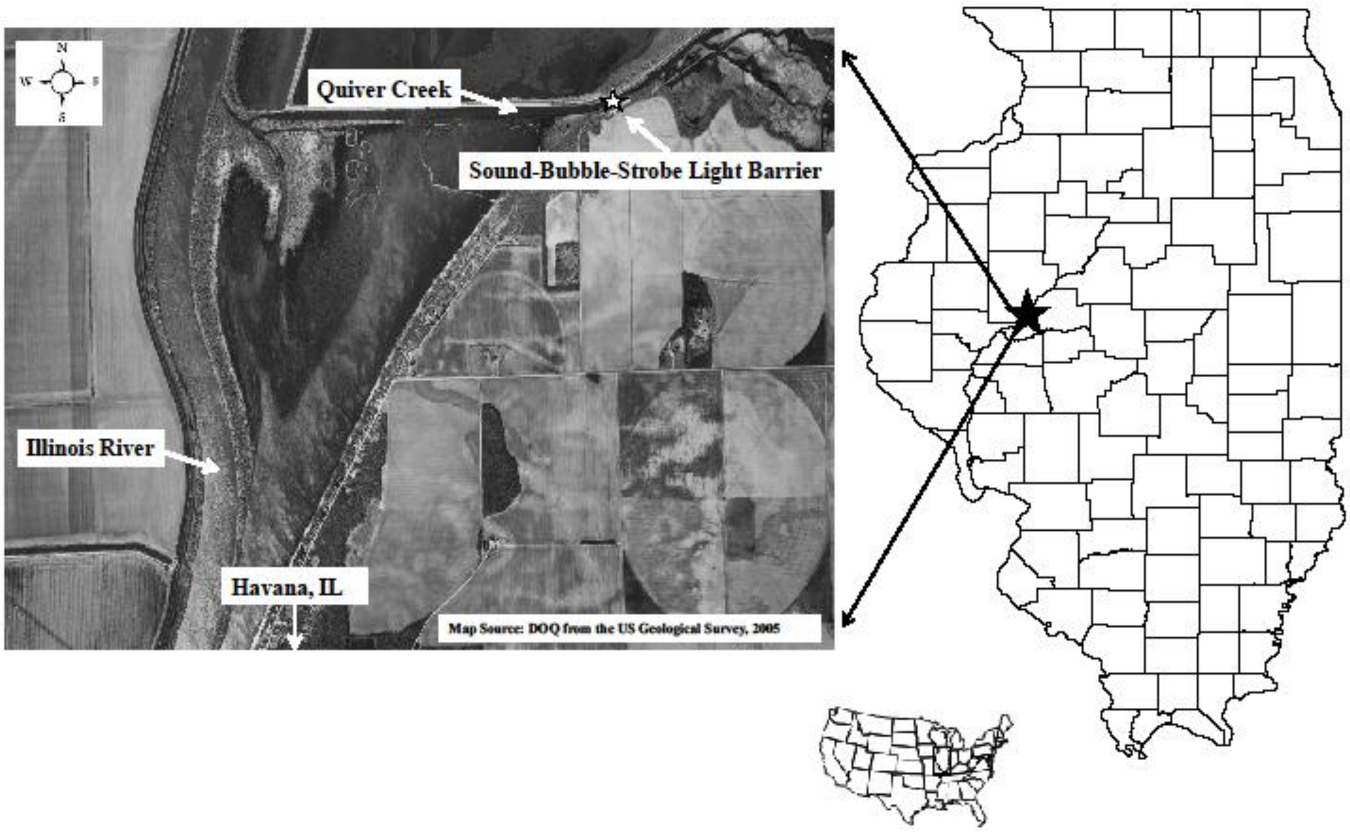


Figure 6. Schematic illustration of the sound-bubble-strobe light barrier in Quiver Creek near the Forbes Biological Station, Havana, Illinois, USA.

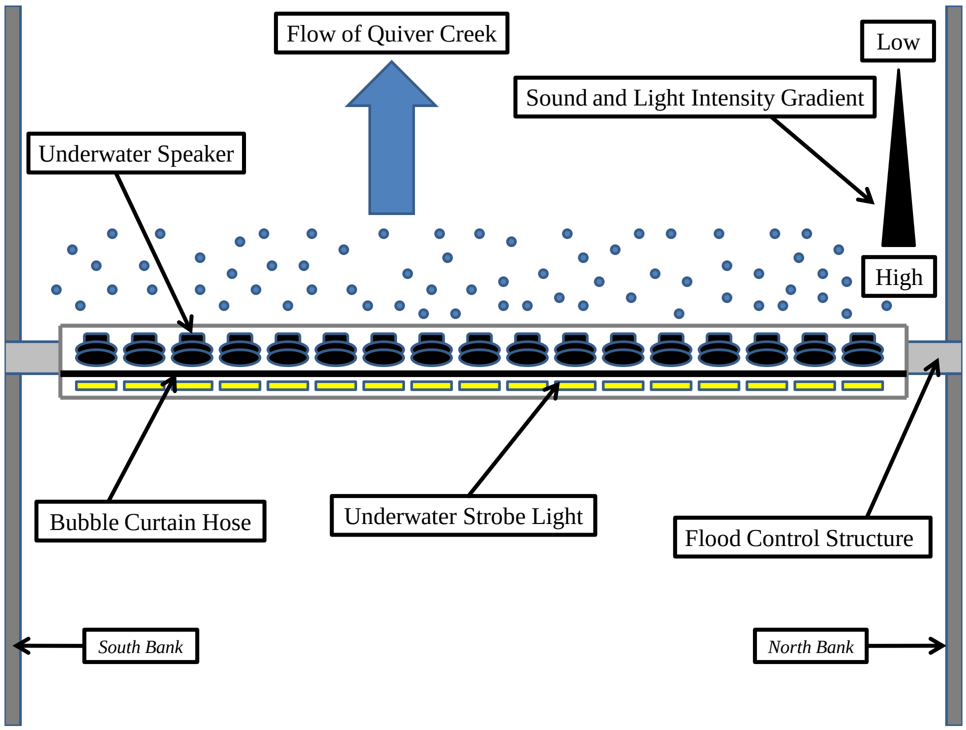


Figure 7. Number of fishes marked and recaptured by species during ON and OFF sound-bubble-strobe light barrier trials in Quiver Creek, Havana, Illinois, USA, 2009-2010. Only species that were recaptured are reported for each respective trial. Please note that no bighead carp were recaptured.

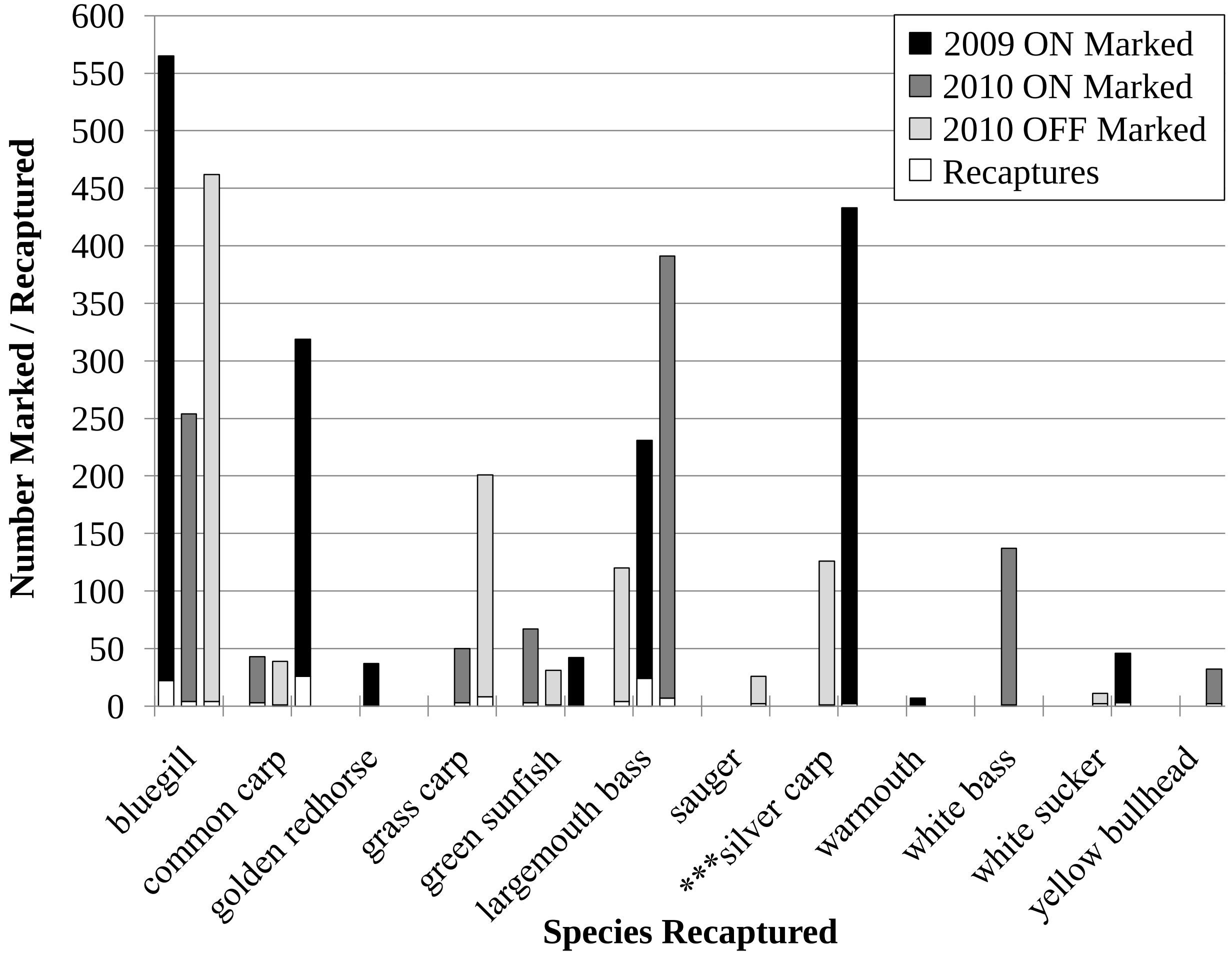
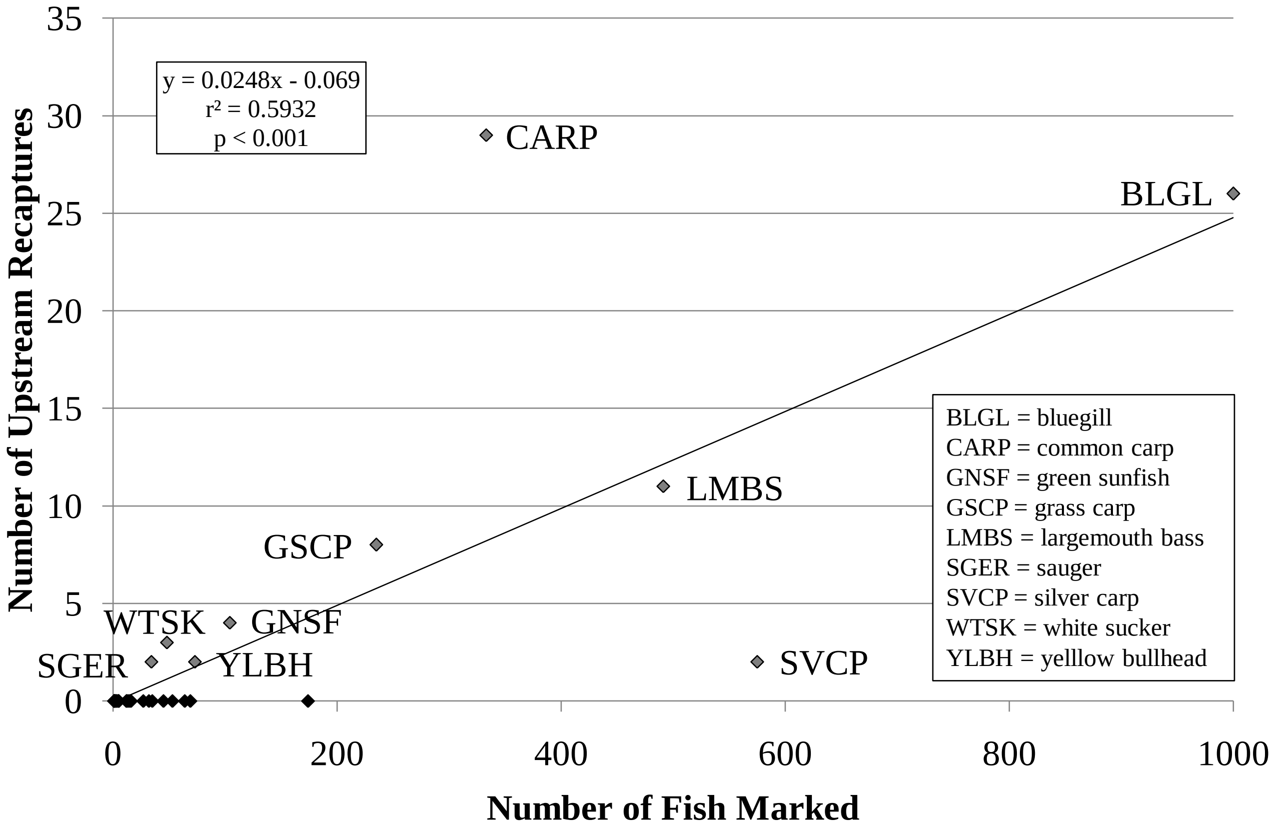


Figure 8. The number of fish marked by species versus the number of fish recaptured by species for all ON trials testing sound-bubble-strobe light barrier technology in Quiver Creek, Havana, Illinois, USA, 2009-2010. Please note that only recaptured species are labeled.



CHAPTER 3: EPILOGUE

Throughout my thesis work, I learned quite a bit about fisheries ecology, Asian carp, and how to be innovative when faced with logistical challenges. I started my Master's project in June 2009, with the anticipation of beginning my field work upon starting. I soon found that large river ecology studies come with unpredictable hydrology and uncontrollable conditions. It was easy to outline the ideal schedule for my study; however, technological issues and high water kept me from starting my project until late August, 2009. The best case scenario would have been a drought in 2009 and 2010, which would have allowed me to conduct my study under low river flood stages. In 2010, the Illinois River was yet again at a record flood stage until August, keeping me from starting my field work. In five months, collectively, I was able to gather enough data for my thesis. During that time, I developed a better understanding of how to use fisheries sampling gear and I greatly increased my knowledge of Asian carp and the Illinois River.

Asian carp are invasive species that are of great concern in Mississippi River Basin. They have the potential to greatly alter aquatic communities and compete with native fishes. Many researchers, like me, are searching for ways to deter, control, and/or eradicate Asian carp. The SBSLB that I tested was designed to deter fishes. I used a sound frequency that was proven to deter Asian carp in hatchery raceways. I tested this equipment at a large enough scale to test whether it was an effective deterrent system. At the end of my project I questioned myself, "What did I find?" Initially, I hypothesized that the SBSLB would either work or it would not. After conducting the study, my thoughts changed. The SBSLB was not an absolute barrier; it did not stop all fishes from making upstream passage. However, it deterred many of the fishes that I marked. In other applications, SBSLB technology is used to guide fishes in a specific direction for management purposes. This is an effective tool, but should not be solely relied upon to prevent passage of fishes.

There are many things that I would do differently, given the opportunity to conduct the study again. The initial set up of all of the equipment was tedious. I had a general idea of what I wanted to do, but because this was a novel study, there was not much information available for me to reference for tips or troubleshooting suggestions. I had many failed attempts in keeping a consistent air supply to the barrier due to compressor malfunction, melting air lines, and power failure. If funding was unlimited, I would use a back-up generator to ensure that the air compressors would remain on if there were a power failure. Each time the power shut off, I had to restart my trials, losing all data for fish that I marked for the current trial.

I would also have changed my sampling gear to boat electrofishing rather than backpack electrofishing. I had a 47% probability of recapturing marked fish using backpack electrofishing, and that probability was likely greater by adding angling and netting as other methods to collect and recapture fishes. However, when boat electrofishing was used I captured more fishes in the deep pool directly below the low head dam. I was missing fish in that pool because it was too deep to access with waders and the backpack electrofisher. The best tool to give me an accurate measurement of barrier effectiveness would have been an automated reading system. If funding would have allowed, I would have liked to mark fish with PIT tags and install an automated reading system at the barrier to record fish passage. I think this technology would have significantly strengthened my project and data set. Given the funding and equipment that I had, I did my best to adequately sample for fishes that made upstream passage and I found that this technology is effective, but not an absolute barrier.