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Research Article

Field test of a low-voltage, portable electric barrier to guide invasive common carp into a mock trap during seasonal migrations

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Abstract

Common carp (*Cyprinus carpio* Linnaeus, 1758), one of the world's most invasive fish, is known for their extensive seasonal migrations. Often, adult carp migrate between lakes and marshes (spawning grounds) in early spring in large synchronized events. If these fish could be directed into traps, sustainable carp management schemes could be developed for many lake-marsh systems. In this study, we used a portable low-voltage electric guidance system (EGS) to direct common carp into a mock trap in a relatively large natural stream. The system was tested on 6 occasions: 3 days with EGS off and 3 days with EGS on. Approximately 40 adult carp were used in each test. All were implanted with passive integrated transponders (PIT) and ten in each group also had visual markers. When the EGS was on, PIT data indicated that 74% of the carp were successfully guided into the mock trap, while visual markers indicated that no carp were able to cross through the EGS despite over 300 attempts. When the EGS was off, PIT data indicated that only 18% of carp swam into the mock trap, and visual markers showed that many were able to swim though the EGS (22 out of 29). The electric field generated by the EGS was mild and did not cause fish paralysis. The EGS required little on-site engineering and was deployed in 2 days. This new type of EGS might prove useful for managing invasive fish or for conservation of native species that employ seasonal migrations.

Key words: *Cyprinus carpio*, guidance technology, invasive species, biological invasions, management, spawning migrations

Introduction

Many invasive fish exhibit seasonal migrations between foraging and spawning habitats. For example, in the Great Lakes region, invasive sea lamprey (*Petromyzon marinus* Linnaeus, 1758) migrate into tributary streams to spawn (Johnson et al. 2009), whereas in western United States, invasive salmonids migrate into headwater reaches of mountain streams for the same purpose (DeHaan et al. 2010). Migrations between overwintering and spawning habitats have been well documented for the common carp (*Cyprinus carpio* Linnaeus, 1758) in lake-marsh systems of the Upper Mississippi River basin in North America (Bajer and Sorensen 2010; Bajer et al. 2015) and in the Murray-Darling basin in Australia (Stuart et al. 2006). Spawning migrations of carp, and other invasive fish, are often synchronized and result in large numbers of fish moving through narrow passages (streams), which creates opportunities for removal. For example, Chizinski et al. (2016) showed that in Minnesota, many populations of common carp migrate *en masse* in a matter of only 1–2 days. Developing technologies that allow for effective removal of invasive fish during their migrations would facilitate management strategies for those populations. Such control strategies are especially needed for the common carp, which is one of the world's most invasive fishes (Lowe et al. 2000) and is known for causing declines in water quality, biodiversity, and ecosystem function in shallow lakes and rivers (Vilizzi et al. 2015; Bajer et al. 2016).

Stream environments where invasive fish migrate often pose challenges to install and operate simple removal devices. Migrations often occur during high water levels when streams carry large quantities of debris (Chizinski et al. 2016), which often precludes the use of simple physical structures to remove the migrating fish. Physical barriers are also expensive because they require substantial on-site engineering and maintenance and often also need specialized systems to keep them clean. In many cases, non-physical barriers are needed to guide migrating invasive fish into traps from which they could be easily removed. Strobe light and acoustic systems have shown promise in guiding migrating fish (Noatch and Suski 2012). For example, Perry et al. (2014) used a strobe-sound-bubble curtain to deflect downstream moving smolts of chinook salmon (*Oncorhynchus tshawytscha* Walbaum, 1792) away from a stream branch associated with low survival in the Sacramento-San Joaquin River delta. Welton et al. (2002) used a similar system to direct the downstream movement of Atlantic salmon (*Salmo salar* Linnaeus, 1758) smolts between alternative fluviarium channels placed in a side channel of River Frome in France. In both of these cases, these non-physical barriers (strobe-sound-bubble) were shown to be 20%–75% effective. Ruebush et al. (2011) used a strobe-sound-bubble curtain system to hinder upstream migration of silver carp (*Hypophthalmichthys molitrix* Valenciannes, 1844) in a tributary of the Illinois River; the results of that study are difficult to interpret, because fish passage was monitored indirectly, from recapture rates, and very few of the test fish were recaptured above the barrier regardless whether it was on or off. Zielinski and Sorensen (2015) used an acoustic barrier (bubble curtain) to hinder the movement of common carp in a small stream in Minnesota. While this system was 59% effective at blocking the downstream movement of juvenile carp, it indicated little effect on the upstream moving adults (16% efficiency and not statistically different than the control treatment). Overall, it appears that while sound-bubble-strobe barriers have some promise (but see Michaud and Taft 2000; Miehls et al. 2017), these technologies that rely on relatively subtle voluntary responses, might be most effective at deflecting fish away from specific areas (e.g. power plant intakes, dam locks, sloughs) rather than directing fish into traps (Noatch and Suski 2012). These systems also are sensitive to sedimentation and water turbidity. Fish have also shown ability to habituate to acoustic stimuli (Vetter et al. 2015), which might decrease the efficacy of acoustic systems for fish that repeatedly approach the barrier, such as adults trying to access their spawning sites.

Electric barriers have been used for decades to block fish migrations (Noatch and Suski 2012). For example, they have been used at lake outlets throughout the Midwest to prevent common carp from re-invading systems treated with rotenone (Verrill and Berry 1995). An electric barrier is also being used in Chicago's Sanitary and Ship Canal to prevent migration of bigheaded carps (*Hypophthalmichthys* spp.) into Lake Michigan (Parker et al. 2015). However, despite their long history of use, the "traditional" electric barriers have multiple limitations. These systems typically consist of electrodes placed on the bottom and sides of the stream, which means that a strong electric current (~ 1 V/cm; Clarkson 2004) needs to be applied to produce a strong-enough electric field that would extend from the bottom and sides of the stream all the way to the surface across the entire width of the stream. These types of barriers often require extensive on-site engineering (a concrete channel to embed the electrodes in the bottom and banks) and are expensive to install and maintain. Because these types of barriers cause paralysis among the fish that try to cross them, they may be best suited for blocking (rather than directing) upstream movement of fish when nearly 100% efficiency is required. These traditional barriers may not be optimal (or too expensive) for applications where temporary barriers are sufficient to guide invasive fish during relatively short seasonal migrations (as in the "intentional fragmentation" concept; Rahel 2013).

Recently, a new type of electric barrier has been developed that may be better suited to guide, rather than block, the migrating fish (Parasiewicz et al. 2016). The primary difference is that the electrodes are positioned vertically, approximately a meter apart, and span the entire depth of the stream from bottom to surface. This allows for producing a mild (~ 0.1 V/cm) and uniform electric field across the entire water column that is designed not to cause paralysis, but rather evoke an involuntary change in the fish's swimming angle to avoid the electric field and guide the fish into a trap. This system has several practical advantages. It is relatively inexpensive, portable, requires minimal amount of on-site engineering and can be deployed or removed within few hours. This electric guidance system (EGS) was designed primarily to guide fish away from power plant intakes or towards fish passage structures (Parasiewicz et al. 2016), but recently, it was shown to be affective at guiding upstream migrating invasive sea lamprey into a trap in a Great Lakes tributary stream (Johnson et al. 2016). The system was also shown to be effective at blocking the upstream passage of common carp in a laboratory channel

(Kim and Mandrak 2017). In this paper, we describe a field test of this EGS for adult common carp moving upstream in a natural environment. Specifically, we used the EGS in a large, natural stream to block upstream carp passage through the EGS and direct them along the EGS into a mock trap. Our results have immediate implications for the management of common carp and other invasive fish that use streams as corridors during seasonal migrations, including spawning migrations. In addition, our results have implications for conservation of native fishes (e.g. by deflecting these fishes from areas where their survival is low).

Methods

Study site

The experiment was conducted in Rice Creek (New Brighton, Minnesota, USA), a natural stream (20 m wide, 1 m deep, ~ 0.3 m/s max velocity, sandy bottom) that connects Long Lake (68.8 hectares; maximum depth 8 m), with five shallow marshes located approximately 10 km upstream (Figure 1). Long lake is inhabited by approximately 20,000 adult carp (400–700 mm in length). The majority of these carp (~ 90%) migrate each spring from Long Lake to the upstream marshes to spawn in the spring, and then come back several weeks later (Banet 2016), which is consistent with other carp spawning migrations occurring in Minnesota (Bajer and Sorensen 2010; Chizinski et al. 2016).

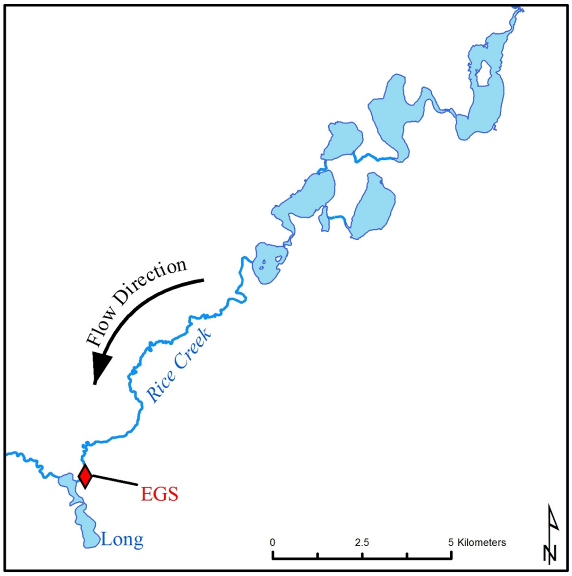

Figure 1. Study site. EGS indicates the location of the Electric Guidance System and the mock carp trap.

EGS and experimental setup

The EGS "Neptun" (Procom Systems, Poland) consisted of two rows of electrodes (stainless steel pipes: 3.7 cm diameter negative electrodes; 4.4 cm diameter positive electrodes), whose bottoms were attached to a metal chain (stainless steel, 5 cm diameter) that was stretched along the bottom of the stream and tops were held upright on the water surface using floats (23 cm diameter) (Figure 2). A cable that supplied power to the electrodes was attached to the chain. Each electrode was attached to the chain using a metal shackle that allowed the electrodes to be pushed out of the way if hit by a large piece of debris (e.g. floating branch, etc.), and then reposition themselves. The electrodes in each row were spaced every 0.7 m (Figure 2). The row of positive electrodes was located 2 m downstream of the row of negative electrodes (Figure 2). The system was powered by a gasoline generator (Honda EU2200i) enclosed with a control unit in a steel work site box on the bank of the stream. The system was supplied with a 70V DC electric current. The control unit autonomously analyzed and adjusted field settings to achieve desired output: ~ 0.16 V/cm mid-way between the two rows of positive and negative electrodes and ~ 0.05 V/cm 1 m downstream of the positive electrodes (approach side); pulse length 0.4 milliseconds; number of pulses 8; gap between pulses 6 milliseconds; repetition every 150 milliseconds. Field characteristics were measured 10 cm under the surface, at mid-depth, and 20 cm above the bottom. The deviations of field parameter were no greater than 15% of the mean. Water conductivity was 410 µS/cm.

The EGS was anchored to the right bank using steel C-channel beams driven into the ground and stretched across the stream at an 45° angle in relation to the axis of the channel (Figure 2). This was designed to direct the migrating carp towards the left bank where we placed a mock trap. The mock trap consisted of a PVC frame ("gate") that was 1.2 m wide and 1.2 m tall (it extended from the bottom of the stream above the surface of the water). We attached green plastic fencing to the sides of the gate, which continued for 10 m upstream creating a long and narrow channel that simulated a trap (Figure 2). The upstream end of the trap was open allowing fish to simply pass through it as we were not intending on removing the carp. We attached a PIT antenna to the frame of the gate to monitor passage of carp through the gate. The antenna was connected to a data-logger (half duplex multi-antenna model; Oregon RFID) located on shore within the same field box that housed the EGS control unit.

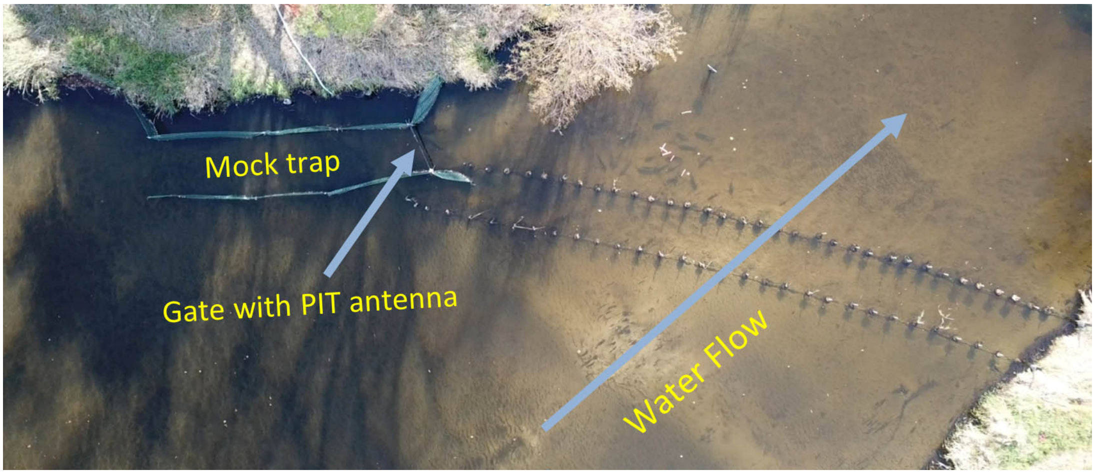

Figure 2. Overhead view of the electric guidance system (EGS) and the study site; photo credit Greg Prunty. Visible are two rows of electrodes (positive row is placed downstream) placed at a 45° degree relative to the thalweg. The carp, also visible on the downstream side of the EGS, were being diverted through a PVC gate into a mock trap (a narrow channel) placed along the left bank. The electric field does not extend inside the mock trap. Carp passage was monitored using a PIT antenna at the entrance to the mock trap (gate). The stream is approximately 20 m wide.

Table 1. Behavioral responses of common carp with floats and PIT tags to the Electric Guidance System (EGS). Carp with floats were observed for 1 h after release to count the number of times they approached the EGS, crossed through the EGS, followed the edge of the EGS, were deflected downstream or crossed through the gate when the EGS was on or off. Carp with PIT tags were monitored for 22 h after release to determine how many of them crossed through the gate when the EGS was on or off.

Date	EGS	Floats						PIT		
		N	Approach	Cross EGS	Follow	Deflect	Gate	N	Cross Gate	% Cross Gate
10/24	Off	10	47	7	5	37	3	47	10	21.3
10/25	Off	9	37	7	9	28	2	54	9	16.7
10/27	Off	10	20	8	0	10	2	33	6	18.2
Total		29	104	22	14	75	7	134	25	
Mean										18.7
10/12	On	12	95	0	20	83	12	41	37	90.2
10/23	On	10	150	0	41	145	5	47	34	72.3
10/26	On	10	114	0	41	111	3	40	24	60.0
Total		32	359	0	102	339	20	128	95	
Mean										74.2

The experiment was conducted between the 12th and 26th of October, 2017 on six separate occasions: three tests with the EGS on and three with EGS off (Table 1). The order of tests was random, except for the first trial. To conduct each test, we captured approximately 40 common carp (400–600 mm total length) in Long Lake using a large baited trap (10 m × 20 m net with mesh sides and mesh bottom) set overnight (Table 1). In the morning, the carp were removed from the trap, transported to the site using a boat, lightly anesthetized with clove oil (until loss of equilibrium) and inserted with PIT tags (half duplex 12 mm; Oregon RFID). For 10 carp from each test group, we also attached small floats (thin strips of pool noodles; 1 cm wide, 30 cm long) to the first ray of the dorsal fin using a monofilament fishing line (preliminary tests suggested that presence of the float did not bias carp's behavior). All carp were then released approximately 20-m downstream of the EGS. Each day, carp were released between 9 am and 1 pm. Green snow fencing secured with metal posts and sand bags was used as a physical barrier immediately downstream of the release site to prevent the carp from swimming back into Long Lake.

We monitored the behavior of the carp with floats for one hour post-release to assess the number of times they approached the EGS (approach), crossed the EGS (cross), were immediately deflected downstream (deflected), followed the edge of EGS in either upstream of downstream direction for at least

1 m (follow) and were either deflected downstream, crossed through EGS or crossed through the gate. These possibilities were not mutually exclusive, i.e. the same fish could approach, follow and cross though the EGS. The behavior was recorded by a single observer positioned on shore. These visual observations were used primarily to determine the probability with which the carp crossed the EGS. Independent of visual observations, the PIT system was used to determine the overall number of carp that passed through the gate during each trial. This was monitored continuously for 22-hours post-release.

Water temperature and stream flow were monitored by a USGS flow gauge located 1 km upstream of the study site. Stream temperature was 8.3 °C at the start and 3.3 °C at the end of the experiment. Flow was relatively stable throughout the experiment and ranged from 2.7 to 3.0 m^3/s.

To analyze the results, we used a Welch's t-test to determine if passage rates through the gate were statistically different during the on versus off settings of the EGS.

Results

Behavioral observations of the carp with floats showed that when the EGS was on, the carp would approach it frequently but maintain ~ 0.5 m distance from the EGS and usually followed it for several meters up or downstream before turning back away from EGS or being directed to cross through the gate. Over the course of the three trials with EGS on, the carp with floats approached it a total of 359 times but never crossed through the EGS (Table 1). Approximately 28% of these approaches (102 instances) were associated with carp following alongside the EGS. Many of the carp with floats (20 of 32) were directed towards the gate and swam through it within the hour of visual observations (Table 1). When the EGS was off, the carp with floats approached it 104 times and crossed it in 22 (21%) of those attempts (Table 1). Only seven out of 29 carp with floats crossed through the gate within the hour of visual observations when the EGS was off.

Data collected by the PIT antenna, which included all carp used in the experiment, indicated that an average of 74% of carp crossed through the gate and moved upstream of the EGS through the trap within the first 22 hours after release when the EGS was on (Table 1). In contrast, 18% of carp crossed through the gate within the first 22 hours post release when the EGS was off (Table 1). Passage rates through the gate were statistically different when EGS was on versus off (Welch's t-test; $P = 0.02$, $t = 6.25$).

We observed no evidence of carp, or other fish species, being paralyzed by the EGS. Also, we observed no mortality of carp or other species.

Discussion

Our experiment suggests that the EGS tested in this study can direct upstream-migrating common carp into a narrow passage that could lead to a trap. Specifically, we observed no evidence that the carp were able to pass through the EGS and we documented that, on average, 74% of all released carp were directed to pass through the gate within 22 hours post release. The results of our tests were similar to those of Johnson et al. (2016), who indicated that 75% of upstream-migrating sea lamprey were directed into a trap in Great Lakes tributaries. Our results also support the findings of a laboratory test that suggested that the EGS is capable of deterring upstream movement of common carp with high efficiency (Kim and Mandrak 2017). While our test was conducted in the fall using carp collected in the lake, we suspect that the EGS might also perform well during natural carp migration in the spring. A preliminary test of that hypothesis was conducted at the same study site in April of 2018, during the first week of carp spawning migration. While the experimental setup was slightly different (passage through the "gate" was effectively blocked due to testing various designs of carp ladders) it showed high capacity of the EGS to deter upstream movement of carp. During April 22–May 1, 2018, there were 753 instances of PIT-tagged carp attempting to cross the EGS, while only 73 crossings were recorded at a PIT antenna that was located approximately 1 km upstream. This suggests ~ 90% barrier efficiency over one-week period of continuous attempts to cross the barrier (P.G. Bajer, unpublished data). The EGS performed well during that time period despite the fact that water level in Rice Creek was approximately 1 m higher than in the fall 2017 and the tops of electrodes were submersed approximately 0.5 m under water. We advocate that other studies test the performance of the EGS under various conditions and in combinations with various traps and removal devices. It is also plausible that the EGS might be used for downstream moving carp (carp nurseries are sometimes located downstream of lakes, e.g. Bajer and Sorensen 2010), by reversing the orientation of the electrodes (positive electrodes upstream of negative electrodes).

Our study suggests that the EGS might be as effective if not more effective, than other non-physical fish guidance systems used to date. For example, tests of the strobe-sound-bubble curtain systems typically showed that 20–75% of migrating fish were able to be deflected away from undesirable passage ways such as power-plant intakes or sloughs. However, these tests typically deflect the fish from entering small passage way and deflect them into wide-open main channel (Michaud and Taft 2000; Perry et al. 2014). Our design was more challenging because we prevented the fish from using the main channel and instead directed them into a narrow passage. Some tests of the strobe-light-bubble systems showed surprisingly little effectiveness (Miehls et al. 2017), but this may be related to how specific fishes react to these behavioral stimuli. Electric guidance systems are less influenced by the vagaries of fish behaviors and responses to light levels or sound profiles that vary among species, and the results of testing electric guidance system appear to be consistent in their high efficacy. On the other hand, the nuanced responses of different fish species to sound and light might allow for designing species-specific sound and/or light guidance systems (Zielinski and Sorensen 2017), which is unlikely with electric systems.

Seasonal, including spawning, migrations of carp might often overlap with migrations of native fish. For example, Chizinski et al. (2016) showed that in Minnesota, common carp spawning migrations often occur just after the spawning migrations of northern pike and some overlap between the two species might occur. They also showed that nine other species of native fish migrated with the carp, of which black bullheads (*Ameiurus melas* Rafinesque, 1820), bluegills (*Lepomis mcrochirus* Rafinesque, 1819), and black crappies (*Pomoxis nigromaculatus* Lesueur, 1829) were the most numerous. We observed all four of the aforementioned species at our study site, in addition to bigmouth buffalo (*Ictiobus cyprinellus* Valenciennes, 1844). Several solutions could be applied to minimize the impact on native fish while using a combination of the EGS and a trap to remove the carp. First, PIT-tagged carp present within the system could be used to inform managers about the timing of carp migrations and could be used to autonomously activate EGS when carp migrations are occurring (i.e. detection of certain number of carp at an antenna would activate the EGS). This would minimize the amount of time the EGS is activated and it would therefore reduce the impact on native fish migrations. Second, migrating fish of all species could be captured in a live trap to allow hand-sorting to release native fish while removing carp. This process could be augmented by incorporating physical grates of specific dimensions within the trap to allow passage of small native fishes (e.g. bluegills, crappies) while retaining carp and other large-bodied native fish. Finally, autonomous species recognition technologies could be incorporated into a trap design to sort carp from native species but these technologies are not yet broadly available. For most immediate applications, we suggest directing all fish into a live trap and hand-sorting the carp.

Ease of installation, maintenance and affordability are critical elements that determine the usefulness of fish guidance systems. The EGS used in this experiment was deployed over two days and required minimal on-site engineering (steel C-channels were driven in the ground to provide anchor points for the electrode arrays on each bank). Because the electrodes were attached to a heavy metal chain, they adhered very well to the uneven bottom of the stream requiring no additional engineering. They can also be easily re-positioned (for example to place them at a more acute angle), by de-attaching one end of the array and attaching it to a new anchor point on the bank. The system used in this study had been placed in the stream for six months, during which time no maintenance or cleaning was conducted. Some drifting macrophytes "hang" on the electrodes but dislodge over time and do not affect the performance of the system. The EGS is also resilient to large debris, because the electrodes are designed to move out of the way when hit by, for example, a drifting log. The EGS used in this study had relatively low power requirements (80W). This suggests that systems of similar size could be powered by solar panels, increasing their applicability in remote areas. Overall, the EGS tested in this study appears to be a relatively affordable, practical, and effective tool for manipulating the behavior of migrating common carp.

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