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Field test of a bubble curtain deterrent system for common carp

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Reducing the movement of invasive fish such as the common carp, *Cyprinus carpio* L., silver carp, *Hypophthalmicthys molitrix* (Val.), and bighead carp, *Hypophthalmicthys nobilis* (Richardson), is one of the greatest challenges fisheries managers are presently facing (Taylor *et al.* 2003, 2005; Ruebush *et al.* 2012). Because physical barriers (dams, screens) and electrical barriers are non-selective, can be prohibitively expensive and impractical to maintain, there has been an increasing interest in barriers that use behavioural deterrents (i.e. sound, light and bubbles) as they have the potential to be safer, inexpensive and species specific (Popper & Carlson 1998; Taylor *et al.* 2003, 2005; Noatch & Suski 2012; Ruebush *et al.* 2012). As behavioural deterrents do not provide a physical obstacle to movement, they are <100% effective. Accordingly, whether these deterrents can be useful depends on their relative efficacy vs cost relative to management goals (i.e. controlling an established population vs blocking a new invasion). This study focused on bubble curtains, a deterrent technology that uses a dense plume of (noisy) bubbles to repel fish with acute hearing (Zielinski *et al.* 2014). These systems are inexpensive, but their performance has not been well documented in the field for invasive carps (but see Ruebush *et al.* 2012). In a previous laboratory study, an optimised bubble curtain deterrent system was found to reduce the movement of small common carp [total length: 259 ± 29 mm (mean $\pm$ SD)] by 75–80% (Zielinski *et al.* 2014). The objective of this study was to test the efficacy of this bubble curtain system in the field.

Cyprinus carpio is a highly invasive fish from Eurasia (Balon 1995), which is already well established and implicated in degrading millions of acres of shallow lake and wetland ecosystems across the globe (Weber & Brown 2009). In Midwestern North America, *C. carpio* abundance appears to be attributable to the tendency of adult fish to leave lakes and use wetlands for spawning, which often lack native predators of juvenile carp (Bajer & Sorensen 2010). A key to the long-term control of this species could lie in blocking a large proportion of downstream-moving juveniles from leaving these wetland systems and/or stopping adults from entering them to spawn. Extant barrier technologies are not suited to this task because screening small enough to stop juvenile fish clogs easily (Bainbridge 1964) and electrical barriers are expensive and cannot stop downstream-moving fish which drift through them.

This study tested the ability of a previously developed bubble curtain system (Zielinski *et al.* 2014) in Kohlman Creek, Maplewood, Minnesota, USA (45°01′36″ N 93°02′48″ W). This stream links a known *C. carpio* nursery and a chain of lakes. At the time of this study, the headwaters of Kohlman Creek supported nearly 30 000 young-of-year *C. carpio* (Osborne 2012), while the downstream lakes contained about 6000 adult *C. carpio* (Bajer *et al.* 2011). Kohlman Creek is about 6 m wide and 0.75 m deep. This study location allowed the testing of both up- and downstream movement, but in other ways was less than ideal because it was narrowly confined and subject to heavy flooding at times. A bubble curtain was installed that had six perforated PVC pipes mounted on a 4-m-long steel frame, which was attached to docks on both sides of the stream (Fig. 1). Netting was placed around the docks along with V-traps to prevent fish from bypassing the bubble curtain. The

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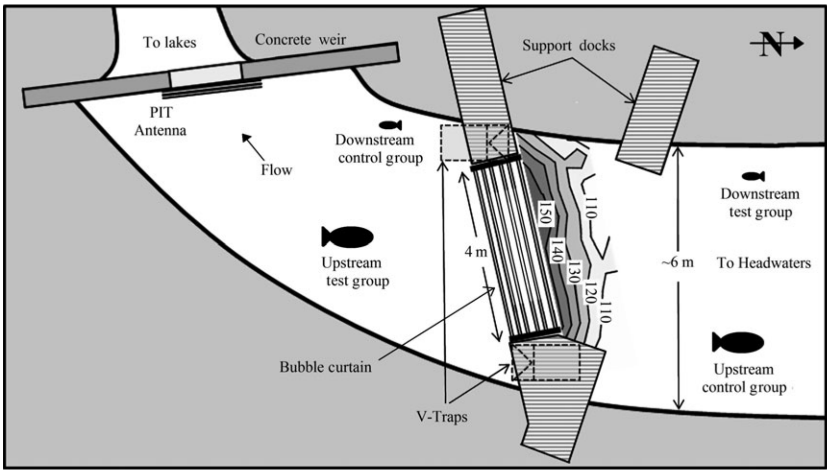

Figure 1. Plan view schematic of the bubble curtain system in Kohlman Creek, Minnesota with locations of release points. The lakes are located downstream, and the headwaters are located upstream. V-traps located on either side of the bubble curtain were ineffective at capturing common carp *Cyprinus carpio*. Sound pressure level contours of the peak frequency (300 Hz) at 30 cm from the channel bottom are provided on the upstream side of the bubble curtain (data could not be collected downstream because of soft sediment).

system was angled to promote deflection, but the V-traps were less effective than anticipated and the bubble curtain acted more like a cross-stream barrier. Two regenerative air blowers (S61 Aquatic Ecosystems, Apopka, FL, USA) supplied 15 L s^{-1} m^{-1} of air in series at 25 kPa. Measurements of the sound pressure field made upstream of the curtain using a CR-55 hydrophone (Cetacean Research Technology, Seattle, WA, USA) found that the sound pressure level decreased exponentially from 150 dB (ref. 1 μPa) to 100 dB (ref. 1 μPa) over 1.0 m (Fig. 1), consistent with theoretical attenuation rates for low-frequency sound in shallow water (Akamatsu *et al.* 2002). The bubble curtain produced a broad-spectrum signal between 100 and 2000 Hz with a peak frequency at 300 Hz, which overlaps the broadband hearing (50–3000 Hz) and sensitivity (>65 dB ref. 1 μPa) of *C. carpio* (Popper 1972). The bubble curtain cost about $5000, while infrastructure (docks and electrical service) cost $15 000.

Two experiments were conducted using locally caught *C. carpio* to test for the efficacy of the bubble curtain to block down- and upstream movement. To test downstream movement, juvenile *C. carpio* [total length 332 ± 27 mm (mean ± SD)] were collected by electrofishing the headwater region, implanting them with 23-mm passive integrated transponder (PIT) tags (Oregon RFID, Portland, OR, USA) and releasing them near the bubble curtain (Fig. 1). *C. carpio* were released either 5 m upstream of the barrier as a test group (~10 fish per group, five trials, $n = 52$) or 5 m downstream of the barrier as a control group (five fish per group, five trials, $n = 25$). Downstream movement of both groups was monitored using a PIT antenna system installed at a downstream concrete weir and culvert. Fish were released midday with the bubble curtain on. After 24 h, the barrier was turned off to test whether fish which had not crossed previously were motivated to do so. Bubble curtain efficacy was calculated as the difference in the number of *C. carpio* that swam downstream and crossed the barrier vs the number of control *C. carpio* that swam downstream (but did not have to cross the barrier). The ability of the barrier to stop upstream movement was tested in the same manner except it used adult *C. carpio* [total length 640 ± 54 mm (mean ± SD)] captured at a downstream weir while swimming upstream. Adult *C. carpio* were implanted with a PIT tag, marked with reflective ribbons tied to the anterior spines of their dorsal fins (control and test fish received different colours) and released midday at locations both above and below the barrier (Fig. 1). The stream was inspected once every three hours during daylight, and the location of marked adult fish was recorded. Ribbons were used because interference from overhead power lines prevented installation of a PIT antenna upstream of the bubble curtain. Adult *C. carpio* were considered to have moved upstream if their position at later observation points was located more than 5 m upstream of their release point. Similar to Welton *et al.* (2002), a 2 × 2 contingency table chi-square test with a z-statistic calculated using the Yates continuity correction (Fleiss 2003) was used to assess whether the proportions of *C. carpio* crossing the bubble curtain were significantly less than those expected from controls. When this test suggested significance ($P < 0.05$), a Mantel–Haenzel chi-square test was used to test for homogeneity. The null hypothesis assumed no difference between the proportions of

C. carpio crossing the bubble curtain than expected from controls.

Six downstream movement trials were performed between August and November 2012 and June to July 2013 during moderate-flow conditions (average discharge: 0.15 $m^3\ s^{-1}$). Of the 43 juvenile test fish to swim downstream, only 12 (28%) crossed the bubble curtain while it was on, while many control fish, 13 of 19 (68%), swam downstream in a 24-h period (Fig. 2a). When the barrier was turned off, 18 of 31 remaining test fish and four of six remaining control fish swam downstream, resulting in a total of 70% moving downstream when released above the curtain and 85% when released below. Thus, the efficacy of the bubble curtain to block downstream movement was 59 ± 14% ($Z = 2.72$, $P < 0.01$) and was consistent across all trials ($\chi^2_{assoc} = 5.15$, $P < 0.001$). Although this value was somewhat less than the 75–80% observed in the laboratory (Zielinski *et al.* 2014), the fish blocked by the bubble curtain were presumably more motivated than in the laboratory and required fish to swim against a current. Nevertheless, most of the introduced fish did not cross the bubble curtain.

Four upstream movement trials were conducted in May 2013. Migratory adult *C. carpio* were marked and then added either as a test group (seven fish per group, three trials, $n = 21$) downstream of the bubble curtain or as a control group (three fish per group, three trials, $n = 9$) upstream of the bubble curtain. Trials were performed during high-flow conditions (average discharge: 3.1 $m^3\ s^{-1}$). Of the 19 test fish found to move from their release point, 14 swam upstream and crossed the bubble curtain within 24 h. Many *C. carpio* were seen stopping at the barrier and reversing direction and two jumped over it. In comparison, seven of eight control fish swam upstream (88%; Fig. 2b). Thus, the bubble curtain blocked upstream movement by 16 ± 11% ($z = 0.28$, $P > 0.05$). The observed reduction in passage could seemingly be attributed to behavioural responses to fluid motion and acoustic stimuli, not visual stimuli, as most movements occurred overnight (87%) – consistent with laboratory observations (Zielinski *et al.* 2014). Ruebush *et al.* (2012) also noted what appeared to be a disproportionate upstream passage of *C. carpio* compared with other native and invasive fishes in sound–bubble–strobe light barrier testing on Quiver Creek, Illinois.

These results support the laboratory studies, which show bubble curtains have the potential to impede movement of downstream-swimming *C. carpio*, safely, and at

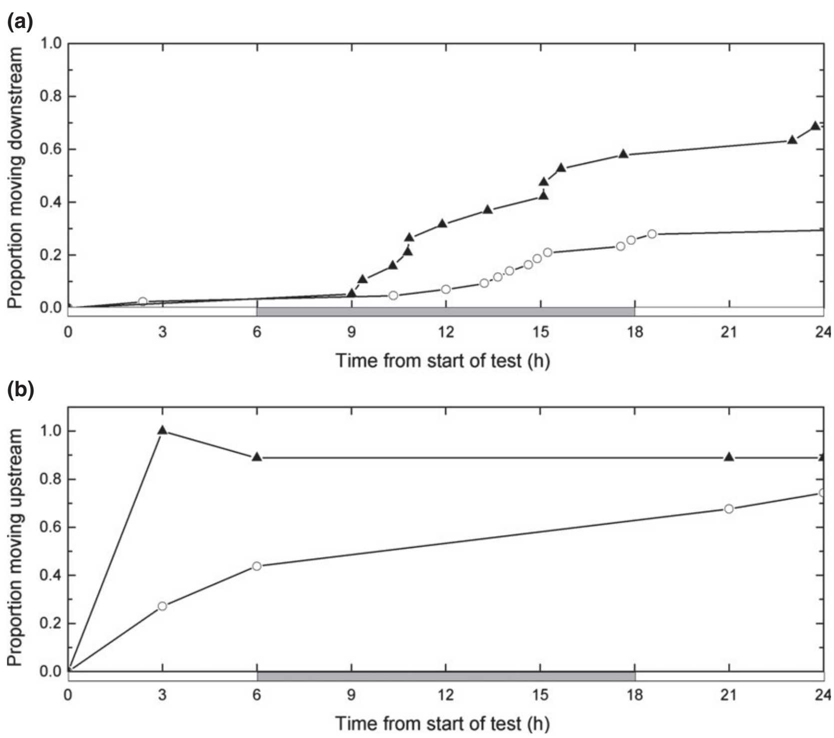

Figure 2. (a). Proportion of test (open circles) and control (filled triangles) juvenile common carp *Cyprinus carpio* that swam downstream. The start time for the downstream movement tests was 12:00 h on Day 1; on Day 2 (not shown), it was turned off. (b). Proportion of test and control adult *C. carpio* that swam upstream. The start time for the upstream movement tests was 12:00 h. Dark and light bars at the bottom indicate night and day.

low cost. Although less success was observed for upstream-swimming adult *C. carpio*, the result for downstream-swimming recruits is relevant because of its low cost, there are no alternatives to block downstream movement and that less than complete efficacy may often be acceptable for an already established species. Moving this bubble curtain to upstream areas with lower flows and refuges (to hold deflected fishes) may also increase its efficacy. Perry *et al.* (2012) and Welton *et al.* (2002) demonstrated that acoustic–bubble barriers were effective at controlling downstream-migrating salmon smolts (*Oncorhynchus* spp.) in a large river when operated as a deflection screen. Others have recommended supplementing bubble curtains with transducer-driven sound fields (Taylor *et al.* 2005) and/or strobe lights (Patrick *et al.* 1985) to increase efficacy (Ruebush *et al.* 2012). In conclusion, these results suggest that bubble curtains are a tractable, low-cost management tool to block juvenile *C. carpio* for sites where reduction, not total elimination, of downstream movement is the primary goal.

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