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Laboratory experiments demonstrate that bubble curtains can effectively inhibit movement of common carp

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ABSTRACT

Although bubble curtains have been proposed many times as practical and inexpensive solutions to hinder the movement of invasive fish, few studies have examined why or how they might work. By understanding how bubble curtains influence fish behavior, management tools could be developed to control movement of invasive fish. In this study, the common carp (*Cyprinus carpio* L.) was used to examine the performance of three different bubble curtains (fine-, graded-, and coarse-bubble) and acoustically enhanced systems in an indoor channel. Trials revealed that the graded- and coarse-bubble systems reduced common carp passage across the curtain by 75–85% in both up- and down-stream directions. Concurrent acoustic field measurements revealed that these bubble curtains generated sound near 200 Hz at approximately 130 dB (ref 1 μPa), well above the common carp hearing threshold. Further testing with speaker arrays and lighting indicated that carp avoidance of the bubble curtain involved responses to sound and fluid motion rather than visual cues. Although field tests are warranted, our results suggest that bubble curtains may be a viable and inexpensive deterrence system to limit common carp movement.

1. Introduction

Fish guidance technologies have long been part of fisheries management efforts to control invasive fishes (Taft, 2000; Lavis et al., 2003; Noatch and Suski, 2012). Physical or mechanical barriers (i.e. dams, screens, or traps) can be effective at stopping both up- and down-stream movement of invasive fish; however, these barriers can be extremely difficult and expensive to maintain because of clogging (Bainbridge, 1964). Consequently, behavioral barriers, which utilize stimuli such as sound and light to target fish sensory systems and guide fish in taxon-specific manners, have been suggested for sites where mechanical or physical barriers are not well suited (Popper and Carlson, 1998; Noatch and Suski, 2012). A behavioral barrier of particular interest is the bubble curtain, which produces a wall of bubbles (e.g. by forcing air through perforated pipes). Bubble curtains are inexpensive, require relatively little maintenance, and generate complex sound, visual, and hydrodynamic fields which may be optimized to deter fish without obstructing water flow.

Initial development of bubble curtain technologies was driven by both commercial fishing (Kuznetsov, 1971), and the need to find alternative solutions to reduce fish impingement at power generation facilities (Taft, 2000; Michaud and Taft, 2000). Although laboratory and field studies have reported fish to be deterred by bubble curtains, these studies did not quantify sound fields or other physical characteristics needed to assess the factors driving the effectiveness of the barrier systems (Brett and MacKinnon, 1953; Kuznetsov, 1971; Zweiacker et al., 1997; Leiberman and Muessig, 1978; Stewart, 1982; Sager et al., 1987; EPRI, 1998, 2004; Sprott, 2001; Welton et al., 2002; Dawson et al., 2006). Further, studies have reached contradictory conclusions (Patrick et al., 1985; Welton et al., 1997). For example, while Patrick et al. (1985) suggested bubble curtains act as a visual deterrent due to a ~20% greater avoidance by gizzard shad (*Osmerus mordax*), alewife (*Alosa pseudoharengus*), and smelt (*Dorosoma cepedianum*) under low light than in darkness, Welton et al. (1997) described the opposite, and suggested that Atlantic salmon smolt (*Salmo salar*) were deterred more during night than daytime trials (42% compared to 0%). Alternatively, Kuznetsov (1971) suggested fish respond to the acoustic fields generated by bubble curtains based on nighttime commercial

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fishing. Overall, studies appear to suggest that bubble curtains inhibit fish movement, but the abiotic parameters that affect fish behavior remains unclear. Importantly, no studies have attempted to individually and collectively assess the influence of sound, visual, and hydrodynamic fields on fish behavior.

By understanding how bubble curtains influence fish behavior, management tools could be developed to control movement of invasive fish. Bubble curtains may influence fish visual, auditory, and lateral line systems by generating visual, sound, and tactile (e.g. fluid flow) stimuli. Sound is generated by bubbles as they detach from the diffuser (Leighton and Walton, 1987; Leighton, 1994; Lin et al., 1994), which at the continuum limit (the curtain of bubbles works as a collection of coupled oscillators) results in low frequency (<1000 Hz) sound emissions (Nicholas et al., 1994; Manasseh et al., 2004). The radiating sound field is comprised of longitudinal particle motion and local pressure oscillations. For all teleost fish, the inner ear detects the particle motion component of the sound wave; however, ostariophysian fish (including common carp) have an anatomical link between swim bladder and inner ear which provides indirect audition of the pressure component as well (Popper and Fay, 2011). Rising bubble plumes also generate turbulence with distinct recirculation currents that are dependent on the upward velocity and density of the bubble plume (Brevik and Kristiansen, 2002; Soga and Rehmann, 2004). The mechanosensory lateral line is the main sensory system for these hydrodynamic signals (Webb et al., 2008). Finally, bubble curtains may serve as a visual barrier by obscuring a fish's line of sight past the barrier (Patrick et al., 1985; Sager et al., 1987).

The present study investigated the impact of a bubble curtain on common carp (*Cyprinus carpio* L.), a cyprinid responsible for degrading water quality in shallow water ecosystems (Weber and Brown, 2009). In Midwestern North America, common carp, hereafter termed carp, often inhabit stable, deep, normoxic lakes for much of the year, but enter interconnected unstable (susceptible to hypoxic conditions), shallow lakes to spawn, so the latter areas frequently serve as recruitment 'hotspots' (Bajer and Sorensen, 2010). Reducing or stopping the migration of adult fish to spawning habitat or young carp back to the stable lakes could dramatically decrease recruitment. Existing barrier technologies are not well suited for the conditions characteristic of streams connecting stable and unstable lakes which typically have low hydraulic head. Bubble curtains could provide a targeted, safe, and inexpensive alternative for sites involving downstream movement of small fishes, especially in waters where reduction, not total elimination of movement, is the management goal. Additionally, bubble curtains could also be readily removed or re-positioned, if needed. A behavioral barrier employing acoustic stimuli – such as the bubble curtain – may also be potentially useful for targeting carp because of their relatively broadband hearing (50–3000 Hz) and sensitivity (>65 dB re: 1 μPa) (Popper, 1972).

The main objectives of the present study were to: (1) develop and test the efficacy of a bubble curtain to inhibit carp movement under controlled laboratory conditions; (2) identify the acoustic and hydrodynamic flow fields generated by the bubble curtain; and (3) determine the effect of visual and auditory components of the bubble curtain to inhibit movement. This study appears to represent the first attempt to quantify the biologically relevant stimuli fields generated by a bubble curtain that inhibits fish movement.

2. Materials and methods

2.1. Experimental setup

Common carp [mass: 204 ± 77 g; total length: 259 ± 29 mm (mean ± S.D.)] were caught in Lake St. Catherine, MN, USA by electrofishing in July 2010 and transported to the laboratory, where the carp were maintained in large tanks supplied with continuously flow-through 20 °C well water. Carp were fed pellets (Silver Cup, Utah) once a day between 10.00 h and 16.00 h.

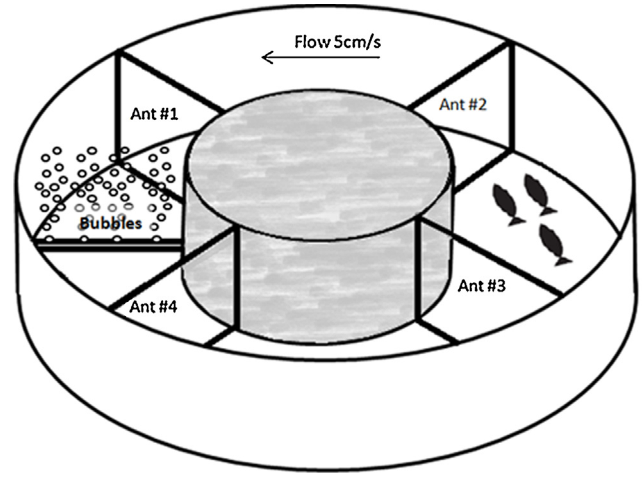

Fig. 1. Schematic of behavioral trial tank with approximate location of bubble curtain and PIT tag interrogation system (PIT antennas are labeled Ant #1-4). The outside diameter of the tank is 3 m and the inside diameter is 1 m, and water depth is 25 cm.

Passive integrated transponder (PIT) tags (OregonRFID, OR, USA) were implanted into a third of the fish. Carp were anesthetized in a 0.05% solution of buffered tricaine methanesulfonate (MS222), a 5 mm incision was made between their pelvic and pectoral fins and the 23 mm-long half duplex PIT tag placed inside their body cavity. Incisions were allowed to heal for three weeks (Skov et al., 2005) prior to the experiments and tagging resulted in no mortality. The remaining carp were left untreated. All experimental procedures were approved by the University of Minnesota Institutional Animal Care and Use Committee.

Experiments were performed in a round tank (3 m diameter) provided with an insert to create a circular channel (I.D. 1 m × O.D. 3 m) and water depth of 25 cm (Fig. 1). Water was supplied to the channel through a submerged pipe, producing an average 5 cm s^{-1} current. Carp were tested in groups of three to facilitate natural shoaling behavior. To track carp movement, a PIT antenna array was constructed using the Oregon RFID Multi-Antenna HDX reader, powered by a 12-V deep cycle marine battery. Each antenna consisted of 5 turns of 16 gauge solid wire (1 m × 0.3 m hoop), tuned to an inductance of ∼60–80 μH. All antennas were connected to tuning modules, which were connected to the PIT reader by twin coaxial cable. Each time a tagged carp passed through an antenna, the time of passage, PIT identification number, antenna number, and time between detections were logged onto a memory card for analysis. The antennas were equally spaced (∼1.6 m) along the circular channel at the quarter points, centered about the bubble curtain (Fig. 1). Manual testing indicated that the detection probability of each antenna was >99%.

2.1.1. Tests of simple bubble curtains

Responses of carp to three different bubble curtain systems were tested. Bubble curtain systems varied in size, configuration, and air supply to help identify features influencing fish behavior. The first system was a fine-bubble system comprised of two 2.5 cm diameter porous polyethylene pipes (Genpore, PA, USA). These pipes had an average pore size of 25 μm over their entire surface. The pipes were placed 30 cm apart on the bottom of the test channel (Fig. 2a). Two S41 regenerative air-blowers (Aquatic Ecosystems, FL, USA), in