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Modeling the preference of ayu (*Plecoglossus altivelis*) for underwater sounds to determine the migration path in a river

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ABSTRACT

Water sounds are believed to be important in triggering the upriver ascent behavior of migratory fish species. Modeling the effect of underwater sound on fish preference represents a promising technique to determine migratory paths for the comprehensive analysis of river habitat suitability. In this study, we aimed to determine the preference and weight of underwater sounds by laboratory experiments using adult and juvenile ayu (*Plecoglossus altivelis*). A watercourse with an underwater speaker installed at one end was used for the experiments. Sound was emitted from the speaker at different sound pressure levels. The sound sources included pure tones (100 Hz, 200 Hz, 400 Hz, and 800 Hz), white noise, recorded sound from a weir on the Fushino River, and recorded sound at a fish ladder on the Misumi River (Japan). The results showed that juvenile and adult ayu avoided the pure sound of 100 Hz and recorded sound of the Fushino River weir. In contrast, both adults and juveniles preferred the pure sound of 200 Hz and recorded sound of the fish ladder. Moreover, by comparing the obtained quantitative preference parameters for sounds, we found that adult ayu expressed higher preference for sound than juveniles. We designed a procedure to calculate sound preference and built it into our fish behavior simulation model on geographic information system (GIS) software. We believe that the model could successfully reproduce observed fish migration behavior in rivers. This technique could be used for designing an underwater soundscape to attract fish to the entrances of fish ladders or to keep fish away from hydropower plants.

1. Introduction

The auditory system allows aquatic animals to perceive intended and unintended acoustic signals in the environment, providing information about food, competitors, predators, and potential mates (Myrberg, 1978). Yet, studies about fish hearing and sound production (bioacoustics), including the importance of sounds to fish life-history parameters, were only initiated in the late 20th century (Moulton, 1963; Tavolga, 1971). The number of studies investigating fish hearing and sound production increased considerably in the second half of the 20th century (Ladich and Popper, 2004; Popper and Fay, 1999; Popper et al., 2003; Zelick et al., 1999). Fishes are able to respond to a wide range of sounds, discriminate between sounds of different magnitudes or frequencies, detect a sound in the presence of other signals, and determine the direction of a sound source, termed sound source localization (Fay and Megela, 1999; Fay, 1988; Hasting and Popper, 2005). In addition, fishes are able to listen to sounds produced by either conspecifics or heterospecifics, and respond by retreating, escalating agonistic behavior, or being attracted to the source if sounds represent courtship signals (Yan et al., 2010).

Sounds are believed to elicit changes in fish behavior (Yan et al., 2010). Few studies have demonstrated that sound may attract or repel fish over great distances or for extended periods. Water sounds are believed to have a considerable role in triggering the ascent behavior of migratory fishes up rivers. Thus, underwater sound preferences of fish are expected to play an important role in determining their migratory pathways, the modeling of which could be used in the comprehensive evaluation of river habitats.

Therefore, this study aimed to model fish preference for underwater sounds. This study involved two experiments. First, we observed fish distribution in relation to various sound sources at

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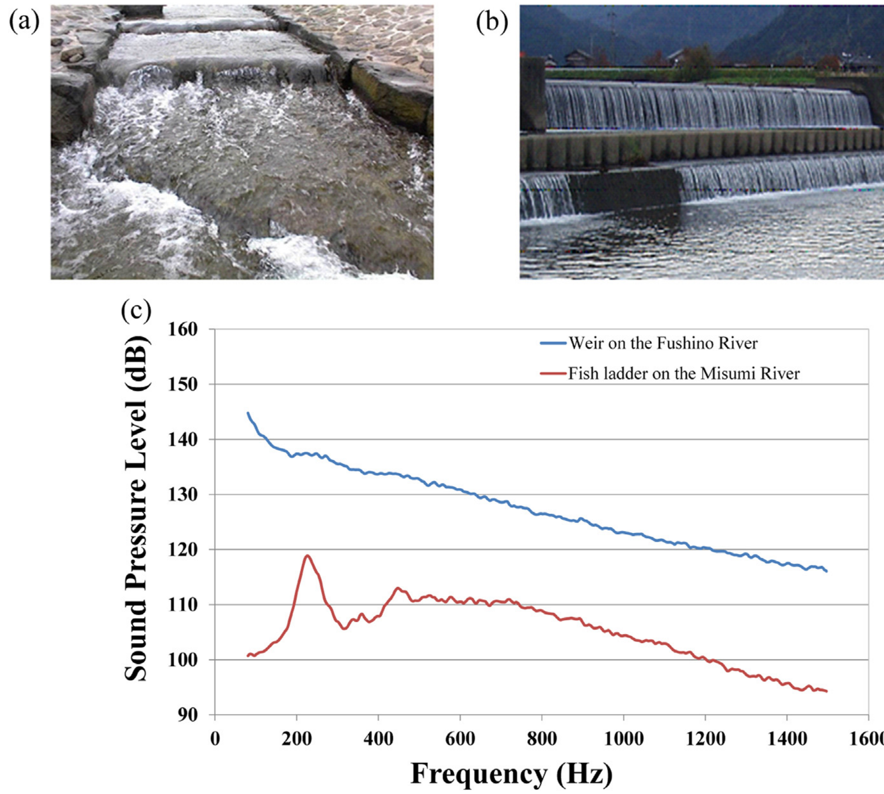

Fig. 1. (a) Fish ladder on the Misumi River; (b) weir on the Fishino River; (c) sound pressure level at the fish ladder and weir.

different sound pressure levels using an experimental tank in a laboratory. Based on the observed fish distribution, we quantitatively described the preference of fish on sounds to generate a preference value, and weight sound preference in relation to other environmental factors. Second, we built the sound preference data into our fish behavior simulation model on geographic information system (GIS) software, and validated its accuracy against observed fish migration in a river based field experiment.

2. Materials and methods

2.1. Experimental sound source

The sound sources used in the experiments included pure sound (100 Hz, 200 Hz, 400 Hz, and 800 Hz), white noise, recorded sound at a fish ladder on the Misumi River, Japan (Fig. 1a), and recorded sound at a weir on the Fushino River, Japan (Fig. 1b). The pure sound frequencies were selected from under 1000 Hz because studies have indicated that common fish species are sensitive to this frequency range (Akamatsu et al., 2000; Fay, 1988; Fujieda et al., 1996; Ishioka et al., 1988; Kojima et al., 1992; Motomatsu et al., 1996; Park and Iida, 1998; Popper and Fay, 1993, 1999; Schellart and Popper, 1992). The fish ladder was selected as an obstacle that fish can pass through, while the weir was selected as a water gap that fish cannot pass through.

Pure sounds were generated using software (Adobe Audition 1.0) on a personal computer. Fish ladder and weir sounds were recorded using a sound monitor (OKI Electric, whale phone) and a digital audio tape recorder (Sony, TDC-D100) with a sampling rate of 44.1 kHz, and the sound pressure level (SPL) was measured with a sound pressure meter (OKI Electric, SW 1020).

Fig. 1c shows the SPL spectrum of the fish ladder and weir sounds using frequency analysis in Adobe Audition 1.0. Twenty seconds of digitized sound data were processed using a Blackman-Harris window and 16,384 FFT size.

2.2. Experimental animal

We selected ayu (*Plecoglossus altivelis*) as the experimental fish because it is an amphidromous species (i.e., migrates between salt and freshwater) and is the most important riverine commercial fish in Japan (Ishida, 1976). Two different sizes of ayu (8 ± 1 cm and 16 ± 1 cm) were purchased from the Fushinogawa Fishing Cooperative. In this paper, we refer to 8 cm ayu as juveniles and 16 cm ayu as adults. We maintained the fish in a stock tank (90 cm long $\times$ 30 cm wide $\times$ 50 cm height) under recirculated with a supplemental aerator. We fed the fish compound feed (0.5 g/fish, *Kawazakana no esa*, KYORIN Co., Hyogo, Japan) once per day after the experiments, or at 15:00 on days that fish were not included in an experiment. The stock tank and the experimental apparatus introduced in the next sub-section were placed in a same air-conditioned laboratory, and approximately one-third of the stock tank water was exchanged with water from the experimental apparatus every day to maintain the same water quality. The preferred water temperature of ayu is 11–23 °C (Koyama, 1978), and the water temperature of the tank and the apparatus was kept at 21 ± 1 °C.

2.3. Set up of the laboratory experiment

To determine sound responses, juvenile and adult ayu were placed in the experimental apparatus (Fig. 2a). The apparatus was constructed from transparent acrylic and an underwater speaker was installed at one end. Inside the apparatus, a frame made of vinyl chloride pipe was installed about 5 cm from the apparatus walls, and 5 cm thick sound absorption material made of white polyester was placed on the interior the frame, except for the speaker face and the top. Another wall of sound absorption material was placed