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Review

Recent biotelemetry research on lacustrine salmon homing migration

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Abstract: One of the most interesting aspects of the salmon's life history and the most challenging to study is the homing migration during which the fish return from their oceanic feeding grounds to the natal river to spawn. However, because of the difficulties encountered in studying the movements of fish, particularly in the sea, there is still very little information regarding this phase in the life cycle of the salmon. Lake Toya in Hokkaido, Japan supports populations of both lacustrine sockeye salmon (*Onchorynchus nerka*) and masu salmon (*O. masou*). The lake provides an ideal model for an “oceanic system” where the physiological and behavioral basis of the homing migrations of salmon can be studied. Previously a number of studies have been undertaken in Lake Toya using biotelemetry techniques to investigate and describe the homing migratory behavior of mature and sockeye salmon. The three principal biotelemetry techniques that have been utilized include ultrasonic telemetry, electromyographic telemetry and micro data logging telemetry. Each of these techniques has been shown to have advantages and disadvantages in describing the movements of adult salmon. Therefore, it was decided to combine all three techniques in a single system and develop a robotic tracking platform (robot boat) that encompassed three interrelated telemetry systems, acoustic telemetry, a signal processing system and a telecommunication system for transmission of data between the boat and a land based station. This review describes the new technology that has provided the opportunity to investigate the physiological and behavioral basis of salmon homing migration using the unique Lake Toya lacustrine salmon model.

key words: biotelemetry, tracking, robot boat, homing migration, salmon

Introduction

A number of studies have used telemetry techniques to describe the various stages in the homing migration of the salmon from their oceanic feeding grounds to their natal rivers to spawn. However, one stage that has always been difficult to study using telemetry techniques is the oceanic migration (Ueda and Yamauchi, 1995; Ueda *et al.*, 2000). Lake Toya in Hokkaido, Japan supports populations of both lacustrine sockeye salmon (*Onchorynchus nerka*) and masu salmon (*O. masou*). The lake provides an ideal model for an “oceanic system” where the physiological and behavioral basis of the homing migrations of salmon can be studied (Fig. 1).

Three different biotelemetry techniques have been used to investigate the physiological basis of the homing migration salmonids (ultrasonic transmitter, electromyographic radio

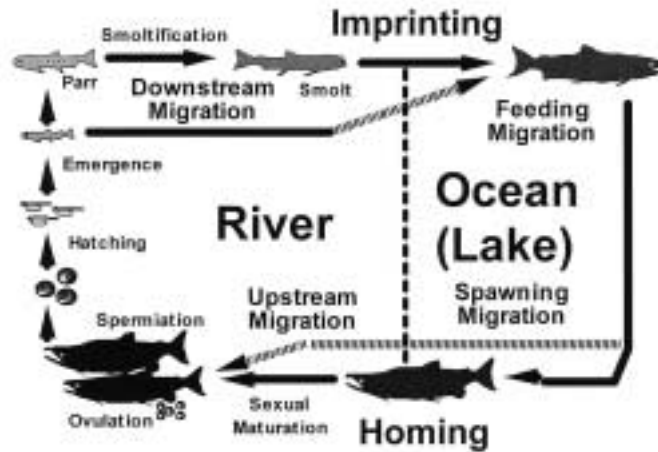


Fig. 1. Life history of two different types of Pacific salmonid species in Japan. Dotted line: chum and pink salmon; Solid line: sockeye and masu salmon.

transmitters, and micro data loggers). Firstly, ultrasonic transmitters were used to study the homing migrations of sensory impaired sockeye and masu salmon from the center of the lake to their natal areas. Secondly, physiological telemetry (electromyographic radio transmitters—EMG) was used to estimate and compare the energetics of adult masu salmon migrating in the lake and in an adjacent stream. Thirdly, information on the swimming depths and ambient water temperature experienced by mature male masu salmon during the spawning season were recorded using micro data loggers.

Each technique has been shown to have advantages and disadvantages for describing the movements of adult salmonids. For instance, active ultrasonic tracking and the use of physiological telemetry requires that the investigator remain in constant contact with the fish to obtain the necessary data. In the case of the micro data loggers they must be recovered from the fish before the data can be downloaded.

In 1999, ten experts in the fields of ship engineering, signal processing, acoustic engineering and computer science collaborated in a research project to develop an automatic salmon tracking-boat, *i.e.* a single telemetry system that would allow all aspects of the physiological mechanisms controlling the homing migrations of salmonids to be studied in Lake Toya. The present paper describes the development of the system and the recent advances made using the lacustrine model to study the homing migrations of salmonids.

Ultrasonic tracking

Ultrasonic transmitters that emit pulsed signals have been used to investigate the migratory behavior of salmonids in the sea (Quinn *et al.*, 1989; Ogura and Ishida, 1994). Further studies have used ultrasonic tracking in combination with sensory ablation experiments, which blocked the visual, olfactory and magnetic senses to examine the oceanic movements of migratory salmonids (Døving *et al.*, 1985; Yano and Nakamura, 1992; Yano *et al.*, 1996). Controlled physiologically manipulated studies are difficult to carry out on anadromous populations which enter the freshwater phase before maturation. However, lacustrine populations offer a suitable model for studying the homing mechanisms of salmon moving from

open water systems to the natal stream for reproduction.

The homing migrations of mature sockeye and masu salmon, whose sensory cues were impaired, were tracked from the center of Lake Toya to the spawning areas using an ultrasonic tracking system (Ueda *et al.*, 1998). In these studies, magnetic rings were attached to mature male sockeye salmon in order to impair their magnetic navigation system. A brass ring acted as a control on another group of fish. These fish were shown to return to their spawning grounds after a 1 hour period of random movement (Points A and B in Fig. 2). A mature male sockeye salmon, whose magnetic and visual senses had both been impaired, moved in the opposite direction but was recovered at the spawning grounds the following evening (Point D in Fig. 2). Another mature male fish which had only its visual system impaired migrated to the shore of Naka-Toya at a significant distance from the spawning areas (Point C in Fig. 2). A visually impaired female masu salmon also showed similar migratory behavior (Point B in Fig. 3). In contrast, the appropriate control mature male masu salmon migrated at a constant speed along the shoreline before stopping at the mouth of the natal river (Point A in Fig. 3). A mature male salmon whose olfactory system had been impaired moved randomly along the shoreline and eventually moved towards the center of the lake (Point C in Fig. 3).

These experiments were designed to investigate the homing abilities and physiological basis for orientation in sockeye and masu salmon. The results indicate that both visual and olfactory cues are involved in the successful homing migration of masu salmon. Similarly, visual cues are important to the sockeye salmon but there does not appear to be a magnetic sense involved in the homing behavior of lacustrine salmon.

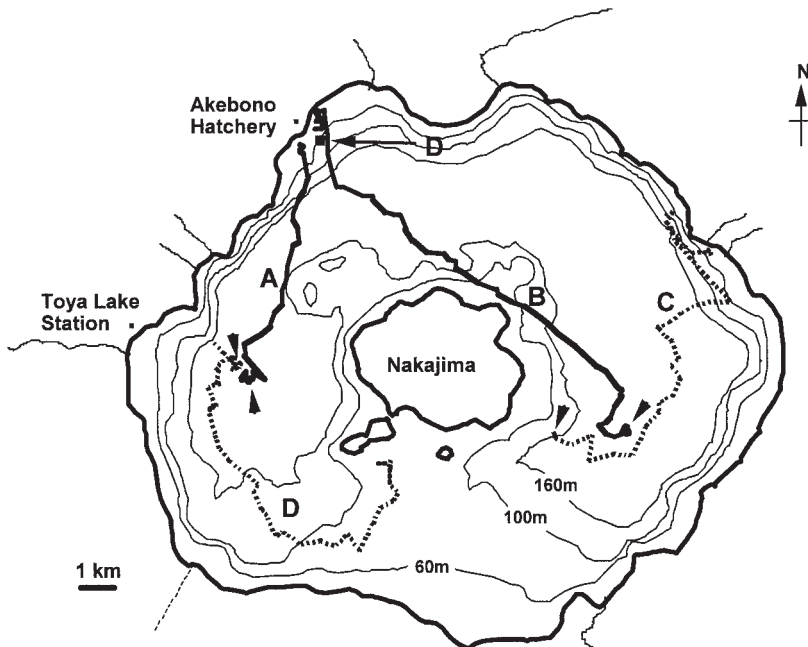


Fig. 2. Tracks of four mature male lacustrine sockeye salmon in Lake Toya during the spawning season. Arrowhead indicates the release point of each fish: control fish (A); magnetic cue-interfered fish (B); visual and magnetic cues-interfered fish (C); visual cue-interfered fish (D).

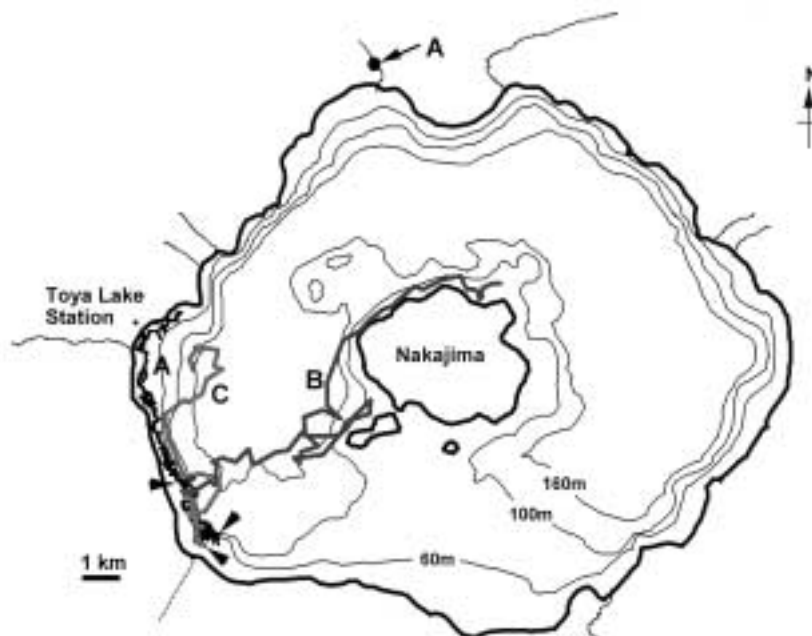


Fig. 3. Tracks of three mature lacustrine masu salmon in Lake Toya during the spawning season. Arrowhead indicates the releasing point of each fish: control male fish (A); visual cue-interfered female fish (B); olfactory cue-interfered male fish (C).

The ultrasonic location transmitters were combined with sensory ablation to evaluate homing capability, particularly orientation ability, of sockeye and masu salmon. Using this method, both visual and olfactory cues were necessary for successful homing in masu salmon. Similarly, visual cues were critical to the homing of sockeye salmon, while magnetic cues did not appear to be necessary for successful return to the natal area. However, magnetoreceptor cells have been identified in the nose of rainbow trout (*O. mykiss*) (Walker *et al.*, 1997), and further studies should be done to investigate magnetic cues in salmon. It is quite interesting to compare the straight movements of sockeye salmon with the coastal movement behavior of masu salmon. These two species show large differences in ocean distribution with sockeye salmon distributed widely in the North Pacific Ocean, while masu salmon are narrowly distributed in the west North Pacific Ocean (Kaeriyama and Ueda, 1998). The phylogenetic analysis among Pacific salmon and trout suggests that masu salmon are more primitive than sockeye salmon (Murata *et al.*, 1993, 1996; McKay *et al.*, 1995). These data suggest some evolutionary aspects of successful homing migration of salmonids where the narrowly distributed masu salmon only need coastal recognition ability, but widely distributed sockeye salmon must obtain open water cues for orientation.

EMG radio transmitters and micro data loggers

Although ultrasonic transmitters have provided much information on the movements of individuals, both electromyographic (EMG) radio transmitters and micro data loggers have

been used in Lake Toya to fully understand the swimming depths and temperature preferences, and to estimate the energetics of migration of the lacustrine salmonids (Ueda *et al.*, 2000). In adult masu salmon, the preferred swimming speeds of individuals within the lake (during their pre-migratory searching phase) were compared with the same individuals in streams using EMG radio transmitters (Leonard *et al.*, unpubl. data). Masu salmon in the lake swam at a preferred speed of approximately 2 FL/s with remarkably little variation. In the stream, the variability in selected swimming speed was much larger, and often showed a bimodal pattern with one peak in the aerobic swimming speed range and the other in the anaerobic speed range (Fig. 4). EMG telemetry had previously mainly been conducted on large river migrations and in the detection of species/stock differences (Hinch *et al.*, 1996; Booth *et al.*, 1997; Økland *et al.*, 1997; Hinch and Rand, 1999).

Micro data loggers (archival tags) assessed the environmental preferences of mature masu salmon during spawning migration. During searching behavior the fish remained in relatively shallow water and moved around the shoreline of the lake. During the period prior to upstream migration, the fish seemed to be selecting habitat by depth or lake area rather than by temperature (Fig. 5). Between two upstream attempts, the fish was characterized as being in the recovery period since it stayed in deep, cool water (Naito *et al.*, 2000). A number of interesting data were obtained from micro data logger deployments in salmonid fishes during their oceanic migration (Naito, 1997; Tanaka *et al.*, 2000).

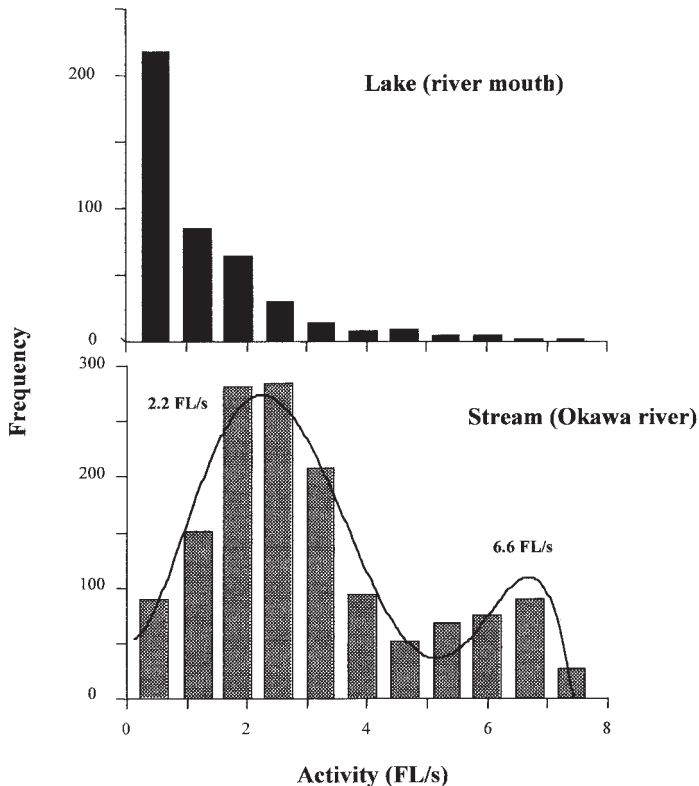


Fig. 4. Frequency diagrams of selected swimming speeds of an adult male masu salmon in Lake Toya and as it migrated upstream in the Okawa River. Peak values of fitted bimodal regression line are shown.

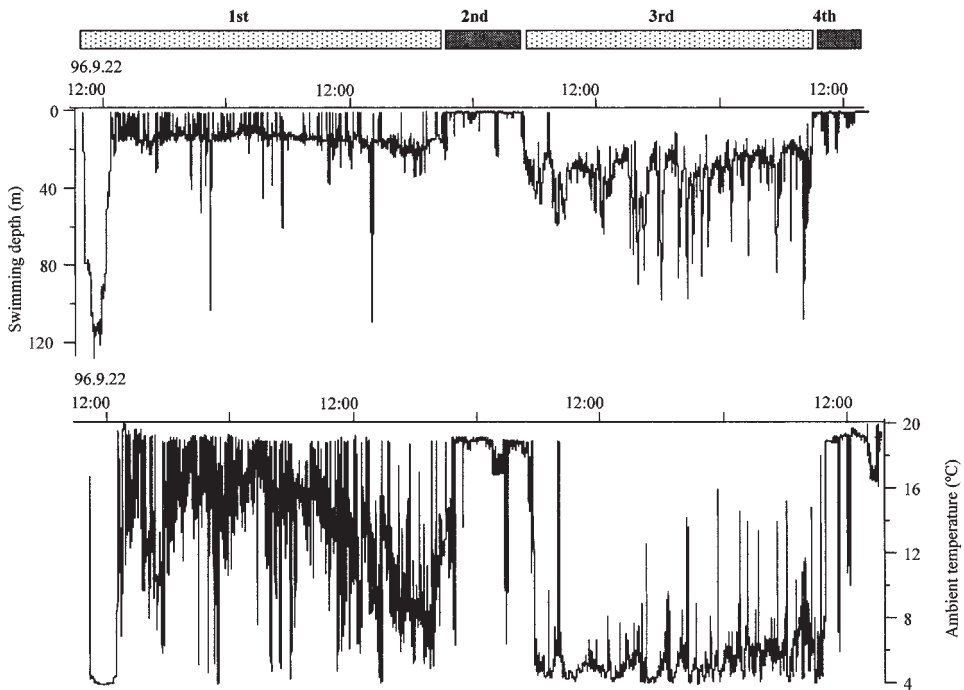


Fig. 5. Time serial records of swimming depth (upper) and ambient water temperature (lower) of an adult male masu salmon during spawning season. Four different phases are identified as 1st, 2nd, 3rd, and 4th.

Robot boat

Although our lake system has provided several interesting findings in salmon homing migration as a result of various types of tracking telemetry, these techniques have many disadvantages. In order to overcome these disadvantages, ten experts in the fields of ship engineering (Drs. K. Karasuno, K. Maekawa, Y. Yoshimura and H. Oda), signal processing (Drs. M. Suzuki and K. Matsuda), acoustic engineering (Mrs. K. Kamada, H. Murakami and K. Minoshima), and computer science (Mr. M. Wada) have carried out a collaborative research project to develop an automatic salmon-tracking robot boat in Lake Toya since 1999.

We have developed four interrelated equipment systems for a proto-type lacustrine salmon tacking robot boat (Fig. 6).

- 1) A robot boat which is a swath type ship with styrofoam twin hull constructed of pipes, 2.5 m in length, 1.3 m in width, with a loading capacity of 120 kg, operating at 2 knots using two electric thrusters. This boat is easy to disassemble, construct and carry to anywhere in the world.
- 2) An ultrasonic tracking system which consists of a miniature ultrasonic transmitter and a position detecting unit. The ultrasonic transmitter is 50 mm in length, 11 mm in diameter, and 15 g weight in water, and 20 kHz in frequency. A position detecting unit, the ALS-20DK (Kaiyo Denshi Co., Ltd.), can detect the distance, depth, and direction of a miniature pinger.
- 3) A signal processing and control system is operated by a personal computer on the boat that

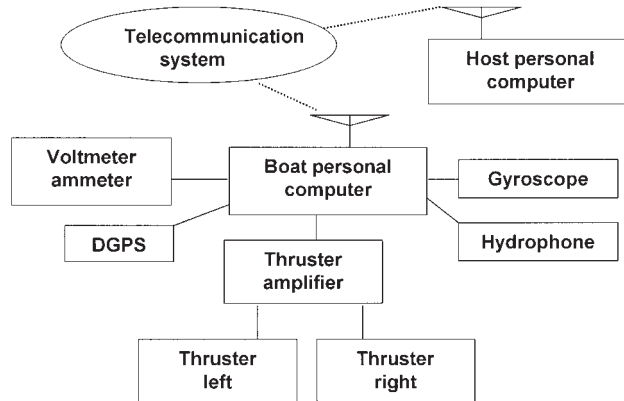


Fig. 6. Interrelated equipment system of salmon tracking robot boat.

receives signals from a DGPS (Differential Global Positioning System) that can detect boat position to 1 m accuracy, a gyroscope that can monitor boat tilting, and acoustic signals from the ALS-20DK. Then, this computer processes these signals, and controls a thruster amplifier for tracking an ultrasonic transmitter attached on the back of a salmon. A telecommunication system between a land base and the boat is operated by NTT-Docomo handy-phone circuit at a speed of 9600 bps.

On October 16, 2001, we attached a miniature pinger to a mature male lacustrine sockeye salmon 1752 g in body weight, and on the following day, the first trial of automatic tracking of free-swimming fish was carried out. The robot boat tracked the sockeye salmon for 66 min for a distance of 800 m, but trouble in the handy-phone circuit stopped the automatic tracking. We are now improving the telecommunication system.

The final goal of this project is to build a robot boat that can track salmon in the ocean. These newly developed biotelemetry technologies will be applicable in 3 dimensional analysis of fish swimming behavior in a stationary fishing net, as well as in self-navigation mode to monitor dangerous area, such as zones of volcanic eruption.

Conclusions

This review describes our recent advances in biotelemetry research on homing migration of lacustrine sockeye salmon and masu salmon in Lake Toya, where the lake serves as a model "ocean". Using these model fish, three different approaches in connection with orientation ability in open water, energetics of migration, and environmental preferences of migrating fish, provide several valuable findings on salmon homing migration. Furthermore, to overcome disadvantages in previous telemetry systems, an automatic salmon-tracking robot boat is being developed by ten experts. Our approach will provide a new concept for the mechanisms of homing migration in salmon from the lacustrine model.

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