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Original research article

Estimating the size of the spawning population and evaluating environmental controls on migration for a critically endangered Asian salmonid, Sakhalin taimen

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ABSTRACT

Sakhalin taimen *Parahucho perryi*, an east Asian fish noted to be one of the largest salmonids in the world, is threatened throughout its range in northern Japan and neighboring Russian Federation. We report here on the first effort to enumerate and characterize the spawning run of a river population. We applied sonar and video methods in a tributary of the Sarufutsu River in Hokkaido, Japan, and evaluated environmental controls on migration. Over two years we estimated the tributary population to range from 335 to 425. We found passage rate by our site to increase with temperature and decrease with river discharge, and migratory cues were reinforced by strong diel fluctuations in environmental conditions. Finally, we report evidence of males arriving early to the spawning grounds in this species. Given our results and data on the recreational fishery, we conclude that a substantial number of individuals in the population are affected by angling, underscoring the need to establish fishing regulations. Further, our study indicates passage success can vary over the migration period, and efforts at modifying or removing impediments, and devoting more research to factors controlling passage, could ultimately improve the status of this species.

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1. Introduction

The precarious status of species in the genus *Hucho* and *Parahucho*, recognized as the largest salmonid fishes in the world, has received little attention (Holčik et al., 1988; Rand, 2013). The five extant species have a broad distribution in the arctic and temperate rivers of Eurasia. Recent status assessments have concluded that all species are either threatened or Data Deficient based on IUCN extinction risk criteria (Rand, 2013). While there are some noted exceptions of innovative, successful field efforts aimed at understanding status of the species (e.g. Fukushima, 2001; Jensen et al., 2009), there are still few examples of field programs to produce reliable status and trend data to help guide ongoing and future conservation programs.

In many respects fisheries science has lagged behind other natural resource fields given the difficulty of estimating population sizes in aquatic ecosystems. A quote from John Shepherd, introduced into the literature by Hilborn (2002), succinctly conveys the core problem: "counting fish is like counting trees-except they are invisible and they keep moving". However, great strides have been made in recent years in our ability to estimate the population size and characteristics of

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salmonids during their spawning run. It has now become routine to use sonar technology to produce reliable population data on which to base fishery management decisions. Many fishery agencies now are applying this sonar technology. The development of multi-beam sonar systems in particular has substantially improved data reliability and expanded our ability to describe characteristics of river migrants, including accurate estimates of fish sizes (e.g. Holmes et al., 2006; Maxwell, 2007; Burwen et al., 2010). These sonar systems now provide high resolution images and produce reliable estimates of fish passage in a variety of river systems in North America. With the deployment of multiple systems, it is now possible to monitor passage in large river systems (e.g. Copper River in Alaska, Fraser River in British Columbia). While this technology is now being applied in many rivers to provide data for managers on major commercial and sport fisheries (for a recent example, see Miller et al., 2013), we see new application opportunities in the use of this technology on threatened and endangered salmonid populations.

While there have been many studies on migration dynamics and factors affecting passage by natural and artificial barriers for Pacific and Atlantic salmon (e.g. Hinch and Rand, 1998; Thorstad et al., 2008), very few studies have been undertaken on other diadromous species (Roscoe and Hinch, 2010). In recent decades, for example, it has been discovered that fish ladders on dams designed for Pacific salmon are not suitable for native Pacific lamprey given important differences in swimming performance (Moser and Mesa, 2009). Work by engineers and biologists has emphasized the need to understand particular requirements of effective passage for different species, and how certain factors, like discharge and temperature, may play an important role (Roscoe and Hinch, 2010). Taimen may experience unique challenges passing river impediments, given their unique body shape (having a relatively high length to height ratio compared to other salmonids, Kawanabe and Mizuno, 1989) and large maximum sizes. One can imagine the difficulty, for example, of a 2 m long adult taimen navigating through a constricted fishway. It is important to describe these species-specific differences as a step toward addressing passage problems, but we are not aware of any directed studies of migration or passage dynamics for species in the genera *Hucho* and *Parahucho*.

Here we describe a simple monitoring effort, based on these well-established protocols to estimate the size of the spawning run of a threatened population of Sakhalin taimen (*Parahucho perryi*) in Hokkaido, Japan. Through an integrated monitoring effort, we estimated passage of taimen by a fixed point in the river and evaluated temporal patterns and environmental controls on fish passage and migration. At the end of the paper, we describe implications of our research on conserving this highly threatened species.

2. Material and methods

2.1. Description of the river, salmonid populations and study site

The Sarufutsu River is located in the Soya Region in northern Hokkaido Island, Japan, and flows into La Pérouse Strait, a body of water separating Sakhalin, Russian Federation and Hokkaido, Japan in the Northwestern Pacific Ocean (Fig. 1). The size of the watershed is 361 km^2. The study area has a cool-temperate climate with heavy snowfall in winter. The region receives an annual average of over 1100 mm of precipitation, with 42% in the form of snow. The upper watershed is under forest cover, and the predominant tree species are acer (Acer mono), birch (*Betula ermanii*), oak (*Quercus crispula*), tilia (*Tilia japonica*) and fir (*Abies sacharinensis*). The forest understory is dominated by Sasa dwarf bamboo (*Sasa senanensis*).

The river supports a number of wild salmonid populations, including white spotted char (*Salvelinus leucomaenis*), masu salmon (*Oncorhynchus masou*), pink salmon (*O. gorbuscha*), and chum salmon (*O. keta*). The river may support the most abundant population of Sakhalin taimen (*Parahucho perryi*) throughout its range in Japan. This species has become highly threatened as a result of overfishing, habitat loss and extensive agricultural development (Fukushima et al., 2011). Our study site is located in the Karibetsu River, a large tributary draining an area of 83 km^2, representing 23% of the entire Sarufutsu watershed. The river is recognized as an important spawning river for Sakhalin taimen.

2.2. Monitoring adult taimen passage and study site conditions

We monitored passage of taimen at a low, concrete weir on the Karibetsu River during the springs of 2013 and 2014 (Figs. 1 and 2). The weir is located 2–3 km downstream of most of the spawning grounds in this tributary system (Fukushima, 2001). We used multi-beam sonar imaging systems (DIDSON, or Dual Frequency Identification Sonar in 2013, and ARIS 3000, or Adaptive Resolution Imaging Sonar in 2014, www.soundmetrics.com) and a CCD video camera to monitor passage. The imaging system DIDSON (set at high resolution, 1.8 MHz) uses 96 sound beams that are focused by a lens to produce video-quality images of underwater targets (Moursund et al., 2003). The newer ARIS system is based on the same technology, but can operate at a higher frequency (3.0 MHz) and resolution, utilizing a total of 128 beams. The units were supported on a metal frame and the beam was oriented across the channel, perpendicular to the river flow, just upstream of the final, upstream weir step (Fig. 2). This position was chosen to ensure fish ascending the weir would pass through the beam on their migration to the spawning grounds, with low probability of passing back downstream. The beam geometry was evaluated using a wood model of the fish fastened to a 3 m long pole. This protocol was carried out at the beginning of the monitoring period each year, and after any adjustments were made to the position of the imaging sonar to assure all taimen

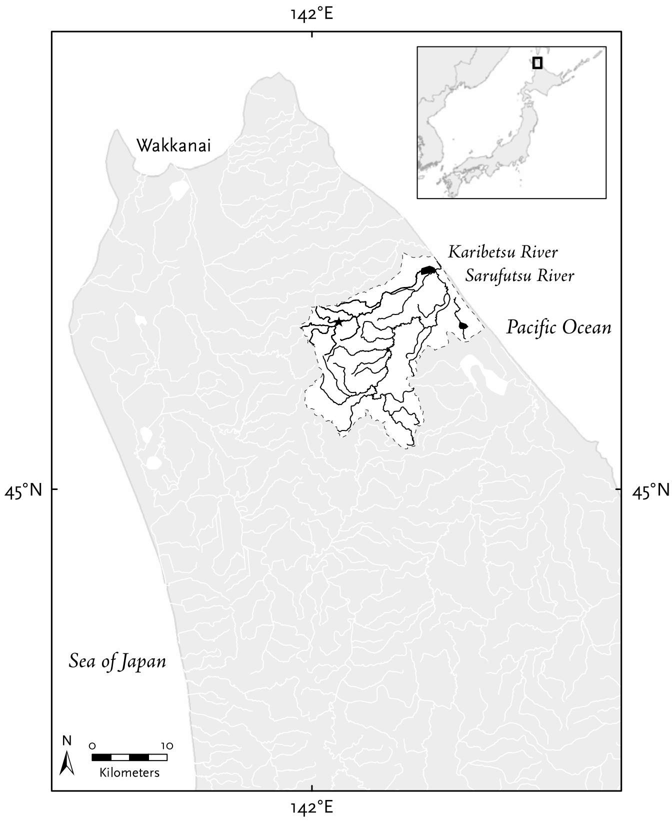

Fig. 1. Map of Sarufutsu watershed in Hokkaido, Japan, including the major tributary, Karibetsu River. Location of the Karibetsu weir study site identified on the map with a star.

Fig. 2. Image of the Karibetsu weir taken just prior to the 2014 sampling period (mid-April). The sonar imaging system and CCD video camera were positioned on the river bank at the top step of the fishway through which all adult taimen passed prior to spawning. We determined that some adults passed over the falls (visible on the left-hand side of the image) while migrating downstream after the spawning period. Photo credit: Pete Rand.

ascending the weir would pass through the beam. The imaging sonar ran continuously during 10 April–16 May 2013 and 19 April–13 May 2014 except during a 15–30 min period every morning (typically between 0900 and 1000) while batteries were refreshed and data were downloaded to an external storage device. We experienced a problem with silt accumulation

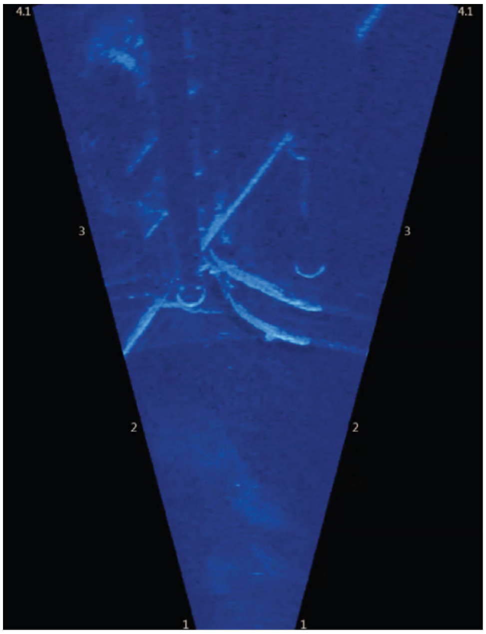

Fig. 3. A still image captured by the ARIS 3000 sonar system during the 2014 monitoring period in a tributary of the Sarufutsu River, Japan. Two adult taimen are identifiable in the image, located just above the upstream step of the fishway.

in the lens of the DIDSON that significantly attenuated the emitted acoustic signal during 23–24 April 2013. We excluded these periods from our data set. We present an example still image of taimen passing our weir site during 2014 created from ARIS 3000 (Fig. 3).

In 2013 we also deployed a charge-coupled device (CCD) video camera (SONY HDR-CX270V, Hi-Vision, 5.4 M pixel resolution, f1.8-3.4) in a water resistant housing mounted above the surface of the river. The camera was fixed to a pole just downstream of the top weir step, and positioned at an oblique angle to provide a full image of taimen passing the site. A polarizing filter was added to the housing port to improve our ability to detect fish passing the weir. Due to limitations in the life of the battery, the camera operated for approximately 8 h a day (generally during 1000–1800 daily). The camera recorded during the period 28 April–17 May 2013. In addition, we examined short clips of CCD video from a camera deployed in a similar configuration during the 2014 sampling period to confirm species identification.

All the data generated from the imaging sonar and CCD video records were produced by visual identification during play back. The review process for the imaging sonar data (including spot checks with CCD video records in both years to confirm species identification) was performed by the senior author and the full 2013 CCD video data review was completed by staff at the National Institute for Environmental Studies in Tsukuba, Japan. Time of passage recorded for the imaging sonar was the point in time when the fish first entered the beam. Passage was recorded only for those individuals that passed through the upstream border of the sonar field of view. We estimated the size of targets produced by the imaging sonar by digitizing the snout and tail of all individuals passing upstream of our site. This approach has been shown to yield reliable estimates of fish size. Burwen et al. (2010) reported high accuracy (root mean squared error of 5.76 cm) for adult Pacific salmon in an Alaskan river using the same approach we used in our study. Only fish targets that were positioned in the beam in full view were chosen for length determination. The ARIS 3000 is capable of estimating lengths with higher accuracy than DIDSON, so we report lengths only for 2014. Because other species are also known to migrate during this period in the Sarufutsu River, we made careful observations during imaging sonar play back to distinguish these other species based on individual sizes. Through careful review of CCD video records, we concluded the other dominant species present was a common cyprinid (*Tribolodon* spp.), a fish that typically does not exceed 40 cm in length (Kawanabe and Mizuno, 1989). Therefore we assumed all targets greater than or equal to 40 cm were taimen. We acknowledge that masu salmon are also known to migrate in the spring, but we did not observe any individuals of this species by eye at our field site or in our review of video records. We suspect masu ascend the river later in the spring. We noted and recorded fish migrating downstream. All analyses of imaging sonar was made using Sound Metrics software (in 2013, DIDSON Control and Display Software Package v. 5.25.24; in 2014, ARISFish v. 2.2).

We monitored air and water temperature at our study site during both sampling years using an ONSET HOBO Pendant temp (UA-001-64). Illuminance (lux) was monitored with an ONSET HOBO Pendant temp/light (UA-002-64). In addition, we recorded the height of the river every day between 0900 and 1000 by reading a scale mounted to the weir in 2013. In 2014, we deployed water and air pressure sensors to estimate river height through the entire sampling period (HOBO Water Level Data Logger, U20-001-01). All data loggers used in this study recorded data at 10 min intervals.

2.3. Data analysis of passage rate

2.3.1. Imaging sonar, CCD video, and environmental monitoring data

We stratified all imaging sonar, CCD video and environmental records into 30 min recording intervals so all passage observations were attributed to day of migration and 1/2 h time interval.

We applied time series models to quantify temporal autocorrelation in the imaging sonar data. These analyses quantified the degree of autocorrelation in the time series to determine if taimen weir passage was uniform and random or if taimen were passing in discrete groups. The variable analyzed was upstream passage rate of taimen, in # of taimen passing our site per 30 min period during the course of the entire sampling period. Because it was an analytical requirement to have values for each sampling period, we assumed passage was nil during the unsampled periods during 2013 (a total of 90 30 min periods, representing $<8\%$ of the entire sampling period). This time interval occurred during the early, pre-peak period of the run and bank-side observations suggested that very few individuals passed during this time, thus we feel this action had a minimal effect on our results. We applied the Dickey–Fuller test for time series stationarity (i.e. absence of an overall trend in the data), and applied the Box–Pierce test to detect autocorrelation in the time series. We fit an autocorrelation function (ACF) and partial autocorrelation function (PACF), to the data to describe the degree and characteristics of the autocorrelation. The ACF is a set of correlation coefficients between the series and lags of itself over time, whereas the PACF explores partial correlations, or how correlations propagate to higher-order lags. More explicitly, PACF measures the amount of correlation between taimen passage and a lag of itself not explained by correlations at all lower-order lags. A general description of the use of the autocorrelations functions in ecological studies is included in Scheiner and Gurevitch (2001). We determined the best autoregressive integrated moving average (ARIMA) model fit to the data, determined by an algorithm that determines goodness of fit by minimizing the Akaike information criterion (AIC Hyndman and Khandakar, 2008).

To explore how environmental parameters might be controlling weir passage and migration, we tested the goodness of fit of Generalized Additive Models (GAM). The response variable was upstream passage rate (# taimen per 30 min period). The following variables were considered candidate explanatory variables: (1) DAY (day of migration), (2) TIME (hour of day), (3) LIGHT (illuminance, in lux), (4) AIRT (air temperature, in °C), (5) WATERT (water temperature, in °C), and (6) RIVERST (river stage or height in cm). To address the issue of collinearity among these variables, we estimated the variance inflation factor (VIF) for all variables in both years. The VIF is an index that measures how much of the variance (the square of the estimate's standard deviation) of an estimated regression coefficient is increased because of collinearity. We applied the common VIF threshold of 5 to determine whether a given variable is highly collinear. After removing air temperature, which was found to be highly collinear in both years, the set of variables in both years was not considered highly collinear (i.e. no variable exceeded the 5.0 VIF threshold). Thus we used all variables except air temperature in our statistical model. We relied on the step.gam procedure of R to arrive at a best fit, parsimonious model (Hastie and Tibshirani, 1990). Goodness of fit was determined by evaluating models that included or removed each of the individual variables. In addition, both linear and non-parametric smooth functions were evaluated to arrive at the best fit model that minimized AIC.

2.3.2. Analysis of passage probability and sex ratio

The CCD video camera monitoring allowed us to evaluate two other phenomena associated with passage by the weir site. The first was the number of successful and unsuccessful passage attempts, and the second was the trend in the sex ratio of the migrating population based on spawning color differences judged by the video technician. This species, and this population in particular, exhibit striking spawning color dimorphism, with males developing bright red coloration posterior to the operculum, whereas female color is muted (Fig. 4). We conducted this analysis with data collected during 2013.

We evaluated whether there were trends in successful passage (expressed as a proportion of total attempts by day) and changes in the sex ratio (expressed as the ratio male:female migrants by day) over the course of the migration using Pearson's chi-squared tests. We chose the sampling frame to be a day to align with the lowest sampling frequency among our environmental data (i.e. river height, measured once each morning). We applied the Marascuilo multiple comparison procedure (as implemented in package 'basicUtils' in R) to conduct pairwise comparison between all proportion (passage success and sex ratio) differences from a contingency table (Marascuilo, 1966). Pair-wise daily proportions were determined to be significant at $p = 0.05$ based on exceeding critical threshold differences. We further evaluated whether passage success or sex ratio changed as a function of environmental variables (LIGHT, WATERT and RIVERST) using analysis of variance on the same response variables. We hypothesized that passage success differed over the course of the migration and was lowest at high discharge given difficulty the fish experience overcoming fast currents over the weir. We also hypothesized passage success would be higher at higher temperature (given that swim performance would be expected to be a positive function of water temperature over the range of temperatures we observed in the study, $\sim$1–8 °C). Based on extensive literature on Pacific salmon (see recent review by Morbey, 2000), we further hypothesized that the population exhibited protandry in spawning ground arrival timing where males would tend to be dominant in the early part of the run, and the sex ratio would become increasingly skewed toward females by the end of the run. Here we make the simplifying assumption that males and females pass with equal probability, thus the data collected on the sex of individuals during passage attempts (i.e. some individuals can be observed more than once in the data set) provides a means of estimating an unbiased sex ratio of the population.

Fig. 4. Photo of a pair of Sakhalin taimen on the spawning grounds of Sarufutsu River, Hokkaido, Japan. The image demonstrates the striking spawning color dimorphism exhibited in this population. The male (left) becomes bright red during the spawning season, whereas the female (right) lacks coloration. Photo credit: Satoshi Adachi. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3. Results

We estimated the size of the taimen spawning run in Karibetsu River to be 335 individuals in 2013 and 425 individuals in 2014. In 2013, we observed the first taimen passing during the morning of 22 April (designated here as day 1 of the migration during that year) and the last fish passed the weir site on 13 May (day 22, Fig. 5). We noted most taimen migrated downstream after 8 May (only 3 downstream taimen migrants were detected prior to 9 May). We enumerated a total of 29 down-migrating taimen during 3–16 May (the DIDSON monitoring terminated on 16 May). In 2014, we observed the first taimen passing during the afternoon of 20 April (designated as day 1 of the migration during that year), and the last taimen passing the weir site on 13 May (day 24, Fig. 6). We observed the highest rate of passage during this year, when 18 taimen passed during 1330–1400 on day 10 (29 April), and the daily count reached 146 individuals, representing 34% of the entire 2014 run. We counted only 4 taimen migrating downstream prior to 29 April, and we enumerated a total of 130 down-migrating taimen during 23 April–13 May (the ARIS 3000 monitoring terminated on 13 May). We confirmed by video monitoring that some taimen pass over the falls on the right bank of the river (Fig. 2) during their migration downstream following spawning (Rand & Fukushima, unpublished data), thus we concluded our imaging sonar undercounts the total number of down-migrating taimen. We suspect our counts of downstream taimen migrants were lower in 2013 because some migrants may have continued to pass downstream after our sampling period (i.e. after 16 May), and relatively higher river flow during the later monitoring period in 2013 likely favored passage over the falls. We quantified individual lengths for 384 individual taimen observed passing the weir during 2014. We estimated a mean length of 74.0 cm (median = 73.7 cm). The largest individual measured was 113 cm. The distribution was unimodal and normal. We observed a significant, negative trend in the lengths of individual taimen over the migration period in 2014 (least square linear regression, $p < 0.05$, Fig. 7). Based on the loess fitted trend, the sizes of taimen reached a peak early during the migration period, reaching 80 cm total length on day 8, and then declined steadily to the end of the migration, reaching approximately 60 cm total length.

We determined the time series of upstream passage rate (in # taimen passing per 30 min period) to be stationary (Dickey–Fuller test, $p < 0.05$) and autocorrelated ($p < 0.05$ at lag = 1) during both years. The results of the time series analysis suggest an "auto-regressive signature" where the autocorrelation function (ACF) trails off slower than the partial autocorrelation function (PACF, Fig. 8). The autocorrelation patterns in 2013 and 2014, which were significant out to 7.5 and 5.5 h lags, respectively, can be explained by adding autoregressive (AR) terms to the time series model. The results of the PACF analysis suggest a 3rd order AR model for 2013, with positive partial correlation over 3 lags, or 1.5 h (AIC of AR(3) model = 2434.54, Fig. 8). Conversely, a lower order AR model is more appropriate for 2014, with partial correlations significant over

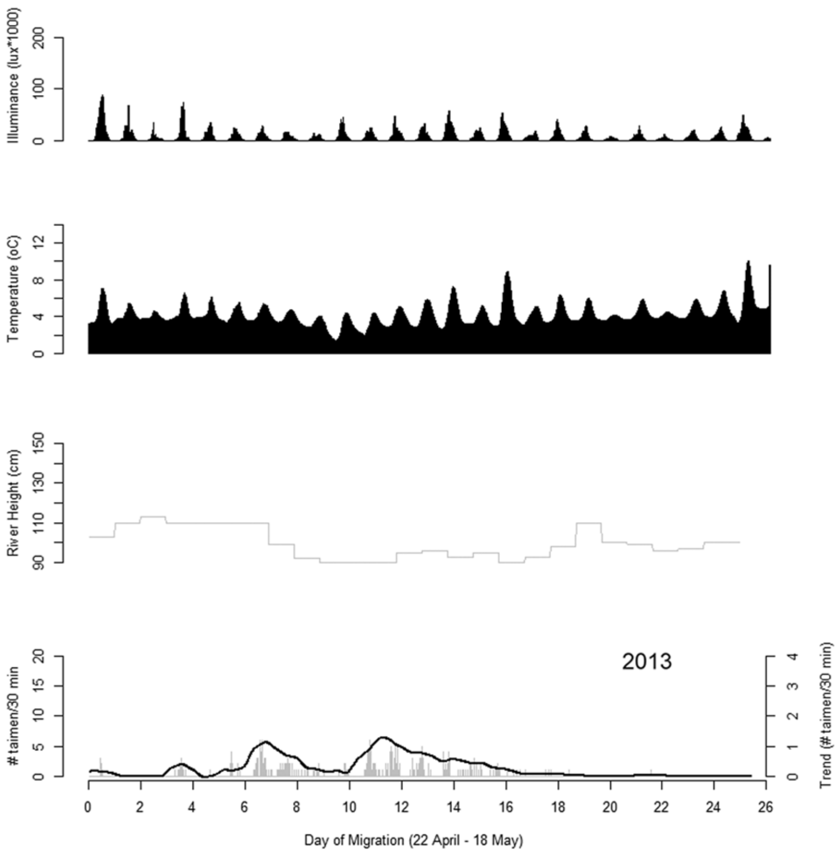

Fig. 5. Time series data on environmental variables monitored during 2013 (solar illuminance, water temperature and river height) and passage rate of taimen by the final, upstream step of the Karibetsu weir (gray bars are raw passage data, and dark line is the loess smoothed trend, span = 0.1).

2 lags, or 1 h (AIC of AR(2) model = 2869.69, Fig. 8). Applying the auto-arima fitting procedure of Hyndman and Khandakar (2008) returned a 2nd order autoregressive model (with first order differencing) for 2013, resulting in a lower AIC (2421.2), while a 0 order (with first order differencing) was the best fit model for 2014 (AIC = 2869.1).

The best fit GAM to explain taimen passage by the Karibetsu weir included the following smoothed variables for 2013: DAY, LIGHT and WATERT (AIC = 2441.569, Fig. 9). All of these variables were found to be statistically significant ($p < 0.05$). The variable RIVERST was found to be significant in this year ($p = 0.02$), but the presence of that variable in the model did not lower AIC enough to warrant its inclusion in the final model. These results indicate that passage at the Karibetsu weir peaked on day 11 of the migration (3 May 2013) and increased significantly over the temperature range between 3 and 6 °C. Passage appeared to change as a non-linear function of ambient light levels, with passage declining with rising light levels to 40,000 lux, then increasing over that threshold.

For 2014, all the smoothed variables were included in the final GAM, adding two additional variables to those found significant in 2013 (TIME and RIVERST, AIC = 3718.52, Fig. 9). An earlier temporal peak in taimen passage is evident during 2014, likely owing to warmer spring conditions compared to 2013. In addition, there was a distinct diel pattern of passage peaking at mid-day. The GAM indicated a negative effect of illuminance, a positive effect of water temperature (very similar to our result from 2013, but expressed over a broader temperature range), and a negative effect of river discharge.

Analysis of the CCD video records during the 2013 season resulted in separate observations for 199 events of passage of taimen. Taimen were observed at the top step of the weir during 0850–1850. We found probability of successful passage to differ over the course of the migration (chi-square = 22.33, df = 8, $p = 0.004$, Fig. 10). Assuming all fish observed ultimately passed upstream at our site, passage probability was ca. 50% during the course of the migration (i.e. on average, a migrating individual made two jumps to pass the weir successfully). Certain days appeared to present difficult passage conditions. On day 9 for example, we observed that failed passes (28) exceeded successful passes (18) by a factor of 1.5 (success ratio significantly different on day 9 compared to days 11, 14, and 17, $p < 0.05$, Fig. 10). Conversely, days 13 and 14 appeared to be a period of easier passage, with passes exceeded failures by a factor greater than 2 (day 13 differed significantly from days 11 and 17; day 14 differed from days 9 and 12, $p < 0.05$, Fig. 10). Environment variables did not explain this pattern. All variables were not significantly related to successful passage ($p < 0.05$).

We found evidence of a significant shift in the sex ratio over the course of the migration. We identified 122 female and 77 male taimen making passage attempts in the CCD video records collected in 2013. Our chi-squared test indicated significant

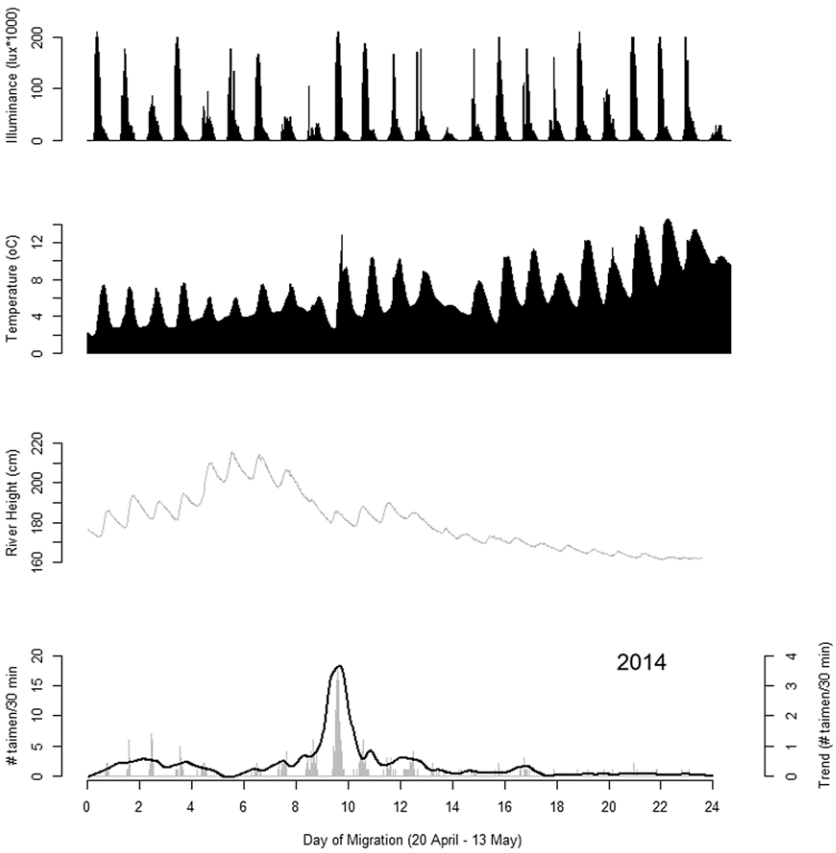

Fig. 6. Time series data on environmental variables monitored during 2014 (solar illuminance, water temperature and river height) and passage rate of taimen by the final, upstream step of the Karibetsu weir (gray bars are raw passage data, and dark line is the loess smoothed trend, span = 0.1).

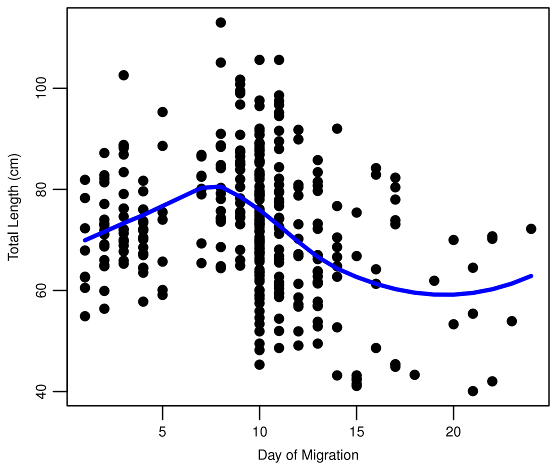

Fig. 7. Estimated total lengths of taimen passing our study site during 2014. Lengths were determined by estimating the distance separating the snout and the tail of each individual in the digital imagery produced by the sonar system. Data are fit to a loess smoothed trend, span = 0.75.

differences across days (chi-square = 34.1, df = 8, $p < .05$, Fig. 10). The female-skewed sex ratio observed during the later days of the migration (days 13 and 15–17) was significantly different than the male-skewed ratios observed early in the run (days 8 and 9, $p < 0.05$, Fig. 10).

4. Discussion

There is growing concern about the status of Sakhalin taimen. The species has undergone a steady decline over the past 50 years and is recognized as a threatened species in Japan and Russia, and was added to the IUCN Red List of Threatened

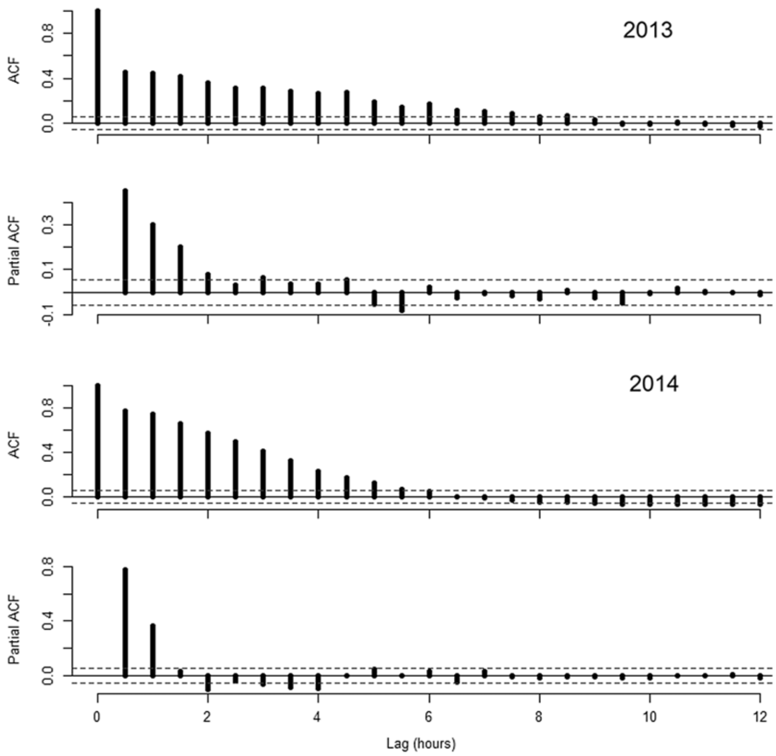

Fig. 8. The autocorrelation and partial autocorrelation functions of the times series of passage of Sakhalin taimen by the Karibetsu weir during 22 April–14 May 2013 and 20 April–13 May 2014. The dashed lines indicate the point of statistical significance ($p < 0.05$).

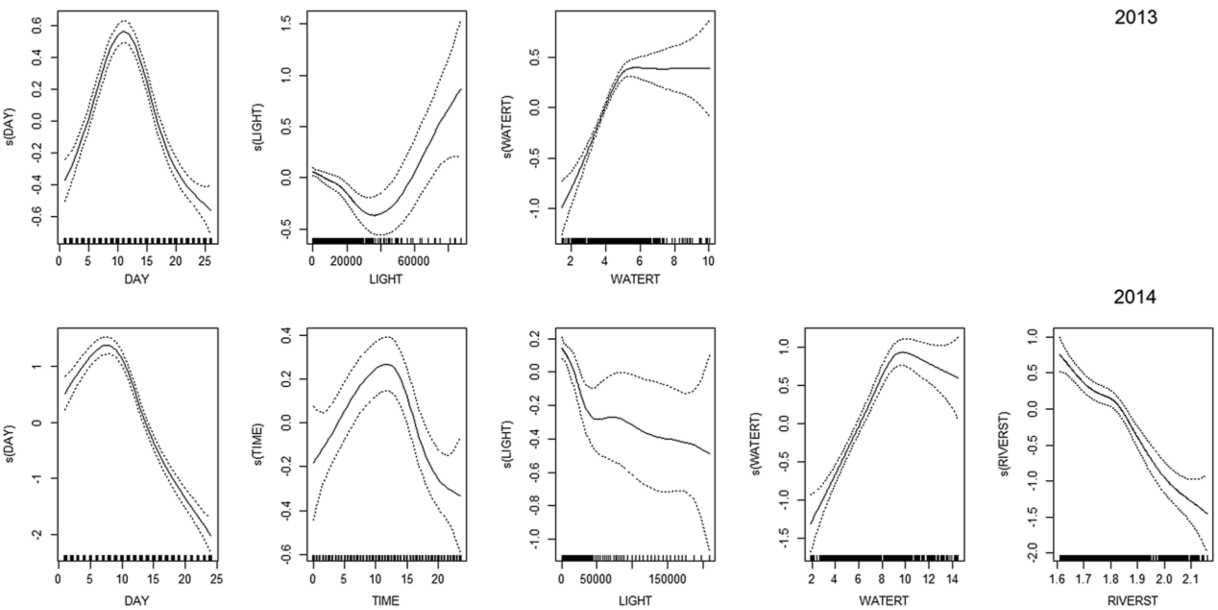

Fig. 9. Smoothed explanatory variables in GAM (DAY = day of migration; LIGHT = illuminance, in lux; WATERT = water temperature; TIME = hour of day; RIVERST = stage of river, in m) predicting passage rate (# taimen passing Karibetsu weir site per 30 min) over the course of the spring spawning migration period during 2013 and 2014. Solid line represents the transformed explanatory variables fit in the model, and the broken lines represent +/ − 1 standard error.

Species as Critically Endangered in 2006. This is the first effort to enumerate the entire spawning run of a population of this endangered species. The Sarufutsu River is recognized as one of the last Sakhalin taimen strongholds in Japan. Based on earlier research (Fukushima, 2001), the spawning tributary we studied (Karibetsu River) accounts for roughly 1/3 of the total spawning grounds in the Sarufutsu watershed. By simply expanding our tributary estimate (335 in 2013, and 425 in

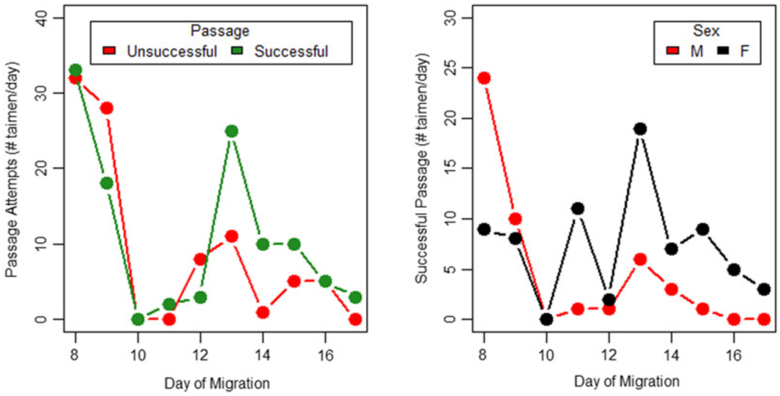

Fig. 10. Result of video monitoring of migrants at the final, upstream step of the Karibetsu weir during 2013. The left panel is a plot of unsuccessful and successful passage attempts over the day of migration (April 22 = Day 1). The right panel includes the time series of the number of successful passage attempts by sex. Sexes were determined based on judging spawning coloration during playback of video records.

2014) to the entire river population based on the proportion of habitat we sampled, we conclude that the total spawning population in this watershed is ca. 1000–1250 individuals. It is important to note here that our estimate may be low. One important unknown here is whether taimen are skip spawners (that is, adults do not necessarily spawn every year, see Rideout and Tomkiewicz, 2011). If this is indeed the case, then we underestimated the true population size. Although we expand our estimate to parts of the river that were not sampled in our study, we feel the expansion factor used is reliable. This expansion is based on the number of spawning redds (fish nests) in the Karibetsu to the total number in the whole basin of the Sarufutsu River (Fukushima, 2001). Results of redd count surveys that began in the early 1990s have indicated the population has been relatively stable over the past 20 years (M. Fukushima, NIES, unpublished results).

Recreational fishing pressure, however, has grown markedly, and concern is growing about whether the current fishing regime is sustainable. A recent recreational fishing creel survey in the lower Sarufutsu River concluded that the number of taimen caught at least once during the May–June period in 2010 was 1237 +/− 389 individuals (Kawamula et al., 2011). Although no fishing regulations currently exist on this population, it is thought that a majority of the fish are released following capture. Catch and release mortality, arguably one of the most important parameters to manage in cases of recreational fisheries on endangered species (Cooke et al., 2014), has not yet been quantified. This recreational fishery is composed of both juvenile (sexually premature) and spawning-aged individuals (catches peak in the lower river approximately 1 month following the spawning period). Based on size and coloration of fish captured in this fishery, it is thought that the majority (over 50%) of the fish captured consists of post-spawners (Kawamula et al., 2011). Based on our extrapolated estimate of the spawning population, we conclude that the current level of fishing pressure is likely affecting a substantial proportion of the spawning population. Actions to reduce the impact of fishing practices and formerly limiting the season will help buffer this population from harmful angling effects.

Past efforts have focused on redd counts (Fukushima, 1994, 2001; Edo et al., 2000) or passing fish by temporary weirs following spawning (K. Edo, Unpublished results). Our approach has several advantages over these more traditional surveys. Our approach requires no handling of the fish and is capable of producing a near census estimate of the population, as opposed to an index count (Holmes et al., 2006). Our method requires much less field effort, and is not as sensitive to river conditions. For example, weirs often fail during high discharge events or periods of high debris flow, and redd surveys are only possible when water discharge and water clarity are in a range to make visual recognition of redds possible. Rain on snow events that lead to elevated discharge and high turbidity, characteristic of the spring period in Hokkaido, makes it difficult to complete these types of surveys. Handling and passing fish at weirs can produce census counts, but requires extensive handling of the fish, and may cause stress. Our sonar method is non-intrusive, and we feel it is more appropriate, particularly for threatened species like Sakhalin taimen. We were able to easily overcome one of the main limitations of the use of sonar, species identification, by clearly distinguishing co-occurring migrating fish based on distinct differences in size.

Ours is the first study to quantify temporal autocorrelation of a taimen spawning run. A biological explanation for the good fit for differenced and autoregressive models is that these fish tend to pass the weir in small, migratory groups during punctuated periods lasting approximately an hour. These punctuated peaks can be seen in the raw data plotted in Figs. 5 and 6. It is important to note this fine grain pattern is not captured in the loess trends (Figs. 5 and 6) and the GAM model (DAY plot in Fig. 9). It is not clear whether this aggregation is based more on behavioral cohesion among individuals during the migration, or some type of aggregating effect created by the weir obstruction, or, alternatively, a combination of both processes. Inter-individual cohesion is very plausible considering the weir is in close proximity to the spawning grounds and sexual pairing and courtship leading to spawning occurs within several days after passage at the Karibetsu weir site.

Further, we found the autoregressive signature of the passage time series to be different between years. The time series of passage during 2014 was explained by a lower order, autoregressive model, exhibiting a stronger autocorrelation (at lag

1, returning a 0.8 correlation coefficient during 2014, compared to 0.4 in 2013, Fig. 8). Further, the scale of autocorrelation in 2013 was greater (> 1.5 h). These results suggest a 2013 pattern with greater "random walk" properties. We suggest that the migratory season of 2014 had much stronger environmental signals over the 24 h cycle (including light, temperature and discharge, Figs. 5 and 6) that resulted in stronger migratory cues, producing a more orderly, less random passage pattern.

Passage during 2014 had a more distinct diel structure. This was supported by the addition of TIME as a significant variable in the GAM model for 2014 (Fig. 9). Given the stronger diel patterns (particularly in light and water temperature) during 2014, it is not surprising to see TIME become significant for explaining variability in passage that year. Perhaps most telling is the rarity of night time passage in 2014 when less than 5% of the upstream migrants that year passed during the night (i.e. periods of zero lux). This differs greatly with 2013, when over 22% of the migrants passed the weir at night.

The seasonal range of discharge was much greater (approximately by a factor of two) in 2014 owing to a more rapid snow melt, and thus may have elicited a more pronounced effect on passage during that year. However, the scale of observations in river discharge in 2013 (daily measurements) was not as resolved as 2014 (sub-hourly measurements), thus our analysis was not capable of fully exploring discharge as an explanatory variable in 2013. In both years the bulk of the migrants passed our site during the falling limb of the spring hydrograph, a pattern also noted by Fukushima (1994).

This is also the first study to document sexual differences in return timing of Sakhalin taimen. Based on CCD video monitoring, we document protandry in return timing of the spawning population. This suggests males have a propensity to arrive early at the spawning grounds. Males arriving early may have an advantage by establishing and defending spawning ground territory (Morbey, 2000). It is important to note that our video monitoring yielded data on "passage events", not individuals (as noted in our methods section). Thus, our conclusions relating to shifts in sex ratios during the migration could be confounded if there is a marked sex bias in passage success.

Further, there is likely a "female-bias" in sex identification in our study. Two phenomena could contribute to false positives in identifying females at our site. First, low light conditions could mask male coloration, leading to misclassifying males as females. This may have contributed to error in our study (particularly contributing to the overall skewed M:F ratio of 77:122). Second, males may not have fully developed spawning coloration at the time of weir passage and could be mistaken as females. Due to the fact that our observations of taimen were close in time and space to spawning (determined through visual surveys upstream on the spawning grounds, M. Kawahara and P. Rand, Unpublished results), we feel male coloration was fully developed at the time of arrival at the weir and this latter bias is inconsequential. It is important to note that our conclusion of protandry in return timing is likely robust given the male dominated ratio we document early in the run countervails this sampling bias. Despite these limitations, we feel CCD video monitoring is a useful tool, particularly in conjunction with sonar monitoring, to obtain additional information on migration and passage success for this species.

We did not find a relationship between passage success and environmental variables in the analysis of the CCD video records during 2013, thus we were not able to show support for our hypotheses regarding the role of temperature and discharge on passage probability that year. There may have been some interaction between body size and passage probability in 2013, although we were not able to explore this due to a lack of data on individual sizes of fish observed passing in the video records. If the same size trend during the migration period (from large to small body sizes) occurred in 2013 that we observed in the sonar data during 2014 (see Fig. 7), then the pattern of increased passage probability we noted later in the migratory season may be a function of smaller taimen being more effective migrants. This is clearly an issue that deserved further research attention, particularly given that the presence of the weir may be causing some passage difficulty for larger individuals in the population.

Our inability to identify environmental variables controlling passage may have been a result of a relatively small sample size, or perhaps the range of environmental conditions we observed in 2013 was not sufficient to produce an effect on passage success. We did, however, document the potential importance of some environmental variables that control the migration process through analysis of our sonar data. Our GAM revealed the importance of some variables, particularly temperature and light level in both years, and an additional effect of river discharge in 2014, that can control migration to some degree. A cold front that passed through the region on day 9 of the migration during 2013 (seen clearly in the times series of illuminance and water temperature in Fig. 5) provided a natural experiment on how river conditions can slow or halt the migration process. Further, a pronounced period of flooding from rapid snow melt during spring 2014 produced high water and likely contributed to a slower passage rate at the weir early in the run (Fig. 6). While it is not possible to rule out the existence of an early and late run component of the population under some form of genetic control, the punctuated change in river conditions that corresponded to the abrupt change in migration pattern we observed over these two years suggests environmental control. Taimen appear to be more likely to migrate during daylight hours, but our data appear to reveal a more complex, non-linear relationship with illuminance (see 2013 results in Fig. 9) that does not lend itself to a simple, biological explanation.

We acknowledge some uncertainty by inferring migration rate from a single point of passage in the river. Some of the patterns we observed, for example, may be influenced by the initial distribution of taimen prior to the start of the spawning migration, or cues specific to conditions in the lower river or estuary (e.g. tidal influences). A more rigorous assessment of migration rate could be accomplished with monitoring at multiple sites along the river coupled with more extensive environmental monitoring, or a telemetry program where individual fish could be tracked at sites throughout the watershed.

5. Conclusions

Our study provides new insight into migratory and weir passage behavior through a combined approach using sonar and CCD video monitoring. We feel our approach provides a robust estimate of population size, which is critically needed to establish abundance baselines in rivers supporting this imperiled species. Given the relatively small size of this population, and the current recreational fishing pressure, we recommend enactment of regulations to conserve this species.

We hope our study will provide a useful model to extend to other taimen rivers within the Japanese and Russian range. This would lead to a better understanding of their current status. Further, our approach provides a means of understanding how environmental factors (particularly temperature and river discharge) can control the migration process and particularly issues related to fish passing obstructions like the Karibetsu River weir. The species range in Japan has been significantly fragmented as a result of dam development (e.g. Fukushima et al., 2011), but there has been no directed research to date on the phenomenon of taimen passage by dam obstructions, and the diversity of behaviors these fish exhibit to navigate through points of difficult passage (including road culverts). Our study indicated that passage success over a low, concrete weir varies over the course of the migration. It is hoped our study will help stimulate further research in this area to better understand passage problems, and help promote solutions to modify or remove dams and other migratory impediments to help ecologically restore these important taimen river systems.

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References

Burwen, D.L., Fleischman, S.J., Miller, J.D., 2010. Accuracy and precision of salmon length estimates taken from DIDSON sonar images. Trans. Am. Fish. Soc. 139 (5), 1306–1314.
Cooke, S.J., Hogan, Z.S., Butcher, P.A., Stockesbury, M.J.W., Raghavan, R., Gallagher, A.J., Hammerschlag, N., Danylchuk, A.J., 2014. Angling for endangered fish: conservation problem or conservation action? Fish and Fisheries http://dx.doi.org/10.1111/faf.12076.
Edo, K., Kawamula, H., Higashi, S., 2000. The structure and dimensions of redds and egg pockets of the endangered salmonid, Sakhalin taimen. J. Fish Biol. 56 (4), 890–904.
Fukushima, M., 1994. Spawning migration and redd construction of Sakhalin taimen, *Hucho perryi* on north Hokkaido Island. Japan. J. Fish Biol. 44 (5), 877–888.
Fukushima, M., 2001. Salmonid habitat-geomorphology relationships in low- gradient streams. Ecology. 82 (5), 1238–1246.
Fukushima, M., Shimazaki, H., Rand, P.S., Kaeriyama, M., 2011. Reconstructing Sakhalin taimen *Parahucho perryi* historical distribution and identifying causes for local extinctions. Trans. Am. Fish. Soc. 140 (1), 1–13. http://dx.doi.org/10.1080/00028487.2011.544999.
Hastie, T., Tibshirani, R., 1990. Generalized Additive Models. Chapman and Hall, London.
Hilborn, R., 2002. The dark side of reference points. Bulletin of Marine Science 70 (2), 403–408.
Hinch, S.G., Rand, P.S., 1998. Swim speeds and energy use of upriver-migrating sockeye salmon (*Oncorhynchus nerka*): role of local environment and fish characteristics. Can. J. Fish Aquat. Sci. 55, 1821–1831.
Holčik, J., Hensel, K., Nieslanik, J., Skácel, L., 1988. The Eurasian Huchen, Hucho hucho, Largest Salmon in the World. Dr. W. Junk Publishers, Dordrecht.
Holmes, J.A., Cronkite, G.M.W., Enzenhofer, H.J., Mulligan, T.J., 2006. Accuracy and precision of fish-count data from a dual-frequency identification sonar (DIDSON) imaging system. ICES J. Mar. Sci. 63, 543–555.
Hyndman, R.J., Khandakar, Y., 2008. Automatic time series forecasting: The forecast package for R. J. Stat. Softw. 26 (3).
Jensen, O.P., Gilroy, D.J., Hogan, Z., Allen, B.C., Hrabik, T.R., Weidel, B.C., Chandra, S., Vander Zanden, M.J., 2009. Evaluating recreational fisheries for an endangered species: a case study of taimen, Hucho taimen, in Mongolia. Can. J. Fish. Aquat. Sci. 66, 1707–1718.
Kawamula, H., Aoyama, T., Shimoda, K., 2011. Effect of catch and release: Creel survey on taimen fishing in the lower reach of the Sarufutsu River. Hokkaido Fisheries Research Institute Newsletter 83, 9–12. [Translated to English from Japanese].
Kawanabe, H., Mizuno, N., 1989. Freshwater Fishes of Japan. Yama-Kei Publishers, Tokyo, Japan, p. 720.
Marascuilo, L.A., 1966. Large-sample multiple comparisons. Psychological Bulletin 65 (5), 280–290. http://dx.doi.org/10.1037/h0023189.
Maxwell, S., 2007. Hydroacoustics: Rivers. In Salmonid Field Protocols Handbook: Techniques for Assessing Status and Trends in Salmon and Trout Populations. American Fisheries Society, Bethesda, Maryland, USA, p. 478.
Miller, J.D., Burwen, D.L., Fleischman, S.J., 2013. Estimates of Chinook salmon passage in the Kenai River using split-beam and dual-frequency identification sonars, 2010. Alaska Department of Fish and Game, Fishery Data Series No. 13-58, Anchorage.
Morbey, Y., 2000. Protandry in Pacific salmon. Can. J. Fish. Aquat. Sci. 57, 1252–1257.
Moser, M.L, Mesa, M.G., 2009. Passage considerations for anadromous lampreys. American Fisheries Society Symposium 72.
Moursund, R.A., Carlson, T.J., Peters, R.D., 2003. A fisheries application of a dual-frequency identification sonar acoustic camera. ICES J. Mar. Sci. 60, 678–683.
Rand, P.S., 2013. Current global status of taimen and the need to implement aggressive conservation measures to avoid population and species-level extinction. Arch. Pol. Fish. 21, 119–128.
Rideout, R.M., Tomkiewicz, J., 2011. Skipped spawning in fishes: More common than you might think. Marine and Coastal Fisheries: Dynamics, Management and Ecosystem Science 3 (1), 176–189.
Roscoe, D.W., Hinch, S.G., 2010. Effectiveness monitoring of fish passage facilities: historical trends, geographic patterns and future directions. Fish and Fisheries 11 (1), 12–33.
Scheiner, S.M., Gurevitch, J., 2001. Design and Analysis of Ecological Experiments. Oxford University Press.
Thorstad, E.B., Okland, F., Aerestrup, K., Heggberget, T.G., 2008. Factors affecting the within-river spawning migration of Atlantic salmon, with emphasis on human impacts. Rev. Fish Biol. Fisheries 18, 345–371.