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Reproductive Biology of *Schizothorax o'connori* (Cyprinidae: Schizothoracinae) in the Yarlung Zangbo River, Tibet

Bao-Shan Ma[1,2], Cong-Xin Xie[1,*], Bin Huo[1], Xue-Feng Yang[1], and Shui-Song Chen[3]

[1]*College of Fisheries, Huazhong Agricultural University, Wuhan, Hubei 430070, China*

[2]*Yangtze River Fisheries Research Institute, Chinese Academy of Fishery Sciences, Wuhan, Hubei 430223, China*

[3]*Yangtze Valley Water Environmental Monitoring Center, Wuhan, Hubei 430010, China*

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Bao-Shan Ma, Cong-Xin Xie, Bin Huo, Xue-Feng Yang, and Shui-Song Chen (2012) Reproductive biology of *Schizothorax o'connori* (Cyprinidae: Schizothoracinae) in the Yarlung Zangbo River, Tibet. *Zoological Studies* **51**(7): 1066-1076. The reproductive biology of *Schizothorax o'connori* (Cyprinidae: Schizothoracinae) was studied by examining 1126 individuals collected between Aug. 2008 and Aug. 2009 in the Yarlung Zangbo River, Tibet. The population had a significantly higher proportion of females than males (χ^2 test, $p < 0.05$). Using a logistic regression, it was determined that the standard lengths at 50% maturity were 304 mm for males and 389 mm for females; the ages at 50% maturity were 8 yr for males and 10 yr for females. Based on the monthly proportions of macroscopic gonadal maturity stages and monthly variations in the gonadosomatic index, *S. o'connori* spawned over a short period, from Feb. to Apr. with a peak in Mar. Females had heavier livers than males for a given eviscerated weight (ANCOVA, $p < 0.05$). According to the size distribution of oocytes, *S. o'connori* appeared to show a high degree of spawning synchronicity. The estimated values of fecundity ranged 8228-39,343 (21,190 ± 6990) eggs/fish. The relative fecundity ranged 6.2-22.2 (14.3 ± 3.3) eggs/g of fish. The fecundity of *S. o'connori* increased linearly with the standard length and total weight, but had no significant correlation with age. http://zoolstud.sinica.edu.tw/Journals/51.7/1066.pdf

Key words: Reproductive biology, Spawning season, Fecundity, *Schizothorax o'connori*, Tibet.

Although the reproductive cycles of fishes have been studied worldwide, the Qinghai-Tibet Plateau region has received much less attention (Wu and Wu 1992). For Schizothoracinae fishes in this region, few data on reproductive traits are available (He et al. 2001, Zhang et al. 2005, Yang et al. 2011). Schizothoracinae fishes are generally long-lived, with low fecundity and late maturity, which make them susceptible to overfishing (Chen and Cao 2000). Biological invasions from lower elevations, such as *Carassius auratus* and *Pseudorasbora parva*, have also increased since the 1990s, and so native fishes are facing serious threats to their survival (Chen 2009). Conservation of their natural populations has; therefore, become a primary concern.

As an endemic species of the Tibetan Plateau, *Schizothorax o'connori* (Cyprinidae: Schizothoracinae) resides only in the middle and upper reaches of the Yarlung Zangbo River and its tributaries at elevations above 3000 m (Chen and Cao 2000). Like other Schizothoracinae fishes of the Tibetan Plateau, few investigations have been carried out on the biology and ecology of *S. o'connori*. Ma et al. (2011) indicated that the age and growth of *S. o'connori* can reliably be estimated from sections of lapillus otoliths. Ma et al. (2010) demonstrated that *S. o'connori* attains a lower growth performance and greater longevity compared to other cyprinid fishes and shows sexual dimorphism in the maximum size, longevity, and growth rate. Available data on the

*To whom correspondence and reprint requests should be addressed. Tel: 86-027-87286862. Fax: 86-027-87282114.
E-mail:xiecongxin@mail.hzau.edu.cn

reproductive biology of *S. o'connori* are scarce. Xu (2011) reported that *S. o'connori* requires a long period of 190 h for embryonic development at a water temperature of 12.1-13.8°C.

Reproduction has 3 key components of sexual maturity, reproductive period, and fecundity, which are vital demographic characteristics essential to an understanding of a species' life history (Cortes 2000). In addition to mortality, the size and age at 1st sexual maturity directly influence the reproductive potential of a species, partly determining the duration of the spawning period for each individual, and also influencing the quantity of the spawning stock (Sinovčić et al. 2008). As an energy source, the liver plays an important role in female reproduction. The energy required for growing oocytes may be derived from the liver (Colonello et al. 2007). Most of the growth of oocytes is a result of the accumulation of vitellogenin synthesized in the liver (Lubzens et al. 2010). Furthermore, ecological conditions such as the water temperature and photoperiod influence gonadal development and the sexual maturity of fish (Wootton 1990).

The specific objectives of this study were to: (1) estimate the sex ratio, size, and age at 50% maturity of *S. o'connori*; (2) describe the spawning season and spawning type of the fish, based on monthly proportions of macroscopic gonadal maturity stages, monthly variations in the gonadosomatic index (GSI), and the size distribution of oocytes; and (3) estimate the fecundity and relative fecundity of *S. o'connori*, and analyze relationships among the standard length (SL), total weight (W_T), age, and fecundity. Effects of environmental factors on gonadal development and sexual maturity were considered when studying the reproductive biology of *S. o'connori*.

MATERIALS AND METHODS

Collection of samples

In total, 1126 specimens were collected in monthly samplings from the Yarlung Zangbo River (98.9%) and its tributaries (Xiang Qu and Nyang Qu) between Aug. 2008 and Aug. 2009 (Fig. 1). More than 30 fish were collected each month. Specimens were sampled using floating gillnets and set gillnets (with a mesh size of 7.5 cm), and trap nets (with a mesh size of 1.5 cm). The SL was measured to the nearest 1 mm with a ruler, and the W_T, gonadal weight (W_G), liver weight (W_V), and eviscerated weight (W_E) of fresh specimens were measured to the nearest 0.1 g with an electronic balance. The sex was identified macroscopically, and the gonads were assigned a gross maturity stage based on their macroscopic appearance (Table 1).

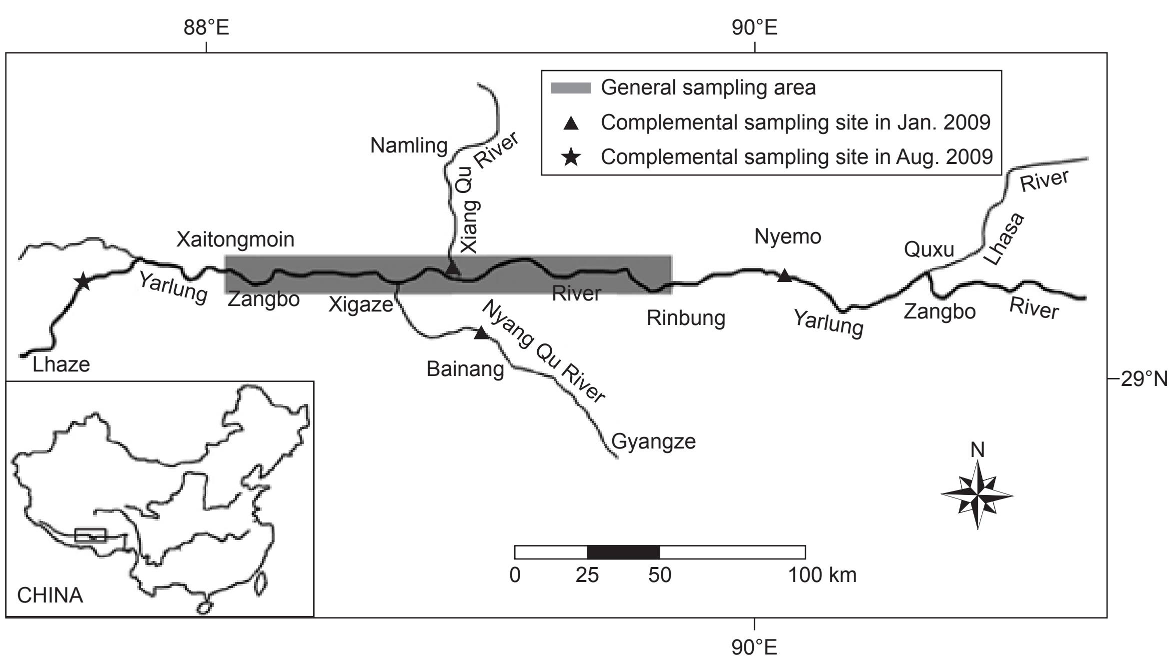

Fig. 1. Sampling locations of *S. o'connori* in the Yarlung Zangbo River, Tibet.

Sex ratio, size, and age at maturity

A χ^2 test was used to determine if the proportions of males and females significantly differed from 1: 1. Since the sex of each individual could not be determined macroscopically before the developing stage as defined in table 1, immature fish were not considered when evaluating the sex ratio.

Maturity was macroscopically assessed for males and females. The SL at which 50% of the fish were 'mature' (maturing stage and onward for males and females) was regarded as the mean size at 1st sexual maturity (L_{m50}), which the mean size at 50% maturity and the mean size at 1st sexual maturity have the same meaning was estimated by fitting a logistic function to the proportion (P) of mature fish using 10-mm (SL) size classes: $P = 1 / \{1 + \exp[-k (L_{Tmid} - L_{m50})]\}$ (Chen and Paloheimo 1994), where L_{Tmid} is the midpoint of the SL class, L_{m50} is the mean SL at 1st sexual maturity, P is the proportion of mature fish, and k is the slope.

The age at 1st maturity (A_{50}) was also estimated by fitting a logistic function to the proportion (P) of mature fish using 1-yr age classes: $P = 1 / \{1 + \exp[-k (A - A_{50})]\}$ (Chen and Paloheimo 1994), where A is the age of the fish and A_{50} is the age at 1st sexual maturity.

Spawning season

The spawning season was established by analyzing monthly proportions of macroscopic maturity stages and monthly variations in the GSI. The GSI of fish at the maturing stage and onward was calculated as $GSI = W_G/W_E \times 100$. In addition, the hepatosomatic index (HSI) of fish at the maturing stage and onward was calculated as $HSI = W_V/W_E \times 100$ (Wang and Chen 1995). An analysis of covariance (ANCOVA) was used to compare W_G-W_E and W_V-W_E relationships between sexes and among months for each sex. All weights were log-transformed before the analysis (Zar 1999).

Table 1. Macroscopic maturity scale and corresponding gonadosomatic index (GSI) of *Schizothorax o'connori* in the Yarlung Zangbo River, Tibet

	Classification	Macroscopic appearance	GSI mean ± S.D. (sample size)
	Immature	Sex cannot be identified macroscopically, gonads are relatively tiny and threadlike	(186)
Male	Developing	Testes increased in volume, filling about 10% of the body cavity, no visible vascularization, whitish in colour and sometimes pinkish	0.18 ± 0.16 (156)
	Maturing	Testes large and plump, occupying 20%~30% of the body cavity, whitish	1.44 ± 0.88 (105)
	Mature	Testes larger, occupying > 1/2 of the body cavity, milt runs under moderate pressure	4.47 ± 1.67 (145)
	Spawning	Milt runs under slight pressure or self-runs with no pressure	4.60 ± 0.98 (13)
	Spent	Testes significantly decreased in size, flaccid, shrunk, and bloodied, no milt expressed	1.53 ± 0.75 (9)
Female	Developing	Ovaries small, translucent, and reddish due to vascularization; oocytes not visually discernible	0.42 ± 0.30 (190)
	Maturing	Ovaries larger with rounded borders, occupying almost 1/2 the body cavity, well-developed vascularization; oocytes relatively small and clearly visible with the naked eye, some oocytes translucent	2.19 ± 1.39 (105)
	Mature	Ovaries distinctly bulging, occupying almost all of the body cavity, yellow, full of large mature oocytes, ovarian wall thin and flexible; oocytes run under moderate pressure	7.48 ± 3.62 (198)
	Spawning	Oocytes run under slight pressure or self-run with no pressure	9.25 ± 4.92 (9)
	Spent	Ovaries significantly reduced in volume, flaccid, shrunk, and bloodied; some scattered residual vitellogenic oocytes visible; ovarian wall thicker	1.76 ± 0.65 (10)

The GSI was calculated as $GSI = W_G/W_E \times 100$.

Oocyte diameter distribution

To establish the monthly size-frequency distribution of oocytes in *S. o'connori*, females with vitellogenic ovaries representing mature individuals were subsampled and fixed in 10% formalin. Sizes of the oocytes were measured using Image-Pro Plus software after taking photos with Leica Application Suite (vers. 15; Leica, Wetzlar, Germany) under a dissecting microscope linked to a CCD video camera (Leica, Wetzlar, Germany). For each individual, 100-150 oocytes (with a sample size/month of 3-10) were measured (Poisson and Fauvel 2009).

Fecundity

Individual fecundity was assessed by a gravimetric method (Bagenal and Braum 1978). Oocytes were sampled from the anterior, median, and posterior portions of the right lobe of each ovary. To determine fecundity, all oocytes that had begun vitellogenesis were counted as potentially ripe eggs. The relative fecundity was expressed as the number of oocytes per gram of female body weight. Relationships among the SL, W_T, age, and fecundity of *S. o'connori* were studied using a regression analysis (Duponchelle et al. 2000).

Environmental factors

Water temperature was measured and recorded twice a day (08:00 and 20:00), and the mean of the 2 values was used in our analysis. Data of the photoperiod (http://www.time.ac.cn/serve/sunriseset) and water level (http://www.xzsw.com.cn) were available online.

Statistical analysis

Data are presented as the mean ± standard deviation (S.D.). A difference was regarded as significant at $p < 0.05$. Analyses were conducted using SPSS 16.0 (SPSS, Chicago, IL, USA) and Origin 8.0 (OriginLab, Northampton, USA).

RESULTS

Sex-ratio and length composition

The SL of 1126 *S. o'connori* specimens ranged 33-553 mm, and the W_T ranged 4.3-2982.6 g. Of the 1126 *S. o'connori* collected, 428 were males with an SL of 178-460 mm, 512 were females with an SL of 177-562 mm, and 186 were immature with an SL of 33-309 mm (Fig. 2). The overall sex ratio significantly differed from 1:1 ($\chi^2 = 7.506$, *d.f.* = 1, $p < 0.05$), with 45.5% males and 54.5% females. Length-frequency distributions significantly differed between sexes (Kolmogorov-Smirnov $Z = 7.607$, $n_1 = 428$, $n_2 = 512$, $p < 0.05$). The proportion of males in the 200-400-mm SL group was substantially higher than that of females, whereas the proportion of females in the > 400 mm SL group greatly exceeded that of males (Fig. 2).

Size and age at maturity

Age data of *S. o'connori* came from our previous studies (Ma et al. 2010 2011). Size and age at maturity showed clear differences between males and females (Fig. 3). Length (L_{m50}) and age (A_{50}) at 50% maturity were estimated by fitting a logistic function to the proportion (P) of mature fish, and the functions are described as follows:

Length at 50% maturity

Male: $P = 1 / (1 + \exp(-0.028\ (SL - 304)))$, $n = 428$, $R^2 = 0.972$ and

Female: $P = 1 / (1 + \exp(-0.061\ (SL - 389)))$, $n = 512$, $R^2 = 0.974$; and

Age at 50% maturity

Male: $P = 1 / (1 + \exp(-0.434\ (A - 8)))$, $n = 416$, $R^2 = 0.904$ and

Female: $P = 1 / (1 + \exp(-0.829\ (A - 10)))$, $n = 493$, $R^2 = 0.967$.

Estimated L_{m50} values for sexually mature males and females were 304 and 389 mm, respectively (Fig. 3A). Estimated A_{50} values of sexual maturity were 8 yr for males and 10 yr for females (Fig. 3B). According to the length-weight relationship of *S. o'connori* (Ma et al. 2010), the corresponding total weights were 405.5 g for males and 837.1 g for females.

Spawning season

Based on the distribution of macroscopic maturity stages of males and females and monthly trends of the GSI, the reproductive cycle was divided into 3 main phases: (1) a phase of gonad development; (2) a period of spawning; and (3) a resting phase.

The monthly proportions of different developmental stages of ovaries and testes are shown in figure 4. Proportions of mature ovaries were high from Jan. to Mar., with a peak in Feb.

(80.65%). Spawning ovaries were found in Mar. and Apr., and spent ovaries from Mar. to May. The monthly trend of testes was similar to that of ovaries, but was slightly delayed (Fig. 4B). Proportions of mature testes were highest in Feb. and Mar., while a few spawning testes were also observed in May (Fig. 4A).

For a given eviscerated weight, females had a significantly higher gonadal weight than males (ANCOVA, $F = 177.286$, $d.f. = 2$, $n_1 = 272$, $n_2 = 322$, $p < 0.05$). The mean GSI of females was much higher than that of males (10.60 for females and 4.05 for males in Mar.). There was a significant difference among months in the W_G-W_E relationship of female *S. o'connori* (ANCOVA, $F = 16.003$, $d.f. = 12$, $p < 0.05$, numbers are given in Table 2). Females showed a higher GSI from Jan. to Apr., with a peak in Mar. From May to Aug., females were in the resting phase characterized by the lowest GSI. After that, a long phase of gonadal development continued from Aug. to Dec. (Fig. 5A). There was also a significant difference among months in the W_G-W_E relationship of males (ANCOVA, $F = 14.704$, $d.f. = 12$, $p < 0.05$, Table 2). Monthly GSI variations of males were similar to those of females, with the highest levels also being recorded from Feb. to Apr. (Fig. 5A). It seemed that the spawning period coincided with increases in the water temperature and photoperiod (Fig. 6). Suitable water temperatures for reproduction of *S. o'connori* are 2-10°C.

There was a significant difference among months in the W_V-W_E relationship of female *S. o'connori* (ANCOVA, $F = 16.904$, $d.f. = 11$, $p < 0.05$, Table 2). The HSI of females rose from Sept. to Jan., fell sharply in February, and then remained at a low level until July (Fig. 5B). There was also a significant difference among months in the W_V-W_E relationship of males (ANCOVA, $F = 26.967$, $d.f. = 10$, $p < 0.05$, Table 2). The HSI of males had a similar trend to that of females, except for Dec. (Fig. 5B). Furthermore, there was a significant

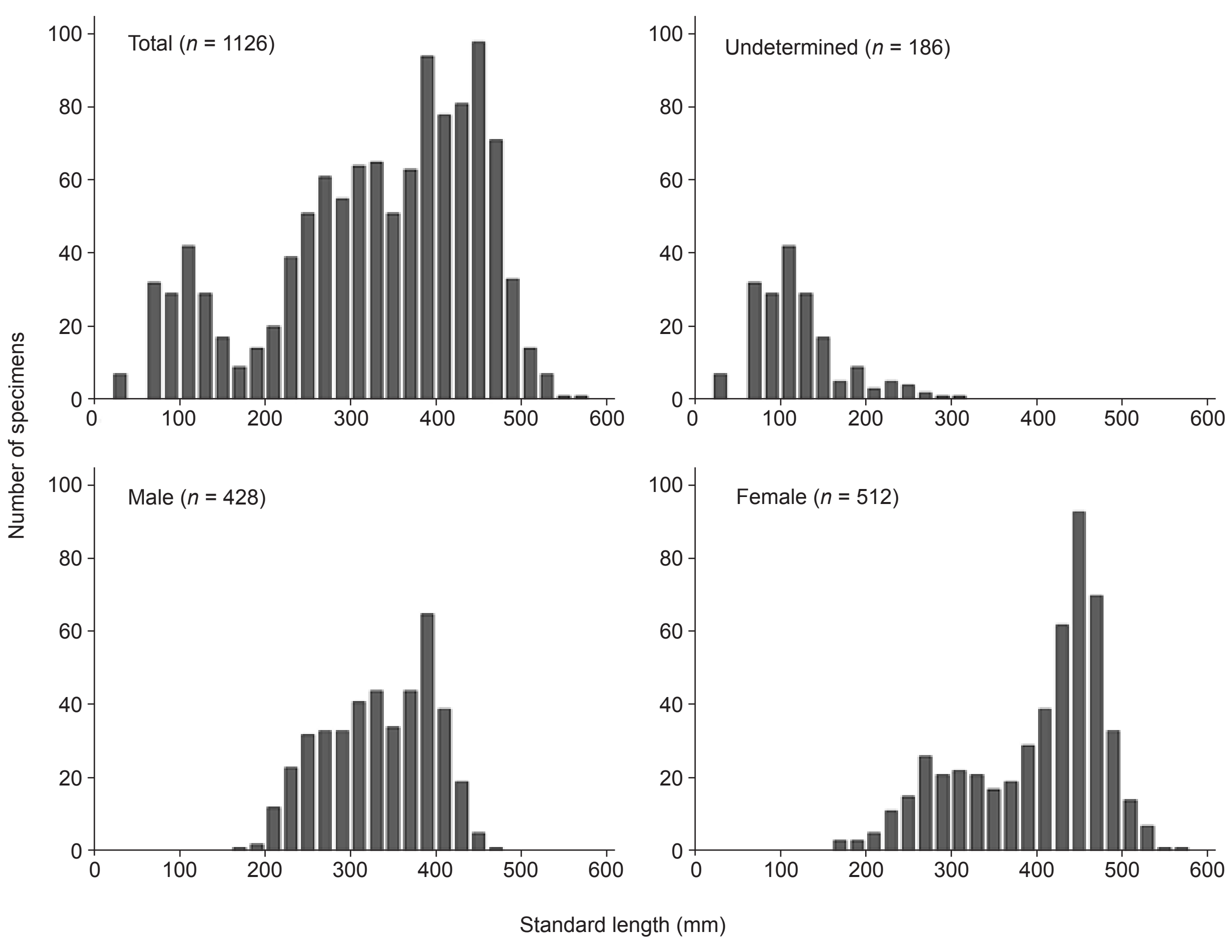

Fig. 2. Distributions of the standard length frequency of *Schizothorax o'connori* in the Yarlung Zangbo River, Tibet.

difference between sexes in the W_V-W_E relationship (ANCOVA, $F = 81.984$, $d.f. = 2$, $n_1 = 98$, $n_2 = 128$, $p < 0.05$), indicating that females had heavier livers than males for a given eviscerated weight.

Oocyte diameter distribution

Egg sizes were measured from mature ovaries in July 2008 to Apr. 2009 (Fig. 7). The yolk began accumulating in July and Aug., and oocytes continued growing until Apr. Oocytes with a diameter of > 2.0 mm formed a high proportion from Feb. to Apr., with a peak in Mar. Oocyte diameter had a unimodal distribution every month (Fig. 7), indicating that there was a high degree of spawning synchronicity in the *S. o'connori* population.

Fecundity

Fecundity was estimated from 109 mature females which ranged 390-562 mm in SL. Estimated values of fecundity ranged 8228-39,343, with a mean of 21,190 (± 6990) eggs/fish. The

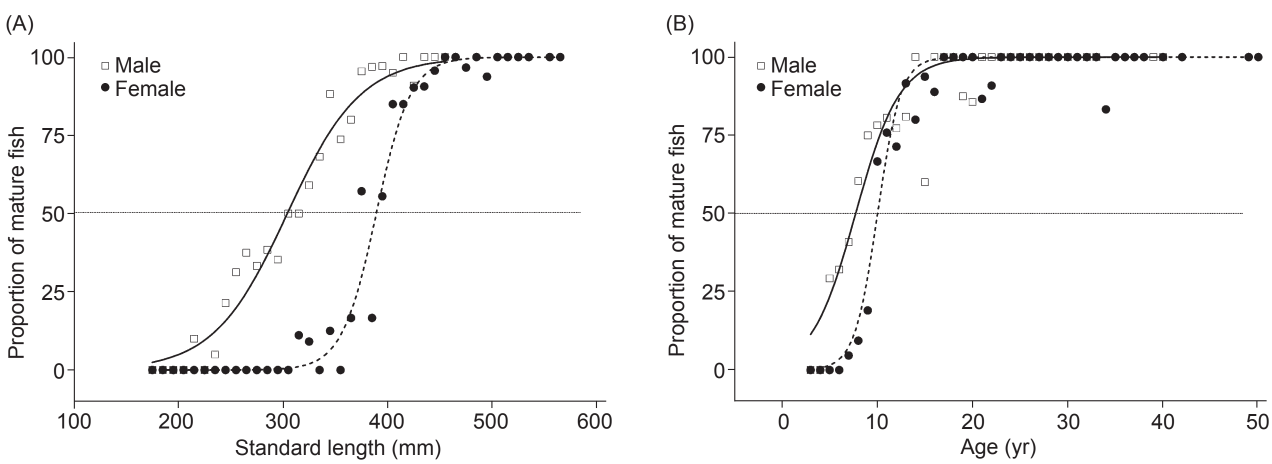

Fig. 3. Logistic functions fitted to the percent mature individuals using 10-mm standard-length and 1-yr age classes of male and female *S. o'connori* in the Yarlung Zangbo River, Tibet, showing the mean standard length (A) and age (B) at 50% maturity.

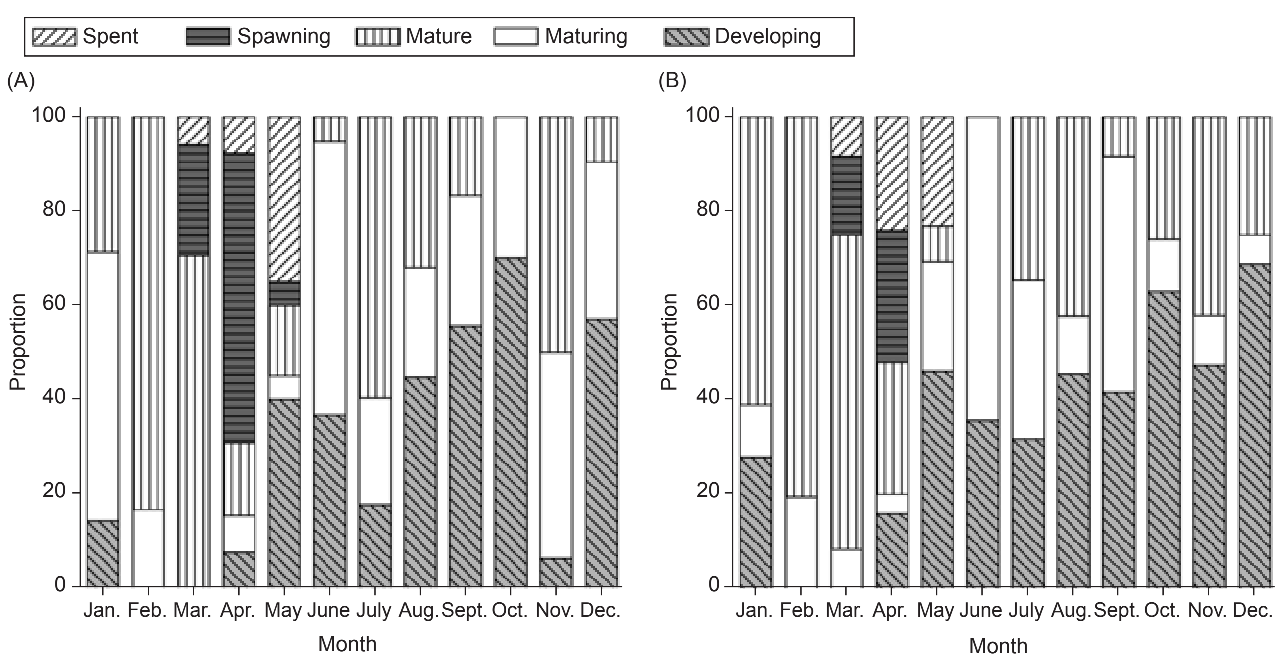

Fig. 4. Proportion of males (A) and females (B) of *S. o'connori* in the Yarlung Zangbo River, Tibet with different gonadal developmental stages in different months.

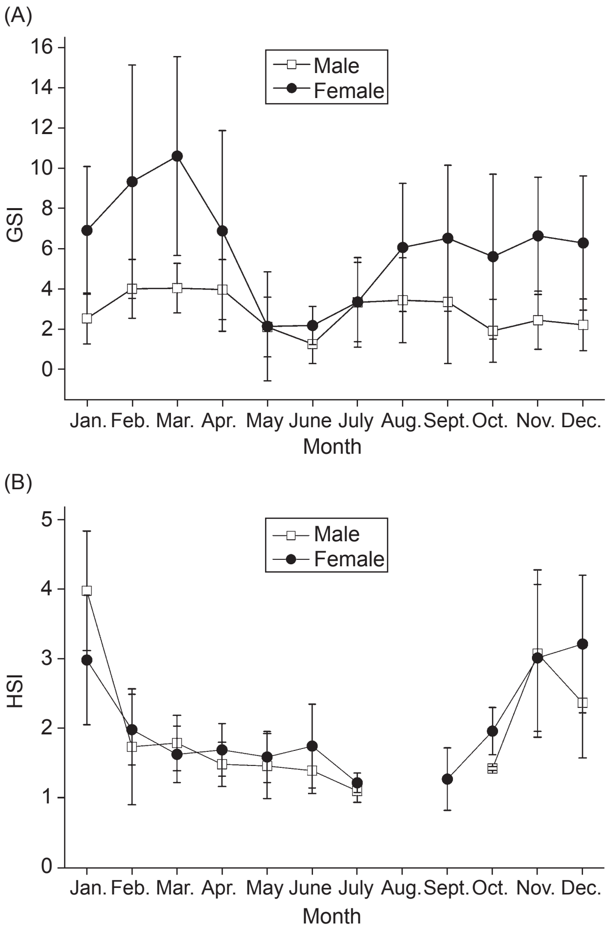

Fig. 5. Monthly changes of the gonadosomatic index (GSI, A) and hepatosomatic index (HSI, B) in *S. o'connori* in the Yarlung Zangbo River, Tibet. Error bars represent the standard deviation.

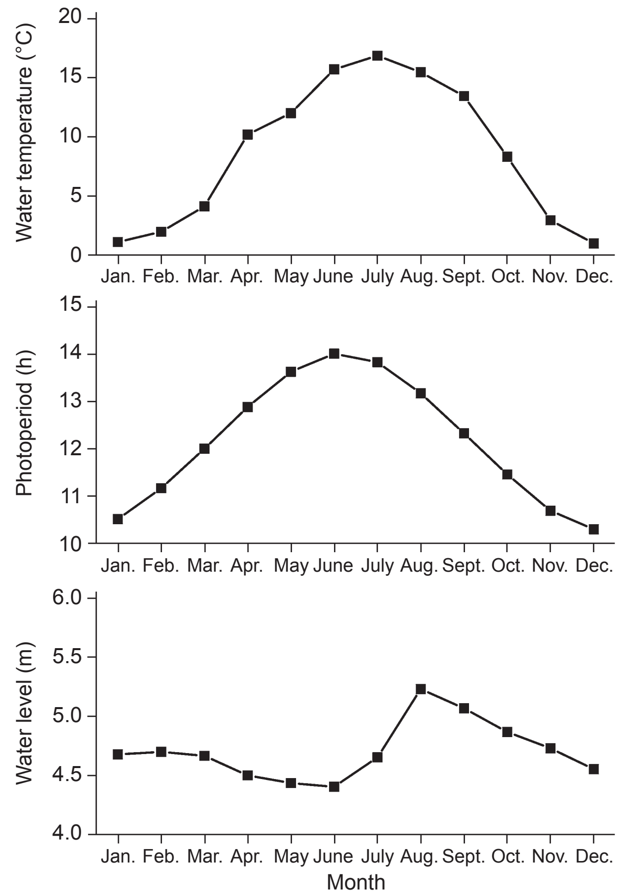

Fig. 6. Monthly variations in the water temperature, photoperiod, and water level in the Yarlung Zangbo River between Aug. 2008 and Aug. 2009.

Table 2. Numbers of male and female *S. o'connori* for the statistical analysis of W_G-W_E and W_V-W_E relationships

Month	W_G-W_E relationship		W_V-W_E relationship	
	Males	Females	Males	Females
Jan.	6	13	6	13
Feb.	6	31	6	31
Mar.	17	12	17	13
Apr.	12	21	12	20
May	12	7	12	7
June	12	9	12	9
July	51	99	6	7
Aug.	121	98	-	-
Sept.	8	7	-	3
Oct.	3	10	3	10
Nov.	15	10	15	10
Dec.	9	5	9	5
Total	272	322	98	128

relative fecundity ranged 6.2-22.2 eggs/g of fish, with a mean of 14.3 (± 3.3) eggs/g of fish.

The fecundity of *S. o'connori* increased linearly with an increasing SL (Fig. 8), and the fitted regression equation was $F = 158.5SL - 5.226 \times 10^4$, $n = 109$, $R^2 = 0.425$. Fecundity also increased linearly with an increasing W_T (Fig. 8), and the fitted regression equation was $F = 14.405W_T - 97.661$, $n = 109$, $R^2 = 0.480$. Fecundity was not significantly correlated with age ($p > 0.05$).

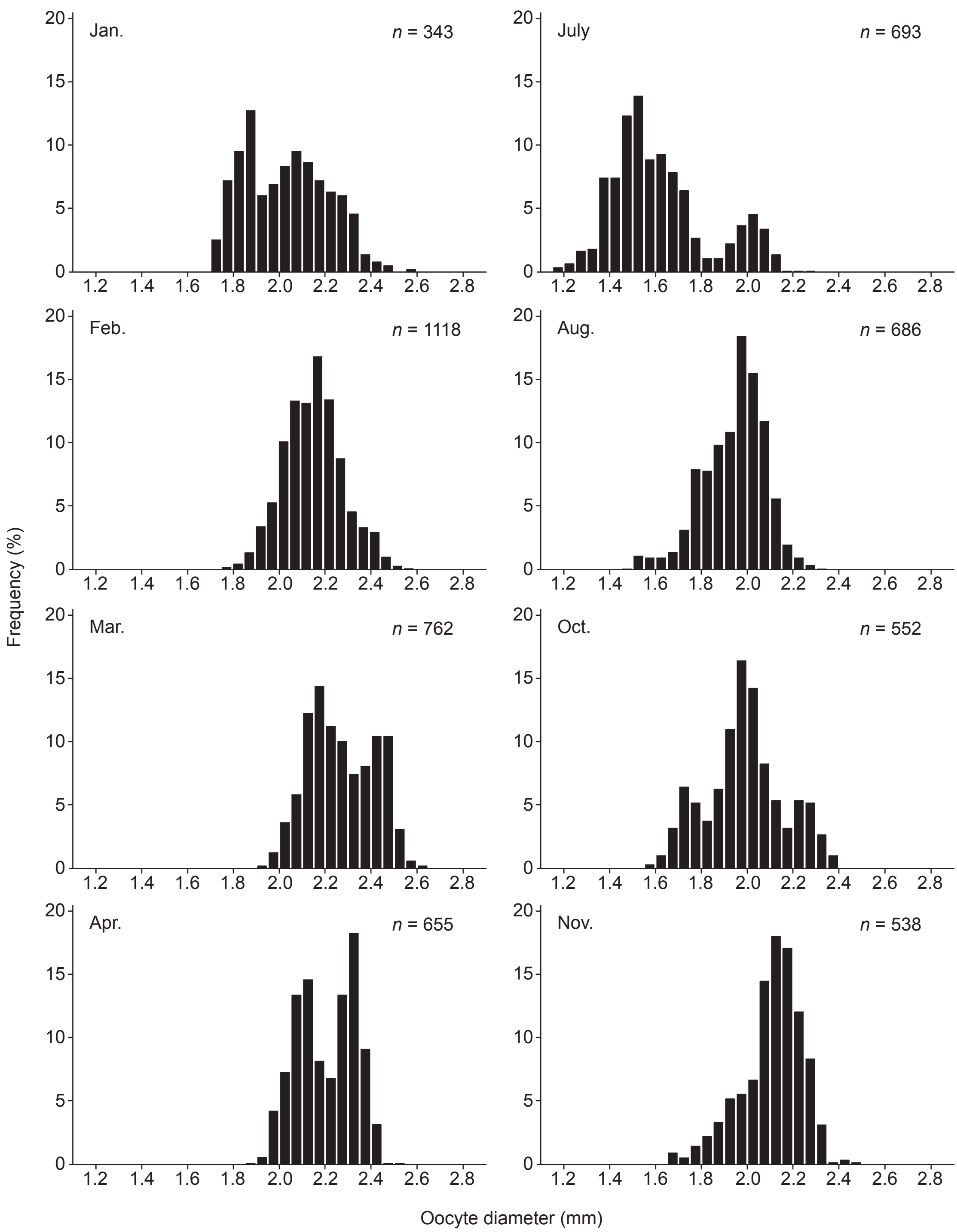

Fig. 7. Monthly size-frequency distribution of oocytes of *S. o'connori* in the Yarlung Zangbo River, Tibet from July 2008 to Apr. 2009 (except for Sept. and Dec.)

DISCUSSION

The sex ratio may be influenced by a number of factors including a sex difference in longevity, a sex difference in growth, and the sampling methodology (Wu and Wu 1992, Liao and Chang 2011). In the present study, proportions of females in the overall population and in the population of larger adults were greater than those of males, reflecting faster growth and a greater longevity of females; these results also corroborated the findings of Ma et al. (2010).

Size and age at 1st maturation, and mortality directly influence the reproductive potential of a fish population (Beacham 1983). Ecological conditions (such as the water temperature and photoperiod) greatly influence the sexual maturity of fish (Pawson et al. 2000, Rodríguez et al. 2001). In this study, males and females respectively reached the mean size at 1st sexual maturity at 304 and 389 mm SL, indicating that *S. o'connori* is characterized by relatively late maturation. For other cyprinid fishes of low-elevation rivers, size and age at 1st maturation were estimated to be much smaller and younger (Rutaisire and Booth 2005, Liu et al. 2011). In addition to late maturation, low fecundity was another reproductive trait of *S. o'connori* compared to other cyprinids at low elevations (Abedi et al. 2011, Liu et al. 2011). This reproductive characteristic of *S. o'connori* may be related to ecological conditions at this high elevation. This phenomenon was also described in other Schizothoracinae fishes by Zhang et al. (2005) for *Gymnocypris przewalskii przewalskii* and Yang et al. (2011) for *Gymnocypris waddellii*, which also reside on the Qinghai-Tibet Plateau.

Reproductive processes of fishes are controlled by endogenous and exogenous aspects; exogenous aspects are represented by environmental characters, which vary seasonally (Jobling 1995). Water temperature and photoperiod are thought to be the principal environmental factors used to synchronize the endogenous rhythms of reproduction of many cyprinid fishes (De Vlaming 1975, Papoulias et al. 2006). In the present study, gonadal development of *S. o'connori* was initiated in July, suggesting that gonadal development may be induced by

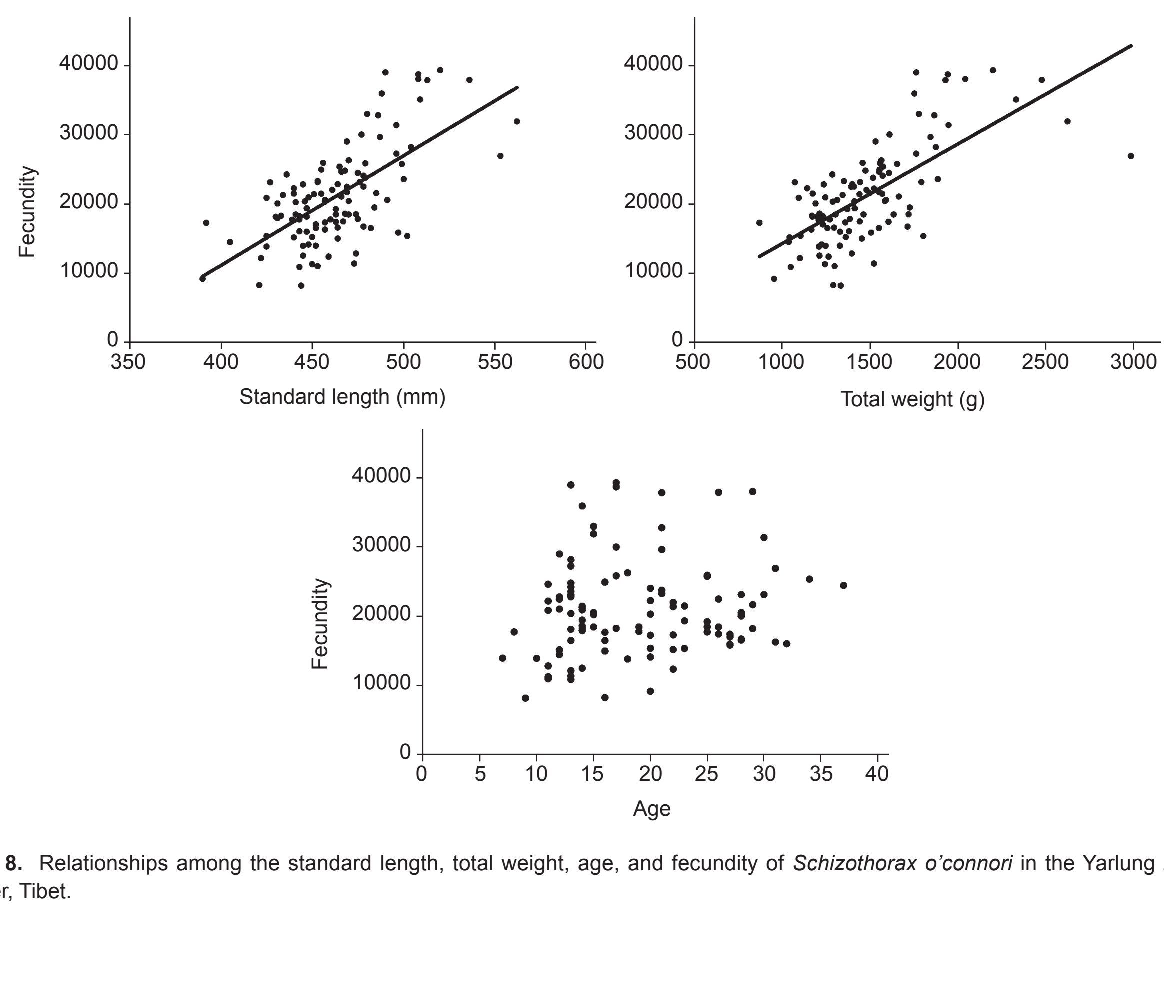

Fig. 8. Relationships among the standard length, total weight, age, and fecundity of *Schizothorax o'connori* in the Yarlung Zangbo River, Tibet.

high water temperatures and a long photoperiod. The fish did not begin to spawn until the water temperature and photoperiod began increasing in Feb., suggesting that increasing water temperature and photoperiod might be cues leading to final maturation of oocytes and the initiation of reproductive activities.

Results of this study provide the 1st evidence from observations of ovaries that *S. o'connori* in the Yarlung Zangbo River has a high degree of spawning synchronicity, with a short spawning season from Feb. to Apr. and a spawning peak in Mar. Reproductive activities of this species were completed in May when environmental conditions became suitable (high water temperatures, a long photoperiod, and low water levels) for embryonic development. Low water temperatures on the Tibetan Plateau lead to a long period of embryonic development in *S. o'connori* (Xu 2011). The early spawning season might ensure favorable ecological conditions during the long period of embryonic development and represent an adaptation to riverine conditions on the Tibetan plateau.

Fish can store energy in the liver and other tissues to meet the requirements of spawning (Liao and Chang 2011). In this study, female *S. o'connori* had heavier livers than males for a given eviscerated weight, suggesting that the importance of the liver as an energy source was greater for females than males, which probably reflects its role in synthesizing vitellogenin. In addition, an opposite trend between the GSI and HSI (Fig. 5) of females also suggested that the required energy for vitellogenesis by female *S. o'connori* may be derived from their liver.

The effects of fishery management on population dynamics depend on the biological and environmental characteristics of the fish. Our findings indicated that late maturation, low fecundity, and aggregation-spawning were typical characteristics of *S. o'connori*, and these characteristics render the population particularly vulnerable to overexploitation. More-restrictive harvest regulations, such as catch size limits and seasonal closure, may prevent overexploitation of these stocks, thereby providing better spawning opportunities to ensure sustainable utilization of this species.

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