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Life-history characteristics of the endangered Aristotle's catfish (*Silurus aristotelis* Garman, 1890), Lake Pamvotis, north-western Greece

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Summary

The life history characteristics of Aristotle's catfish, *Silurus aristotelis* (Agassiz 1856) were studied in Lake Pamvotis (northwestern Greece). Samples were collected on a monthly basis using gillnets, trammel-nets and traps. Total lengths ranged from 11.1 to 36.7 cm. Sex ratio was biased toward females (F : M = 1.8 : 1) and was statistically different from unity ($\chi^2 = 46.94$, $P < 0.001$). Spawning is from April to June. The relationship between total length and total weight showed positive allometric growth for males ($TW = 0.0035 \times TL^{3.21}$, $r^2 = 0.93$, $n = 198$, $P < 0.001$) and females ($TW = 0.0066 \times TL^{3.02}$, $r^2 = 0.95$, $n = 363$, $P < 0.001$). Age was determined on the annual growth marks formed on the spine of the pectoral fin. Based on cross-section readings of the spine, lifespan of the Aristotle's catfish was 5 years. Age classes 1 and 2 dominated the catches (39.1 and 40.0% of the total sample, respectively). Back-calculated lengths at age showed a rapid increase in fish size during the first year of life, reaching 61.1% of maximum attainable length, and a declining growth rate thereafter. Growth parameters were calculated as $L_\infty = 36.12$ cm, $K = 0.37$ year^{-1}, $t_0 = -0.76$ year based on the observed lengths at age and as $L_\infty = 28.19$ cm, $K = 0.53$ year^{-1}, $t_0 = -0.62$ year based on the back-calculated lengths at age. It seems that some of the life history traits (longevity, growth pattern, reproductive period) are influenced significantly by adverse effects of pollution and eutrophication on the lacustrine ecosystem.

Introduction

Aristotle's catfish, *Silurus aristotelis* Garman, 1890, is a species endemic to the lower Acheloos River system (western Greece), which includes four lakes (Trichonis, Lysimachia, Ozeros and Amvrakia) (Economidis, 1991). Two non-native populations have been established by translocation of fish from Lake Trichonis to Lake Pamvotis (northwestern Greece) between 1950 and 1955 and to Lake Volvi (northern Greece) in 1986 (Economidis et al., 2000; Leonardos et al., 2007). In Lake Volvi, Aristotle's catfish established an exploited population, which competed with the native population of the congeneric European wels (*S. glanis*) and eventually lead to its extinction (Economidis et al., 2000). Although it was originally abundant across its distribution area, in recent years most populations tend to decline in the area of origin due to high mortalities arising from water pollution and fishing pressures (Leonardos et al., 2007). Today, viable populations (successful translocation) are present only in Pamvotis Lake and smaller populations inhabit the lakes Trichonis, Lysimachia, Ozeros and Amvrakia, whereas the species seems to be extinct in Lake Volvi (unsuccessful translocation).

Aristotle's catfish occurs in the slow flowing reaches of rivers with turbid water, streams and canals, in lakes with dense weed-bed and muddy bottoms. It feeds at night primarily on fish and secondarily on crustaceans, gastropods, insects, small frogs and snakes (Iliadou and Ondrias, 1986). It is listed as 'endangered' in the EU Habitat Directive 92 ⁄ 43 ⁄ EEC (Annexes, IV), as 'strictly protected' by the Bern Convention (Appendix II) and as 'protected' by the Greek State (Presidential Decree 67 ⁄ 1981). Aristotle's catfish was named after Aristotle (384–322 BC) who first described the spawning behaviour of the members of the genus (Leonardos et al., 2007).

Data on the biology of Aristotle's catfish are rather limited for Greek freshwater systems (Iliadou and Ondrias, 1986; Triantafyllidis et al., 2002; Leonardos et al., 2007) and hence the aim of the present study was to quantify some biological parameters such as age and growth, condition and reproduction of the species in Lake Pamvotis, in which it apparently thrives well while highly endangered in nearby habitats of origin. An attempt was made to investigate the discrepancy of the life history traits of this endangered species with those observed in previous studies.

Study site

Lake Pamvotis is located in the north-western part of Greece, (39°40′N, 20°53′E) and is a relatively small (occupying a total area of about 22 km^2) and shallow lake (mean depth of 4.5 m and maximum depth of 7.5 m). Because of the anthropogenic pollution, the lake is increasingly eutrophic with frequent algal blooms, depletion of dissolved oxygen and a rapid sediment accumulation caused by high productivity decreases the depth and extension of the macrophyte zone (Sarika-Hatzinikolaou, 1994). Moreover the lake seems to have been heavily polluted from pesticides (Hela et al., 2005), heavy metals (Albanis et al., 1986; Stalikas et al., 1994; Papagiannis et al., 2002) and microcystins (Kagalou et al., 2008). In the course of the last decades, the ecosystem of Lake Pamvotis supported many activities such as irrigation, discharge of domestic sewages and sediment deposit, which caused serious problems in its trophic state (Kagalou et al., 2003).

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Materials and methods

Sampling was conducted in Lake Pamvotis during the period November 2002–December 2003 (with exception of February 2003 when the lake was frozen and consequently sampling was impossible); 417 specimens were collected on a monthly basis, and additional samples of 205 specimens were collected in 2005 in order to study the population structure. Gillnets, trammel nets and fish traps were used in six sampling sites of the pelagic zone, which differed in depth, ranging from 1.5 to 7.5 m. Four types of gillnets with mesh sizes of 6, 12, 14 and 20 mm and four types of trammel nets with 28 ⁄ 160, 32 ⁄ 200, 60 ⁄ 240 and 80 ⁄ 300 mm inner ⁄ outer mesh sizes were used. Traps with mesh sizes of 6, 12 and 16 mm were also deployed. All fishing gear were placed from dusk until dawn.

Total (TL, 0.1 cm) and standard (SL, 0.1 cm) lengths, and total (TW, 0.1 g) and net weights (NW, 0.1 g) were recorded. The gonads and the liver were removed and weighed separately to the nearest 0.1 g. Sex was determined macroscopically. A χ^2 test (Zar, 1999) was used to assess whether sex ratios were different from 1.

Length–weight relationship ($W = aL^b$), was calculated with W the weight (g) and L the length (cm) (Froese, 2006). In the linear (after logarithmic transformation) form of the equation, a is the intercept to the y-axis of the best-fit line and b is the slope of the line. The regressions were performed separately for males and females and then tested for differences in slopes and intercepts between sexes using analysis of covariance (ANCOVA, Zar, 1999). A t-test (Pauly, 1984) was used to test whether Aristotle's catfish grows isometrically ($b = 3$) or allometrically (positive: $b > 3$ or negative: $b < 3$).

The Fulton condition factor (Fc) was used to examine the well-being of the fish, which is given by the formula: $Fc = (TW / TL^3) \times 100$, where TW is the total weight (g) and TL is the total length (cm). The hepatosomatic index (HSI) was calculated as: $HSI = (LW / TW) \times 100$, where LW is the liver weight (g) and TW is the total weight (g). Finally, the gonado-somatic index (GSI), commonly used as indicator of reproductive activity, was calculated as: $GSI = (GW / TW) \times 100$, where GW is the gonad weight (g) and TW is the total weight (cm). All indices were calculated on a monthly basis.

The spines of the pectoral fins were used for age determination. Otoliths in catfishes are relatively small (Buckmeier et al., 2002) and were excluded from the analysis because the growth marks were not clearly visible. The periodicity of growth mark formation in spines has been recently validated (I.D. Leonardos and A.C. Tsikliris, pers. obs.). Thus, spines can be used for age determination in Aristotle's catfish. From each specimen, the spines were extracted and cleaned to remove all unneeded tissues. Although the left and the right spines do not differ significantly in their dimensions (I. D. Leonardos and A. C. Tsikliras, pers. obs.), the right spines were consistently used for age determination. After removal and cleaning, the spines were cross-sectioned on a microtome (Isomet 1000) at 0.2–0.3 mm. Prior to their observation under a light microscope the cross-sections were placed in acetic acid 70% for 15–20 s and then rinsed with tap water.

The relationship between fish total length (TL, cm) and spine cross-section radius (R, mm) was examined with linear regression (TL = a + bR). A statistically significant linear regression between these two is a necessary prerequisite for the back-calculation of length at growth mark formation (= age). Back calculated lengths at age were then estimated using the Fraser-Lee equation (Francis, 1990):

$$TL_i = a + (TL - a)\left(\frac{R_i}{R}\right),$$

where TL_i is the total length of the fish when growth mark i was formed, TL is the total length at time of capture, R_i is the distance from spine cross-section centre to growth mark i, R is spine cross-section radius and a is the intercept on length axis of the linear regression between total length and spine cross-section radius.

The growth parameters were estimated iteratively by fitting the von Bertalanffy growth curve on the mean back-calculated lengths at age and on the mean observed lengths at age. Mean lengths at age were used in order to assign equal weight to each age class. The von Bertalanffy growth curve is expressed by the homonymous equation:

$$L_t = L_\infty (1 - e^{-K(t - t_0)}),$$

whereL_t is the total length (cm) at age t (year), L_∞ is the asymptotic length (cm), i.e. the mean length the fish in a population would reach if they were to grow indefinitely, K is a constant expressing the rate at which L_∞ is approached (year^{-1}), and t_0 the theoretical age (year) at which predicted mean length is zero.

Results

Overall total length of Aristotle's catfish in Lake Pamvotis ranged between 11.10 and 36.70 cm. Males ranged from 14.30 to 36.70 cm and females from 11.10 to 35.37 cm. Unsexed individuals were observed across the length range of the species.

From the 622 specimens caught, sex was determined in 566 specimens (91%) and 56 (9%) were unidentified. Of the 566 individuals sexually identified, 365 were females (F = 64.49%) and 201 males (M = 35.51%), yielding a F : M ratio of 1.8 : 1. Sex ratio was statistically different from the 1 : 1 ratio ($\chi^2 = 46.94$, $P < 0.001$).

The relationship between total and standard lengths was positively linear for males ($TL = 1.136 + 1.075 \times SL$, $r^2 = 0.988$, n = 198, $P < 0.001$) and females ($TL = 1.073 + 1.080 \times SL$, $r^2 = 0.988$, n = 363, $P < 0.001$). The slopes (ANCOVA: $F_{1.561} = 0.18$, P = 0.67) and intercepts (ANCOVA: $F_{1.561} = 0.53$, P = 0.46) did not differ significantly between sexes and hence the combined sexes relationship emerged, which included the unsexed individuals ($TL = 1.034 + 1.080 \times SL$, $r^2 = 0.987$, n = 617, $P < 0.001$).

The relationship between total length and total weight (Fig. 1) was exponential for the males ($TW = 0.0035 \times TL^{3.213}$, $r^2 = 0.929$, n = 198, $P < 0.001$) and females ($TW = 0.0066 \times TL^{3.016}$, $r^2 = 0.947$, n = 363, $P < 0.001$). Comparison of the exponent (= slope at the linear form of the equation) with the theoretical value 3 indicated positive allometric growth for both sexes (males: $t = 37.30$, $P < 0.001$, n = 198; females: $t = 4.092$, $P < 0.001$, n = 363). The slopes were significantly different between sexes (ANCOVA: $F_{1.561} = 6.18$, P = 0.013), while the intercepts were not (ANCOVA: $F_{1.561} = 0.57$, P = 0.448). Hence, the data were not pooled together to a single combined sexes length–weight relationship.

The monthly fluctuation of the condition factor was similar for both sexes presenting two distinct peaks, before and after

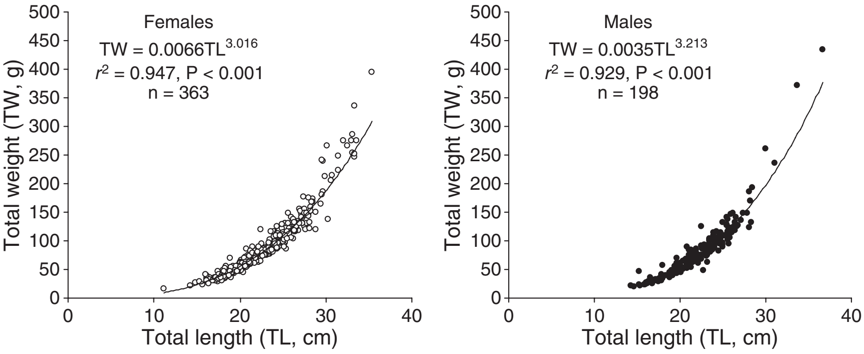

Fig. 1. Relationships between total weight (TW, g) and total length (TL, cm) for males (•) and females (○) of Aristotle's catfish (*Silurus aristotelis*) collected from Lake Pamvotis, western Greece, November 2002–December 2003, July and October 2005

the spawning season (Fig. 2). The highest values were recorded in March for both sexes and the lowest values in May for males and in November 2003 for females. The first peak was observed around March–April following the low condition of the winter and preceding the energy-demanding spawning season. During and soon after the spawning period (April–June), the condition factor values were low. Generally, the hepatosomatic index was higher for both sexes during the cold season and lower during the spring ⁄ summer months (Fig. 3). The pattern was clearer for males with a sharp decline in April, stability to low values during the warm season, and an increase in November. In contrast, the female HSI spring ⁄ summer fluctuation was rather unstable and the decline was smoother.

Based on the monthly variation of their GSI values, the females began their maturation in March and exhibited a peak of reproductive activity in April (Fig. 4). The female maturation could have started earlier but the February values are missing because the lake was frozen. Similarly, the maturation of the males began in March and peaked in April. The birth date of all individuals was set as 1 May.

Age was successfully determined in 558 out of the 622 individuals (90%). The spines of the remaining individuals were damaged, missing or inconclusive. Based on the spine readings, the lifespan of the Aristotle's catfish in Lake Pamvotis was 4 years (Table 1). Age classes 1 and 2 dominated the catches, accounting for 39.1 and 40.0% of the total sample, respectively (Table 1).

Spine cross-section radius (R) was linearly correlated to fish length, thus indicating that spines grow proportionally to fish size (TL). The regressions of TL on R for males and females were:

Males: $TL = 10.60 + 3.43\ R$ ($r^2 = 0.52$, n = 180, $P < 0.05$),
Females: $TL = 10.22 + 3.07\ R$ ($r^2 = 0.53$, n = 323, $P < 0.05$).

The slopes did not differ significantly between sexes ($F_{1.503} = 1.38$, $P = 0.24$), indicating proportional growth rate between the spine and the body. However, the intercepts were statistically different ($F_{1.503} = 16.86$, $P < 0.001$), indicating that female spines appear before those in males. Male and female data were pooled for growth analysis and the combined slope, which included 55 unsexed individuals) was used for the back-calculation:

$$TL = 9.66 + 3.50\ R\ (r^2 = 0.54,\ n = 558,\ P < 0.01).$$

Back-calculated standard lengths showed a rapid increase in fish size during the first year of life, reaching 61.1% of maximum attainable length. The growth rate declined with increasing age (Table 1). The results of the back-calculation

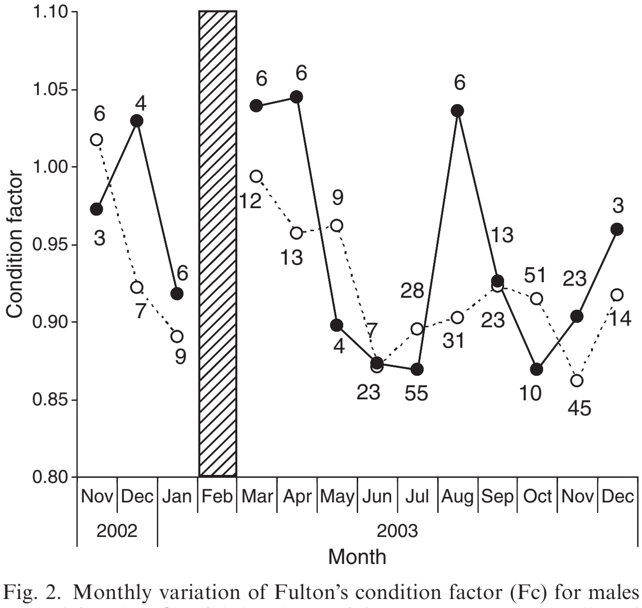

Fig. 2. Monthly variation of Fulton's condition factor (Fc) for males (•) and females (○) of Aristotle's catfish (*Silurus aristotelis*) collected from Lake Pamvotis, western Greece, November 2002–December 2003. Numbers indicate sample size. In February 2003 (hatched area) the lake was frozen and no samples were collected

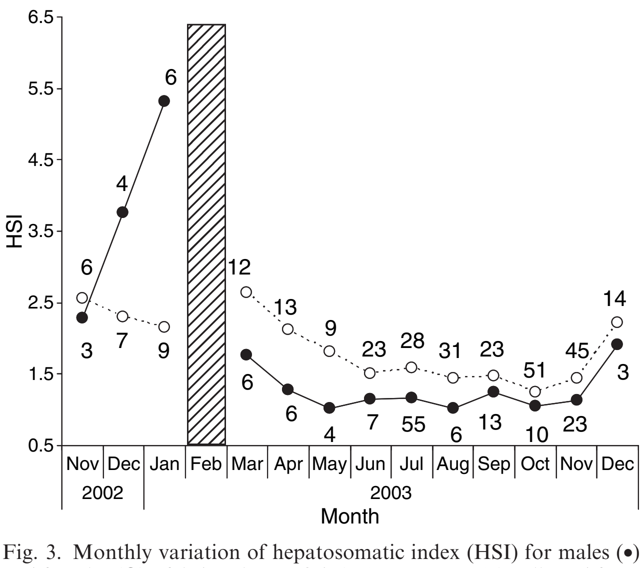

Fig. 3. Monthly variation of hepatosomatic index (HSI) for males (•) and females (○) of Aristotle's catfish (*Silurus aristotelis*) collected from Lake Pamvotis, western Greece, November 2002–December 2003. Numbers indicate sample size. In February 2003 (hatched area) the lake was frozen and no samples were collected

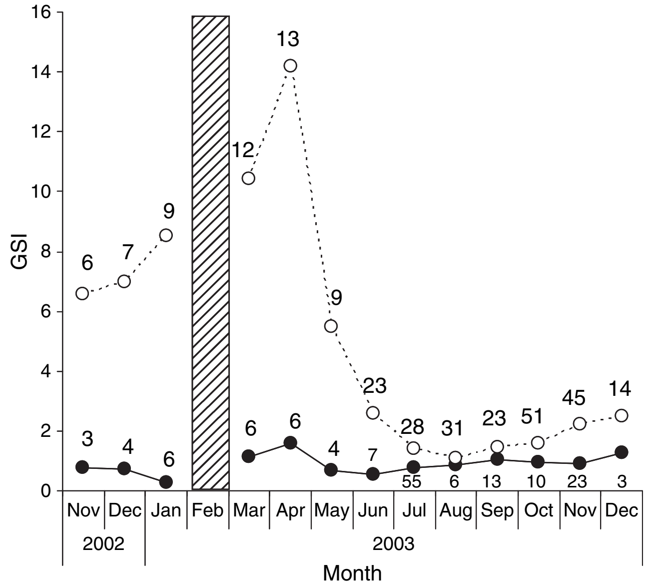

Fig. 4. Monthly variation of gonadosomatic index (GSI) for males (•) and females (○) of Aristotle's catfish (*Silurus aristotelis*) collected from Lake Pamvotis, western Greece, November 2002–December 2003. Numbers indicate sample size. In February 2003 (hatched area) the lake was frozen and no samples were collected

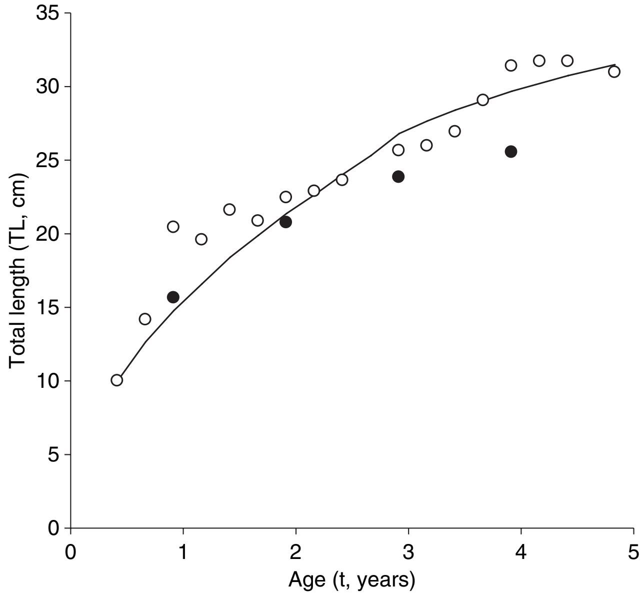

Fig. 5. Von-Bertalanffy growth curve fitted to mean observed lengths at age (○) for Aristotle's catfish (*Silurus aristotelis*) collected from Lake Pamvotis, western Greece, November 2002–December 2003. Numbers indicate sample size. Mean back-calculated lengths at growth mark formation also indicated (•)

were confirmed by the growth parameters that were calculated as: $L_\infty = 28.19$ cm, $K = 0.53$ year^{-1}, $t_0 = -0.62$ year based on the back-calculated lengths at age and as $L_\infty = 36.12$ cm, $K = 0.37$ year^{-1}, $t_0 = -0.76$ year based on the observed lengths at age (Fig. 5).

Discussion

The ecosystem of the lake seems to be polluted by heavy metals (Albanis et al., 1986; Stalikas et al., 1994; Papagiannis et al., 2002), pesticides (Hela et al., 2005) and microcystins (Kagalou et al., 2008). Concentrations of heavy metals (Zn, Cu) have been detected in muscle, liver and gonads of Aristotle's catfish (Papagiannis et al., 2004) along with various other fish species in the Lake Pamvotis. It is well documented that many parameters of the life history traits of the fishes (longevity, growth, sex ratio, survival) are negatively influenced by pollution and/or eutrophication of aquatic ecosystems (Heath, 1995; Leonardos, 2004; Leonardos et al., 2005).

A skewed sex ratio towards females is characteristic of the populations of Japanese catfishes (see table 2 in Maehata, 2007 for other *Silurus* spp.) and of *Silurus glanis* in Turkey (Alp et al., 2004). However, in Ataturk dam lake (Turkey) the percentage of females of *Silurus triostegus* was lower, albeit not statistically significant, than that of males (Oymak et al., 2001). The lack of any general trend among catfishes is the diverse reproductive strategies among them (Bruton, 1996) as they are found among all breeding guilds as defined by Balon (1975). Unbalanced sex ratios may be related to the reproductive strategy or to sexual differences in growth and mortality (Wootton, 1998). Aristotle's catfish is a nest spawner with the males being the constructors and guarders of the nest that is built in sand (Bruton, 1996). Thus, given the similar growth patterns (and hence mortality) between sexes in Aristotle's catfish, it seems that it is the reproductive strategy which determines sex ratio. The nest building and parental care provided by males excludes them from any exploitation (fishing or sampling).

The dominance of females in overall sex ratio may reflect a high mortality rate in males. Probably the strategy of *S. aristotelis* in Pamvotis Lake in terms of sex ratio is the investment in females, a strategy characteristic of species from unstable and variable environments. Consequently, the differences between the sexes could be explained on the basis of the way in which eutrophication and pollution affect fish. It seems

Table 1
Specimens of Aristotle's catfish (*Silurus aristotelis*) successfully aged (n), mean back-calculated total lengths (± SD, cm) at growth mark formation based on cross-sections of the spines, annual increment and % annual increment per age, Lake Pamvotis (2002–2003)

		Back-calculated total lengths at growth mark formation			
Age (year)	n	1	2	3	4
0	42				
1	218	16.04 ± 2.65			
2	223	15.63 ± 5.04	21.14 ± 2.35		
3	67	14.22 ± 2.11	19.60 ± 2.18	24.06 ± 2.76	
4	8	13.72 ± 3.17	18.27 ± 3.53	22.28 ± 3.90	25.52 ± 4.56
Weighted mean		15.59	20.72	23.87	25.52
Annual increment		15.60	5.10	3.20	1.60
% annual increment		61.10	20.10	12.40	6.40
Total	558				

that males are more vulnerable to pollution than females, as has been previously reported for other species of the same ecosystems (Leonardos et al., 2005).

Despite their minor differences, length–weight relationships indicated positive allometric growth for both sexes, a pattern confirmed by the subsequent growth analysis on spines. The estimation of the parameters of the length–weight relationships may be considered valid because sampling was performed based on the criteria set by Froese (2006), i.e. sampling throughout the year, wide size range, non-selective sampling gear, large sample size. The condition was generally higher just prior to and after spawning, a pattern characterizing several spring spawners. The spawning energy requirements are high (Xie et al., 1998) and since maturation begins soon after the lowest water temperatures (here in March), the fish had to store energy (mainly in the form of fat) prior to the onset of their maturation. The stored energy is consumed during spawning and the condition factor declines (Xie et al., 1996). The higher summer values are the result of high water temperatures, increased food availability and the lack of any energy consuming processes besides immediate metabolic needs such as locomotion and maintenance. The winter fluctuation was irregular but this could have been an effect of small sample size during the winter months and the lack of February sampling. In contrast, the hepatosomatic index exhibited a clear pattern with higher values observed during the winter months and lower values during spring and summer. This variation could also be related to the energy cost that is needed for the formulation of the gonads. The vitellogenin is synthesized by the liver (Chen, 1983; Bidwell and Carlson, 1995) and transported to the ovaries by blood circulation (Ng and Idler, 1983) where it is sequestered to serve as an energy reserve for the developing embryo (Celius and Walther, 1998).

Based on the gonadosomatic index values, Aristotle's catfish is a spring spawner (April–June). A spring ⁄ summer spawning strategy has been generally observed for congener catfishes. Iliadou and Fishelson (1995) report that the breeding season of Aristotle's catfish in Greece is protracted (March–August) but less pronounced than in other species. In Turkey, the gonads of *S. glanis* develop in spring and spawning occurs between June and August (Alp et al., 2004), while *S. triostagus* spawns earlier and over shorter time periods in May and June and its maturity is related to water temperature (Oymak et al., 2001). The spawning activity of Japanese catfishes is confined to between May and September (Maehata, 2007). This spawning pattern, which has been observed in several freshwater fishes including catfishes (Maehata, 2007), needs to be explored further and complemented with histological analysis. Frequently the duration of the reproductive period is reduced under the influence of adverse environmental parameters (Leonardos and Sinis, 1998).

It has been reported that the growth performance of the *S. glanis* is largely dependent on the water temperature, among other factors, and may fluctuate annually responding to temperature fluctuations (Britton et al., 2007). In any case, the rapid growth during the first year of life in the present study will increase the survival probability by minimising the predation pressure upon the population within a short time.

The estimation of growth parameters differed depending on the length at age used. When mean back-calculated lengths at age were used, the asymptotic length was underestimated by 30% compared to the value estimated based on the mean observed lengths at age. Although the estimation and fitting method was the same (non-linear estimation with the same settings for both variables), the differences are attributed to the lack of coincidence between actual age (based on birthdate) and assigned age (based on growth mark formation), and to the fact that some spines of large sized specimens were damaged. The former is 8 months higher than the latter because the birthdate was set in May and the growth marks were formed in January. Thus, the mean back-calculated lengths that are based on growth mark formation correspond to the length of the fish at an age of 6 months. The use of back-calculated lengths gives rise to another issue, that of the lifespan. Based on back-calculated lengths, the lifespan of Aristotle's catfish is 4 years (Table 1) because four annuli were present in the spines of the older (and largest) specimen. When the mean observed lengths at age are also considered and examining the time of annuli formation as well as on the time of birth and time of capture, we are able to assign the real age to each specimen. Thus, the lifespan of the species in Lake Pamvotis is almost 5 years. In fact, the older and largest (in theory, not necessarily the same individual) specimen is aged 4 year based on the former method and 4.83 year based on the latter.

The lifespan of Aristotle's catfish in this study is much lower compared to a population of lakes Lysimachia and Trichonis where it reached 10 years of life (Iliadou, 1981). This could be attributed to the negative influence of the altered polluted and eutrophic ecosystem of Lake Pamvotis. The maximum size attained and the subsequently estimated asymptotic size is also lower at the origin of its Greek distribution (Lysimachia and Trichonis: $L_{\max}$ = 40 cm, L_∞ = 46 cm) (Iliadou, 1981). As the data of Iliadou (1981) were collected 30 years ago, it seems that the original populations have been either overfished or suffered an environmental disturbance that altered the age and size structure. In a related study (Leonardos et al., 2005) it has been proved that in an eutropic and more polluted lake the sex ratio, survival, growth rate and longevity are negatively affected than in an clearer and non-polluted lake.

Respectively, other fish species such as *Rutilus ylikiensis* (Leonardos et al., 2005) and *Scardinius acarnanicus* (Leonardos, 2004), which are found in lakes in western Greece, show similar life history traits. In the polluted eutrophic ecosystems the species show a lower number of age classes, the sex ratio is skewed towards the more abundant females, which survive to higher ages (Leonardos, 2004; Leonardos et al., 2005). The lifespan of Aristotle's catfish is also low compared to the largest species of the genus *S. glanis* (14 years: Alp et al., 2004) and *S. triostegus* (11 years: Oymak et al., 2001) in Turkey.

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