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13- year population survey of the critically endangered European eel in the southern Mediterranean region (Algeria)

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Abstract :

A 13-year biomonitoring survey was carried out on the European eel, Anguilla anguilla for the first time in North Africa (Algeria) where there is a serious lack of information on the species. The study targeted specimens populating the only four sites where the species is both potentially present and legally exploited (Lake Oubeira, Lake Tonga, Mellah lagoon, and Mafragh estuary). A total of 1,370 individuals were sampled ranging from 17 to 113 cm in length, 19 to 2,642 g in weight, and 0.7 months to 6.6 years old, age being estimated from otolith growth marks. Otolith interpretation and age estimation were generally unambiguous at all four sites. According to the EELREP silvering index, the highest proportion of silver females was captured in freshwater (46% in Lake Oubeira and 25% in Lake Tonga), whereas a third were present in brackish water (Mafragh and Mellah). The sex ratio was in favor of females, silver males were found to mature early (mean length 40 ± 1 cm, mean weight 123 ± 28 g, and mean age 2 ± 0.6 years). Growth differed at the four sites, the growth rate was highest in Lake Oubeira and asymptotic length highest in Mellah lagoon. Metamorphosis from the yellow resident stage to the silver migrating stage occurred very early in the eels' continental life (between 3 and 4 years of age). Results highlight rapid growth in these Algerian sites, and earlier silvering than in eels living in European waters, suggesting different life history traits of A. anguilla in North African waters, influenced of environmental conditions.

Keywords : Anguilla anguilla, silvering, growth, conservation, endangered species, North Africa

1 INTRODUCTION

The European eel, *Anguilla anguilla* (L.) 1758, has stimulated curiosity and interest since at least the 4th century (Cresci, 2020), due to its peculiar body shape and complex life cycle. It is catadromous, spends its adult life in continental waters, and then migrates to the ocean to reproduce in the Sargasso Sea (Tesch & Thorpe, 2003). For a long time, it was a common species and a major component of coastal and continental aquatic environments, particularly in areas close to estuaries (Moriarty & Dekker, 1997; Feunteun *et al.*, 1998; Baisez *et al.*, 2000). However, according to the International Council for the Exploration of the Seas, in the last 40 years there has been a decline of around 95% in the numbers of elvers, the young stage that colonizes continental waters (ICES, 2022). The European eel has most recently been assessed for The IUCN Red List of Threatened Species in 2018, listed as Critically Endangered species, suggesting an increased risk of extinction (Pike *et al.*, 2020). The decline in abundance has been ongoing for decades and was already reported in the mid-1800s (Dekker & Beaulaton, 2016). The species is currently no longer within its "biological safety limit" (ICES, 2012), and a large number of factors have been put forward to explain the decline that can affect each stage of the life cycle (ICES, 2008). These factors include predation (Carpentier *et al.*, 2009; Wahlberg *et al.*, 2014), parasitism mainly by *Anguillicoloïdes crassus* (Gollock *et al.*, 2005; Fazio *et al.*, 2012), pollution (Robinet & Feunteun, 2002; Palstra *et al.*, 2006; Geeraerts & Belpaire, 2010), climate change (Miller *et al.*, 2009), habitat fragmentation (Piper *et al.*, 2013), and above all, overfishing (Dekker, 2003).

Life history traits and data on fish age and growth are essential to assess the status of a species and its populations (lifespan, age at recruitment, age at first sexual maturity, reproduction periods, migration, and mortality). Estimation of the individual age of eels in continental waters, which mainly uses otolith growth marks, is still the subject of debate (ICES,

2013) and there is still no consensus on the subject at the European level (ICES, 2013). Age is usually assessed at the level of sub-populations in the different areas concerned, and has never been assessed on the southern shore of the Mediterranean. After growing in continental waters, yellow eels mature during a process known as silvering, the skin color changes, the eyes increase in size, and the number of photoreceptors increases, making them more efficient in low-light conditions (Pankhurst, 1982a), the pectoral fins become longer and the skin thickens (Durif *et al.*, 2009b). In parallel, the silvering process is accompanied by anatomic changes: regressive alterations of the gut due to the end of feeding (Bertin, 1951), increased muscle power output to economize energy during the non-feeding migratory life stage (Ellerby *et al.*, 2001; Lokman *et al.*, 2003), change in the swim bladder (Kleckner, 1980) and gonads (Dufour, 1994). This stage is the important since it is the 'final' life stage and the closest to reproductive success, enabling return migration for reproduction, and subsequent population resilience. The migrating stage and the associated morphological changes have not been exhaustively characterized in the southern Mediterranean region, despite the fact that a deeper knowledge of this stage is required for a better assessment of the migratory strategies. Very little is known about the population biology of the North African distribution of the species (Jacoby & Gollock, 2014; Pike et al., 2020). A regional Red List assessment in North Africa also suggested that *A. anguilla* should be considered as 'endangered', because of the 50% drop in recruitment over the last 10 years with annual catches declining by between 10% and 25% since the 1980s, and by even more but only in Tunisia (Azeroual, 2010).

No national monitoring of the various eel stages is conducted in the southern Mediterranean, and there are virtually no regular routine surveys of yellow and silver eels in freshwaters or coastal environments. In terms of consumption, the European eel is not a prized fish in North Africa, and is consequently not widely consumed. This explains the significant lack of data in this region, although fragmentary data were acquired by Djebbari *et al.* (2009) and Tahri *et al.* (2016, 2018), and there is no global comprehensive knowledge of the ecology of this species. Many questions remain: Can the age be estimated accurately in this region? Do eel growth patterns differ in the southern Mediterranean? How and when does the silvering metamorphosis take place? Ours is the first study of trends in European eel morphometrics and growth over a long period in several environments in eastern Algeria where the species is potentially present. The sampling campaigns started in 2007 and continued for 13 years, growth rates were estimated using otoliths, and links between the silvering stage and local environmental conditions (lakes, lagoon and estuary) were established. The specific objective of our study was to evaluate key life history parameters and infer the status of the European eel in Algeria, in order to produce the data required for actions aimed at its conservation in the southern Mediterranean region.

2 MATERIAL AND METHODS

2.1 Study area and sampling

The study area included four different sites (Figure 1). Lake Oubeïra (N36°50, E08°23) is a freshwater environment with a surface area of 2,200 ha and a maximum depth of 4 m. It is located approximately 4 km from the Mediterranean Sea. It is a designated wilderness area (registered in the "Ramsar" Convention) of the Park National of El Kala that has the unique distinction of hosting the most important wetland complex in North Africa (Boumezbeur, 2003). There is currently no hydraulic management framework for the lake, and eel recruitment occurs naturally. Lake Tonga (36°53'N and 08°31'E) is a wetland area and has been a "Ramsar site" on the list of wetlands of international importance since 1982. It is part of the National Park of El Kala wetland complex. The site consists of a freshwater basin marsh with a maximum depth of 6 m. It is a eutrophic lake bounded on the north by an extensive sand-dune system, and connected to the Mediterranean Sea by a channel. Mellah lagoon (36°54' N- 8°20' E) is a brackish coastal lagoon (salinity between 27 and 34) located on the extreme northeastern section of the Algerian coast. It has also been classified as a Ramsar site since 2004, and is part of the El Kala National Park, covering 865 ha with an average depth of 2.7 m (Embarek *et al.*, 2017). Its hydrological regime is influenced by the movements of marine waters that enter through a channel, and by the direct inputs of freshwater during rainfall events. The Mafragh estuary (36° 50' N- 7° 56' E) stretches for 2 km and its width ranges from 50 m upstream to 100 m close to the sea. It is a brackish water environment for much of the year, but salinity sometimes decreases in winter. The depth of the estuary is between 2 and 3 m depending on the location. All these environments present natural eel recruitment. In Algeria, eel fishery activity is artisanal in natural waters, and is mainly centered on the extreme north-eastern part of the country. Data used in the present article on the annual production of *A. anguilla* in this area since 1998 were obtained from the Directorate for Fisheries and Aquaculture DPA-2022 (Ministry of Fisheries and Fish Production, Algeria). These were rough data of catches, without the possibility to calculate a fishing effort per year.

Sampling was undertaken in 21 survey campaigns at the four sites starting in summer 2007 and ending in winter 2020. Eels were caught by artisanal fishers who are using the same type of fyke nets in the whole area, and the entire capture was recovered at landings or directly purchased from fishmongers. A total of 1,370 eels were captured and placed on ice to kill them gently by euthanasia (see 2.6 ethical statement). Afterwards, eels were weighed (total weight, Wt, to the nearest g) and measured (total length, Lt, in mm) (Table 1).

2.2 Length-weight relationship (LWR)

The LWR was calculated using the equation:

$Wt = a \times Lt^{b}$

where a and b are the parameters, b being the coefficient of isometry. If b is equal to 3.0 there is an isometric relationship, when $b > 3$, a positive allometry, and when $b < 3$, a negative allometry (Froese, 2006).

2.3 Silvering indexes

The silvering metamorphosis was estimated according to the estimation of the reproduction capacity of European eel (EELREP) index (EELREP, 2005). This index uses different growth stages, labelled as SI and SFII (non-migrant undetermined, and non-migrant females), SFIII (pre-migrant stage for females), SFIV and SFV (migrating stages for females), and SMII (migrating males). Morphological changes are evaluated using different measurements in length (Lt), weight (Wt), length of the pectoral fin (Lf), horizontal and vertical diameters of the right (Ar, Br) and left (Al, Bl) eyes, and the following formulae:

Fin index, FI (%) = $(Lf/Lt) \times 100$

Ocular index, OI = $[(Ar + Br)/4 \times (Al + Bl)/4] \times \pi / Lt$

The gonadosomatic index (GSI), the hepatosomatic index (HSI) and the empty gut-somatic index (GI) were calculated after removing and weighing the gonads (G), the liver (H) and the empty gut (Ge), respectively (Durif *et al.*, 2005). The indexes were calculated using the following formulae:

$GSI = (G/Wt) \times 100$

$HSI = (H/Wt) \times 100$

$GI = (Ge/Wt) \times 100$

2.4 Age and growth analysis

Otoliths were removed from all individuals, rinsed with distilled water, and stored dry in reference microtubes. The whole right otoliths were observed in 96% ethanol against a dark background and a reflected light using a Leica WILD M3Z binocular. The age during the continental life (i.e. after entering in inland waters) was estimated by counting of the number of opaque rings, a method that has been validated for Mediterranean eels (Panfili and Ximenes, 1994). The exact continental age was calculated in months using four variables: the number of opaque rings, the "date of birth in inland water" (set at June 1 each year, Panfili and Ximenes, 1994), the date of capture and the nature of the otolith edge (opaque vs. translucent) (Panfili *et al.,* 2002).

Growth was calculated using the von Bertalanffy (1957) growth function (VBGF):

$Lt = L\infty\ (1 - e^{-K(t - t_0)})$

where $L\infty$ is the theoretical asymptotic length, K is the growth coefficient, and t_0 is the theoretical time at which the length is null. All the parameters were calculated using R statistics with the "TropFishR" package (Mildenberger *et al.*, 2017).

2.5 Statistical analysis

Differences in morphometric parameters and indexes between males and females, and differences between the lengths of eels captured at the four study sites were tested using Student's t-test or ANOVA after checking for data normality. These statistical analyses were performed with Statistica® 8.0 software.

2.6 Ethical statement

The care and use of experimental fish complied with national authorities for animal welfare laws, guidelines and policies as approved by Schedule 1 of the Animals (Scientific Procedures) Act 1986.

3 RESULTS

3.1 Algerian eel fisheries

Annual captures of *A. anguilla* have declined regularly in this area since 1998 (Figure 2). During the monitoring period (2007-2020), eel captures were very low (between 10 and zero tons). Captures in Lake Tonga and in the Mafragh estuary stopped after 2009, whereas captures in Mellah lagoon started at this time. Captures in Lake Oubeira were low, but existed since 1998, with a null period (2010-2016). A late production peak was observed in 2018-2019 (Figure 2). It should be noted that there was no possibilty to calculate a precise fishing effort per year.

3.2 Length frequency distribution and LWR

The length of the individuals captured ranged from 173 to 1,130 mm, and their weight from 19 to 2,642 g (Table 1). Mean lengths and weights differed significantly between sites ($P < 0.001$), and all pair comparisons differed (post-hoc test, t between 6.5 and 21.5; $P < 0.001$). Large individuals (≥ 500 mm) were more frequent in freshwater bodies (Lake Tonga and Lake Oubeira). Most specimens belonged to length classes 300-700 mm (Figure 3).

The parameters b and a of the L-W relationship ranged between 2.35 and 3.38, and between 0.049 and 0.086, respectively. In Lake Tonga and Mellah lagoon, b values were significantly different from 3 ($P < 0.001$), indicating negative allometric growth, while the opposite relation was found for Lake Oubeira and the Mafragh estuary (Table 2).

3.3 Eel silvering in Algerian environments

In Lake Oubeira (Autumn 2010-Winter 2020) and Lake Tonga (Autumn 2015-Winter 2020), respectively almost 50% and 25% of the females were silver. Conversely, 33% of the eels captured in brackish water of Mafragh estuary (Summer 2007-Spring 2008) and Mallah lagoon (Winter 2014-Spring 2017) were still growing (stages SFI and SFII). The highest proportion of silver males was found in Mellah lagoon (23%). Females at silver stages (SFIV and SFV) were 889 ±12 and 570 ± 7 mm long, weighed between 1,487 ± 529 and 350 ± 183 g, and were relatively young: 4.1 ± 1.4 and 3.5 ± 0.8 years old. Silvered males (SMII) were 405 ± 16 mm long, weighed 124 ± 28 g, and were young (2.1 ± 0.6 years old). At the pre-migrant stage (FIII), eels appeared to be silver and the same pattern was observed at all four sites. The year 2011 was exceptional in terms of the number of silvering eels (Figure 4). The liver and gut resorption was deduced by the decrease in HSI and GI values following the FIII stage; whereas gonad development tends to increase as a function of the life stage. Exophthalmia and the development of the pectoral fin were also observed from the SFIII stage on (Figure 5). The sex ratio revealed significant differences between male and female eels, with males reaching the silver stage before females: Lt (t = 25.56, $P < 0.0001$), Wt (t = 16.89, $P < 0.0001$), FI (t = -3.29, $P = 0.001$), OI (t = 14.56, $P < 0.0001$), HSI (t = -63.39, $P < 0.0001$) and GSI (t = -77.86, $P < 0.0001$), but there were no difference in GI between the sexes (t = -0.49, $P = 0.6$).

3.4 Age and growth

Among the 1,370 otoliths sampled, 87.5% were easily interpretable thanks to visibler alternation of growth rings (Figure 6). The remaining 12.5% otoliths were not used to estimate age due to the difficulty of observing the growth marks or of deducing a precise age. These uninterpretable otoliths belonged mainly to stages SI and SFII, thus immatures, whereas silver females and males represented 2.7% and 0.3% of those, respectively. Estimated continental ages ranged between 0.67 and 6.6 years in Lake Oubeira, 1.25 and 5.5 years in Lake Tonga, 0.75 to 4.5 years in Mellah lagoon, and 0.5 to 4.5 years in Mafragh estuary. Concerning the data related to males (SMI) and females (SFV/SFIV), ages were 2.08±0.6 years and 3.47±0.8/4.12±1.4 years respectively.

The growth was similar at the four different sites (Table 3, Figure 6). The asymptotic lengths were between 656 and 735 mm, with the highest value found in Mellah lagoon. The growth coefficient K (0.47 to 0.83) was lowest in Lake Tonga.

4 DISCUSSION

For more than four decades, stocks of European eels have decreased up to 95% throughout its distribution range (ICES, 2022). In 2008, the International Union for the Conservation of Nature (IUCN) listed the European eel as 'Critically Endangered' (Pike *et al.,* 2020), and the CITES (Convention on International Trade in Endangered Species of Wild Fauna and Flora) gave different recommendations for protecting the species. Furthermore, the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR Convention) issued a recommendation to strengthen the protection of the European eel at all life stages (ICES, 2021). In 2010, the EU's Scientific Review Group (SRG) concluded that it was not possible to perform a Non-Detriment Finding (NDF) for the export of *A. anguilla* at the time, and subsequently a zero-import/export policy was set for the EU, which still remains in place (Musing *et al*. 2018). Outside of Europe, NDFs have been made by Algeria, but this country was cited among the main for direct exports of live eels and fingerlings during the period 2009–2016 (Musing *et al*. 2018). Algeria's authorities stated that the exploitation of *A. anguilla* was considered artisanal, and, in the absence of a national management plan for the species, a precautionary annual quota of 12 tons has been set, and the country requested for an expert assessment of the national status of *A. anguilla* (Musing *et al*. 2018). The silvering process of the European eel has never been studied on the southern shore of the Mediterranean Sea and its life history traits remain poorly known. The present 13-year survey of eel sub-populations living in natural environments in Algeria, free of industrial activity and that were never previously stocked, thus provides critical information for eel conservation.

In Algeria, eel catch trends have witnessed three important periods: the highest production was between 1998 and 2004 (41-75 tons), mainly in Lake Tonga (70 tons) which, like Mafragh estuary, was managed by private operators. In this period, most of the eel production was exported to Italy. Lake Oubeira and the Mellah lagoon were under government control, and their eel production has never exceeded 5 tons. During the second period, between 2005 and 2017, total catches were around 10 tons per year; data concerning this period had to be obtained from local markets, because these water bodies were not under water management. Finally in 2018, catches began to increase (13 tons) and private operators again took control of both Lake Oubeira and Mellah lagoon. For the sake of comparison, France hosts one of the largest commercial landings of yellow and silver eel in Europe, with 294 tons landed in 2021, followed by the United Kingdom with 244 tons and Denmark with 233 tons (ICES, 2022). The levels of catches in Algeria were not negligible, but a significant decrease was also recorded. The decline in Algerian eel stock over the last two decades can be primarily attributed to a shift in the activity of artisanal anglers, who have become more interested in agriculture during the summer (e.g. seasonal fruit production such as watermelon, more profitable during this season). Moreover, since 2018, this area has experienced an unprecedented invasion of the American blue crab *Calinectes sapidus* (Tahri & Boutabia, 2022) which could be a fearsome predator of small eels. Another disruptive factor could be the allochthone nematode *Anguillicoloides crassus* that has progressively settled in the zone with increasing rates of infestation in recent years (Tahri & Bensouilah, 2022).

In the different Algerian aquatic ecosystems colonized by the European eel, estimating age has relied on the clarity of growth marks on whole otoliths observed directly without prior preparation, and revealed a high percentage of interpretable otoliths (87.5%). Marks on whole otoliths have already been proved as accurate for giving a validated age (Panfili & Ximenes, 1994; Panfili *et al.*, 1994). The present study reinforced the extreme variability of length-at-ages observed for wild sub-populations of this species, as already reported in other Mediterranean environments (Panfili *et al.*, 1994; 2022) and in other European ecosystems

(Vollestad & Jonsson, 1988; Vøllestad, 1992; Poole & Reynolds, 1998; Pujolar *et al.*, 2005). Other studies reported great variability in growth of eels between and within local stocks (e.g. Vøllestad, 1992; Moriarty, 1987). In the present study, eels exhibited a high growth rate over the years, and the highest growth coefficient was found in Lake Oubeira. At the species distribution scale, the growth rate is known to decrease according to latitudinal temperature gradients (Vøllestad, 1992). However, an increase in growth can only take place if sufficient prey is available, coupled with an increase in the metabolic rates linked with increased temperatures (Graham & Harrod, 2009). In Algerian aquatic ecosystems, the climate is mild throughout the year, and could be a determining factor for the growth and development of individual specimens. This observation is consistent with that made in the study by Acou *et al.* (2003), who confirmed that silver eel production in the Mediterranean region is fast, between three and six years after the arrival of the eel in continental waters, compared with in northern European environments (Svedang *et al.*, 1996). Other environmental drivers of growth include salinity (Yahyaoui, 1988), oxygen (Martinköwitz, 1981), distance to the sea and productivity (Berg, 1990; Fontenelle, 1991; Meunier, 1994; Panfili & Ximenes, 1994; Daverat *et al.*, 2006; Lasne *et al.*, 2008), morphology (Leopold & Bninska, 1984) and undulation and flow (Einsele, 1961) of the water body, hereditary disposition (Sinha & Jones, 1967; Meylahn, 1977), sex (Sinha & Jones, 1967; Penàz & Tesch, 1970), diet relationship (Wundsch, 1953; Meylahn, 1977) and length of the yearly growth period (Nordqvist & Vallin, 1923; Sinha & Jones, 1967), population density of eels (Sinha & Jones, 1967; Aprahamian, 2000), and inter- and intraspecific food competition (Müller, 1975; Jörgensen, 1988b). In conclusion, Algerian aquatic ecosystems seem to be optimal for the growth of the European eel.

The sex ratio revealed significant differences in growth patterns between males and females in Algerian water bodies, with males reaching the silver stage before females. In males, the success of the spawning migration is maximized by maturing at the smallest possible size whereas females maximize fecundity (Vollestad & Jonsson, 1988; MacNamara & McCarthy, 2012). Nevertheless, both sexes must reach a sufficiently large body size to survive the spawning migration (Boetius and Boetius, 1980). In less productive environments, females of the European eel may reach the silver stage at the minimum length that enables a successful reproductive cycle (Yokouchi *et al.*, 2018), while in more favorable environments, migration may be delayed until a larger body size is reached (Davey & Jellyman, 2005). Among the four sampling sites in the present study, the proportion of silver females was higher in freshwater than in brackish waters, and the highest proportion of silver males was found in Mellah lagoon. This distribution could be due to the sex ratio, which is mainly determined by eel density, low densities favoring the development of females (Tesch & Thorpe, 2003; Melia *et al.*, 2006). Indeed, high proportions of females are generally found in rivers where densities are low, whereas males tend to dominate estuaries and lagoons where densities are high (Tesch & Thorpe, 2003; Walsh *et al.*, 2004). Typically, males occupy the most downstream reaches, grow quickly and mature earlier at a smaller size, whereas females develop more slowly in upstream reaches and mature later at a larger size (Tesch & Thorpe, 2003). All these observations were confirmed by the life history traits of eels sampled in the Algerian brackish and freshwater environments.

The silvering process described by EELREP (2005) comprises six stages representing different growth stages (stages SI and SFII), a pre-migrant stage for females (SFIII), and migrating stages for females (SFIV, SFV) and males (SMII). This classification gives a more precise and accurate ecological description than the terms "yellow" and "silver" stages that are sometimes used to describe eels. EELREP reflects the continuous nature of the silvering process and the fact that although silvering may have started, some individuals are nevertheless not ready for active migration. The threshold values of the ocular index indicating the beginning of the silvering process vary widely in the literature: Pankhurst (1982) estimated that silvering started at an OI > 6.5, Fontaine (1994) showed that individuals that had not started the pre-silvering stage had an OI of 4.33 ± 0.24 (min-max=2.94-5.70), while OI in the later stages was 8.48 ± 0.42 (min-max= 5.58-11.4), Marchelidon *et al.* (1999) and Acou *et al.* (2003) estimated that the critical OI was 8. The increases in eye diameter and retinal surface area during eel metamorphosis from yellow to silver is also observed in *A. japonica* (Yamamoto & Yamauchi, 1974), *A. rostrata* (Cottrill *et al.*, 2002), *A. dieffenbachia* and *A. australis* (Lokman *et al.,* 1998). In the European eel, the eye index value (OI) has been often used as a quantitative criterion to distinguish silver eels from yellow eels (EELREP, 2005). However, the 6.5 threshold value is not necessarily suitable for all anguillids worldwide. Our results revealed the beginning of the silvering transition at an OI value of 8.5 for females and 7.5 for males (Fig. 5), supposing that this value could be more adequate for silvering *A. anguilla* in the southern Mediterranean region.

The increase in gonad size has been shown to be a good criterion to estimate the state of advancement of the silvering process (Durif *et al.*, 2005; Marchelidon *et al.,* 1999). Indeed, the GSI of the Algerian eels in our study increased progressively from 0.26 ± 0.09 % at SI to 0.96 ± 0.16 % in silver females. The increase in the follicular diameter, the thickening of the follicular wall, and the appearance of many lipid vesicles during silvering was also reported by Fontaine (1976) and Lopez (1990). Conversely, the opposite phenomenon was observed in the liver and the gut, where the HSI and the GI decreased from 1.64 ± 0.16% (at SI) to 1.37 ± 0.19% (at SFV) and from 2.28 ± 1.57% (at SI) to 1.13 ± 0.16% (at SFV), respectively. Recent isotopic analyses indicate that eels do not feed during the long spawning migration (Chow, 2010), even if reversals have been observed (Tesch & Thorpe, 2003); indeed, the end of feeding prior to migration means that the metabolic demands of migration and spawning have to be met from reserves accumulated before migration (Durif *et al.,* 2005). Although there have been several studies on the silvering processes of anguillid eels, the majority concern more temperate species and sub-populations, while information on anguillids found in the African continent is generally still lacking.

CONCLUSIONS

In view of the alarming status of the European eel, substantial measures for its conservation have been introduced at the European level (Hanel *et al.,* 2019), with fisheries management recommendations (GFCM, 2019; ICES, 2021), and are recognized as crucial for the maintenance of stocks of the European eel. For example, the ICES Advice in 2021 was for zero catch (ICES, 2021). In Algeria, eel fishery is mainly focused on the yellow and silver stages, but is still a basic activity practiced by anglers for their survival. Monitoring eel catches highlighted a real decrease in recent years, and, according to the same source, eel fishing is becoming increasingly difficult. The causes of decline listed above merit consideration by decision-makers before more verifications and specific procedures are implemented. In the present study, the aim of the biomonitoring survey was to improve our knowledge of the past and current status of the eel in Algeria. Our increased knowledge of eel sub-populations is a first step toward the design and implementation of conservation strategies, and of a national management plan for the European eel. The key points that emerged are the fast growth of *A. anguilla* at all stages (pre-migrant and migrant) in all four Algerian sites surveyed (Lake Oubeira, Lake Tonga, Mellah lagoon, and Mafragh estuary). These results underline the effect of latitude and temperature on growth. The silvering process occurred at a very early continental age (3-4 years), which implies reducing fishing pressure after their arrival in continental waters. In addition, a difference in growth between the sexes was observed, males growing less big than females, and individuals living in freshwater growing faster. These finding should play a central role in the future assessment of eel stocks in Eastern Algeria with the aim protecting the species in the region.

AUTHOR CONTRIBUTIONS

MT collected the data; MT and JP conceived the framework of the study; MT was responsible for data processing; MT and JP wrote the manuscript, and critically reviewed it.

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Table 1. Morphometric data of sampled eels (N=1370).

Sites	**Sampling date**	**N**	**Total length (mm)** min-max	**Mean length ±SD** (mm)	**Total weight (g)** min-max	**Mean weight ±SD** (g)	**Age range (year)** min-max	**Mean age ±SD** (year)
Lake Oubeïra	autumn 2010 - winter 2020	552	173 – 895	601±125	42 – 1330	484±290	0.67–6.58	3.3±1.7
Lake Tonga	winter 2015 - winter 2020	280	254 – 670	511±80	29 – 610	246±115	0.67–5.5	3.3±1
Mellah lagoon	winter 2015 - spring 2017	178	251 – 1130	460±86	68–2642	177±222	0.75–4.5	2.3±0.8
Mafragh estuary	winter 2007 - spring 2008	360	246 – 702	461±103	19 – 650	179±129	0.75–5.5	3.1±0.9

Table 2: Length-weight relationship of *A. anguilla* in the different sampling sites. **a** describes the rate of change of weight with length (intercept), and **b** is the weight at unit length (slope), t-test, $P < 0.001$

Sites	**N**	**a**	**b**	R^2	**p value**	**Allometry type**
Lake Oubeira	552	0.069	3.38	91%	0.000 ***	+
Lake Tonga	313	0.086	2.85	81%	0.000 ***	-
Mellah lagoon	178	0.175	2.35	81%	0.000 ***	-
Mafragh estuary	360	0.049	3.11	96%	0.000 ***	+

Table 3: Parameters of the von Bertalanffy growth function of *A. anguilla* in the different Algerian sites.

Sites	L∞	K	t_0
Lake Oubeira	683	0.83	-0.12
Lake Tonga	709	0.47	-0.29
Mellah lagoon	735	0.75	-0.13
Mafragh estuary	656	0.73	-0.23
All eels	845	0.52	-0.09

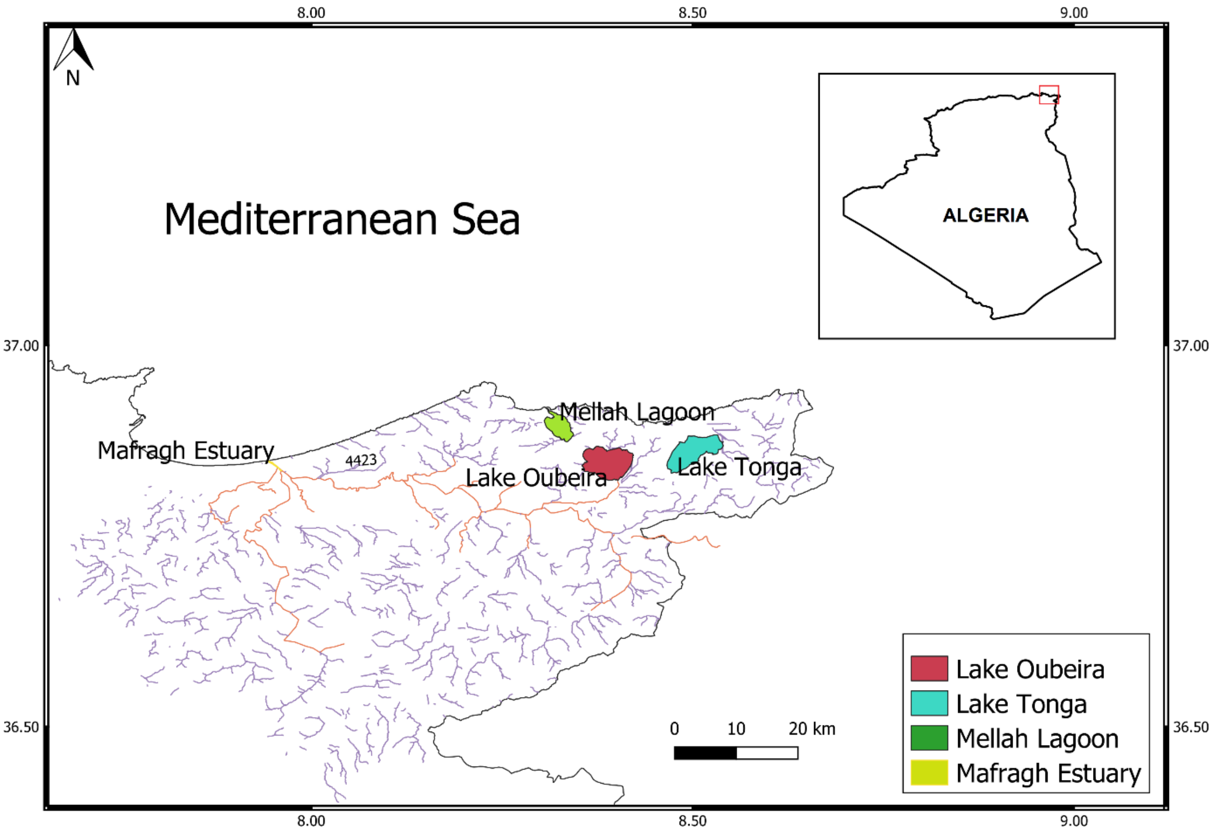
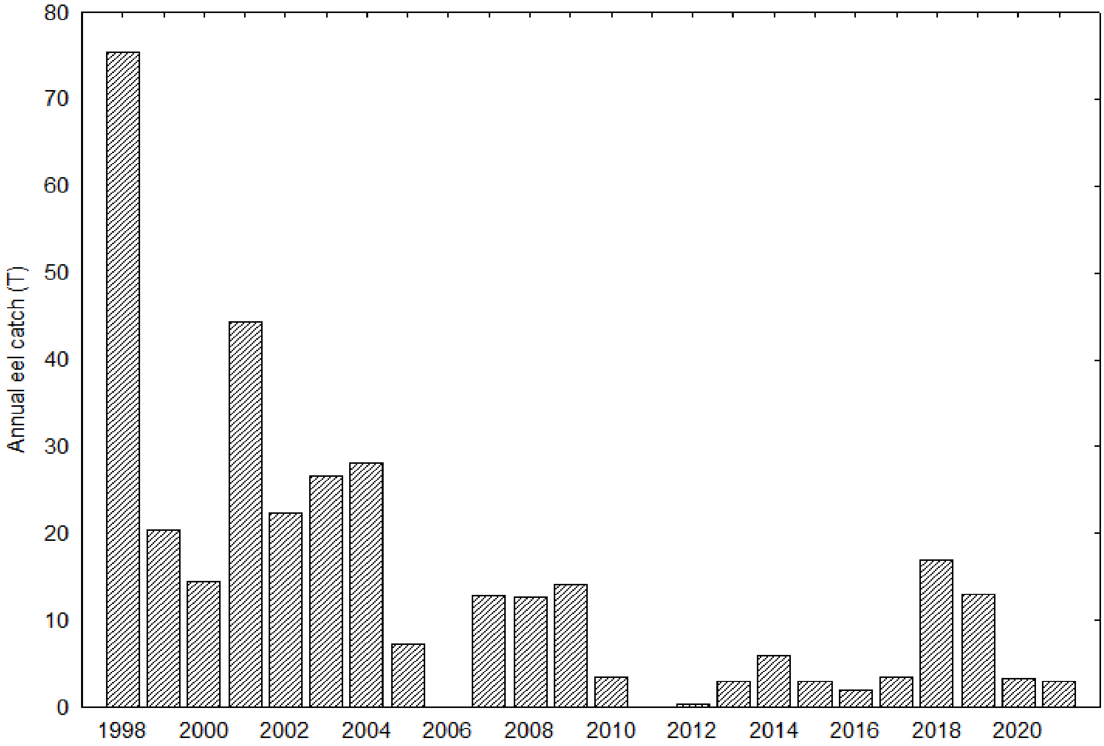
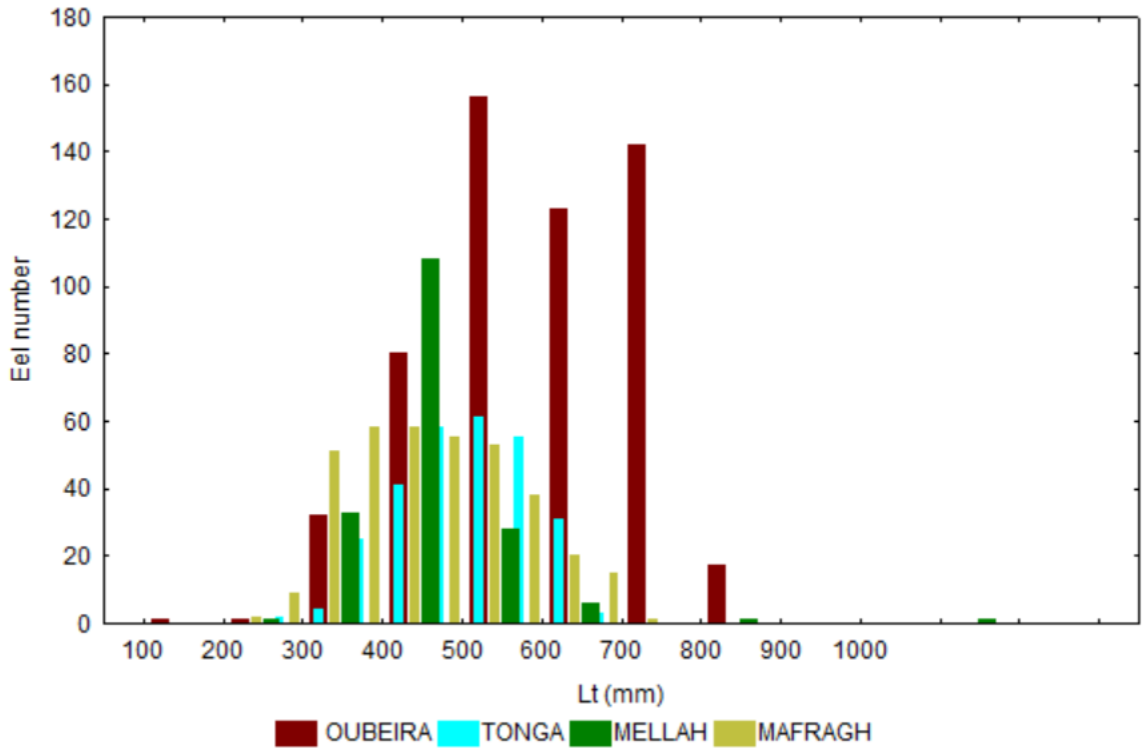

8.00
8.50
9.00
37.00
36.50
N
Mediterranean Sea
ALGERIA
Mellah Lagoon
Mafragh Estuary
4423
Lake Oubeira
Lake Tonga
0
10
20 km
Lake Oubeira
Lake Tonga
Mellah Lagoon
Mafragh Estuary

Figure 1



Annual eel catch (T)
0
10
20
30
40
50
60
70
80
1998
2000
2002
2004
2006
2008
2010
2012
2014
2016
2018
2020

Figure 2



180
160
140
120
100
80
60
40
20
0
Eel number
100
200
300
400
500
600
700
800
900
1000
Lt (mm)
OUBEIRA
TONGA
MELLAH
MAFRAGH

Figure 3

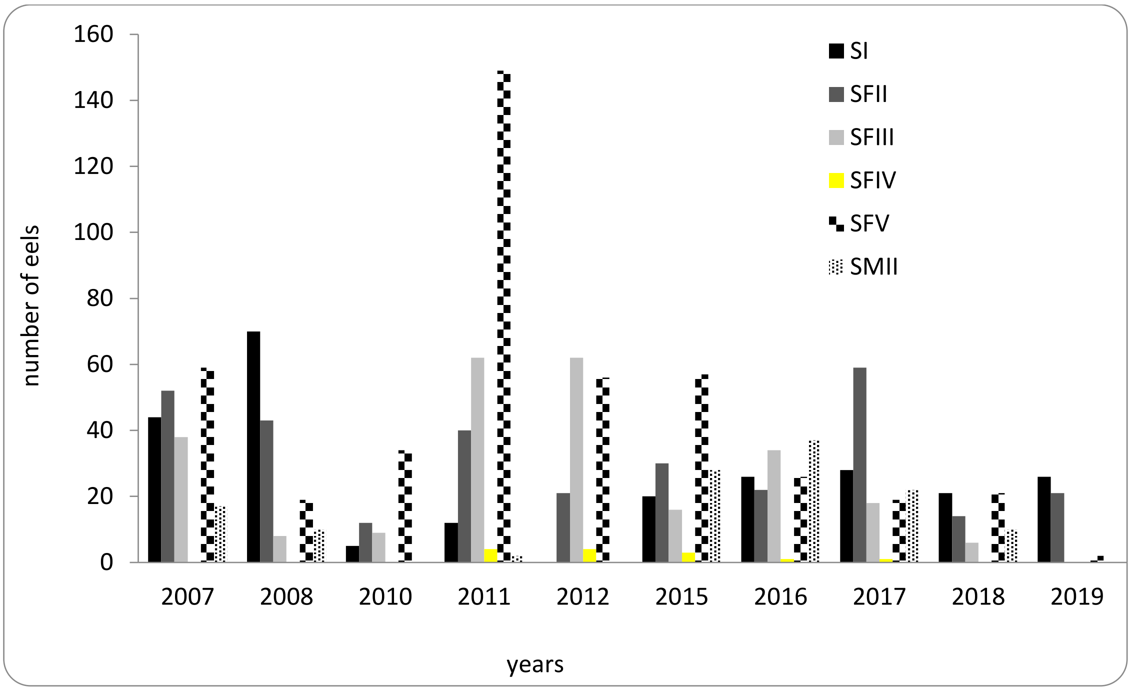

160
140
120
100
80
60
40
20
0
number of eels
SI
SFII
SFIII
SFIV
SFV
SMII
2007
2008
2010
2011
2012
2015
2016
2017
2018
2019
years

Figure 4

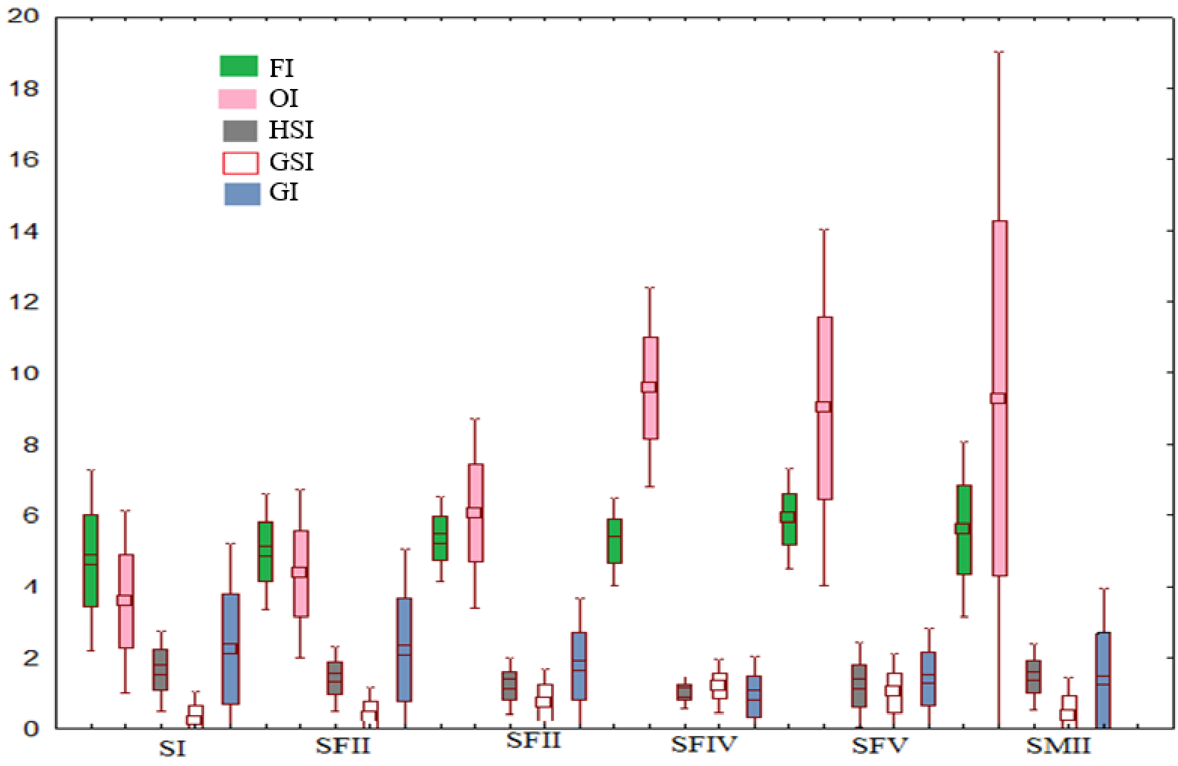

20
18
16
14
12
10
8
6
4
2
0
FI
OI
HSI
GSI
GI
SI
SFII
SFII
SFIV
SFV
SMII

Figure 5

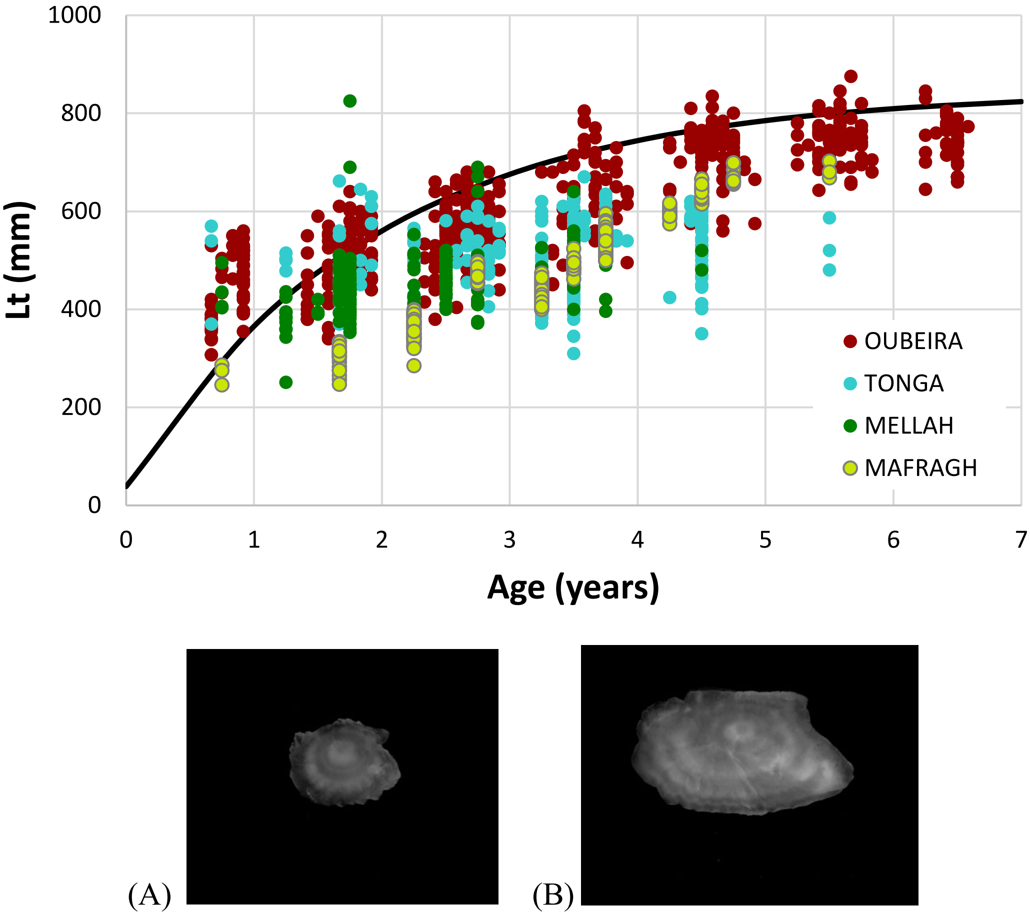

1000
800
600
400
200
0
Lt (mm)
0
1
2
3
4
5
6
7
Age (years)
OUBEIRA
TONGA
MELLAH
MAFRAGH
(A)
(B)

Figure 6

Figure captions

FIGURE 1: Study area showing the four sites: Lake Oubeïra, Lake Tonga, Mellah lagoon and Mafragh estuary.

FIGURE 2: Algerian annual eel catch from 1998 to 2021 (data from Directorate for Fisheries and Aquaculture DPA-2022, Ministry of Fisheries and Fish Production, Algeria). Catches in the different sites.

FIGURE 3: Length distributions of captured eels among sites (N = 1,370).

FIGURE 4: Proportion of silver eel stages over time (N = 1,370).

FIGURE 5: Boxplot of morphometric and internal parameters of eel stages. Friedman ANOVA and Kendall Coefficient of Concordance, ANOVA Chi Sqr. (N = 12, df = 29) = 315.0215 p =0.00000, Coeff. of Concordance = .90523 Aver. rank r = .89662). FI: fine index; OI: ocular index; HSI: hepato-somatic index; GSI: gonadosomatic index; GI: empty gut-somatic index.

FIGURE 6: Age and growth estimations. Examples of otoliths of Algerian eels observed under reflected light and a dark background (scale bar = 1mm): (A) otolith with 1 opaque ring (individual Lt = 340 mm of 19 months) and (B) otolith with 4 opaque rings (individual Lt = 670 mm of 54 months). (D) von Bertalanffy growth function adjusted with all sampled eels from the different sites.