L’ANGUILLA EUROPEA NEL BACINO IDROGRAFICO MARTA-BOLSENA VALUTAZIONI PRELIMINARI DI COLONIZZAZIONE ED EMIGRAZIONE AI FINI DELLA GESTIONE PER LA SALVAGUARDIA DELLA BIODIVERSITÁ.

INTEGRATING RIVER RESTORATION AND SUSTAINABLE MANAGEMENT OF EEL FISHERY IN A LAKE-RIVER SYSTEM IN THE MEDITERRANEAN REGION: A SMALL-SCALE CASE-STUDY TO SUPPORT EEL CONSERVATION AT GLOBAL SCALE

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Riassunto

Anguilla anguilla (L., 1758) è una specie panmittica, catadroma, altamente migratoria. Risorsa condivisa tra i vari paesi europei e mediterranei, è oggetto di interesse internazionale per il drastico e prolungato declino del reclutamento che si osserva dagli anni ’80, cui è seguita una contrazione delle catture delle anguille adulte. Tra le cause principali della riduzione globale dello stock vi sono certamente il sovra sfruttamento, la riduzione degli habitat disponibili e l’inquinamento degli ambienti acquatici che si verificano alla scala dei singoli bacini idrografici. A fronte di questa situazione, nel 2007 è stato approvato il Reg. CE 1100 che istituisce “Misure per la ricostituzione dello stock di anguilla europea”. La specie è inoltre inserita negli elenchi dell’All. II della CITES e della Red List (IUCN) nella categoria “In pericolo critico”.

Questo lavoro presenta un caso di studio relativo al bacino idrografico Marta-Bolsena che rappresenta un sito interessante per la presenza di un potenziale collegamento tra mare e lago. Il fiume Marta infatti è l’emissario naturale del lago di Bolsena, il suo tracciato naturale risulta tuttavia interrotto da sette sbarramenti e da una cascata naturale (Salombrona), inoltre all’incile del lago vi è una traversa che impedisce il collegamento lago-fiume. Attualmente questo stock di anguille, bersaglio di un’attività di pesca professionale, è sostenuto da pratiche di semina attuate dall’Amm. Prov. di Viterbo poiché la colonizzazione del lago risulta impedita, nonostante il consistente reclutamento naturale di ceche ancora presente alla foce del Marta. Al fine di stimare la densità delle anguille presenti alle attuali condizioni di gestione e la biomassa dei riproduttori potenzialmente migranti è stata effettuata una valutazione preliminare di colonizzazione ed emigrazione mediante l’applicazione del modello demografico DEMCAM che tiene conto dei processi di reclutamento, accrescimento e differenziamento sessuale, mortalità naturale e da pesca. Per questa applicazione un campione dello stock locale (177 ind.) è stato caratterizzato: la frazione di anguille mature risulta pari al 45% (79 ind.), il rapporto sessi è a favore delle femmine (ca. 5:1), la struttura delle taglie è ben distribuita (range 24-92 cm), la struttura in età presenta ca. il 62% degli individui (109 ind.) compreso tra le classi 7+ e 11+, il tasso di accrescimento osservato in cm per anno è pari a 4,86 per le anguille femmine e 4,92 per i maschi. Il modello DEMCAM ha calcolato un valore di densità attuale, pari a ca. 36 ind./ha per le anguille femmine e ca. 26 ind./ha per i maschi e valori di produzione di anguille gialle ed argentine rispettivamente pari
a 0,65 kg/ha e 0,38 kg/ha. Sulla base di queste stime il livello attuale di riproduttori potenziali emigranti è pari a 0,12 kg/ha (vs densità pristina stimata: 6 kg/ha).
A fronte dei risultati ottenuti, vengono discusse diverse politiche di gestione della risorsa al fine di consentire sfruttamento razionale e contribuire alla salvaguardia della specie.

Abstract
The European eel is a diadromous species for which an urgent conservation issue exists since its entire population has been declining at least since the 1980s. For this species, an economically and culturally important fishery resource throughout Europe, a framework has been set up for management and conservation, based on allowing an adequate escapement of silver eel biomass from continental waters to the sea.
Aim of this work was the setting up of a methodological framework for the management of eel local stocks at the catchment scale, based on integrating habitat restoration and sustainable management of fisheries. The reference system is the Bolsena lake, a natural growing habitat for eel, with its emissary, the river Marta that flows in the Mediterranean sea and whose course is fragmented by a number of dams. Following interventions to restore physical as well as hydraulic continuity of the river, samplings were carried out on the river and in the lake. A detailed demographic model was developed to allow to simulate the fishery yields and silver eel production under different recruitment and management scenarios, as a tool to assess escapement from the system and thus compliance to the management target. The simulations yielded interesting results concerning potential escapement from the lake in pristine conditions, estimated in 36,7 t, compared to conditions of high harvest level. The actual level is estimated in 23,7 t, more than 60 % of the pristine level: this represents nevertheless a potential escapement, that could become effective, leaving unchanged the present level of fishery effort, if the connection between lake and river was definitively re-established.
The opportunity of an integrated approach to management at the catchment scale is evidenced for eel: for this species local scale actions shall hopefully contribute to conservation at the global scale.

Key words: River restoration, eel conservation, Anguilla anguilla, Mediterranean, fishery management.

Introduction
Over the past 100 years, inland water habitats have suffered most among all ecosystems as result of a wide variety of uses of aquatic systems that all entail a legacy for impacting on the environment (Cowx, 2002). Impacts range from pollution to species introductions, flow regulation and impoundments, overexploitation. Tourism, climate change, land use are also relevant: these activities do not have a direct impact on the environment, but could bring about several consequences, which are only apparently less important (Maitland, 1995; Cowx and Welcomme, 1998; Poff et al., 2001; Tancioni et al., 2006).
The major changes to the habitat resulting from these interventions led to a series of threats to freshwater fish and fisheries. In order to protect threatened fish populations, several conservation strategies have been developed and applied. Key actions rely on habitat restoration, stock enhancement, and establishment of protected areas, the latter being scarcely achievable in inland waters because of the multiple uses of these ecosystems. However, concern has been expressed about the contribution of management initiatives to effective conservation (Cowx, 2002), because of the problems occurring when pursuing fish conservation in a multiple user environment. Fish biodiversity, as well as fisheries, have in
fact a marginal importance and are poorly represented from an economic and social perspective. A possible exception to this general picture might be the case of the catadromous European eel, *Anguilla anguilla*, an economically and culturally important fishery resource throughout Europe (Feunteun, 2002; Ringuet et al., 2002). Eel is exploited by capture fisheries in a wide range of habitats, such as estuaries, rivers and lakes, targeted to all life stages of the species, and is also farmed throughout Europe, an activity based on the rearing of wild-caught juvenile glass eels.

The European eel is a species for which a urgent conservation issue exists. This species shares the fate of many diadromous species: because of the complexity of their life cycle and of the fact that they use different environments in marine and continental waters, these species are particularly vulnerable to both direct and indirect anthropogenic impacts. Eel larvae, the leptocephali, cross the Atlantic Ocean from the spawning area in the Sargasso Sea to European and North African coasts. After metamorphosis to glass eels, eel complete migration into continental waters (coastal lagoon, rivers, lakes, ponds and canals), where they grow into yellow eels. After a feeding period of several years, they make the final transition into silver eels that migrate back to the Sargasso Sea, where they reproduce and then die (van den Thillart et al., 2009). The panmictic eel population (Dannewitz et al., 2005) shows major problems in relation to a continent-wide decline in recruitment observed in the last decades, and to a contraction in adult eel capture fisheries (Moriarty and Dekker, 1997; ICES, 2004, 2005; Dekker, 2008). A number of potential causes have been summoned, ranging from climate change and its influence on oceanic factors and predation to anthropogenic factors such as overexploitation, pollution, parasite infection, obstacles to migration and turbine mortality, habitat loss (Feunteun, 2002; ICES, 2007; Dekker, 2008).

Following concern raised by this situation, at the end of a long political and scientific process (Bevacqua et al., 2009a) a framework was set up aimed at establishing both a policy and practices for eel management and conservation, in order to reverse its decline. In September 2007 a Council Regulation (EC 1100/2007) established a framework for the recovery of the European eel stock. In 2007, the European eel was added to the CITES Annex II in order to control its international trade, and in 2008 it was listed as critically endangered in the IUCN Red List of Threatened Species (IUCN, 2010).

Managing a fish population as complex as the European eel’s faces a number of constraints, the main one being that restoration measures cannot target oceanic life stages and consequently protective measures are restricted to the continental phases. In conservation terms, the main objective of eel management actions is to allow an adequate escapement of silver eel biomass, silver eel being the key stage to be controlled if a positive effect on recruitment, i.e. glass eels ascending continental waters, is to be expected after management interventions. A number of actions intended to develop a comprehensive basis for rebuilding eel stocks, based on locally-appropriate actions and targets, can be identified. Against this background, the present work aims at setting up a methodological framework for the management of eel local stocks at the catchment scale and for the evaluation of the biomass of escaping mature eels. The reference system is the Bolsena lake with its emissary, the river Marta. This system is representative of many lentic systems in central Italy, where a number of lakes of volcanic origin represent a potential growing habitat for eel, because of their natural productivity and of the potential recruitment occurring at the mouth of their connections with the Thyrrenian sea, up to now prevented by river fragmentation.

Combining restoration of natural connectivity with a sustainable management of fisheries, and by assessing escapement based on a modelling approach, this study aims at defining basic elements for the implementation of a specific management strategy tailored to local conditions. Indeed it is widely agreed that at present case-adapted management options
represent the way ahead for eel, with the ultimate goal to protect the species and to generally contribute to delay biodiversity loss.

Materials and methods

Study site

The present study was carried out on the Marta-Bolsena system, consisting of a lake of volcanic origin connected to the sea through a tributary river. The Bolsena Lake (Fig. 1), the largest in central Italy covering a surface of 114 km$^2$, is circular in shape, has a volume of 9.2 km$^3$ and drains a catchment area of 159 km$^2$. The Bolsena watershed is directly connected to the river Marta, emissary from the lake, that flows directly into the Tyrrhenian Sea, with a total drainage basin of 1091 km$^2$ (Fantucci, 2007). The maximum lake depth is 151 m. Water supply to the lake is reduced, and is due to some creeks on the northern side and to a greater extent to rain. The Marta river, 49 km long, is supplied by the lake, water exchanges being regulated by a sluice, as well as from a number of tributaries. Its natural course presents a gap of about 10 m in height, at the Salombrona waterfall, 11 km from the lake outlet. The longitudinal profile of the Marta river is heavily modified by the presence of four power stations (S. Savino III, S. Savino II, S. Savino I and Fioritella), and of the Tuscania paper mill intake and by some small dams for agricultural use. Between 2006 and 2007, several interventions (by-pass channels and fish passes) were implemented by the Province of Viterbo, to restore both the physical and the hydraulic continuity on the river course, with the aim of compensating impacts of habitat fragmentation on fish populations (AGEI, 2008).

In the whole system, eel are present and sustain capture fisheries both in the Marta river and in the Bolsena lake. A small glass eel fishery takes place in the river Marta estuary, where a single licensed fisher installs glass eel fyke nets during fishing ascent, usually in November-February. Yields vary among years depending mostly on the river hydrological regime, but have remained fairly stable between the end of the 1990’s and 2010, notwithstanding the progressive drop in recruitment observed everywhere (ICES 2009). Catches are usually sold
for aquaculture and restocking purposes, and a quota is usually employed to stock Bolsena lake. In the lake, 65 fishers with 152 boats practice commercial fisheries, on several fish species. A characterization of the eel fishery was carried out in 2007-2010 by detailed interviews to the fishers to assess fishing effort and catch by stage. Fishing yields from 1996 to 2006 were recorded (Arsial, 2009). All Bolsena eel yields depend on stockings, that are performed by the Province of Viterbo and rely on glass eel and bootlace eel. Restocking data from the ’90s up to 2008 were obtained by the Province of Viterbo to be used for the model estimates of escapement.

**Sampling procedures**

To assess effectiveness of restoration interventions for eel colonization and escapement, a sampling campaign was carried out in November 2009 on the river Marta, in three stations (St. A at the connection between lake and river, just below the sluice gate, St. E and St. H in correspondence of the two main restoration interventions). Fishing was carried out by standard shoulder-bag (4 KW) electrofishing, counter-current wading a river stretch long twenty times its width in each sampling station. Between May and October 2009 three samplings were organized in the lake, in the southern side of the basin, each campaign lasting three days: three fyke-nets were installed each fishing day and retrieved after 72 hours when catches were collected. Fyke-nets consisted of four chambers (diameter from 2 m to 30 cm), 16 mm codent mesh size, endowed of two 10 m long lateral wings (mesh size 18 mm) and of a 25 m long leader central net (called “longarina”, mesh size 20 mm).

Catches from both electrofishing on the river and fyke-netting in the lake were weighted and eel were counted. The collected samples were transported to the laboratory for further processing.

**Sample examination**

A total of 177 eels was sacrificed, measured for total length (L), weight, and three morphometric parameters (i.e. pectoral fin length, vertical and horizontal eye diameters), aged through otolith reading, and visually inspected to determine sex and maturation stage. Otoliths were extracted, embedded in epoxyn resin and stained with 3% toluidine blue following grinding of the convex side (grinding and polishing method; ICES 2009). Fish age was determined by reading annual otolith rings (annuli), using a light stereomicroscope, from the first growth check (age 1+) outside the so called “zero band”. This band is commonly assumed as the beginning of continental growth in eel (Moriarty, 1983; Poole et al., 2004; ICES 2009). Sex was assessed macroscopically whenever possible, or by histological examination of gonads (Colombo and Grandi, 1996). Maturation stage was determined combining gonad development, Pankhurst’s (1982) ocular index (OI) which reflects changes in eye diameter during metamorphosis to the silver stage (Acou et al., 2009) and Durif’s silvering index (Durif et al., 2005).

**Data analysis**

Theoretical body growth of the local eel stock of Bolsena lake was described using the von Bertalanffy (1957) growth equation for male and female silver eels separately:

\[ L_t = L_\infty - (L_\infty - L_0)e^{-kt} \]

where \( L \) is total length at time \( t \), \( L_\infty \) is the asymptotic length, \( K \) the rate at which asymptotic length is approached \( L_\infty \), and \( L_0 \) body length at recruitment. In the case of glass eels recruited to the Marta river, average \( L_0 \) was observed to be equal to 63 mm.

The mean annual growth rate of sampled eels of age \( t \) was computed as a relationship between fish length and age from the glass eel stage, such that:
The growth rate of fish at capture, $L_c$, is the mean glass eel length (63 mm) and $t$ is the continental age estimated by counting the rings after the glass eel mark. The model describing eel demography in the continental phase (i.e. from glass eel stocking to silver eel escapement) explicitly accounts for key aspects of its life-history, such as high natural mortality in the acclimation phase and lower natural mortality in the following phase (Dekker 2000), body size and effort dependent fishing mortality (Bevacqua et al., 2009b), sex specific body growth as silver females are remarkably larger than silver males (Melià et al., 2006a), size- and sex-specific maturation rates as females takes substantially longer than male to reach sexual maturity (Bevacqua et al., 2006). A detailed demographic model was developed accordingly to allow to realistically simulate fishery yields and silver eel production under different recruitment and management scenarios. A detailed description of the full demographic model and its parameterization is reported in Appendix A. The only unknown parameter of the model (i.e. catchability $q$) was assessed in order to obtain estimates of actual harvest, with a fishing effort and a restocking set equal to the average of the those obtained by surveys. Annual fishing effort is expressed as net per days, and eel harvest is in kg/ha referred to about 20 % of the total surface of the lake, only the perimeter band from 0.5 to 12 m depth has been considered suitable for eel. Once calibrated, the model has been used to estimate levels of fishery yields and silver eel escapement in different management and stocking scenarios. Namely, an actual (actual fishing effort = 7410 net-day) a pristine (i.e. no fishing exploitation and an ideal maximum recruitment until lake carrying capacity is reached) and an heavily exploited scenario (past fishing effort = 99.750 net-day and actual stocking level = 848 ind/ha) have been considered. Two scenarios for recruitment were considered: the first refers to a ideal maximum recruitment, i.e. ad libitum until carrying capacity is reached, and the other to a stocking of 848 glass eels/ha, calculated averaging stocking data from the 1990s up to present.

Results

Samplings carried out on the Marta river yielded a total of 19 eels: five were glass eels, 13 yellow eels and one silver eel (Tab. 1).

<table>
<thead>
<tr>
<th>SITE</th>
<th>N.</th>
<th>Size class (mm)</th>
<th>Stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>H &quot;Isola Ecologica&quot;</td>
<td>5</td>
<td>&lt; 100</td>
<td>Glass eel</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>100 - 210</td>
<td>Yellow</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>210 - 500</td>
<td>Yellow</td>
</tr>
<tr>
<td>F &quot;Cartiera Tuscania&quot;</td>
<td>1</td>
<td>100 - 210</td>
<td>Yellow</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>210 - 500</td>
<td>Yellow</td>
</tr>
<tr>
<td>A &quot;Barriera Marta&quot;</td>
<td>4</td>
<td>210 - 500</td>
<td>Yellow</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>&gt; 500</td>
<td>Silver</td>
</tr>
</tbody>
</table>

Tab. 1: Sizes and stage of eels from electro-fishing on the Marta River.

Samplings in the lake allowed to characterize the demographic structure of the Bolsena local stock (177 eels). Yellow eels represented 60 % of the catches, and silver eels 40 %. Size ranged between 250 mm and 920 mm. Yellow eels had a mean body size of 459 ± 114 mm and a mean weight of 210 ± 201 g, while silver eels had an average size of 548 ± 150 mm and a mean weight 373 ± 310 g.
Size frequency distributions (Fig. 2) show L ranging between 250-800 mm in yellow eel, 46% of individuals falling into the 400-450 mm class. Silver eels body sizes range between 350-920 mm.

Fig. 2: Length frequency distributions (5 mm) of yellow eels (A, grey bars), and male (white bars) and female (black bars) silver eels (B).

Tab. 2: Mean, standard deviation and range of biometric measures of yellow and silver eels of the Bolsena Lake samples.

<table>
<thead>
<tr>
<th>BOLSENA SAMPLE</th>
<th>N</th>
<th>Mean ± SD. (mm)</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>YELLOW</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TL (Total length)</td>
<td>458.5 ± 114.4</td>
<td>245.0 - 800.0</td>
<td></td>
</tr>
<tr>
<td>W (Weight)</td>
<td>210.1 ± 201.4</td>
<td>19.6 - 1070.7</td>
<td></td>
</tr>
<tr>
<td>Ov (Vertical Eye Diameter)</td>
<td>4.6 ± 1.2</td>
<td>2.2 - 8.0</td>
<td></td>
</tr>
<tr>
<td>Oh (Orizontal Eye Diameter)</td>
<td>5.1 ± 1.3</td>
<td>2.6 - 8.9</td>
<td></td>
</tr>
<tr>
<td>Lpf (Pectoral fin length)</td>
<td>19.2 ± 6.3</td>
<td>5.1 - 39.7</td>
<td></td>
</tr>
<tr>
<td>SILVER</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TL (Total length)</td>
<td>548.2 ± 150.0</td>
<td>345.0 - 920.0</td>
<td></td>
</tr>
<tr>
<td>W (Weight)</td>
<td>372.5 ± 309.5</td>
<td>67.1 - 1333.4</td>
<td></td>
</tr>
<tr>
<td>Ov (Vertical Eye Diameter)</td>
<td>7.0 ± 1.1</td>
<td>4.4 - 9.3</td>
<td></td>
</tr>
<tr>
<td>Oh (Orizontal Eye Diameter)</td>
<td>7.5 ± 1.2</td>
<td>5.4 - 10.4</td>
<td></td>
</tr>
<tr>
<td>Lpf (Pectoral fin length)</td>
<td>27.0 ± 7.4</td>
<td>17.2 - 40.9</td>
<td></td>
</tr>
</tbody>
</table>

The population sex ratio, only considering sexually differentiated individuals, appeared displaced toward females (83%). Gonad developmental stages were accurately described (Fig. 3, Tab. 3). Age estimated by otolith reading ranged from 3+ to 19+ years (Fig.4). Modal age was 12+ in females and 8+ in males.

The proportion of mature individuals ready to escapement as assessed by Pankhurst OI is 34%.
Fig. 3: Macroscopic and histological features of *Anguilla anguilla* gonads from Bolsena lake. Gonad developmental stages are: undifferentiated, A-A1; mature male, B-B1; immature female with early previtelligenic oocytes (OOEP), C-C1; Intermediate female with growth oocytes, D-D1, Mature female with oocytes with large nucleus (Nu) and lipid droplets (L), E-E1.

Tab. 3: Number, mean total length, TL standard deviation and range, mean weight, w standard deviation and range, of eels at different gonad developmental stages from the Bolsena lake.

<table>
<thead>
<tr>
<th>Gonad developmental stage</th>
<th>N</th>
<th>Mean TL ± SD. (mm)</th>
<th>Range</th>
<th>Mean ± SD. (g)</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Undifferentiated</td>
<td>4</td>
<td>276,3 ± 43,9</td>
<td>245 - 340</td>
<td>30,3 ± 17,9</td>
<td>19,6 - 57,1</td>
</tr>
<tr>
<td>Mature male</td>
<td>30</td>
<td>398,7 ± 2,6</td>
<td>345 - 445</td>
<td>109,5 ± 21,1</td>
<td>67,1 - 147,0</td>
</tr>
<tr>
<td>Immature female</td>
<td>71</td>
<td>410,8 ± 58,6</td>
<td>305 - 570</td>
<td>123,0 ± 57,9</td>
<td>52,0 - 301,3</td>
</tr>
<tr>
<td>Early female</td>
<td>23</td>
<td>550,1 ± 123,1</td>
<td>435 - 720</td>
<td>333,7 ± 132,8</td>
<td>147,1 - 645,9</td>
</tr>
<tr>
<td>Mature female</td>
<td>49</td>
<td>662,8 ± 97,8</td>
<td>490 - 920</td>
<td>590,0 ± 281,6</td>
<td>213,5 - 1333,4</td>
</tr>
</tbody>
</table>
Fig. 4: Age frequency distributions of *A. anguilla* from the Bolsena lake (A: yellow eels, grey bars; B: silver eels, males, white bars, and females, black bars).

Assessment of resident to migratory stages by Durif’s Silvering Index yielded 58% of resident eels (Undifferentiated 38%, 67 individuals, FII 20%, 36 individuals), 18% of potential migrant eels (FIII) and 24% of mature individuals (FIV and FV respectively 1% and 7%; MII 15%).
The female growth parameters calculated from Bertalanffy equation (Fig. 5a) were $L_\infty = 952.98$ with a value of $k = 0.08$, $L_0 = 63$ and $t_0 = -0.76$. Male growth parameters (Fig. 5b) were $L_\infty = 392.58$ with a value of $k = 0.54$, $L_0 = 63$ and $t_0 = -0.29$.

The mean annual growth (all ages) for female eels averaged $47.68 \pm 12.42$ mm/y, while for males was $45.38 \pm 12.69$ mm/y.

With regards to eel fishery in the lake, eel average yield amounted to $33$ t/y average in the '90s, dropped to less than $5$ t/y average in the period 2004-2006 and amounted to $5$ t/y in 2010.

Catchability $q$ resulted to be equal to $0.007$ net$^{-1}$ day$^{-2}$ and permitted to estimate actual harvest as equal to the observed value of $2.1$ kg/ha.

Silver eel escapement from the lake (Tab. 4) in pristine scenario is evaluated in $16.1$ kg/ha. When considering the heavily exploited scenario silver production drops to $1.1$ kg/ha. Present escapement level is estimated in $10.4$ kg/ha and is sustained by the same level of stocking but allowing a much lower level of fishing exploitation. Note that these values per hectare refer to eel production of suitable eel habitat, estimated in $20$ % of the total area of the lake, and amounting therefore to $2,280$ ha. Pristine total biomass escaping the lake is therefore estimated in $36.7$ t of silver eels, and actual level is $23.7$ t.

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Fig. 5: Theoretical growth curves of Bolsena Lake *A. anguilla* sample population female group (A) and male group (B).
Tab. 4: Results of demographic simulations. Stocking density for scenarios 2 and 3 is a average on the restocking data series (17 years). Lake area refers to suitable surface for eels (estimated in 20% of the total 11,400 ha lake surface, corresponding to 2,280 ha).

<table>
<thead>
<tr>
<th>Stocking (ind/ha) of glass eel or equivalent</th>
<th>Annual fishing effort</th>
<th>Silver eel production</th>
<th>Eel harvest</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1 bootlace eel = 0.25 glass eel.)</td>
<td>( fyke nets · days).</td>
<td>(escapement in kg/ha)</td>
<td>(kg/ha)</td>
</tr>
<tr>
<td>Pristine scenario:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ad libitum until carrying capacity is</td>
<td>0</td>
<td>16.1</td>
<td>0</td>
</tr>
<tr>
<td>reached</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heavily exploited scenario (1990’s):</td>
<td>99,750</td>
<td>1.1</td>
<td>7.15</td>
</tr>
<tr>
<td>848 ind/ha</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Actual scenario (2010):</td>
<td>7,410</td>
<td>10.4</td>
<td>2.15</td>
</tr>
<tr>
<td>848 ind/ha</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Discussion

Demography of the Bolsena local stock

The Bolsena lake eel local stock shares features with several other eel populations, such as bimodal length and age distributions, and migrating females being considerably larger and older than males (Tesch, 2003). Sex dominance is skewed towards female eels, and 40% of the eels caught are mature and ready to migrate.

Females and males mean annual growth in length is similar (45.38 and 47.68 mm/y respectively). These growth parameters are higher of those found in northern and central Europe freshwater populations (Barrow River (N. Ireland): 33 mm/y, Moriarty, 1983; Burrishoole lakes (N. Ireland): 15 mm/y, Poole and Reynolds 1996b; Lough Neagh (N. Ireland): 26.50 mm/y, Rosell et al., 2005; River Havel system lakes: 45 mm/y, Simon, 2007. Jeziorak Lake (Poland): 41 mm/y, Nagiec and Bahnsawy, 1990). On the other hand, a more rapid growth is observed in other Mediterranean populations (Vaccarès Lagoon (France), 90 mm/y; Acou et al., 2003. Tiber River (Italy): 53.78 mm/y, Fogliano Lagoon (Italy): 61.67 mm/y, Lesina Lagoon (Italy): 88.30 mm/y; Capoccioni et al., in prep.)

Performances of the model

The model was able to mimic observed catches, both in the actual and in the past fishing exploitation regime. The estimated parameter of catchability is lower than what estimated by a similar modelling approach (Bevacqua, in prep.) in a shallow Mediterranean lagoon habitats (q = 0.1 net⁻¹ day⁻² in Camargue, southern France). This result is likely to reflect the higher probability for the gear to intercept eel in shallow waters, water depth in the Camargue lagoon is indeed lower, comprised between 1-2 m.

Escapement estimates and changes in management

The simulations yielded by the model provides interesting results concerning potential escapement from the lake. Against a potential escapement estimated in 36.7 t of silver eel biomass, the actual level is estimated in 23.7 t, more than 60 % of the pristine level. Therefore, the target of 40 % of the pristine escapement from this single catchment as indicated by the management framework established by the CE Regulation 1100/2007 would be attained, if the effective escapement from the lake and the downstream migration were ensured. The model also allowed estimating the detrimental role of over-fishing in lowering the effective number of escapements. In fact, with the same stocking level, but an high fishing pressure comparable to those of the 90s, the model predicts only 2,5 t of silver eel escapement.

The recovery of silver eel production and hence of the potential escapement from the lake seems due mainly to the decline of the fishery. The factors involved pertain more to the socio-economic dimensions (shift towards other more lucrative target species, reduced interest of the market towards eel, fishers ageing) rather than to the biological dimensions of the local eel stock. This is a feature common to many small scale eel fisheries, but was also reported for
the Lough Neagh (Rosell et al., 2005), one of the largest fisheries in Europe. In this scenario stocking, albeit still practiced to sustain the local eel stock and related fishery, plays a different role, sustaining silver eel production and escapement, with important implication for eel conservation.

**Restoration of river connectivity**

Assessment of the efficiency of the restoration interventions with specific reference to eel, as carried out within this study, is at an early stage, and is at present being extended by further investigations. Sporadic catch of eel during electro-fishing seems to point to an improved chance for colonization, impossible up to 2007, as attested by previous campaigns (Agei, 2008; Andreani et al., 2010). Thus, recruits to the river Marta mouth have now enhanced probabilities to colonize the upper stretch of the river and its tributaries. On the other hand, escapement from the lake strictly depends on the management of the sluice connecting the lake to the river, and this compromises effective escapement to the sea.

**Implications for management**

The importance of re-establishing or maintaining river continuum and longitudinal connectivity in rivers for fish conservation and more specifically for eel has been repeatedly stressed (Cowx, 2002) and even more specifically for eel (Laffaille et al., 2005). In the Bolsena-Marta system, this appears fundamental for allowing colonization of ascending elvers from the river mouth and the low river stretch, but even more because this will enable escapement of the silver eel biomass already present in the lake.

The present experience highlights the fact that individual actions, such as reduction of fishing mortality, sustaining local fisheries by stocking, or habitat restoration plans even implying relevant efforts and technologies, could fail to bring about significant contributions to the restoration of the stock if they are not integrated into a management scheme, and that the relative roles of individual actions have to be tailored to the local situation. In this framework, models assume a fundamental role in assessing different scenarios and quantify figures difficult to determine, such as effective escapement. The latter remains the key feature to assess (Bilotta et al., 2011): although escapement evaluation cannot do without direct counts based on mark-recapture or possibly tagging and telemetry, the modelling approach is the suitable instrument to assess compliance to targets and effectiveness of management measure.

**Conclusions**

A most general issue is whether the Bolsena-Marta system can be considered as a key site for eel conservation, and whether this habitat typology can provide a contribution to the global conservation of eel stock. Productivity, as demonstrated by eel production and eel growth in the Bolsena lake, is good, if management practices finalised to sustain local eel stocks are pursued, and will bring about a definite effect if escapement routes are guaranteed. Thus, the maintenance of traditional enhanced fisheries is a specific tool allowing a contribution to overall eel escapement at regional scale (Ciccotti, 2005). With regards to fishery management, recent analyses show that cases exist where the conservation target can be achieved without further reductions in harvest (Bevacqua et al., 2007), and this is the case of the Bolsena and Marta eel fisheries, that have decreased spontaneously to a level compatible also for eel conservation targets. Conflicts that are likely to arise between fishers and policy makers could be further reduced if the interests of fishers are explicitly accounted (Bevacqua, 2009), or if they are involved directly in the management process.

Finally, an integrated approach to management must be addressed at the catchment scale, as evidenced by Collares-Pereira and Cowx (2004), when freshwater fish conservation is dealt with. This appears to be true also when referred to the conservation of the European eel, a species for which local scale actions shall hopefully contribute to conservation at global scale.
Appendix A: Demographic model

Individuals are structured in classes according to life stage and sex. Any class $i$ is identified by an Acronym where the first letter denotes the life stage (i.e. G, Y, S for Glass/Yellow/Silver) and the second one the sex (i.e. M, F for Male/Female). Variable $n_i(x, t)$ indicates the abundance of eels of age $x$, at time $t$, in class $i$. The model was run with constant recruitment and fishing effort until equilibrium was reached.

1. Glass eel recruitment

The number of glass eel $G$ entering the system was computed from data on stock recruitment, considering that one individual on average weighs 0.3 g. In the case of elvers stocking the weight was assumed to be 70 g. Considered an average survival probability of 0.25 from glass to elver stage (Dekker 2003), single one elver was considered as equivalent of stocking 1/0.25 glass eel.

Then, the number of stocked eels surviving acclimation to the new environment and successfully settling was computed as:

$$n_{ym}(x, t) + n_{ys}(x, t) = j r_m \cdot \sigma_G \cdot n_G(x, t)$$

$$n_{ys}(x, t) = (1 - j r_m) \cdot \sigma_G \cdot n_G(x, t)$$

where the survival fraction of glass eel $\sigma_G$ is a density-dependent function $\sigma_G = k f(k + G^*)$. Where $G^*$ is the abundance of glass eel recruitment (even considering the equivalent quantity of stocked elvers) and $k$ indicates the carrying capacity for annual settlement of new eels in the system. $k$ was estimated to be equal to 450 Ind./ha in a the Camargue lagoon (Bevacqua in prep.) and was assumed halved in the freshwater study case, given the fact that brackish system are more productive eel habitat. Fraction males was set = 1/3 and for females = 2/3, considering that this case study is female skewed.

2. Population dynamics the continent

The population dynamics during the continental phase are described by the following recursive equations:

$$n_{YMj}(x + 1, t + 1) = \sigma_{YMj}(1 - \gamma_{YMj}(x)) n_{YMj}(x, t) \quad (A 1)$$

$$n_{YFj}(x + 1, t + 1) = \sigma_{YFj}(1 - \gamma_{YFj}(x)) n_{YFj}(x, t) \quad (A 2)$$

$$n_{SMj}(x + 1, t + 1) = \sigma_{SMj} \gamma_{SMj}(x) n_{SMj}(x, t) \quad (A 3)$$

$$n_{SFj}(x + 1, t + 1) = \sigma_{SFj} \gamma_{SFj}(x) n_{SFj}(x, t) \quad (A 4)$$

where $\sigma_{ij}$ is annual survival and $\gamma_{ij}$ is the fraction of yellow eels metamorphosing to the silver stage. Values and meaning of all the parameters included in these equations are further discussed in the following sections.

Yellow eel survival. Natural ($M$) and fishing ($F$) mortality rates were computed respectively as $M = 0.14 \, yr^{-1}$ (Dekker 2000) and $F = q^*E^*\phi$ (Bevacqua et al., 2009b) where $q$ is a catch ability parameter (to be estimated), $E$ is the annual fishing effort as total number of nets installed in the year (net day) ($n.nets \times n.fishing \, day$).

Selectivity $\phi$ of the fishing gear was estimated following Bevacqua et al. (2009b). Probability of surviving fishing and natural mortality was hence computed as

$$\sigma_{TU} = \exp\left(-M + F\right)$$

Body growth. Body growth is modeled according to the von Bertalanffy growth curve
estimated in the present work.

Sexual maturation. Maturation rates $\gamma_{ij}(\omega)$ represent the fraction of individuals that undergo sexual maturation in region $j$ at age $x$. Maturation rates are sex- and size-dependent and were estimated as in Bevacqua et al., (2006):

$$\gamma_{ij} = \gamma_{\text{MAX};i} \left( \exp \left( \lambda_i - L_{ij}(\omega) \eta_i \right) \right)^{-1} - 1$$

(A 15)

where $L_{ij}(\omega)$ is body length, $\gamma_{\text{MAX};i}$ the maximum rate of maturation, $\lambda_i$ a semi-saturation constant and $\eta_i$ is a parameter inversely proportional to the slope of the metamorphosis curve at $L_{ij}(\omega) = \lambda_i$.

The values of $\gamma_{\text{MAX};i}, \lambda_i$, and $\eta_i$ are taken from Bevacqua et al., (2006).

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