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Quantifying 60 years of declining European eel (*Anguilla anguilla* L., 1758) fishery yields in Mediterranean coastal lagoons

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The European eel *Anguilla anguilla* is thought to be in a multi-decadal decline across its range. Although its northern Atlantic sub-populations are well-studied, little is known about the historical trend and current status of eel stock in the Mediterranean Sea. To fill this gap, we gathered catch data for 86 lagoon fisheries in nine countries across the Mediterranean basin and analysed historical trends and geographical and environmental patterns. We found a region-wide decline in eel catch, beginning in the mid-1970s and exceeding the simultaneous decline in non-eel fisheries, as well as lower productivity in larger lagoons and those in the southern Mediterranean. Additionally, we developed a population dynamics model to provide a preliminary estimate of pristine, potential, and actual escapement of spawning adults (silver eels) across the Mediterranean basin under historical and current conditions. Model results suggest that current escapement is 35% of escapement at pristine biomass levels, <40% target set by EC regulation 1100/2007. Furthermore, we estimate that a complete closure of lagoon fisheries would achieve 57% of pristine escapement under current recruitment levels. Though preliminary, this analysis represents a first step towards a full assessment of the role of the Mediterranean sub-population in overall eel stock recovery.

Keywords: *Anguilla anguilla*, demographic management model, escapement, European eel, fisheries, fishery management, lagoons, Mediterranean, population dynamics, stock decline.

Introduction

Widespread concern for the global stock of the European eel, *Anguilla anguilla*, stems from a noticeable and prolonged decline in recruitment spread across the continent, estimated to be <10% of what was observed in the past (ICES 2007), and to the contraction in catches of adult eels in many regions (Moriarty and Dekker, 1997; ICES, 2001, 2002, 2004, 2006). The severity of this decline was formally recognized in 1998 (ICES, 1999; Dekker, 2003a; Bilotta *et al.*, 2011), with eels now thought to be seriously threatened (Freyhof and Kottelat, 2010). Debate on the measures to be undertaken to protect the global eel stock and to ensure its recovery has been going on since the end of the 1990s (ICES, 2002). Despite some doubts about the role of ocean processes (Baltazar-Soares *et al.*, 2013; Melià *et al.*, 2013; Pacariz *et al.*, 2014), recruitment decline has been commonly assumed to be a consequence of low spawning stock (Dekker 2003b) and measures to safeguard and enhance the spawning-stock biomass (SSB) are considered a priority. In 2007, the European Union issued the Regulation EC 1100/2007 (Council of the European Union, 2007) requiring member states to reduce anthropogenic mortalities so as to permit the escapement to the sea of at least 40% of the silver eel biomass relative to the best estimate of pristine escapement, i.e. the escapement that would have existed if no anthropogenic influences had impacted the stock. However, due to the eel's complex life cycle, both the current recruitment-limiting level of SSB and the target level of SSB to ensure stock recovery are particularly difficult to assess.

European eel conservation policies thus crucially rely on establishing the pristine biomass of escaping eels before the stock decline—a difficult parameter to estimate because of the long history of anthropogenic impacts on the eel stock—and the present and future levels of escapement under alternative management strategies. At the local scale management units are made up of single river catchments, lakes or lagoons, or alternatively administrative districts, and operate independently but within the context of the overall management framework. However, the panmictic nature of the eel stock (Andrello *et al.*, 2011) raises questions about the proper spatial scale of the management framework. Despite the absence of geographical genetic structure (Als *et al.*, 2011), the European eel exhibits a high plasticity in body growth and age at maturity (Nielsen and Prouzet, 2008, Daverat *et al.*, 2012), sex ratio, migratory behaviour (Edeline and Elie 2004), and feeding preferences (Edeline *et al.*, 2005). Some of these differences have been associated with broad geographical gradients, such as latitude and longitude (Vøllestad, 1992), and environmental factors, such as stock density, water temperature, food availability (Tesch, 2003), productivity (Gross, 1987), and salinity (Tzeng *et al.*, 1997).

At a broad geographical scale, the eel stock in the central and northern range of its distribution has been the subject of extensive analysis, especially in the Baltic and the central area in the Bay of Biscay, but much less is known about the eel stock in the southern range of the distribution. In particular, the Mediterranean Sea is characterized by local stocks with a short biological cycle (i.e. early age at maturity), sustained by sparse glass eel recruitment and largely confined to coastal lagoons and brackish habitats (Nielsen and Prouzet, 2008). Historically, these conditions allowed for the development of small-scale glass eel fisheries in some Italian estuaries (Ciccotti, 2005) and of consistent eel fisheries in many coastal lagoons in southern France, Spain, and Greece, in many North African countries (Pérez-Ruzafa and Marcos, 2012), and in the northern Adriatic sea, most notably the valliculture in the Comacchio lagoons (Carrieri *et al.*, 1992) where permanent fish barriers were placed along the canals linking the lagoons to the sea to exploit the seasonal migration of mature eels (Cataudella *et al.*, 2014). Today, the Mediterranean coastal habitat still constitutes a non-marginal fraction of the overall continental habitat of the European eel with roughly 400 lagoons in 23 countries and a combined surface area of ~580 000 ha (Cataudella *et al.*, 2014, excluding wetlands and saltmarshes not suitable for eels). Based on the spatial pattern of larval migration and juvenile recruitment, it has been conjectured that the recovery of the eel global stock may depend closely upon the contribution of Southern European and North African countries within the Mediterranean basin (Dekker, 2003c; ICES, 2007). This hypothesis has received some criticism (Kettle *et al.*, 2011), but a formal assessment of the Mediterranean portion of the *Anguilla* stock and the impact of lagoon fisheries has never been carried out.

The aim of this work was to assess the current status and recent trend of eel fisheries in the Mediterranean coastal lagoons and to estimate historical, present, and potential spawning biomass escaping from these habitats. Specifically, we first gathered Mediterranean catch data from a broad variety of academic and non-academic sources. We then analysed trends in annual eel catches and contrasted them to total catch of species other than European eel for 45 lagoons in 9 Mediterranean countries for which data were available in the period 1950–2012. We analysed the environmental characteristics of these lagoons and assessed whether annual eel catches per hectare were associated with any of these features. Finally, we used available lagoon data to calibrate a demographic model of the continental life cycle of the European eel and estimated spawner escapement from the Mediterranean lagoons under pristine and present conditions. The present work represents the first preliminary quantitative assessment of eel escapement for this region.

Material and methods

Data collection

We carried out a thorough literature search to build a database with the information necessary to conduct the analyses and assessment aims of the present study. We conducted the search at two levels, one intended to collect fishery data and the other to collect useful information to describe the lagoons from an ecological point of view. We used the Scientific Citation Index, Aquatic Science and Fisheries Abstracts, and Google Scholar (www.scholar.google.it); in addition, we contacted a number of authors in search of grey literature, internal reports, and unpublished data.

For fishing yields from Mediterranean lagoons, we focused specifically on obtaining annual *total landings* and *eel landings* for individual lagoons, as far back in time as possible and at the minimum within the years 1950–2012. For each source, we retained the data if commercial landings were reported as kilograms or tons per year disaggregated by species and if eel catch or catch proportion of the total catch was specifically reported. We did not include aggregated data for all fish species and/or crustaceans or shellfish and also discarded generic indications of fisheries production without specification of year. All data refer to individual lagoons, except in two cases in which substantial time series consisted of data pooled for grouped lagoons. The first was cumulated yields from the Mediterranean Spanish coastal lagoons (Albufera de Valencia, Albufera de Mallorca, Delta de l'Ebro lagoons, Albufera de Adra, Mar Menor, and Lagoons of Moreras) and the second those from the Corse lagoons (Diana, Biguglia, and Urbino).

We gathered information from the same documents and additional sources regarding the lagoon *environment*, including morphological traits (such as surface area, maximum and average depth, and sea channel characteristics), hydrographic and environmental features (such as average annual temperature, salinity and saline typology), and trophic status (eu-, meso-, or oligotrophic). Because most environmental data were available only for the recent period (1990–2012), we did not consider trends over time for environmental characterization of lagoons.

Finally, for each lagoon, we identified the prevalent fishing technique and classified it as either fykenets, gillnets with fixed fishing barriers (such as Comacchio lagoons' *lavorieri*), or a combination of both. For the vast majority of the lagoons in the dataset, no systematic and reliable data were available to measure fishing effort in terms of boats, gear size, number of fishers, or changes in effort over time.

Data treatment and statistical analysis

We converted catch time series of annual total fish yield and eel yield to log-transformed kilogram per hectare to standardize landings over the lagoon surface. To allow log-transformation, we set all zero catch values to half the minimum non-zero catch. Post-transformation, we identified and excluded outliers using outlier labelling (Tukey, 1977; Hoaglin and Iglewicz, 1987). We carried out a principal component analysis (PCA) on the environmental dataset to explore differences among lagoons and to investigate the possibility of grouping lagoons based on environmental (trophic and salinity typology) or geographic (European and Afro-Asiatic basin) criteria.

Using linear mixed-effect (LME) modelling, we analysed total eel catch (kg ha^{-1}, log-transformed) and total fishery catch (kg ha^{-1}, log-transformed) for yearly trends and for correlations with geographical (latitude, longitude, and surface area) or environmental (temperature and salinity) factors. We selected the best model by adding terms in a stepwise fashion and determining significant improvement using ANOVA comparisons of Akaike information criterion (AIC) values. The base model treated lagoon identity as a random factor and year as a fixed effect with a lag-1 autocorrelation structure. We considered both spatial and more complex temporal autocorrelation structures but found that neither improved the model significantly. To identify the onset of catch decline, we used a binary "breakpoint" variable and fitted two slopes for annual catch trend. For the final model, we selected the median breakpoint year out of all significant breakpoint values.

We tested each geographical and environmental factor paired alone with year as fixed effects, then added significant factors to the base model one at a time until there was no significant improvement in AIC. We compared the final LME model with a similar generalized additive mixed model (GAMM) but found no significant improvement. Additionally, the more complex annual effect in the GAMM does not provide a simple estimate of the approximate year for the start of eel catch decline. We used the *nlme* package (v3.1-119) for R (v3.0.2—R Core Team, 2013) for all LME models and *ggplot2* (v1.0.0) to produce Figures 2 and 3.

Escapement model

To estimate escapement, we decided, based on the statistical trend analysis results, to simulate yields per hectare averaged for each lagoon over three different periods (the first two of equal length, the third reflecting most recent management and regulations): 1950–1974, 1975–1999, and 2000–2012. We developed a simplified age-, sex-, and stage-structured population dynamic model based on Bevacqua *et al.* (2007) and Schiavina *et al.* (2015), updated to make an approximate estimation of the spawner production of the Mediterranean area. The model accounted for the main biological features of eel such as density-dependent settlement and sexual differentiation, dimorphic body growth with length-dependent maturation, and both natural and fishing mortality (see Supplementary material for full description). We ran the model under the hypotheses that recruitment was near saturation during the first period before decline in catch, then dropped exponentially as shown by ICES (2012) toward the current value of 10% of pristine recruitment. For the baseline scenario, we assumed that all sites had the same settlement potential (=0.12 kg ha^{-1}, the mean value of settlement potential derived by Bevacqua *et al.*, in press). We then relaxed the hypothesis of constant settlement potential and, following the results of our statistical analysis, assumed that settlement potential was either (i) an increasing function of lagoon trophic state (lower for oligotrophic lagoons and higher for eutrophic lagoons, as suggested by Schiavina *et al.*, 2015); (ii) a decreasing function of lagoon size (ha), as observed also by Pérez-Ruzafa *et al.*, (2005, 2007, 2010) and by Katselis *et al.* (2013); or (iii) both. For each case (i.e. baseline scenario plus the three additional alternative assumptions on settlement potential), we calibrated fishing mortality for yellow eels in each site by minimizing the sum of squares errors between the predicted and the observed average catches (yellow + silver eels) over the three reference periods, setting silver eel fishing mortality to a multiple of yellow eel mortality depending on the type of gear used, and assuming constant effort during the simulation (see Supplementary material).

We then used the model to estimate fishery performances in each of the three reference periods using eel-specific ICES (2011) fishery reference points: the average SSB under current recruitment levels and with existing fishery activities (B_{current}, ICES, 2011), and potential SSB under current recruitment levels but with no fishing mortality (B_{best}, ICES 2011). By further assuming that the high recruitment levels before the end of the 1970s represented quasi-saturated recruitment potential, we used the potential SSB during the first period (1950–1975) as a draft approximation of spawner escapement in the so-called pristine condition (B_0, ICES 2011).

Results

The literature search identified 64 documents matching our selection criteria. We gathered extensive information on environmental and fishery descriptors for 84 Mediterranean coastal lagoons in nine countries of the Mediterranean basin, five in Southern Europe, and four in Northern Africa and Middle East (see online Supplementary material: *Coastal lagoons dataset*). Total surface area was ~490,000 ha (82% of the total surface covered by ~400 Mediterranean lagoons; Cataudella *et al.*, 2014) made up primarily of Italian and Egyptian lagoons (22.6 and 35.9%, respectively). Mean annual temperature ranged between 15 and 28°C. Salinity range was wide (from 1.5 to 64.7 PSU) with high variability of salinity typologies often within a single country. For statistical analysis (i.e. trends in annual eel and total catches), we selected a subsample of 45 lagoons with one or more catch record in at least two of the three reference periods considered.

Italy, Greece, and Egypt had the most fishery data available. Figure 1 shows the location of the 84 coastal lagoons considered in this study; for nine of these, chosen based on the consistency of the data, eel and overall yields (kg ha^{-1}) are given in the three historical periods considered. Eel yields varied between 1 and 168 kg ha^{-1}, and overall yields ranged between 3 and 1600 kg ha^{-1}.

Lagoon environmental variability

Although the lagoons included in our database show high variability in size and hydro-morphological features as well as in water quality, the PCA performed with salinity and trophic status designated as *a priori* environmental grouping criteria (59.3 and 53.0% of variance explained, respectively) did not identified any discernible clustering. Similarly, ordination plots obtained by the PCA performed to test geographical location (European or Afro-Asiatic basin) as the *a priori* grouping criterion did not display any significant clustering of lagoons (55.9% of variance explained).

Trends analysis

There were significant overall negative yearly trends in both eel catch per hectare (solid black lines; Figure 2a) and overall catch (dashed black line; Figure 2a). The decline in eel catch, beginning in the

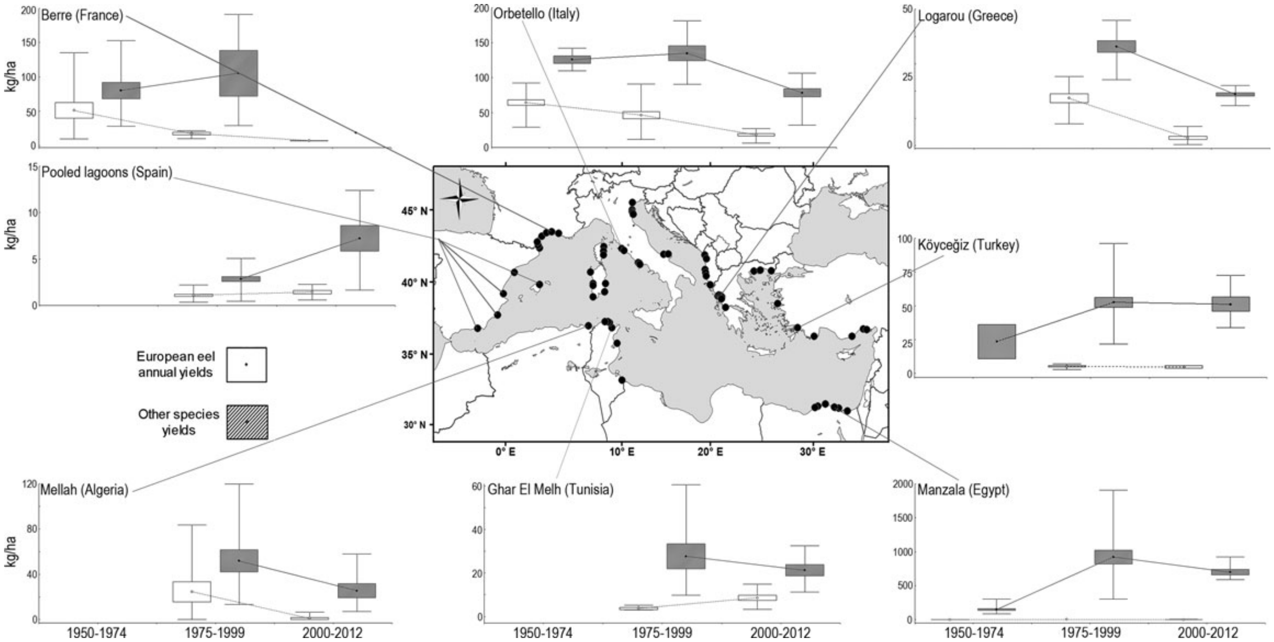

Figure 1. Map of the Mediterranean area indicating the locations of the coastal lagoons included in the analysis. Box-plots show mean, SE, and min – max fish yields (kg ha^{-1}) in some representative sites of the Mediterranean basin.

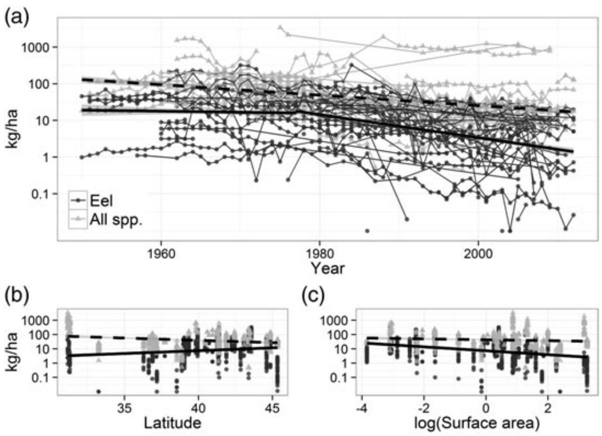

Figure 2. Trends in catch for eel fishery and overall fishery. Each graph shows catch (kg ha^{-1}) in log scale vs. a continuous factor. Eel-only catch is shown in dark grey and overall catch (all species) is shown in light grey. The trend lines (solid for eel, dashed for overall catch) show trends from the linear mixed-effect model analysis, not a simple regression, and account for the effects of multiple factors. (a) Catch vs. year. Lines connect catch series for individual lagoons. (b) Catch vs. latitude. (c) Catch vs. surface area (log-transformed hectares).

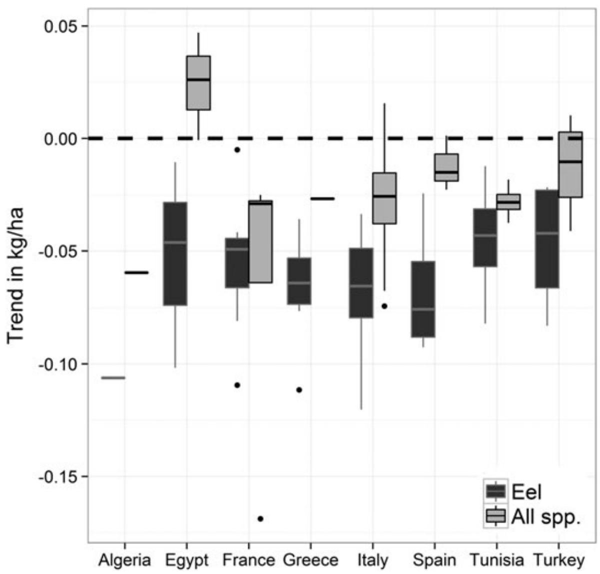

Figure 3. Variation in lagoon yearly trends by country. Range of lagoon-specific eel catch trends within each country are shown in dark grey, overall fishery trends in light grey. Dashed line at zero indicates no annual change in catch, with negative values indicating a decline and positive values an increase. Note that trends are in log-abundance, and for eel are over the decline period only (1977 – 2012).

mid-1970s and thus more recent than the onset of overall catch decline, was approximately twice as fast as that for overall catch (year-post-1977 coefficient, Table 1). After adjusting eel catch for the annual effect, we also found a positive trend with latitude (Figure 2b) and a negative trend with surface area (Figure 2c). Overall, catch had a similar though less steep trend with surface area (Figure 2c). Lagoon-specific yearly catch trends varied by country but were more strongly negative for eel catch in all countries except Tunisia (Figure 3).

The best model for eel catch prediction was:

$$\log(Y_{\mathrm{eel,lag}}) \sim (\alpha_{\mathrm{e}} + \alpha_{\mathrm{e,lag}} + \alpha_{\mathrm{BP}<1977}) \times \mathrm{year} + \beta_{\mathrm{e}} \times \log(\mathrm{area}_{\mathrm{lag}}) + \gamma_{\mathrm{e}} \times \mathrm{lat}_{\mathrm{lag}} + \delta_{\mathrm{sal,lag}} + \eta_{\mathrm{e,lag}} + \varepsilon_{\mathrm{e}}, \quad (1)$$

where $Y_{\mathrm{eel,lag}}$ is eel yield for lagoon lag (kg ha^{-1}), year is the centred

Table 1. Model selection and parameters

Model	**d.f.**	**AIC**	***p*-value**[a]
Eel catch			
eel ~ year			
eel ~ bp_year	8	2040.5	0.033
eel ~ bp_year + area	9	2029.7	0.000
eel ~ bp_year + area + lat	10	2022.5	0.002
eel ~ bp_year + area + lat + sal	14	2015.9	0.006
Final model parameters	*Coef.*	*SE*	*p-value*
Year (pre-1977) $\alpha_e + \alpha_{BP<1977}$	0.049	0.008	0.001
Year (post-1977) α_e	−0.062	0.007	0.000
Area β_e	−0.320	0.086	0.001
Latitude γ_e	0.133	0.052	0.015
Salinity type δ_{sal}			
Oligohaline	−0.223	1.202	0.854
Mesohaline	0.144	0.380	0.778
Polyhaline	0.124	0.008	0.747
Euhaline	0.000	n/a	n/a
Hyperhaline	−3.026	0.000	0.001
Model	**d.f.**	**AIC**	***p*-value**[a]
Overall catch			
overall ~ year	7	1042.7	
overall ~ year + area	8	1039.4	0.021
Final model parameters	*Coef.*	*SE*	*p-value*
Year α_0	−0.028	0.008	0.001
Area β_0	−0.241	0.099	0.021

[a]Model *p*-value indicates significance of an ANOVA comparison with the model directly preceding it.

year (ranging from −31 to +31 to encompass 1950–2012), $area_{lag}$ is surface area (ha), lat_{lag} is the centred latitude, $\delta_{sal,lag}$ is the coefficient of the categorical salinity type specific to the lagoon, $\eta_{e,lag}$ is the lagoon-specific intercept, ε_e is the error term, and α_e, β_e, and γ_e are regression coefficients (i.e. the slopes) specific to the factors for eel catch (see Table 1). The slope for year is further modified by a lagoon-specific parameter $\alpha_{e,lag}$ and a breakpoint value $\alpha_{BP<1977}$ which is non-zero before 1977 and equal to zero for that year and thereafter (raw year is used here rather than centred year for clarity). There were five significant breakpoint values, ranging from 1964 to 1984 with median value of 1977, and significance values did not differ greatly.

The general annual trend for eel did not show a decline before the breakpoint (1950–1976), but was significantly negative thereafter (1977–2012). Predicted eel catch per hectare decreased with year, increased with latitude, decreased with lagoon area, and was significantly lower for hyper-saline lagoons (Table 1). The addition of other individually significant factors did not significantly improve the combined model.

The best model for overall catch prediction was

$$\log(Y_{overall,lag}) \sim (\alpha_o + \alpha_{o,lag}) \times year + \beta_o \times \log(area_{lag}) + \eta_{o,lag} + \varepsilon_o, \quad (2)$$

where $Y_{overall,lag}$ is overall yield for lagoon *lag* (kg ha^{-1}), and other parameters and variables are similar to those described above for Equation (1) but specific to overall catch (Table 1). Predicted overall catch per hectare decreased with both year and lagoon surface area. There was no significant breakpoint year and the addition of other individually significant factors did not significantly improve the combined model.

Table 2. Estimate of fishing mortality rates (yr^{-1}) for yellow eels (F_Y) and silver eels (F_S) of lagoons grouped by prevalent fishing technique

	F_Y	F_S
Gillnets	0.35	0.52
Fykenets	0.25	0.37
Barriers	0	1.72
Fykenets and barriers	0.12	1.23

Assessment of eel escapement by the population dynamic model

Under the assumption of a single level of settlement potential for all the simulated Mediterranean sites, model accuracy was modest for the complete dataset ($R^2 = 0.10$), but fitting was significantly better if considering only lagoons with medium-low productivity (i.e. catches <30 kg ha^{-1}, 83% of the data, $R^2 = 0.61$). Additionally, the model systematically underestimated catches during the period 1950–1974 and overestimated catches in the period 2000–2012. Table 2 shows estimates of fishing mortalities for lagoons grouped by prevalent fishing technique: yellow eel fishing mortality ranged between 0 and 0.35 yr^{-1} and silver eels fishing mortality ranges between 0.37 and 1.72 yr^{-1}. The model accuracy improved under the alternative assumptions of settlement potential dependent upon lagoon trophic state ($R^2 = 0.39$), lagoon size ($R^2 = 0.25$), or both ($R^2 = 0.47$). Catch underestimation during the period 1950–1974 was drastically reduced when trophic state was accounted for, though overestimation increased in the period 2000–2012. The estimate of yellow eel fishing mortality in these scenarios did not significantly vary, while silver eel mortality in the best fitting scenario was slightly lower and ranged between 0.25 and 0.78 yr^{-1}.

The escapement in pristine conditions (B_0), averaged over all the Mediterranean lagoons, was estimated to be ca. 20 kg ha^{-1} corresponding to an overall silver eel production of ≈11 000 t yr^{-1} (Table 3). The potential escapement (B_{best}) during the 1950–1974 period was equal to the pristine escapement and only decreased slightly in the following period (≈18 kg ha^{-1}, ≈10 000 t yr^{-1}, 1975–1999), as shown in Figure 4. The effect of recruitment decline is much more evident in the 2000–2012 periods with an average potential escapement ≈11 kg ha^{-1} (≈6100 t yr^{-1}). The estimated actual silver eel escapement follows the same trend of B_{best} showing reduction across the three periods with a pronounced drop in 2000–2012, as a consequence of the recruitment decline, from almost 11 kg ha^{-1} (≈6200 t yr^{-1}) in the previous periods to <7 kg ha^{-1} (≈3800 t yr^{-1}; Figure 4). The best fitting alternate scenario shows a similar trend of escapement (results of all alternative scenarios are reported in Supplementary material: *Escapement model description and parameterization*) with a higher escapement biomass predicted. The estimate of pristine escapement (B_0) was ca. 32 kg ha^{-1} (≈18 200 t yr^{-1}) with a current and potential escapement for the period 2000–2012 of ≈12 kg ha^{-1} (≈7100 t yr^{-1}) and ≈18 kg h^{-1}a (9800 t yr^{-1}).

Discussion

Eel and overall yields decline in Mediterranean lagoons

This study represents the most comprehensive synthesis of eel catch data on eel in the Mediterranean basin to date and the first analysis of its historical trend. Our statistical analysis of fishery outputs presents several interesting findings, including a clear declining trend in both eel catch and overall fishery landings in Mediterranean

Table 3. Results of the population dynamic model.

Geographic area	Country	Estimated spawner production (kg ha^{-1}) Pristine B_0	1950–1974	1975–1999	2000–2012	Considered surface (ha)	Total Surface (ha)	Surface coverage (%)	Spawner production extended to whole MED lagoons surface (t yr^{-1}) Pristine B_0	1950–1974	1975–1999	2000–2012
European	Spain	19.55	12.52	16.28	10.03	20,328	20,328	100.0	397	255	331	204
European	France	19.55	2.67	2.43	1.47	53,036	57,002	93.0	1,115	152	139	84
European	Italy	19.55	11.79	10.51	6.11	92,575	149,575	61.9	2,925	1,763	1,572	913
European	*Slovenia*	19.55	*12.18*	*11.33*	*6.90*	*0*	*14*	*0*	*0*	*0*	*0*	*0*
European	*Montenegro*	19.55	*12.18*	*11.33*	*6.90*	*0*	*1,642*	*0*	*32*	*20*	*19*	*11*
European	Albania	19.55	10.88	9.98	6.14	11,204	11,204	100.0	219	122	112	69
European	Greece	19.55	10.49	9.63	5.93	26,190	34,507	75.9	675	362	332	205
Afro-asiatic	*Morocco*	19.55	*12.18*	*11.33*	*6.90*	*0*	*11,800*	*0.0*	*231*	*144*	*134*	*81*
Afro-asiatic	Algeria	19.55	1.33	1.21	0.74	865	865	100.0	17	1	1	1
Afro-asiatic	Tunisia	19.55	16.72	15.35	9.46	52,050	52,050	100.0	1,018	870	799	492
Afro-asiatic	*Malta*	19.55	*12.18*	*11.33*	*6.90*	*0*	*11*	*0*	*0*	*0*	*0*	*0*
Afro-asiatic	*Libya*	19.55	*12.18*	*11.33*	*6.90*	*0*	*3,390*	*0*	*66*	*41*	*38*	*23*
Afro-asiatic	Egypt	19.55	13.74	12.61	7.77	176,000	176,000	100.0	3,441	2,418	2,220	1,367
Afro-asiatic	Turkey	19.55	16.90	15.52	9.57	19,520	34,250	57.0	670	579	532	328
		Mean estimated production					Total surface area		Total extended production			
		19.55	12.18	11.33	6.90	451,768	552,637	81.7	10,806	6,727	6,229	3,779

The spawner production (kg ha^{-1}) is estimated through the calibration of the fishing mortality minimizing the sum of squares error between observed and predicted catches. For all countries where no data were available (Morocco, Slovenia, Montenegro, Malta, and Lybia, in italic) the spawner production has been assumed equal to the average over the Mediterranean basin. The extended spawner production (t yr^{-1}) has been obtained using the estimated spawner production per country extended to the overall surface. The variable B_0 should not be considered as a per country estimation but as an average pristine production for Med lagoons.

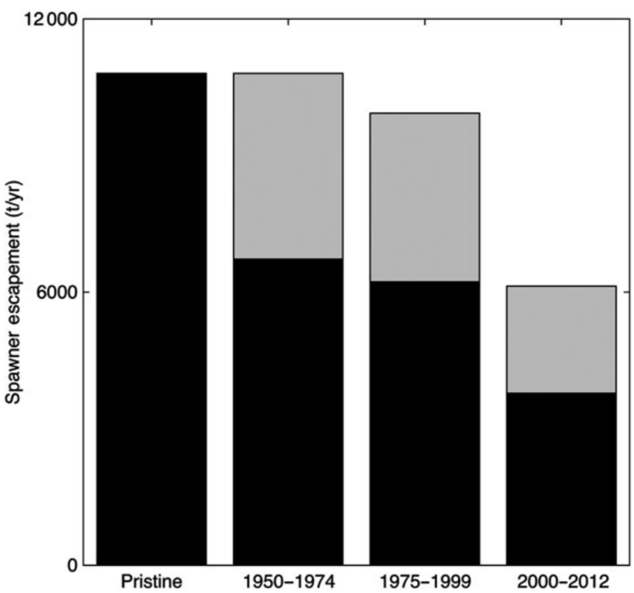

Figure 4. Spawner production estimated with the population dynamic model and extended to the overall lagoon surface of the Mediterranean basin for the pristine conditions (B_0) and the three reference periods (black columns). Potential escapement (B_{best}) of the three reference periods is represented by grey columns in addition to the actual escapement.

lagoons over the past 60 years (Figure 2a), a time lag for the onset of decline between the two catch series, and illustration of the effect of some ecological features on between-lagoon differences.

The declining trend in catches mirrors the decline in the overall catch observed in some Mediterranean lagoons across productivity levels (Cataudella *et al.*, 2014; Ciccotti, 2014; Figure 1), and is consistent with the reductions in eel catch documented by Dekker (2003b). According to our analysis, eel catches started to decline between 1964 and 1984 (median value 1977), about a decade later than estimated by Dekker (2003b) using a dataset comprising mostly fishery data from central and northern Europe. We identified no significant breakpoint in the trend of overall fishery catch which, in contrast to eel catch, smoothly declined during the entire observational period. In addition, our analysis showed that, when eel catch started to drop in the seventies in the overall Mediterranean basin, its trend of decline was steeper than the declining trend for overall fishery yield, a pattern noted also by Katselis *et al.* (2013) when comparing eel landings in six Greek lagoons with landing of other species.

The steeper decline of eel catch suggests that factors specific to *A. anguilla* Mediterranean stock may have contributed to its dynamics in addition to other factors and processes broadly affecting the overall catch in the Mediterranean lagoons. General factors affecting fishery productivity are typically driven by anthropogenic pressures—such as organic and chemical pollution, increased solid transport and altered hydrology—that are ultimately responsible for important changes in environmental quality and ecosystem functioning in coastal lagoons, including water contamination, algal blooms (whether toxic or not), anoxic crises, increased turbidity and silting, changes in aquatic vegetation, etc. Factors specific to eel decline may include a reduction in glass eel recruitment due to either increasing fishing activities along the coasts or declining spawning stock, altered glass eel settlement dynamics within the lagoon, local eel stock overfishing, and the effect of increased abundance of predators such as ichthyophagous birds (Kindermann, 2008; Carpentier *et al.*, 2009; Bevacqua *et al.*, 2011). Most of these factors affecting fisheries and aquaculture in coastal lagoons have been extensively documented (Ardizzone *et al.*, 1988; Koutrakis et al., 2007; Pérez-Ruzafa et al., 2010; Katselis et al., 2013; Cataudella et al., 2014; Ciccotti 2014).

Our analysis showed that, in addition to "year", the most important explanatory factors of between-lagoon differences in catch-per-hectare are, in order of importance, lagoon size, salinity, and trophic state. Specifically, we found that catch-per-hectare decreased with lagoon size (ha) for both eels and all other species (Figure 2c). This pattern is consistent with previous observations by Pérez-Ruzafa et al. (2007, 2010) using two large datasets of Atlanto-Mediterranean coastal lagoons and by Katselis et al. (2013) on six Greek lagoons, and could be attributed to better management in smaller lagoons (Koutrakis et al., 2007).

It is widely recognized that eel growth rate is usually higher in brackish waters, low river stretches, freshwater marshes close to the sea, and lagoons (Fontenelle, 1991; Panfili et al., 1994; Acou et al., 2003; Edeline and Elie, 2004; Daverat et al., 2012; Capoccioni et al., 2014). Salinity has been found to have a positive effect on eel growth rate (Boeuf and Payan, 2001; Edeline and Elie, 2004), but other habitat characteristics, particularly temperature, may potentially affect growth as well. Our analysis found a large negative effect on catch for hyperhaline lagoons but no other significant effects from salinity and only a small positive effect from temperature for overall catch (Table 1). Due to limited multiyear environmental data, we were unable to assess trends over time for the environmental factors.

Eutrophic lagoons are characterized by high primary productivity which is believed to be the most significant driver of eel productivity (Vøllestad and Jonsson, 1988; Bark et al., 2007), potentially affecting both settlement potential and growth (Schiavina et al., 2015). Although we also found that eutrophic lagoons were significantly more productive than mesotrophic lagoons for both eel and the overall catch ($p = 0.032$ and 0.035, respectively, model not shown), the inclusion of trophic state did not significantly improve the final model.

A key unknown factor for estimation of eel production in lagoons is actual eel settlement, a process affected by the interaction of several factors including local habitat quality and hydrodynamics, small-scale spatial and temporal heterogeneities in recruitment and global population dynamics of the eel panmictic stock. Though recruitment is thought to be at very low quantitative levels today (Dekker, 2003b), settlement has always been partially dependent on external factors such as lagoon morphology and hydrology and the influence of meteorological patterns on glass eel movement (Finiger, 1976, Crivelli et al., 2008). The result is an extremely variable level of recruitment to lagoons in the present as well as in the past, making it very difficult to evaluate if recruitment is the main limiting factor for eel production or simply one of several.

Escapement model

According to the demographic analysis, the present actual escapement ($B_{current}$) is ~35% of the pristine silver eel escapement (here estimated under assumption of saturating recruitment and no fishing mortality), thus <40% threshold set as the recovery target by EU Regulation 1100/2007. Consequently, the EU target escapement could theoretically be achieved by reducing fishing mortality: in fact, the current potential escapement (i.e. the escapement under current recruitment but with no fishing mortality) was estimated to be ca. 57 (54% in the best fitting alternative scenario) of the pristine one.

Although model fitting under the equal settlement potential assumption was unsatisfactory, we obtained a considerable improvement in model simulations when the model was calibrated only on low- and mid-productivity lagoons. In addition, modulating settlement potential as a function of lagoon trophic state and lagoon size, in agreement with the results of the statistical analysis, further improved model performance, showing that the inclusion of even minimal information on lagoon ecology and morphology can explain a significant component of the observed between-sites variance in catches. However, we stress that the model results, as well as the alternate scenarios, represent a preliminary exercise valuable primarily as a qualitative rather than quantitative assessment.

In all scenarios analysed in the present study, our model tended to overestimate eel catch in the last period, 2000–2012. This mismatch in model projections can be ascribed to a number of processes not accounted for in our simplified demographic model, including a drop in recruitment faster than that estimated by ICES (2012); a drop in fishing effort, possibly following the EU regulation 1100/2007; and a reduction in the quantity or quality of suitable lagoon habitat.

Although we cannot rule out regional differences in recruitment patterns and trends, consensus an ~90% drop in recruitment with respect to pre-1980s levels is strong within the ICES/EIFAC Working Group on eel (ICES, 2012) and is supported by a number of scientific publications (Bonhommeau et al., 2008a, b); available data did not allow us to assess whether the drop in recruitment at the Mediterranean level was more severe than that of central and northern Europe. At the local level, year-to-year variation or a decrease in glass eel recruitment to lagoons can also be due to a general decline in management efficacy, particularly affecting the efficiency of tidal channels (Crivelli et al., 2008).

On the whole, a reduction in quality and quantity of suitable habitat seems the most plausible hypothesis for the lower-than-estimated catch. Although in our simulations we assumed that both settlement potential and lagoon area were constant throughout the study period, this may not be the case: Kettle et al. (2011) argued that eel habitat dramatically decreased in the last 50 years in Portugal, Spain, and Morocco as a consequence of dam construction and the development of other water management infrastructures. Recent theoretical work by Bevacqua et al. (in press) suggests that habitat loss might have played a very relevant role in the decline of the panmictic stock of eel. Further demographic analysis will include a more detailed analysis of rate of habitat loss at the Mediterranean level.

Management implications

The escapement model allowed us to estimate, for the first time, preliminary reference values for eel escapement from Mediterranean lagoons from pristine to present levels. These values should be taken cautiously because of several untestable assumptions in the model but given the lack of better information, especially for the southern Mediterranean lagoons for which no general assessment was available up to now, our estimates can be considered a starting point to assess present management strategies and explore alternative new ones in Mediterranean lagoons for increasing silver eel production and escapement. Traditional lagoon management practices were developed in the past to sustain local eel stocks, and the current environmental quality of Mediterranean lagoons is still sufficiently good to support very high production so long as the conditions for glass eel to recruit and mature eels to migrate are maintained. In lagoons, therefore, the strongest impact on eel stock recovery may come from measures that increase the nursery function for marine migrant species, such as ensuring the functionality of the tidal channels connecting the lagoons to the sea. Also required are local regulations and management strategies to ensure glass eel recruitment and protect the escapement in the tidal channels where eel are most vulnerable. Silver eel fishing using fish barriers, typical of the Italian tradition in the North Adriatic but widespread in the Mediterranean area (present in 55% of lagoons analysed), has the capacity to capture almost 100% of the potential spawning stock, and therefore, fish barriers need to be managed so as to allow at least a 40% escapement or more if yellow eels are also a fishery target. Artisanal fykenet eel fishery (37% of lagoons) can also be managed for maximal escapement while still taking into account the interest of fishers: for example, in an analysis of small artisanal fisheries in the Camargue lagoon (France) Bevacqua *et al.* (2009) showed that both catch and escapement can be increased by using larger mesh sizes to reduce selectivity towards smaller sizes and younger stages. Management that enhances the current escapement by decreasing overall mortality from fishing pressures (currently estimated at ca. 38%) is a prerequisite to reversing the recruitment trend.

Caveat and limitations

The statistical and modelling analyses presented in this work are by no means free of limitations. The lack of site-specific data on fishing effort prevented us from computing proxy indicators of stock density for each lagoon in the database. Though year-to-year variations in yield can be partially ascribed to changes in fishing effort, fishing techniques, and environmental variability, long-term trends in fishery yield can still provide useful information on the status of the target fish stock (Yáñez-Arancibia *et al.*, 1994; Cataudella *et al.*, 2014), on long-terms changes in fish assemblage and, ultimately, on the condition of the lagoon ecosystem (Franco *et al.*, 2006; Pérez-Ruzafa and Marcos, 2012; Katselis *et al.*, 2013). Often, this approach has proven to be informative given the lack of better data (Pauly *et al.*, 2013). As for our analysis, the general decreasing trend detected in eel catch over >80 lagoons spanning a wide range of latitudes and longitudes, countries, fishing strategies, and management settings can be considered an indication of progressive decline in both eel stock and recruitment, at least so long as no major changes in fishing pressure have occurred across countries in the Mediterranean sea. We feel that this assumption can be considered reasonable because the majority of Mediterranean lagoons have been managed for decades by traditional fisheries in a similar and very consistent way, as argued by Pérez-Ruzafa and Marcos (2012) and Ciccotti (2014). This is especially true for the 55% of lagoons in our database with eel fisheries managed through fixed fishing barriers; these exert a systematic and constant fishing mortality through optimized catch and fishing effort, both independent of personnel involved and dimensions from year to year (Pérez-Ruzafa and Marcos, 2012).

Our escapement model took into account the main biological features of eel life cycle and was based on current knowledge of eel population dynamics, but also incorporated several simplifying assumptions due to lack of available data. Specifically, we assumed constant fishing mortality over the last 60 years and homogeneity of both population distribution and within-site habitat features. Fishing mortality has probably remained constant in those lagoons implementing fixed fishing barriers and may have gone through limited changes in the northern Mediterranean. The model also relies on, and is strongly affected by, the recruitment trend proposed by ICES (2012) that includes the Mediterranean area along with the Atlantic coast despite incorporating little Mediterranean data. Recent studies pointed out variation in the average latitudinal arrival of recruitment at the European shelves (Schiavina *et al.*, 2013; Pacariz *et al.*, 2014) with a possible movement southward unaccounted for in the currently accepted recruitment condition and trend, which will need to be accounted for in future recruitment analyses.

Even with the above limitations, we believe that our work presents the first comprehensive statistical analysis of eel catches in Mediterranean coastal lagoons and, despite the lack of fishing effort data, clearly shows robust evidence of a general declining trend of eel stock and recruitment across the Mediterranean basin—both East and West, North and South—that is in agreement with the well-documented declining catches and recruitment in Northern Europe. In addition, with the demographic model analysis, we provide for the first time a preliminary assessment of past, present, and potential escapement from Mediterranean coastal lagoons. Future work will consider important river habitats for eel in the Mediterranean region (Ebre, Rhone, Tiber, Po, and Nile), excluded from our analysis because data proved to be scarce, rough, and unreliable. In addition, future work will have to focus on greatly refining the calibration of the demographic model and on retrieving further biophysical data on Mediterranean lagoons and detailed quantitative information on habitat loss, catches, and effort especially in the south and east Mediterranean coasts. However, we are confident that our analysis provides compelling evidence that the Mediterranean stock might still provide a significant, though limited, and contribution to the recovery of the European eel.

Supplementary data

Supplementary material is available at the *ICESJMS* online version of the manuscript.

Authors' contributions

E.C. with F.C., and G.D.L. conceived, designed, and supervised the work. F.C. and J.T.M., with C.L., performed the bibliographic search, critically examined papers and reports and compiled the database, whose structure was revised and agreed to by all authors. E.A. and G.D.L. designed and performed the statistical analyses and organized results. Marcello Schiavina performed the escapement assessment by refining and running the model. All authors co-wrote the paper, and revised and approved the manuscript.

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