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# Environmental influences on the recruitment dynamics of juvenile European eels, *Anguilla anguilla* (L.), in a small estuary of the Tyrrhenian Sea (Sardinia, Italy)

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**Abstract:**

1. The European eel, *Anguilla anguilla* (L.), is a catadromous and migratory species of commercial importance. Its complex life cycle results in its exposure to many risk factors, which have resulted in stock declines across all life stages since the 1970s.
2. The temporal recruitment dynamics of juvenile eels (glass eels and elvers) were investigated in a small Mediterranean estuary (Sardinia ï Italy). The composition of the population and the monthly and seasonal variations in the abundances of juvenile eels was assessed over 80 sampling events (February 2017 ï February 2018). Furthermore, the effects of abiotic variables on the abundances of glass eels and elvers were investigated using Generalised Additive Models (GAMs).
3. Glass eels had the greatest abundance during the winter months, whereas elvers had the greatest abundance during spring. Modelling revealed that the abundance of glass eels was mostly explained by the combined effects of water temperature (12.3-14-5 °C), tidal coefficient (40-110 cm), moon phase, season and river mouth condition, whereas the abundance of elvers was associated with water temperature (14-21 °C), dissolved oxygen content (> 7 $mg\cdot l^{-1}$) and season. These results suggest that the annual recruitment of juvenile eels occurs throughout the year with clear seasonal migration dynamics.

4. The use of multiple statistical approaches allowed us to identify the importance of several environmental variables in regulating the recruitment dynamics, providing useful information for conserving eel stocks through the restoration of the natural flow regime and the connectivity between freshwater habitats and sea.

**Keywords:**

*Anguilla anguilla*, juvenile recruitment, Mediterranean Sea, small estuary, GAM, environmental factors.

## 1. Introduction

The European eel, *Anguilla anguilla* (L.), is a catadromous, highly migratory and euryhaline species of commercial importance (Tesch, 2003). The speciesô continental distribution extends over Europe and northern Africa, from Morocco to Norway and throughout the Mediterranean and the Baltic Sea (Dekker, 2003; Tesch, 2003). The European eel has a complex life cycle, during which a growth phase occurs in continental waters and panmictic reproduction occurs in the Sargasso Sea (Als et al., 2011; Amilhat et al., 2016; Andrello, Bevacqua, Maes, & De Leo, 2009). After spawning events, leptocephali are transported along the Gulf Stream and North Atlantic Drift on a long journey that lasts 7ï 12 months (Arai, Otake, & Tsukamoto, 2000; Boetius & Harding, 1985; Lecomte-Finiger, 1992). On reaching the continental shelf, leptocephalus larvae undergo a first metamorphosis into glass eels and colonize estuarine, coastal and river habitats (Kleckner & McCleave, 1982; McCleave & Kleckner, 1982). After entering in the continental waters eels undergo an acclimation period to adjust to freshwater (Birrel, Cramb, & Hazon, 2000; Ciccotti, Macchi, Rossi, Cataldi, & Cataudella, 1993) before completing their migration into continental feeding habitats as elvers and yellow eels (Van Ginneken & Maes, 2005). After a long feeding and growing period (more than 20 years) (Naismith & Knights 1993; Tesch, 2003), eels undergo a second metamorphosis into adult silver eels and finally migrate and spawn in the Sargasso Sea (Amilhat et al., 2016).

This complex life cycle exposes European eels to many risk factors determining the decline of the species, although the exact causes have not yet been clearly established due to difficulties in assessing the spawning stock abundance (Knights, 2003; Friedland et al., 2007; Dekker, 2001; Moriarty & Dekker, 1997; Harrison et al., 2014). However, several factors have been proposed as being responsible for this crisis (Dekker, 2003; Miller, Feunteun, & Katsumi, 2016), including potential threats related to the cumulative effects of human impacts, such as overfishing (Dekker, 2004; ICES, 2002), habitat loss (Knights, 2003; McCleave, 2001), the presence of pathogens (Culurgioni et al., 2015; Lefebvre, Contournet, & Crivelli, 2007; Palstra et al., 2007), pollution

(Capaldo et al., 2012; Van Ginneken et al., 2009) and ocean climate changes (Castonguay et al., 1994; Jacoby et al., 2015; Miller et al., 2016, 2009). European eel stock has declined in all life stages since the early 1970s, reaching its lowest level in the last few decades with variable impacts on fisheries (Aalto et al., 2015; Bornarel et al., 2018; ICES, 2015). In Sardinia, based on commercial fishery data recorded in coastal lagoons  this decline was already observed since the 1950s (Moriarty & Dekker, 1997). As consequence, in 2007 an European Council Regulation has established that all EU members have to define measures implementing the protection and conservation for the recovery of the European eel stock (European Council, 2007). In Italy, the national plan indicates Sardinia as a single Eel Management Unit (EMU). In Sardinia, fishing of glass eels is forbidden, and it is expected that any individual of total length less than 28 cm is immediately released (Regional Decree n. 2617/DECA/53 27th September 2018). The European eel was also added to the CITES Annex II to control its international trade, and in 2008, it was listed as Critically Endangered in the IUCN Red List of Threatened Species (IUCN, 2014).

Juvenile eels (glass eels and elvers) represent the recruitment phase to continental waters (ICES, 2011) and exhibit variable abundances depending on latitudinal, morphological, climatic, hydrodynamic and site specific abiotic factors (Harrison, Walker, Pinder, Briand, & Aprahamian, 2014; Trancart, Lambert, Daverat, & Rochard, 2014). The timing of recruitment and its spatial dynamics at a local scale have already been characterized for many estuaries and rivers located on the Atlantic coast of Europe (Arribas, Fernández-Delgado, Oliva-Paterna, & Drake, 2012; Beaulaton & Castelnaud, 2005; Bru, Prouzet, & Lejeune, 2009; Harrison, Walker, Pinder, Briand, & Aprahamian, 2014; Walmsley, Bremner, Walker, Barry, & Maxwell, 2018). However, only sporadic information is available along the Mediterranean coastline and most of this is restricted to the northern part of the western basin (Ciccotti, Ricci, Scardi, Fresi, & Cataudella, 1995; Crivelli, et al., 2008; Gandolfi & Tongiorgi, 1984; Leone et al., 2016; Westerberg et al., 2018; Zompola, Katselis, Koutsikopoulos, & Cladas, 2008). Juveniles may settle coastal waters throughout all the year, recruitment peaks occurring at different times depending on latitudinal gradients (Zompola, Katselis, Koutsikopoulos, & Cladas, 2008 and references therein). In the north-western coast of the Mediterranean Sea the recruitment peaks are usually observed from autumn to spring (Crivelli et al., 1995, 2008;), while, in the Tyrrhenian Sea the peak occurs indeed also during winter (Ciccotti, Ricci, Scardi, Fresi, & Cataudella, 1995; Gandolfi, Pesaro, & Tongiorgi, 1984).

The recruitment process have been studied along the Mediterranean and Atlantic European coasts and appear to be controlled by an interaction between physiological and abiotic factors (water temperature, river discharge, salinity, lunar phases, tidal cycle, turbidity, rainfall, water odours) (Edeline, Lambert, Rigaud, & Elie, 2006; Jellyman, Booker, & Watene, 2009; Zompola, Katselis, Koutsikopoulos, & Cladas, 2008). However, most of the data currently available concerned almost exclusively large estuary systems. The influence of environmental factors on eel recruitment in small-scale systems remains poorly studied. Although the behavioural and environmental processes that modulate recruitment patterns are reasonably well understood, site-specific factors may play a significant role in determining fine-scale distribution patterns at an individual small coastal system level. Therefore, the aims of this study were (1) to analyse the temporal recruitment pattern of juvenile eels in a small Mediterranean estuary and (2) to model the effects of abiotic factors on the recruitment dynamics.

## 2. Methods

### *2.1. Study area*

The study was conducted in the Pramaera River (Sardinia ï Italy), a typical Mediterranean small watercourse characterized by a temporary torrential regime and summer dryness. The watercourse is 10 km long, has a catchment basin of 180.7 km$^2$ and is entirely located in central-eastern Sardinia (Figure 1). The Pramaera River does not currently experience fluvial interruptions of anthropogenic origin (i.e. dams or other artificial barriers). The study focused on the stretch of the river that is located near the river mouth (39°58.312'N; 9°41.175'E). This area is characterized by brackish water with a mean river width of 15 m. In the Pramaera estuary, artisanal fishing is carried out in freshwater marshes and in the river mouth using fyke nets and gillnets to target euryhaline fish species (mullets and seabass), and particularly eels. The Pramaera river mouth has an estuarine typology, assuming a funnel shape when the watercourse flows into the sea, and it is characterized by a substrate largely dominated by sand. Such substrate together with hydrological forces, river flow rate, precipitations and tidal flow, mainly affect changes in the river mouth hydromorphology. Sudden extreme events (flood, sea storms) can modify the river mouth morphology in a very short time. The shores of the river mouth near to the sea are characterized by a lack of vegetation, while the area further back from the sea is characterized by the presence of reeds and rushes, which is typical of the Mediterranean retrodune environment.

### *2.2. Data collection*

Sampling campaigns were carried out monthly from February 2017 to February 2018 during the weeks of the new moon (De Casamajor, Bru, & Prouzet, 1999; Elie & Rochard, 1994), with the goal of catching juvenile eels at different times during the upstream migration and different phases of the settlement process. To evaluate the abundance of juvenile eels entering the watercourse from the sea, three experimental fyke nets (3.2 m long, 2 chambers, 31 and 28 cm wide, with 2 mm mesh size and 2 wings of 2.5 m) were installed near the river mouth approx. 50 m from the sea (two along the banks and one in the middle) with their mouths facing to the sea in order to capture individuals arriving from the sea. The sampling started at sunset and ended in the early hours of dawn. The fyke nets were inspected, when possible, every morning during 7 consecutive days. Although this sampling allowed all eel stages to be captured, it was designed to be stage selective (mesh size of 2 mm). Only glass eels (< 7.4 cm, unpigmented eels) and elvers (< 15 cm, pigmented eels) were considered separately in the present analysis.

All captured individuals were immediately placed in containers (20 L) filled with river water and anesthetized by immersion in a bath of clove oil (eugenol dissolved in ethyl alcohol) (Walsh & Pease, 2002). The total of glass eels and elvers that were captured on each sampling day were counted and weighed separately. Catch Per Unit Effort (CPUE, hereafter referred to as óabundanceô) correspond to the total number of individuals caught per day divided by the total number of fyke net used the same day (n. individuals/n. fyke nets). When total catches were high, a subsample of 50 individuals was randomly selected for further measurements. The Total Length (TL, to nearest mm) and Total Weight (TW, to nearest 0.01 g) of each individual were measured directly into the field. Once measures are done, eels were transferred to another container (20 L) with a continuous supply of river water for recovery and were monitored for 1 hour before their release upstream to the fyke nets.

These biotic data were used to analyse the relationship between TL and TW for both the glass eel and the elver stages using regression analysis (Ricker, 1975, 1973). Monthly and seasonal size differences were compared separately for each stage using the Kruskal-Wallis non-parametric test (K-W, $p < 0.05$). Seasonal variation in abundance was assessed by plotting the mean monthly capture trend (±ES, Standard Error) for each stage.

Environmental parameters were also measured on each sampling day using a multiparameter probe (smarTROLL Multiparameter Handheld), including the water and air temperatures (°C), salinity, pH, dissolved oxygen content ($mg \cdot L^{-1}$) and oxygen saturation levels (%). In addition, rainfall (mm), moon phase, tidal coefficient (cm) and river mouth condition were recorded. Rainfall data were provided by the Regional Meteorological Department (Sardinia Environmental Protection Agency ï ARPAS) from three meteorological stations situated in the area of the Pramaera River basin and were estimated as the average rainfall recorded during the week before each sampling date. Moon phases data were collected using an online application produced by the United States Naval Observatory (http://aa.usno.navy.mil/data/docs/RS_OneDay.php). Because samplings were performed during the week of the new moon during each sampling campaign, the days of sampling were waning (days before the new moon), new moon and waxing (days after the new moon) phases. The tidal coefficient was also recorded for each day of sampling, which was calculated as the difference in height between the consecutive high tides and low tides. Finally, river mouth condition was considered as a local factor (open or nearly open river mouth). A summary of the environmental features of each season is given in Table S1.

### *2.3. Models analysis*

Before undertaking the modelling, the abundance data were tested for normality (Shapiro-Wilk test, S-W, $p < 0.01$) and homogeneity of variance (Levene test, $p < 0.01$), which showed that they had a non-normal distribution. Therefore, to address this and to handle zero inflation, which seriously affects juvenile eel samples, a Tweedie distribution family was fitted to the abundance data (Augustin, Trenkel, Wood, & Lorance, 2013; Shono, 2008).

For the abiotic parameters, the Zuur et al. (2010) protocol was followed, whereby collinearity was examined by computing pairwise scatter-plots that compared continuous covariates, and those combinations that had relevant Spearmanôs rho coefficients (ɟ > 0.7) were discarded prior to modelling. The Variance Inflation Factor (VIF) was also used to check collinearities among the predictive variables, and variables with VIF > 3 were discarded. Data exploration revealed non-linear patterns among the response variables, so juvenile abundance (dependent variable) and its relationships with environmental, temporal and local variables were described using Generalized Additive Models (GAMs) using a log link function (Hastie & Tibshirani, 1990; Maunder & Punt, 2004). Seasons and moon phases (waning, new or waxing moon) were included as temporal factors, while river mouth conditions (open or nearly open) were included as a local factor. Only those days on which the river mouth was open or nearly open were included in the analysis, because a closed river mouth represents a physical barrier to the ascent of juvenile eels. A GAM can be considered a generalized linear model in which part of the linear predictor is specified as a sum of the smooth functions (smooth function = $s$) of the predictor variables and where the challenge is to find suitable parametric representations for the smooth functions and to control the degree of smoothness appropriately (Wood & Augustin, 2002). A stepwise backward selection procedure was implemented to identify the best-fitting model, based on minimization of Akaikeôs Information Criterion (AIC) (Akaike, 1973). At each step in the selection procedure, the variables with the highest p-values ($p > 0.05$) were dropped to produce a model with a lower AIC, and backward selection continued until the lowest AIC was reached.

The total explained deviance and the relative contribution of each factor were evaluated for each model, and the performance of the models was evaluated with cross-validation using the Pearsonôs correlation coefficients between the observed and predicted abundances. All statistical analyses were performed using R 3.3.1 with a significance level of $p < 0.05$ (R Core Team, 2018), and the GAM approach, as proposed by Wood (2006), was performed using the library *mgcv* (version 1.8ï 12).

## 3. Results

### *3.1. Population structure and seasonal migration*

A total of 12 sampling campaigns were carried out from February 2017 to February 2018 during the new moon weeks. The river mouth was closed during the November 2017 campaign, so these data were not considered in the analysis. The total catches over the entire study period were 28999 glass eels weighing 7212.68 g and 620 elvers weighing 640.28 g. A total of 2064 glass eels and 313 elvers specimens were measured during the 78 sampling events. There was a negative allometric relationship between size and weight for the glass eels that favoured body length development (b=2.70, $R^2$=0.82, $y = 0.0014x^{2.70}$) (Figure 2a). The mean TL and TW (mean ± SE) for glass eels were 6.3 ± 0.33 cm and 0.25 ± 0.04 g, respectively. The largest individual was captured in winter (7.4 cm and 0.33 g) while the smallest was captured in spring (5.2 cm and 0.12 g). However, there was no significant difference in the median TL of glass eels among months and seasons (K-W, $p > 0.05$) (Figure 3a). On average, higher glass eel abundances (mean ± SE) occurred during the winter months (February 2017 = 281.8 ± 242.24, January 2018 = 371.68 ± 98.63 and February 2018 = 555.54 ± 153.66 individuals/per day, respectively), whereas the lowest recruitment was observed from late spring to early autumn (minimum mean value in September: 1.5 ± 0.27 individuals/per day) (Figure 3b). Overall, 80.45% of the glass eel catches were recorded in February (2017-2018) and January 2018.

The sizeï weight relationships for elvers had allometric coefficients that were superior to 3 (b=3.19, $R^2$=0.91, $y = 0.0008x^{3.19}$, Figure 2b). The mean TL and TW (mean ± SD) for elvers were 9.4 ± 2.4 cm and 1.03 ± 7.35 g, respectively, and size differences were detected among months, with the smallest elvers being captured in spring, following which there was a progressive increase in the TL during the summer and autumn months so that the largest individuals were captured during the winter months (K-W =, $p < 0.001$) (Figure 4a). The elvers abundance (mean ± SE) was highest during spring, with two peaks in May and June (17.15 ± 4.59 and 12.62 ± 9.54 individuals/per day, respectively) (Figure 4b), representing 71.60% of the total catches. No elvers were captured in July and December.

### *3.2. Factors affecting juvenile eels abundance*

Air temperature (°C), oxygen saturation (%), pH and salinity were eliminated from the analysis based on the VIF criteria that were used. Therefore, in the modelling, water temperature (T), dissolved oxygen (DO), rainfall (Rain) and tidal coefficient (Tide) were considered as continuous variables and season (Season), moon phase (Moon) and river mouth condition (Mouth) as categorical factors.

Four models were tested for glass eels (Table S2). The best model include 5 exploratory variables (AIC = 842.3): water temperature (T), tidal coefficient (Tide), seasons (Season), moon phase (Moon) and river mouth condition (Mouth) (Table S3). The final model had a statistically significant goodness of fit and explained 66.1% of the total deviance. Examination of the relative contribution of each variable to the total explained deviance revealed that water temperature was the most important factor (48.7%) followed by tidal coefficient (10.4%). In addition, season, moon phase and river mouth condition showed some importance, explaining 7% of the total deviance. Response plots for each variable that was included in the best-fitting GAM are shown in Figure 5. Glass eel abundance decreased from 10 to 12 °C to reach a local minimum at about 12 °C then increased to reach a maximum at approx. 14-15°C. Temperatures above this resulted in relatively high variation. The probability of glass eels abundance was also significantly affected by season, reaching a maximum value in winter and a minimum value in summer. The likelihood of a large increase in abundance was clearly associated with an open river mouth condition. The abundance of glass eels increased steadily and positively with tidal coefficient ranging from 40 to 110 cm. Finally, the model revealed that the rising moon phase appeared to have slightly, but statically significant effect, on the glass eels abundance. Cross-validation indicated a moderate correlation between the observed and fitted abundance values (CPUE) ($R^2$=0.52) (Figure S1a).

Six GAM models were tested for elvers, the best fitting (AIC = 270.93) (Table S4) of which retained three of the nine covariates and include: water temperature (T), dissolved oxygen (DO) and season (Season).The final model explained 74.1% of the total deviance and all the terms were significant. Examination of the relative contribution of the individual covariates indicated that water temperature (67.7%) and dissolved oxygen (5.09%) explained the largest amount of the observed variation in elvers abundance, whereas season had a relatively lower contribution to the model (1.31%). Response plots showed that elver abundance was positively related to water temperature, with a highest abundance occurring at 21 °C (Figure 6). In addition, the abundance of elvers was significantly affected by season, with a greater abundance being observed in spring, and was slightly positively related to the dissolved oxygen content (DO) for values >7 $mg \cdot L^{-1}$. The model validation that was developed showed a good predictive power ($R^2$ = 0.68) (Figure S1b).

## 4. Discussion

The recruitment of juvenile eels in a small estuary on the coast of the Tyrrhenian Sea in Sardinia occurred throughout the year, with evident seasonal migration dynamics. The period of maximum recruitment for glass eels was between winter and early spring, with peaks from January to March, matching the findings of previous studies conducted in estuaries along the Atlantic coast of south-western Europe and in the Mediterranean Sea (Aranburu, Estibaliz, & Briand, 2016; Arribas, Fernández-Delgado, Oliva-Paterna, & Drake, 2012; Aschonitis et al., 2017; Ciccotti, Ricci, Scardi, Fresi, & Cataudella, 1995; Gandolfi, Pesaro, & Tongiorgi, 1984; Zompola, Katselis, Koutsikopoulos, & Cladas, 2008). Our findings also confirmed the results of previous studies conducted in Sardinia, which reported maximum concentrations of glass eels during the first few months of the year (Cau, Cannas, Gandolfi, & Rossi, 1982).

The TL of glass eels recorded in the Pramaera estuary ranged from 5.2 cm to 7.4 cm, which is lower than previous data reported for the eastern coast of Sardinia (Flumendosa River) (Cau, Cannas, Gandolfi, & Rossi, 1982). At a wider geographical scale, data from the Atlantic coast confirmed a decrease in TL in association with a decrease in recruitment (Desaunay & Guerault, 1997). At a seasonal scale, the differences in mean TL were quite moderate, with the lowest values recorded in spring. Similarly, Cau et al. (1982) found that glass eels that were captured in spring were smaller than those captured in the other seasons, and previous studies conducted in the European Atlantic and Mediterranean Tyrrhenian coast reported that glass eels entering the estuary in spring are shorter and lighter than those arriving in autumn and summer (Bardonnet & Riera, 2005; Gandolfi, Pesaro, & Tongiorgi, 1984).

Recruitment of the elver stage in the Pramaera estuary began in late winter, peaked sharply in May and persisted through October, supporting the findings of other studies conducted in both Mediterranean (Boëtius & Boëtius, 1989; Ezzat & El Serafy, 1977; Gandolfi, Pesaro, & Tongiorgi, 1984; Leone et al., 2016) and Atlantic estuaries (Naismith & Knights, 1988). The seasonal occurrence of elvers near the river mouth suggests a temporary period of residency in their upstream migration and results in an increase of their abundance and therefore of their catchability. This pattern, which has also been observed in many previous studies (Bardonnet & Riera, 2005; Gascuel, Feunteun, & Fontenelle, 1995; Laffaille, Caraguel, & Legault, 2007; Naismith & Knights, 1988), was confirmed by the fact that the mean size of elvers in the Pramaera estuary increased from May to October. We hypothesize an horizontal active movement of the elvers from the river to the estuary because they are prone to use the sandy area near the river mouth as a foraging ground.

The use of multiple statistical approaches allowed us to identify the importance of some environmental variables in the recruitment of juvenile eels. Our models, which were based on correlational observations in the field, revealed that water temperature is the most important factor controlling the abundance of glass eels. Similarly, water temperature has previously been reported as being one of the most significant predictors of the periodicity and magnitude of upstream eel migration among the numerous potential environmental factors (Arribas, Fernández-Delgado, Oliva-Paterna, & Drake, 2012; Crivelli et al., 2008). Our results support the findings of previous studies that glass eels become inactive and less susceptible to capture when the water temperature drops below a threshold of 10ï12 °C (Edeline, Lambert, Rigaud, & Elie, 2006; Gascuel, 1986). However, the active migration of glass eels was associated with temperatures of 12.3ï14.5 °C, which were often recorded during the winter season (12 ± 0.15 °C), and this was statistically confirmed by the model.

The conspicuous abundance of glass eels was predicted to be associated with the open river mouth condition. Sardinian rivers tend to represent intermittently estuarine systems due to the large water-level fluctuations that are caused by summer drought conditions (Sabatini et al., 2011; Sabatini et al., 2018). Such estuaries are closed off from the sea for varying periods by a sandbar that develops at the mouth when there is little to no water discharge (Suari et al., 2019). However, these systems are also subject to rapid changes over short periods of time during mouth opening and river flooding events, which are generally associated with large amounts of rainfall. In these types of estuaries, prolonged mouth closure leads to a cumulative discharge of freshwater, which acts as a lure that guides glass eel migration (Crivelli et al., 2008). Supporting this, laboratory experiments have shown that chemical stimuli, such as geosmine, play an important role as inland water markers that are involved in the orientation of glass eels towards freshwater (Tosi, Spampanato, Sola, & Tongiorgi, 1989; Tosi & Sola, 1993). The recruitment of glass eels was also associated with an increase in the tidal coefficient. Even if the tidal range is extremely reduced in the Mediterranean Sea in comparison to Atlantic Ocean, the tides would continue to move water in and out of the estuary, potentially exerting a strong influence on glass eels, which might be carried by the tidal currents. This result confirms previous experimental evidence, indicating that the tidal cycle plays a pivotal role as a migration vector to freshwater for glass eels (Aranburu, Estibaliz, & Briand, 2016; Ciccotti, Ricci, Scardi, Fresi, & Cataudella, 1995; Gandolfi, Pesaro, & Tongiorgi, 1984). The moon phase also influenced the upstream migration of glass eels in the estuary, with higher catches being obtained around the time of the rising moon. An association between glass eel migration and lunar phases has been widely reported in the literature (Leone et al., 2016; Milardi, Lanzoni, Gavioli, Fano, & Castaldelli, 2018; Sorensen & Bianchini, 1986) but this link has been mainly attributed to the coupled relationship between the moon and the tide (Tesch, 2003). Finally, the results revealed that oxygen concentration, salinity and rainfall were not significantly correlated with glass eel abundance in the study area. Other environmental factors, not investigated in this study, could explain the observed patterns in glass eels abundance. In this regard, coastal storms from the sea, wind speed and direction, have been suggested to effect glass eel migration toward the river mouth (Lecomte-Finiger and Razouls, 1981; Arribas et al., 2012; Leone et al., 2016).

Temperature was also found to be the most important predictor of the abundance of elvers in the Pramaera estuary, with higher abundances being observed at temperatures of 14ï 21°C, which occur during spring. Seasonal water temperatures are often considered to influence the movements of elvers in lagoons (Leone et al., 2016), with most studies arguing that seasonal increases in water temperature are positively correlated with active swimming, upstream migration, growth, metabolism and pigmentation along both the Atlantic and Mediterranean coasts (Boëtius & Boëtius, 1989; Edeline, Lambert, Rigaud, & Elie, 2006; Ezzat & El Serafy, 1977). Dissolved oxygen showed remarkable temporal variability as a result of the combined effects of climatic factors, anthropogenic activities and specific features of the system. Seasonally, the maximum of dissolved oxygen recorded in spring could be related to the autotrophic production of oxygen by phytoplankton. Therefore, we hypothesize that the association with dissolved oxygen for values above 7 mg·L$^{-1}$ could be interpreted as an indirect effect related to the greater abundance of elvers during spring rather than an active preference. On the other hand, the European eel is able to tolerate relatively high levels of hypoxia (Trischitta, Takei, & Sébert, 2014), thanks to its ability to use both branchial and cutaneous modes of respiratory gas exchange (Tesch, 2003).

The present study has provided, for the first time, information on the behavioural and environmental factors that control juvenile eel recruitment in a small Mediterranean estuary. In this context, site-specific data on juvenile eels recruitment represent a valuable and robust tools to assess the stock status, especially in data-poor situations as asserted by the International Council for the Exploration of the Sea (ICES, 2016). Our analysis suggests that the seasonal recruitment of European eels at the study site is similar to the patterns seen along the Atlantic coast of south-western Europe and the Mediterranean coast. Furthermore, the model demonstrated that the migration dynamics of juvenile eels is related to environmental, temporal and site specific factors, such as the water temperature, tidal coefficient, oxygen concentration, moon phase and river mouth condition. One key management to preserve the juvenile eels recruitment in small Mediterranean watersheds could be to restore the thermal regime trough the river flow control. In particular, in Sardinia many of the small estuaries are intermittently and partly closed due to the reduction of natural freshwater flow as consequence of the presence of dams and weirs. In this context, many authors stressed the critical importance of maintaining the natural flow condition and connectivity between freshwater habitats and sea (Lafaille et al., 2005; Moriarty et al., 1997; ICES, 2011; Ciccotti et al., 2014; Besson et al., 2016).

Therefore, further studies should be carried out to investigate the role of marine currents on the differences in the fluctuation dynamics of juvenile eels that are observed between the western and eastern sides of Sardinia (Cau, Cannas, Gandolfi, & Rossi, 1982). The use of Lagrangian models, which are already used to assess other species with pelagic larval forms in the Sea of Sardinia (Palmas et al., 2017), could represent an important tool for investigating the dispersion and recruitment of larvae in the Mediterranean Sea. Such studies will be important not only for understanding the recruitment dynamics of European eels in the Mediterranean Sea but also to predicts the time of arrival of glass eels in proximity of the estuaries and developed local management strategies.

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## Author Contributions

Conceptualization, A.S., C.P., F.P., G.C., J.C., N.F., R.D.; software, C.P., F.P.; formal analysis, A.S., C.P., F.P., R.D.; investigation, A.S., C.P., F.P., G.F., J.C., R.D.; writing-original draft preparation, A.S., C.P., F.P.; writing-review & editing, A.S., C.P., F.P., G.C., G.F., J.C., N.F., R.D.; funding acquisition, N.F., G.C., A.S.

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## Conflicts of Interest

The authors declare no conflicts of interest.

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