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A user-friendly tool to assess management plans for European eel fishery and conservation

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ABSTRACT

The European eel Regulation EC 1100/2007 establishes measures to recover the European eel stock. The Regulation requires Member States to guarantee a spawner escapement ≥40% of pristine levels by reducing eel mortality. The complexity and plasticity of eel life history make it difficult to assess the effectiveness of alternative management options, and tools allowing decision makers and fishermen to quickly assess the effectiveness of proposed management scenarios are urgently needed. We used state-of-the-art knowledge to develop a user-friendly simulation software allowing users to evaluate if current management policies meet the conservation target and evaluate the expected performances (spawner escapement and fishing yield) of alternative management scenarios. The software relies upon a demographic model explicitly accounting for the most relevant features of eel demography and has default settings for specific geographical areas and water systems. We demonstrate the software by exploring a variety of management plans in three European water systems.

Software availability

Name of software: Eel Management Software
Developer: Marcello Schiavina
Availability and documentation: software and user guide freely available for online use at www.eelmanagement.eu
Year first available: 2012
Software required: any internet browser supporting JavaScript
Programming languages: HTML, PHP, JavaScript and MATLAB®

1. Introduction

Mathematical models provide effective tools to analyse fishery dynamics and identify trade-offs between conservation and management goals (Quinn, 2003). Unfortunately, developing reliable models requires specific training in mathematics and/or computer science and the availability of long-term datasets: this is particularly critical for small-scale, data-poor fisheries lacking the financial and institutional capacity typical of more lucrative industrial fisheries. Decision makers often swing between two extreme behaviours. On one hand, the decision process may be at risk of paralysis due to the lack of data, models and a good understanding of how the system responds to different management strategies. On the other hand, decisions may be taken on the basis of subjective and non-formalized considerations. Therefore, there is an urgent need to develop user-friendly, cost-effective instruments to quickly perform preliminary screenings of costs and benefits of alternative management scenarios.

The European eel (*Anguilla anguilla*) fishery is a paradigmatic case of small-scale, data-poor fishery requiring urgent management measures. *A. anguilla* is a catadromous fish with a wide distribution along European coasts and a complex life cycle. Eel juveniles (glass eels) enter continental waters, where they become yellow eels, grow and feed for a variable number of years (from 3–5 to 10–20 for males in Mediterranean coastal lagoons up to 10–20

Abbreviations: EMP, Eel Management Plan; EMS, Eel Management Software; ICES, International Council for the Exploration of the Sea.

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or more for females in freshwater bodies of northern Europe). Eels eventually metamorphose into silver eels, become sexually mature and swim towards the Sargasso Sea, where they spawn and die. Every year, a new wave of recruits migrates toward Europe riding the Gulf Stream to constitute a newly recruited cohort (Melià et al., 2013).

Eels were a crucial source of income for over 25,000 fishermen in at least 15 European countries. Starting from the 1980's, *A. anguilla* experienced a continent-wide decline in recruitment and stock abundance caused by the synergy between overfishing, habitat loss, pollution, parasites and obstacles to migration (ICES, 2012). Present recruitment is less than 1/10 of its historical level (Dekker, 2003; ICES, 2012) and the species is considered critically endangered (UN CITES Appendix II, IUCN Red List).

To overturn the collapse, the European Commission issued a Regulation (EC No.1100/2007) requiring Member States to adopt and implement Eel Management Plans (EMP). The default management scale is the river basin, but Member States can refer to other management units (such as the districts identified under the European water framework directive or other local administrative units). The aim of the Regulation is to allow at least 40% of the pristine escapement of spawners: this limit reference point is referred to as the Regulation target in the following. The ratio between current and pristine escapement is an index of stock status. However, there can be a considerable time lag between current human pressure and its consequences on spawner escapement. This, together with the panmictic nature of the species, which decouples spawner escapement from recruitment at the local scale, can impair the attainment of the target in the short term. For these reasons, the International Council for the Exploration of the Sea (ICES) advised to integrate the current/pristine ratio with the ratio between current and potential escapement. Potential escapement indicates the number of spawners that would escape, at present recruitment levels and habitat availability and quality, if fishing were halted and all barriers removed (ICES, 2012). The corresponding reference point (ICES target in the following) is a function of the current/pristine ratio (the so-called precautionary diagram; ICES, 2011). The minimum value of the ICES target is 0.4 if the current/pristine ratio is >0.4 (i.e. when the Regulation target has been attained), while it increases (creating a safety margin for uncertainty) for lower values, approaching one as the current/pristine ratio approaches zero. In other words, if the current escapement is much lower than the pristine one (current/pristine ratio <<0.4), an EMP might have not only to close the fishery, but also to remove obstacles to migration to achieve the potential escapement.

The assessment of EMPs requires to perform a number of challenging tasks: a) to estimate the pristine (i.e. preceding the demographic collapse) spawner escapement from continental waters, as well as the potential escapement under current recruitment and habitat availability; b) to check whether current management attains the management targets (current/pristine ratio > Regulation target, and current/potential ratio > ICES target); c) to estimate the effect of proposed measures on spawner escapement and fishing yield.

As it is neither conceivable nor practical to proceed by trials and errors, the expected effectiveness of proposed measures should be projected through models, as done for other fishery management assessments (e.g. Scrimgeour and Oxley, 2001; Halide et al., 2009; Worrapimphong et al., 2010; Gao and Hailu, 2012). In particular, for the European eel, recruitment-settlement, body growth, natural and fishing mortality, sexual differentiation and maturation are all non-linear functions of age, body size and/or population density and are affected also by environmental variables such as salinity, temperature and productivity of the water body (Edeline et al., 2005; Daverat et al., 2012). Consequently, the ultimate response to conservation measures depends upon the interaction between demographics processes and environmental drivers. A number of demographic models for the European eel have been published in the last 30 years (Vøllestad and Jonsson, 1988; De Leo and Gatto, 1995; Aprahamian et al., 2007; Bevacqua et al., 2007; Lambert and Rochard, 2007; Andrello et al., 2011; Oeberst and Fladung, 2012; Prigge et al., 2013a). Despite their accuracy in reproducing observed data, they have been used mainly for research purposes, as their complexity prevents application outside the academy. On the other hand, general-purpose software packages (e.g. those developed by Pauly et al., 2000; Kell et al., 2007; Lembo et al., 2009) are not structured to grasp the complexity of eel demography nor to guide users to properly define the functions describing the relevant processes and set up model parameters accordingly.

The aim of the present work is to bridge the gap between advanced demographic models and the need for easy-to-use tools to explore the performance of conservation measures. To this end we developed the "Eel Management Software" (EMS), a flexible and user-friendly model allowing the user to quickly perform a screening assessment of alternative management plans before decision. On the basis of simple and easy accessible information, the software a) estimates spawner escapement under pristine conditions; assesses the compliance of management alternatives with b) the Regulation target and c) the ICES target; and d) estimates the expected fishing yield. The software provides default settings for demographic parameters to simulate eel demography in different geographical areas (Mediterranean basin, Atlantic coasts, North and Baltic seas) and water bodies (brackish waters vs. freshwaters). When more information is available, EMS allows the user to modify model parameters according to site-specific conditions via an advanced user interface.

2. The EMS software

EMS is structured into two main components: the core demographic model and the user interface. The latter is organized into three input panels – for the description of site location and environmental features, the configuration of the management policy and (when available information is sufficient) the input of specific demographic parameters – and output tables and graphs reporting the results of the simulations of the proposed management alternatives.

The core demographic model is a Matlab® compiled application hosted by a high-performance server at Politecnico di Milano, which runs the simulations in a few seconds. The interface is handled by an HTML + PHP + JavaScript code for on-line use, allowing the developers to keep the model up-to-date with scientific progress and users to easily customize the settings of the demographic model. A detailed user guide is also provided on the web site, along with a contact email for support.

2.1. The population dynamics model and its parameters

EMS model builds up on early work on eel demography and management by De Leo and Gatto (1995, 1996, 2001) for the Comacchio lagoons (Italy), on subsequent developments by Bevacqua et al. (2007) for the Camargue lagoons, and on a generalization at the European scale by Andrello et al. (2011). The demographic core is a spatially implicit, size-, age-, sex- and stage-structured dynamical model. Juvenile settlement is assumed to be an increasing and saturating function of recruitment (Bevacqua et al., 2007). Sex ratio is assumed to shift in favour of males as eel density increases (Lambert and Rochard, 2007). Body growth is described by a von Bertalanffy curve (Melià et al., 2006a, 2006b;

Andrello et al., 2011) with gender-specific parameters depending upon the geographical location: in fact, in colder waters eels grow more slowly but become larger than in warmer waters (Daverat et al., 2012). Inter-individual variation in body growth is accounted for through an assignment-at-birth approach (Kirkpatrik, 1984). Maturation rate from yellow to silver eel is represented by an increasing function of body size (Bevacqua et al., 2006; Andrello et al., 2011). Natural mortality rate is assumed to decrease with body size and to increase with temperature (Bevacqua et al., 2011). Fishing mortality is computed as the product of gear selectivity, eel catchability and harvesting effort (De Leo and Gatto, 2001; Bevacqua et al., 2009a). Catchability is differentiated for yellow and silver eels and increased in case of dystrophic crises, which increase the probability to be caught by the fishing gears. Parameter values can be selected from a set of default settings, based on the available knowledge on how European eel vital rates vary across water bodies and geographical locations, or specified by the user through an advanced “Model settings” frame.

The time step of dynamical simulations is one month. For simplicity, recruitment is kept constant year after year and considered net of possible mortality due to glass eel fishing. Silver eel escapement and fishing yield (catches) are computed at the equilibrium. Pristine escapement is estimated by setting fishing mortality to zero, habitat area to its maximum potential level (including reclaimed land and/or areas currently out of reach of eels) and recruitment ten times higher (for the Mediterranean basin and Atlantic coasts) or hundred times higher (for the North and Baltic seas) than the current one (according to ICES, 2012). Potential escapement is estimated by setting fishing mortality to zero, with habitat area and recruitment at their present levels. Further details on the model and on the mathematical formulation of each process are provided in the Appendix.

2.2. Site characterization

The user is guided through the input panels, organized into a number of frames, to characterize the environmental and management features of the water body (Fig. 1) as described here below.

Site location is identified at the macro-geographical scale as in Andrello et al. (2011) with three possible options, namely “Mediterranean basin”, “Atlantic coasts” or “North and Baltic seas”. EMS associates to the selected location a mean annual water temperature and specific somatic growth patterns for males and females. The area of suitable habitat has to be entered under both present and pristine conditions: according to the EC Regulation, the latter refers to the area potentially available before any significant intervention of land reclamation or construction of dams, hydropower facilities, sluice gates, or other anthropogenic influence occurred in the last century. As the maximum settlement potential of the water system (expressed as a biomass of eels settling per hectare) depends upon the primary productivity and suitability of the water body (Vøllestad and Jonsson, 1988), the user has to select the type of water body under investigation – lagoon, lake or river estuary – and its trophic state (in the case of lakes and lagoons). The user can also specify whether dystrophic crises regularly occur during the summer season. Water exchange between sea and inland waters can be either free (unregulated) or managed through sluice gates that, when closed, may prevent glass eel recruitment from and/or silver eel migration to the sea. By selecting the “connection” check box, a new frame opens where the user can specify, on a monthly basis, when sluice gates are closed. A further check box is available to inform the software whether a hydroelectric power plant is operating, as water turbines are known to cause mass mortality of migrating silver eels. Finally, the user has to specify the abundance of glass eel recruitment (net of possible fishing mortality due to glass eel fishery) on a five-level qualitative scale ranging from “much below the average” to “much above the average”. The qualitative information provided is transformed into numbers on the basis of type and geographical location of the water body. The wide range of values into which the qualitative scale is mapped encompasses the few available estimates (Rosell et al., 2005; Alain Crivelli, unpublished data) integrated with anecdotic information.

2.3. Configuration of the management plan

The second input panel (Fig. 2) is used to define existing or proposed EMPs. First, the user has to specify whether a commercial fishery operates in the water system and if it targets yellow eels, silver eels or both. If so, the minimum information required to run the model is the total number of operating fishermen or an estimate of the fishing mortality rate. When available, further information about gear type, mesh size (knot to knot) and fishing effort (e.g. mean number of nets per day on a monthly basis) can be entered in this panel. As for the gear type, the basic model interface allows the user to choose between fyke nets or fishing barriers (such as the “Lavorieri”, used in Italy for silver eel fishing), while the advanced model interface includes also trawl nets and longlines.

When the number of fishermen is specified, four reference cases are possible:

- case 1: effort and mesh size are both known (the ideal case)
- case 2: mesh size is known, but effort is unknown
- case 3: effort and mesh size are unknown
- case 4: all fishermen use the same mesh size and fishing effort is known only as a whole.

When effort and/or mesh size are unknown, the effort per fisherman is set by default to a typical seasonal fishing pattern with peaks in spring and fall, as depicted in Table 1, and the mesh size is set to 10 mm. A fisherman using two gears with different mesh size and/or different effort deployment corresponds to two virtual fishermen, each one with her/his own specific gear and effort.

By selecting the “Set eel management plan” check box, the user can describe which of the following actions can be performed on a specific month for both yellow and silver eels, namely: to keep fishing as usual in that month, to halve the fishing effort, or to stop fishing. In addition, the user can impose a lower bound for the mesh size of the fishing gear (overwriting fishermen's mesh sizes below this threshold) or a minimum landing size (setting to zero the fishing mortality for length classes below the imposed threshold). As conservation targets at the regional scale may be met also through compensation measures among different catchments (avoiding the need for a strict compliance with conservation targets at the local scale), the user is also allowed to define a custom target for silver eel escapement as a percentage of the pristine value.

2.4. Simulation output

The output of the demographic model is reported numerically and graphically at the long-term equilibrium. The main results for each simulation are:

- the estimate of spawner escapement under pristine conditions;
- the estimate of (maximum) potential spawner escapement under present conditions;
- the estimated spawner escapement under the chosen management policy;
- the ratio between current and pristine escapement and the ratio between current and potential escapement;

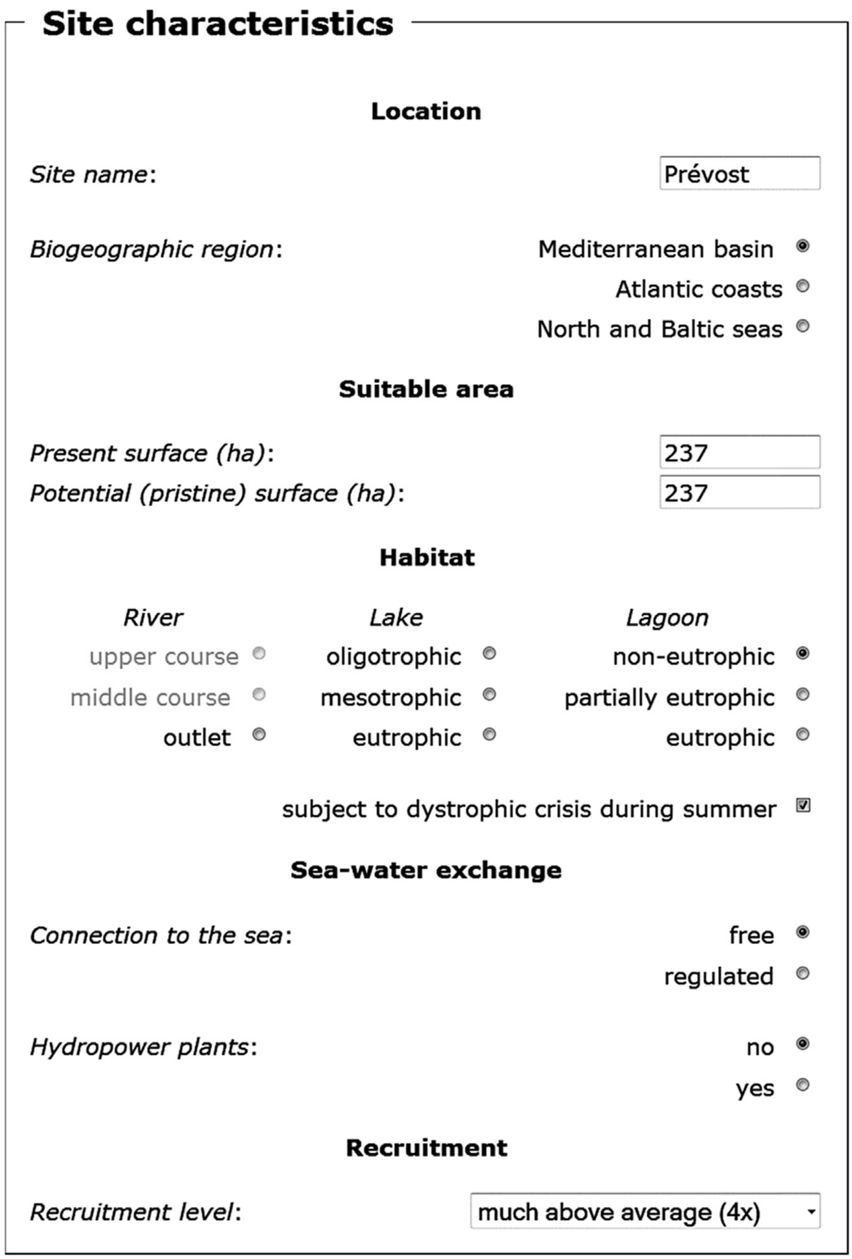

Fig. 1. EMS interface: site characteristics.

– whether the chosen management policy meets the Regulation target, the ICES target and (if set) the custom target;
– the fishing yield under the chosen management policy;
– the corresponding catch of each fisherman.

The graphs allow to quickly identify the performance in terms of spawner escapement, catch and length structure of the catch under different EMPs: when a series of alternative management strategies are analysed within the same session, the software updates the graphs by adding the results of the most recent simulation so as to ease the comparative analysis of the proposed management alternatives.

3. Case studies

In this section we provide a practical demonstration of how the software allows the user to painlessly explore the effectiveness of existing and alternative EMPs, to evaluate whether and to what extent an increase in mesh size or a reduction in fishing effort may help to meet the Regulation target, and how the proposed plan may ultimately affect fishing yield. Here below we first illustrate the analysis of the EMP of Lough Neagh, a freshwater system in Ireland. Then, we assess the effectiveness of, and propose changes to, existing EMPs of two French coastal lagoons that are geographically close (less than 60 km) but have different environmental features and exploitation effort. Third, we use the software to briefly explore a more general question, namely whether it is better, in terms of spawner escapement, to stock glass eels in coastal lagoons in the southern Mediterranean range of eel distribution or in equivalent (i.e. with the same surface) lagoons in the northern range of the distribution, where water temperature and primary production are usually lower, eel grow more slowly and mature later, but their natural mortality rate is lower than in Mediterranean lagoons.

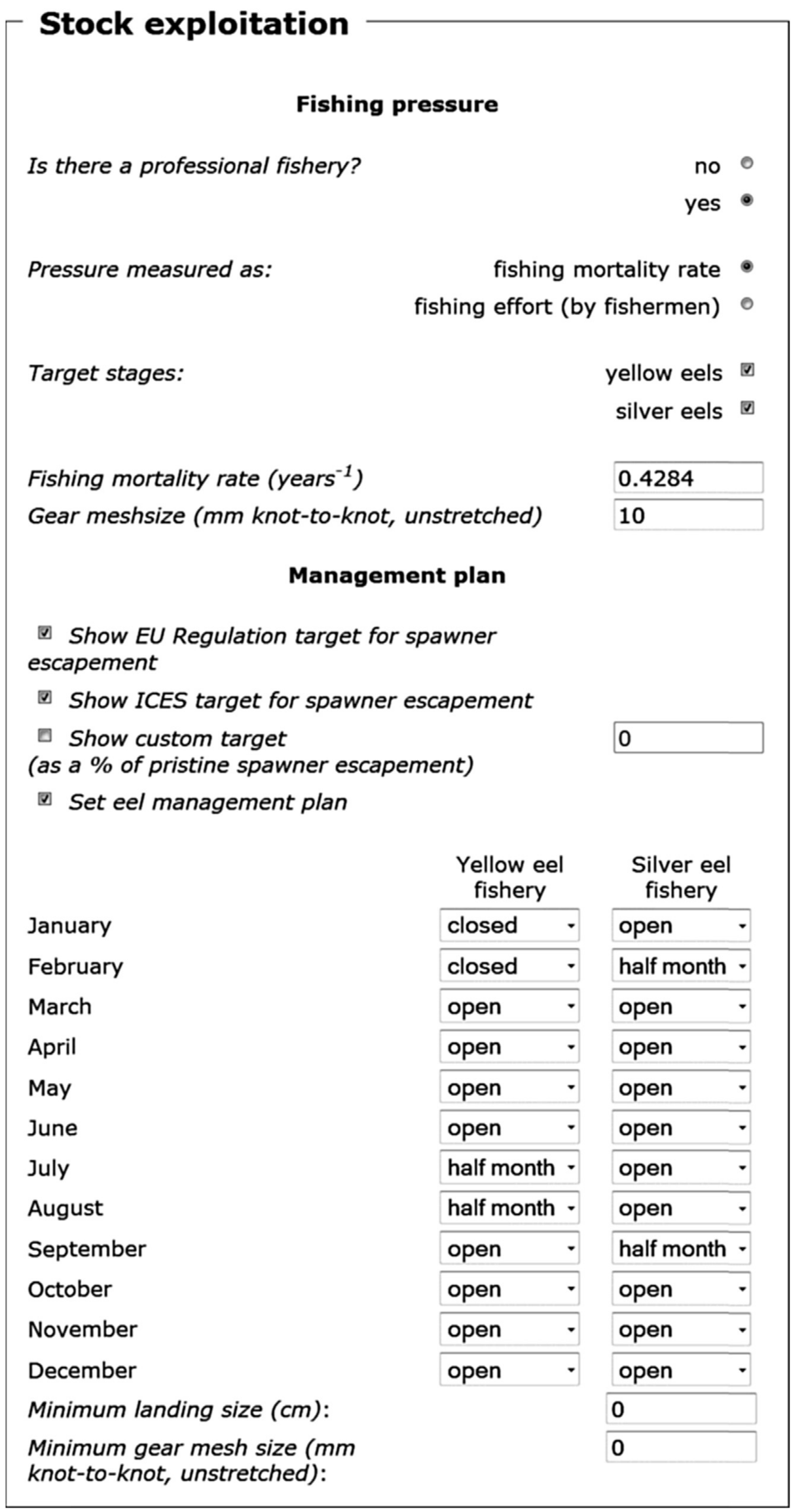

Fig. 2. EMS interface: stock exploitation and management plan.

Table 1
Effort per fisherman (average number of fyke nets in each month) in the Vaccarès-Impériaux water system (average 1993–2009), in the Prévost lagoon (2010–2011), and default effort used in the EMS when actual effort is unknown.

Month	Vaccarès-Impériaux	Prévost	Default
January	14.1	6.0	10.0
February	14.1	0.0	7.5
March	37.5	22.8	30.0
April	37.5	37.2	37.5
May	37.5	44.7	40.0
June	30.0	21.0	25.0
July	7.5	23.7	15.0
August	7.5	33.9	20.0
September	36.6	30.3	32.5
October	45.0	42.0	42.5
November	45.0	43.8	45.0
December	29.7	19.5	25.0

3.1. Lough Neagh (Ireland)

Lough Neagh is a 40,000 ha eutrophic lake where eel recruitment comes from traps intercepting glass eels (which would otherwise be blocked by sluices set at the outlet of the River Bann, the emissary of the lake) and, since 1984, from stocking glass eels bought on the European market in order to ensure an annual recruitment of ca. 8 million juveniles (Rosell et al., 2005), equivalent to 0.05 kg/ha. From a long time series, recorded since 1936, it is possible to estimate the recruitment abundance before the collapse (around 0.2 kg/ha, on average, between 1936 and 1946) and use it as an input to the model. The fishery is carefully managed since the 1960's by the Lough Neagh Fishermen's Co-operative Society Ltd. Yellow eels are fished from May to September with minimum marketable size of 41 cm. There are 100 licences for yellow eel fishing with an unknown effort, while silver eel fishing is interdicted within the lake. Rosell et al. (2005) reported that 30% of migrating silver eels are fished along the outgoing channel, while the remaining part reaches the sea thanks to by-passes allowing the passage of fish through the sluice gates. To incorporate this information into the model, we considered a fishing barrier working for 30% of the time, i.e. 9 days per month. Input data are reported in Table 2 and the results of the demographic and management analysis carried out with EMS are shown in Table 3. Simulations show that, although this is considered a sustainable fishery (Rosell et al., 2005), current escapement is only 20% of the pristine one and 44% of the present potential one, therefore well below the Regulation target and the ICES target (which, for this case study, would correspond to a current/potential ratio of 70%). On the other hand, we also show that in the absence of any management of the eel fishery (i.e. no limit to the yellow eel season and to the landing size), total catches would be lower than current ones (211 t/yr vs. 228 t/yr) and silver eel escapement would be even lower (99 t/yr vs. 220 t/yr under current management).

Table 2
Environmental settings used for the case studies considered in the analysis.

Site[a]	Location[b]	Surface[c]	Habitat	Water exchange[d]	Recruitment[e]
VI	MED	9200	Lagoon: partially eutrophic	Regulated	Much above avg.
P_{before}	MED	237	Lagoon: eutrophic with dystrophic crises	Free	Much above avg.
P_{after}	MED	237	Lagoon: non-eutrophic with dystrophic crises	Free	Much above avg.
LN	ATL	40,000	Lake: eutrophic	Free	Advanced

[a] VI: Vaccarès-Impériaux; P_{before}: Prévost, before WWTP construction; P_{after}: Prévost, after WWTP construction; LN: Lough Neagh.
[b] MED: Mediterranean basin; ATL: Atlantic coast.
[c] In ha; for all sites the pristine surface has been set equal to the current one.
[d] In VI sluice gates are closed from May to November.
[e] Recruitment at LN is known for pristine and current conditions (0.20 and 0.05 kg/ha, respectively) and it has been entered using the "advanced" frame.

Table 3
Estimated pristine and current spawner escapement, current/pristine ratio (c/p) and landings for each management scenario.

Site[a]	Scenario[b]	Pristine		Current		c/p	Landings
		(t)	(kg/ha)	(t)	(kg/ha)	(%)	(t/yr)
VI	no EMP	232	25.3	65	7.1	28.1	66
VI	EMP	232	25.3	72	7.8	30.9	63
VI	14 mm	232	25.3	100	10.9	43.1	72
VI	EMP + 14 mm	232	25.3	105	11.5	45.5	68
VI	Aut	232	25.3	76	8.3	33.0	55
VI	EMP + Aut	232	25.3	85	9.2	36.4	52
VI	EMP + 14 mm + Aut	232	25.3	123	13.4	53.1	52
VI	North	156	16.9	21	2.3	13.7	42
P_{before}		12.0	50.5	0.2	0.8	1.7	2.6
P_{after}	no EMP	2.0	8.4	0.03	0.1	1.7	0.4
P_{after}	EMP	2.0	8.4	0.11	0.5	5.6	0.5
P_{after}	14 mm	2.0	8.4	0.22	0.9	10.8	1.0
P_{after}	EMP + 14 mm	2.0	8.4	0.4	1.7	20.0	0.9
P_{after}	North	1.2	5.1	0.002	0.01	0.2	0.2
LN	no EMP	1083	27.1	99	2.5	9.1	211
LN	EMP	1083	27.1	220	5.5	20.3	228

[a] VI: Vaccarès-Impériaux; P_{before}: Prévost, before WWTP construction; P_{after}: Prévost, after WWTP construction; LN: Lough Neagh.
[b] No EMP: no management plan; EMP: application of the EMP; 14 mm: minimum mesh size of 14 mm; Aut: forced opening of sluice gates in Autumn; North: all settings as in "no EMP", but location changed from "Mediterranean basin" to "North and Baltic seas".

3.2. Vaccarès-Impériaux and Prévost (France)

We analyse two coastal systems in the Mediterranean area, one in the Camargue (Rhône River delta, southern France), the Vaccarès-Impériaux lagoon system, and the other along the Languedoc-Roussillon coast, the Prévost lagoon. In spite of being only 60 km apart, so that weather conditions and mean recruitment abundance are likely very similar (as confirmed by data on glass eel catches per unit effort), these two systems are completely different for the environmental/hydrological conditions and the fishery. Vaccarès-Impériaux (9200 ha) is isolated from the Rhône River and from the Mediterranean Sea by dykes at Grau de la Fourcade, near Saintes-Maries-de-la-Mer, with sluice gates that regulate the water flow with the sea. Drainage of cultivated land, prevention of flooding and control of salinity level are the main aims of water management. Glass eel recruitment, estimated from the analysis of catch per unit effort data and the results of Capture-Mark-Recapture experiments (Alain Crivelli, unpublished data), is, on average, about 2.5×10^7 individuals (0.65 kg/ha). On the other hand, the Prévost lagoon is much smaller (only 237 ha) and is not completely isolated from the surrounding lagoons. The canal linking the lagoon to the sea allows juveniles and spawners to freely enter and leave the lagoon. Prévost used to be a eutrophic lagoon, very suitable for eels despite the periodic occurrence of dystrophic crises during summer. The construction of Montpellier's wastewater treatment plant (WWTP) in 2005, which diverted towards the sea sewage previously reaching the lagoon, led it into a non-eutrophic state, with an important loss of suitability for eels. Recruitment abundance is presently sufficient to reach the maximum settlement potential, leading to an almost constant settlement over time. Both lagoons are heavily exploited, Vaccarès-Impériaux by 19 professional fishermen and Prévost by only one fisherman, all of them using 6-mm capétchades (passive nets composed by three cones, which we considered to be equivalent to 3 fyke nets). Average monthly efforts are reported in Table 1. On average, the whole Vaccarès-Impériaux fishery (yellow and silver eels) yields 55 t/yr (Bevacqua et al., manuscript in preparation), while in Prévost it yielded 3.1 t/yr before the WWTP and 432 kg/yr after WWTP (local fisherman, pers. comm.). Both lagoons are currently managed following the French EMP "*Plan de Gestion Anguille de la France*" adopted in 2010. Accordingly, yellow eel fishing is allowed from March 1st to July 15th and from August 15th to December 31st. The silver eel fishery is open from September 15th to February 15th. No limit to gear mesh size is imposed nor to the minimum landing size, yet a single fisherman cannot use more than 20 capétchades per day. Input data are listed in Table 2. We used the software to compute spawner escapement before and after the implementation of the French EMP. As for the Prévost lagoon, we also computed spawner escapement before and after the construction of the WWTP. Finally, for both lagoons we explored the effect on spawner escapement and fishing yield of: a) imposing a minimum mesh size of 14 mm (the optimal mesh size indicated by Bevacqua et al., 2007 to maximize fishing yield); b) the full opening of the sluice gates connecting the lagoons to the sea during the silver eel migration season (September to November); c) the combination of the two measures with the current management plan.

Our simulations show that current management plans in the two water systems do not meet the Regulation target (Fig. 3), although the recent implementation of the French EMP has improved spawner escapement with respect to historical management (Table 3). Simulations also show that enforcing a 14-mm minimum mesh size before the implementation of the French EMP would have allowed long-term catches to increase by 10% in Vaccarès-Impériaux and 240% in Prévost, thus achieving the highest absolute yields in both lagoons among all the alternative management strategies analysed in the present study. Moreover, the increase in minimum mesh size would have been sufficient in Vaccarès-Impériaux (but not in Prévost) to attain the 40% escapement target set by the EC Regulation. The best trade-off between conservation and fishery goals in Vaccarès-Impériaux is achieved by combining the 14-mm mesh size limit with the current French EMP: this management would produce a 6% improvement in fishing yield along with a 47% increase of spawner escapement (compared to the current management), that would slightly exceed (45.5%) the Regulation target.

The fishing effort exerted in the small Prévost lagoon, even though below the maximum effort imposed by the French EMP, generates a density of nets higher than in the Camargue system (11.43 nets km^{-2} and 5.88 nets km^{-2}, respectively) and causes a very small fraction of the potential spawners to leave the lagoon, even after the implementation of the French EMP. Further, increasing the mesh size to 14 mm in addition to the French EMP would significantly improve the escapement, even though this would still remain at a mere 20% of the potential one in the absence of fishing activities. A 40% reduction of fishing effort would thus be necessary in order to match the Regulation target.

If limiting the gear mesh size to 14 mm or above could benefit both fishing yield and spawner escapement, opening the sluice gates in Vaccarès-Impériaux during the silver eel migration season would produce only a marginal increment in silver eel escapement (+7% alone, +18% combined with the current EMP), but it would affect annual catches with a reduction of 14% (18% if the measure were combined with the current EMP). Nevertheless, the joint implementation of the three measures, namely the enforcement of French EMP, the limitation on gear mesh size and the opening of sluice gates during the migration season, remains the best conservation scenario in Vaccarès-Impériaux. In fact, this management

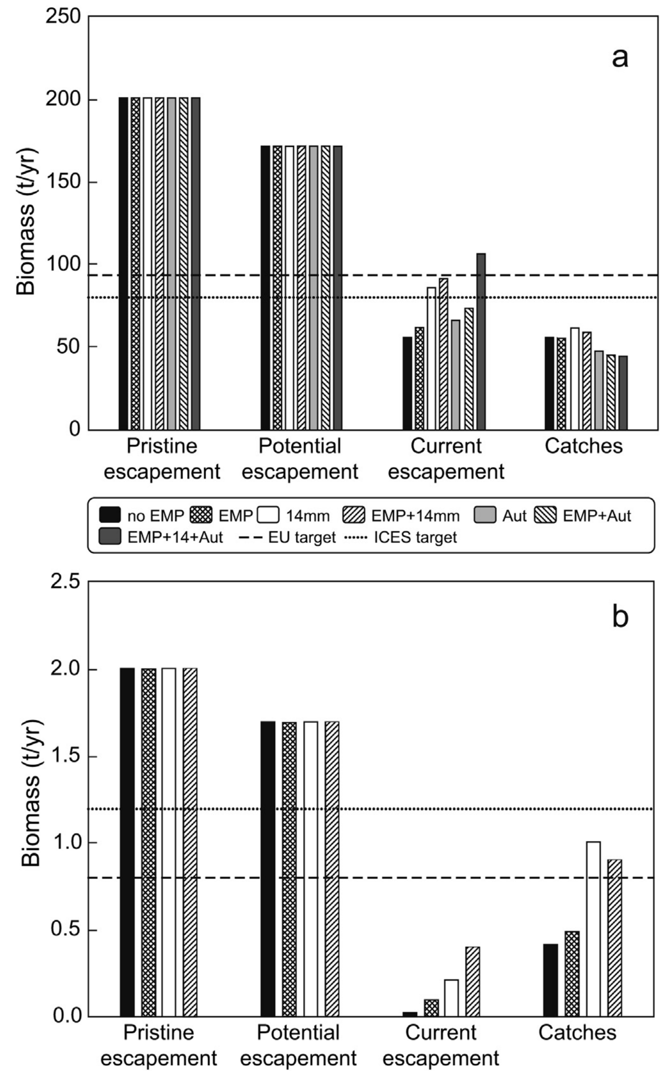

Fig. 3. Comparison among different management plans for Vaccarès-Impériaux lagoon (a) and Prévost lagoon (b). "no EMS": before the application of the French EMP; "EMP": current management under French EMP; "14 mm": 14-mm minimum mesh size; "Aut": forced opening of sluice gates in Autumn.

would increase spawner escapement up to 53% of that in pristine condition, safely above the Regulation target. The drawback, however, would be an 18% loss of the current catch.

3.3. Geographical alternatives for eel stocking

Finally, we also compared the production, in the absence of any management, of the two Mediterranean sites with two imaginary sites with the same physical features but located in northern Europe (i.e. changing the location from "Mediterranean basin" to "North and Baltic seas" and setting the same glass eel recruitment through the advanced interface), thus considering different body growth, maximum settlement potential and mortality, in order to have some suggestions regarding the so-called restocking dilemma (i.e. whether it is better to restock in a Mediterranean site, where eels grow faster but smaller, mortality is higher and productivity too, or in a site of Northern Europe, where eels grow more slowly but larger, mortality is lower and so is productivity). Our simulations show that, considering a same amount of glass eel recruited in an imaginary north European lagoon instead of a Mediterranean one, these demographic differences would lead to a reduction of both spawner escapement (about −50%) and fishing yield (about −25%). While these shall be intended as preliminary results, our analysis evidences that there could be quite remarkable difference and, therefore, further investigation is certainly welcome to compare alternative strategies of glass eel restocking aimed to improve the conservation of the European eel. Research in this direction will also have to address the effect of restocking on the migration ability of future spawners, which might impair the actual effectiveness of restocking for the conservation of the species (Westin, 2003; Prigge et al., 2013b).

4. Conclusions

In this paper we presented EMS, an easy-to-use and flexible software allowing users to perform a screening of Eel Management Plans in a variety of water systems and to assess their compliance with the conservation target set by the EC Regulation. The analysis of selected case studies shows that EMS can be effectively used to assess conservation and fishery performances of alternative management scenarios and even to start to tackle more fundamental questions, such as the effectiveness of restocking measures in water bodies of different type or in different geographical areas.

The analysis of existing management plans of two French lagoons and the local management plan of Lough Neagh in Ireland reveals that apparently they do not fulfil the Regulation target. We found out that the French management policy could be improved by introducing measures limiting the minimum mesh size used by fishermen.

The modelling approach implemented in EMS is not exempt from criticism. Despite our effort to derive a comprehensive demographic model, provide a wide set of model parameters and allow experienced users to play with the advanced setting of the model, EMS requires to provide a schematic representation of the system under study, which can in some cases be too simplified to grasp the relevant features of specific fisheries. For instance, in its current version, the basic interface of EMS does not allow the user to choose the upper section of rivers as a habitat type. In fact, most rivers have specific topologies that may determine spatially heterogeneous patterns of habitat suitability, recruitment and eel productivity, which may be difficult to describe via a spatially implicit model such as that underlying the EMS. Nevertheless, rivers in which the assumption of habitat homogeneity may be acceptable can be dealt with through the advanced model interface. Simplifications were introduced in EMS to keep the model manageable and easy-to-use for those lacking programming and/or mathematical skills. As a consequence, we do not expect EMS projections to closely reproduce observed catches of each specific eel fishery in Europe – as this would be possible only by performing fine-tuned site-specific and time-consuming calibration of model parameters. The values of recruitment and settlement potential selected by the user (either indirectly, via the basic interface, or directly, via the advanced one) are critical to determine the magnitude of model outputs such as spawner escapement and catch. Therefore, rather than using the software to make accurate estimations (in absolute terms), EMS should be used to compare the relative performances of one management alternative with respect to another. In this sense, EMS should be intended as a tool for *ex ante* evaluation (i.e. to support a decision before it is taken) and not for *ex post* evaluation (i.e. to assess the goodness of a decision after it has been taken). In fact, *ex post* evaluation of management measures must be driven by, and compared with, actual data deriving from the accurate monitoring of the system. When EMS is used in a decision process, the consequences of the uncertainty associated to the specific settings should be carefully discussed (e.g. by running simulations with slightly different settings) to avoid controversies.

Anyway, the fraction of potential spawners leaving the Vaccarès-Impériaux lagoon estimated with the EMS (28% before the implementation of the EMP and 31% after) is in tight accordance with the projections of a much more sophisticated model currently under development and accurately calibrated on the Camargue lagoons (28% vs. 30%, Bevacqua et al., manuscript in preparation). The EMS also matches the observed 86% drop in catches (84% predicted by the model) from the Prévost lagoon due to water quality improvement after the construction of the wastewater treatment plant. We thus believe that our modelling approach is able to capture with some confidence the fundamental processes driving eel dynamics.

To make the interpretation of model outcomes simpler, we decided to present the model output only at the long-term equilibrium under the hypotheses of constant recruitment and constant environmental conditions. Uncertainty affecting expected fishery productivity and spawner escapement due to inter-annual variation in recruitment is an important information, which would allow decision makers to formulate risk-averse management policies (Bevacqua et al., 2009b). However, dealing appropriately with uncertainty would require a stochastic formulation for the core demographic model, which in turn would dramatically increase computational times. In addition, the EC Regulation requires to implement long-term plans to be revised on a periodic basis, and not a scheme for adaptive management (Walters, 1986). Therefore, we believe that the assessment of alternative management plans on the basis of their average long-term performance is appropriate and in line with the conservation goals of the Regulation.

Transients (i.e. the dynamics of the system after changing the management policy and before a new long-term equilibrium is reached) can also be quite important for their consequences on the performances of the fishery in the short term. Their duration depends upon the pace of the demographic processes characterizing the continental phase of eel life cycle and can range from 5 years in the Mediterranean area up to 15 years in northern Europe. During this transient, some compensation measures to sustain potential losses in fishery revenues might have to be considered. These compensations should account also for the cost of changing fishing gears and the effect that the EMP can have on the catches of other small fish species targeted by the same fishery (e.g. the sandsmelt *Atherina boyeri*).

Despite these limitations, we are confident that our software can be valuable for the assessment of EMPs in a number of small-scale, data-poor eel fisheries for which no viable, cost-effective and timely alternatives exist to modelling projections.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.envsoft.2014.10.008

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