Ecological Modelling 331 (2016) 56–67

Contents lists available at ScienceDirect

Ecological Modelling

journal homepage: www.elsevier.com/locate/ecolmodel

Modeling population dynamics and small-scale fisheries yields of fish farming escapes in Mediterranean coastal areas

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ARTICLE INFO

Article history:
Available online 15 February 2016

Keywords:
Ecopath
Aquaculture
Sustainable
Sea cages
Gilthead seabream

ABSTRACT

Coastal ecosystems put up a number of impacts from human activities in the sea; the most recent is fish farming, interacting synergistically with the other impacts and with the natural structure and dynamics of the coastal ecosystem. In the Mediterranean Sea, the number of fish farms has increased dramatically from early '80s in coastal waters, releasing a substantial amount of organic matter, modifying the habitat and communities beneath cages and changing the spatio-temporal distribution of species. Among all the effects derived from fish farming, escape events of cultured fish are a relevant issue for management given their potential impact over wild counterparts in terms of habitat and food competition, genetic flow, biodiversity, spread diseases or parasites, and interaction with local fisheries, decreasing the price of the catches. This paper shows the first approach to model the temporal trends of biomass and yields of escapes from aquaculture by means of an EwE model. Three levels of escapes (×1, ordinary level: 5000 ind year^{-1} fish farm^{-1}, corresponding to 1.31 t year^{-1}; massive event: ordinary level × 91; total destruction of fish farm: ordinary level × 1800) and four levels of fishing effort (ordinary E, ×2, ×5, ×10) were modelled as mechanism to recapture escapees. Temporal variation of biomass and yield is used to define how long should be maintained the effort to catch escapees. The total destruction of a fish farm generates the higher increase of escapees' landings, dissapearing in less than 6 months if fishing effort reach 10-fold the ordinary fishing effort. Differences among revenues from recaptures and derived expenses were always negative but tending to be greater for low levels of fishing effort and/or levels of escapes which means no fishery can be expected to be maintained by escapes. In general, fleets benefit from escapees in terms of yield but gains will depend on how escapees affect either positively or negatively the value of the catch. Simulations using EwE models may result a useful tool to design suitable recapture plans of escapees.

1. Introduction

Nowadays, farmed fish contributed a record 42.2% of the total 158 million tons of fish produced by capture fisheries (including for non-food uses) and aquaculture in 2012, accounting for 13.4% in 1990 and 25.7% in 2000 (FAO, 2014). This trend is still to grow and it is predicted that 62% of fish will be aquaculture-produced by 2030. Although the aquaculture output of some industrialized regional producers as Spain, France and Italy, has fallen in recent years, the overall European production trend is still ascending (FAO, 2014). The economic losses associated to fish escaping from floating cages are considered a major handicap for industry showing related to the standard of materials and production procedures at farms (Jackson et al., 2015). While losses in Atlantic salmon (*Salmo salar*) producing countries of northern Europe are estimated in €4.7 million per annum, losses of Mediterranean producers of sea bass (*Dicentrarchus labrax*) and gilthead seabream (*Sparus aurata*) rise up to a staggering €42.8 million (Jackson et al., 2015).

Fish escaping from farms entail ecological risks as feral stock establishment, pathogen transmission, genetic interactions or competition with wild fish for mating, space, and prey, all reviewed, regarding Atlantic salmon, by Naylor et al. (2005). In the same way, escapes of cultured species in the Mediterranean Sea have shown direct effects on the ecosystem (e.g. Diana, 2009), as well as genetic introgression in wild populations (Šegvić-Bubić et al., 2011) or food competition (Toledo-Guedes et al., 2009; Arechavala-Lopez et al.,

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http://dx.doi.org/10.1016/j.ecolmodel.2016.01.012
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2012; Valero-Rodriguez et al., 2015). Escapes occurring in areas where there is no wild population of the cultured species can raise ecological and socioeconomic issues as in the western coasts of both North (Volpe et al., 2000) and South America (Soto et al., 2001) and in the Canary Islands, Spain (Toledo-Guedes et al., 2014).

Fisheries are as well influenced by fish escaping from fish farms. Schiermeier (2003) estimated in two million, the salmon individuals escaping from farms every year into the North Atlantic area. Hansen et al. (1999) estimated the incidence of escaped Atlantic salmon in the North Atlantic High Seas fisheries (off the Faroes islands) between 20% and 40%. In the Mediterranean, there are as well evidences that the wild stock of sea bream is enhanced in areas where aquaculture is present (Dimitriou et al., 2007). The latter, although at a different scale, is in conflict with the stagnation and decline of fisheries catches since late 1980s (Pauly et al., 2003). The future scenario of world fisheries predicts that there will be no fish for developing countries by 2050 (Pauly et al., 2003). At a lower scale, there is an increasing need for a sustainable exploitation of target species in coastal areas (Tzanatos et al., 2013). Ecopath with Ecosim (Christensen et al., 2008) is a well-known tool to model and evaluate the impact of fisheries and ecological changes on the ecosystem (Pauly et al., 2000), however it has never been used to evaluate how fisheries can recapture fish escaping from floating cages in fish farms. In terms of management, the escape events are regulated either in Norway, Canada, United States, Scotland, Chile or Australia (regulations links at Izquierdo-Gomez et al., 2014) all describing fishing actions as part of their contingency plans to be activated as soon as a fish escape occurs. Surprisingly, none of the Mediterranean fish producing countries regulate the escape events under a legal framework, most likely as a consequence of the scarce knowledge about fisheries and escape events interaction, among others.

In this study the ability of a small-scale fleet to recapture escaped fish from a fish farm was modelled and several scenarios of different escape magnitudes and fishing efforts were simulated by using Ecopath with Ecosim. The outputs of the model will be useful to develop management measures by answering questions as (1) how long will the escaped fishes remain in the ecosystem and how will be its population dynamics? (2) For how long would the fishing fleet be able to recapture escaped fish?, (3) Is it cost-effective to recapture the escaped fish as an independent activity?

2. Materials and methods

2.1. Study area

The study area is situated in the southeast of Spain (West Mediterranean Sea) covering 891 km^2, between 38°17–37°36′N and 00°43–00°18′W (Fig. 1). This area includes four floating-cage fish farms, one 14 km^2 marine protected area around Tabarca Island and two fishing ports harboring 60 trammel-netters and 32 bottom-otter-trawlers. This area is characterized by a relative wide shelf with low slopes, reaching 100 m depth at tenths of km's from the shore, exhibiting oligotrophic waters with surface temperature values ranging from 13 °C in winter to 28 °C during summertime. Water clarity (Secchi disk depth) varied between 8 m and 30 m from winter to summer. Bionomically, the shelf is composed by *Posidonia oceanica* meadows, sandy seabeds close to the shoreline, some rocky bottom spots mainly around Tabarca Island, and soft muddy seabeds in the deeper zones and off the Segura River.

Fish farms are located 3 mi offshore on soft muddy bottoms at depths ranging from 21 to 30 m, off the mouth of the Segura River. Each fish farm consists of 20–24 floating cages of 450 m^3, each rearing around 775 t of fish biomass. All together, they grow ca. 6500 t year^{-1} of european seabass (*D. labrax*) and gilthead seabream (*S. aurata*); in average, 5000 fish year^{-1} fish farm^{-1} escape to the wild environment (1.21 t year^{-1}) contributing to the commercial catches or remaining naturalized in the study area (Arechavala-Lopez et al., 2012).

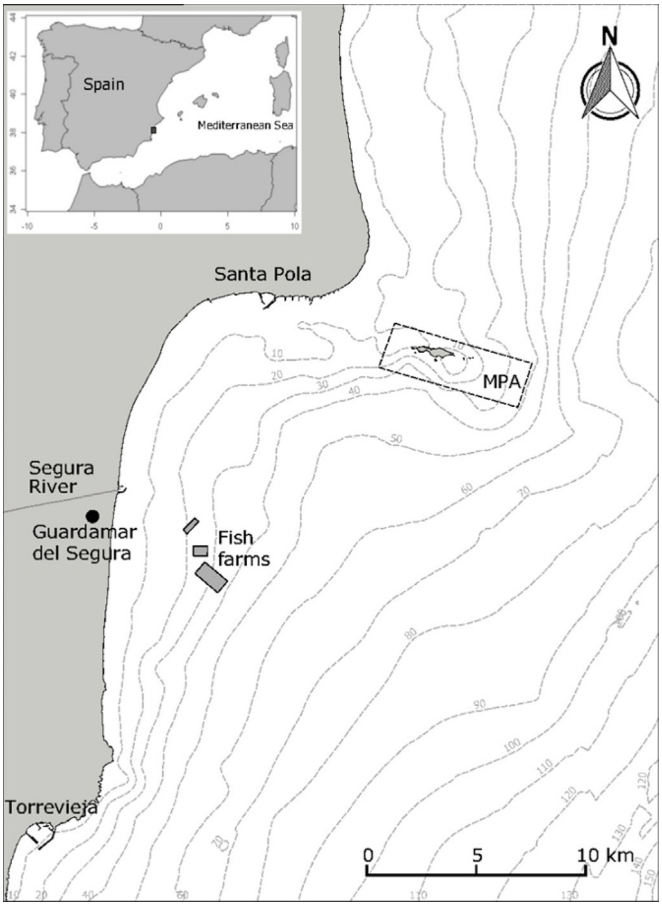

Fig. 1. Location of the studied area.

2.2. The model

An Ecopath model (Christensen et al., 2008) was assembled describing the trophic relationships among 32 ecological groups sharing similar feeding roles, keeping as individual groups those of particular interest (see Table 1). The model provides a static description of an ecosystem at a precise period in time, based on the premise that the considered system is balanced in the given time period (Polovina, 1984); being production equal to consumption following the equation: $B_i\ (P/B)_i\ \mathrm{EE}_i - \Sigma_j\ B_j\ (Q/B)_j\ \mathrm{Dc}_{ji} - Y_i - \mathrm{BA}_i - E_i = 0$; where for an i group, P_i is production, B_i is biomass (t km^{-2}) and EE_i is ecotrophic efficiency. Moreover, Q_j is the consumption for predators, BA_i is the biomass accumulation rate for i and E_i is the net migration rate of the group. Because material transfers among groups take place through trophic relationships, this equation is re-expressed including the biomass of predators and the instantaneous rate of total mortality (Z) at equilibrium (Allen, 1971) in the form of P/B rate, describing the biomass flow balance between inputs and outputs for each group (see Christensen et al., 2008, for a complete explanation). A system of linear equations was established in which three parameters were introduced: biomass (B), total biological production rate (P/B); total food consumption rate (Q/B) and only one, EE, was estimated by the model. Diet composition is expressed as a fraction of prey in the average diet of a predator. Fishing data are also included by adding data on landings (t km^{-2}).

Table 1
Inputs and estimated values (in bold) for the Ecopath model.

	Group name	Trophic level	Biomass in hab. area (t/km^2)	P/B (year^{-1})	Q/B (year^{-1})	EE	Detritus import (t/km^2/year)
1	Pelagic large fishes	**3.91**	0.06	2.9	9.5	**0.3663**	0
2	Wild european seabass	**3.43**	0.34	0.59	2.1	**0.0804**	0
3	Demersal large fishes	**3.36**	0.15	2.05	7.05	**0.3113**	0
4	Birds	**3.31**	0.002	4.6	72	**0.0043**	0
5	Marine mammals	**3.27**	0.05	0.07	13.49	**0.0014**	0
6	Demersal small fishes	**3.18**	0.4	2.1	7.2	**0.5542**	0
7	Pelagic small piscivorius fishes	**3.12**	0.02	6.5	16.9	**0.9294**	0
8	Caramote prawn	**3.12**	0.08	5.15	12.9	**0.9833**	0
9	Sea turtles	**3.12**	0.03	0.15	2.54	**0.4974**	0
10	Wild gilthead seabream	**3.11**	0.588	0.53	1.779	**0.1100**	0
11	Rays	**3.11**	0.15	1.37	8.455	**0.2456**	0
12	Juvenile demersal small fishes	**3.09**	0.00324	5.7	15.1	**0.8891**	0
13	Cephalopods	**3.08**	0.23	1.7	5.8	**0.7702**	0
14	Juvenile pelagic small piscivorous fishes	**3.07**	0.00266	7.5	19.3	**0.7517**	0
15	Juvenile pelagic small planktivorous fishes	**3.05**	0.00271	5.5	14.5	**0.8682**	0
16	Jellyfish	**2.93**	0.4	13.87	50.5	**0.4814**	0
17	Pelagic small planktovorous fishes	**2.93**	0.32	2.691	8.898	**0.7375**	0
18	Escaped gilthead seabream	**2.92**	0.00294	1.365	3.45	**0.9930**	0
19	Molluscs	**2.37**	0.04	1.95	11	**0.9507**	0
20	Crustaceans	**2.22**	33	4.7	22.7	**0.3812**	0
21	Sea urchins	**2.08**	6.93	0.549	3.193	**0.9971**	0
22	Zooplankton	**2.06**	4	30	120	**0.7403**	0
23	Polychaetes	**2.04**	3.887	4.2	10.81	**0.9945**	0
24	Meiobenthos	**2.02**	7.913	4.2	10.81	**0.6826**	0
25	Sea cucumber	**2**	4.2	0.5	3.1	**0.1151**	0
26	Farmed fish	**2**	4.72	1.45	3.1	**0.9994**	0
27	Algae	**1**	9.89	2.7		**0.5277**	0
28	Phytoplankton	**1**	11.55	136.65		**0.2139**	0
29	Artificial food pellets	**1**	14.71			**0.9948**	14.71
30	Terrestrial inputs	**1**	0.686			**0.0954**	0.686
31	Discards	**1**	0.330364			**0.9720**	0.330364
32	Detritus	**1**	169.625			**0.4219**	2.21

The temporal simulations were performed using the Ecosim module (Walters et al., 1997) to analyze the combined hypothetical effects of escape levels and fishing effort on the escapees from fish farms. The routine uses a system of time-dependent differential equations based on the nominal mass-balanced Ecopath model, where the biomass growth rate is expressed as: $dB_i/dt = g_i \cdot \Sigma Q_{ji} - \Sigma Q_{ij} + I_i - (M_i + F_i + e_i) \cdot B_i$; where de dB_i/dt represents the growth rate of group i biomass during the time interval dt, g_i is the net growth efficiency (production/consumption ratio), M_i is the non-predation $((P/B)_i B_i (1 - \mathrm{EE}_i))$ natural mortality rate, F_i is fishing mortality rate, e_i is emigration rate, I_i is inmigration rate (and $e_i B_i - I_i$ is the net migration rate). Q_{ji} express the total consumption by group i, and Q_{ij} is the predation by all groups on the same group i prey. The consumption rates Q_{ji} are calculated based on the foraging arena concept where B_i's are distinguished in vulnerable and invulnerable components (Walters et al., 1997). Ecosim simulations are especially sensitive to the vulnerability settings, which incorporates density-dependent effects and represents how far an ecological group is from its carrying capacity (Christensen et al., 2008). Following these authors and given that we did not fitted the Ecosim model to empirical landing data to adjust vulnerabilities to predation, we estimated baseline vulnerabilities v_{ij} from the nominal data of the Ecopath model, corresponding to the mass balance condition. For this we assume that the maximum possible predation mortality, to maintain such balance, should be at the most, equal to the surplus production of the prey. So, maximum predation mortality (i.e., 1) divided by baseline predation mortality caused by the predator in the underlying mass balance Ecopath model $(P_i/B_i)(Q_{ij}/Q_{i}\square)$, being (P_i/B_i) the surplus production and $(Q_{ij}/Q_{i}\square)$ the fraction consumed by predator j over consumption by all predators on prey i. Rearranging terms, this means $(Q_{ij}/B_i)(P_i/Q_{i}\square)$, where Q_{ij}/B_i is the natural mortality of prey i due to consumption, and $(P_i/Q_{i}\square) \leq 1$, indicating that maximum consumption by all predators on i cannot be higher than surplus production. This approach results in direct estimates of vulnerabilities from the mass-balanced situation defined in the Ecopath model and avoid assuming simple ordinary default values.

2.3. Field data

The annual base average on the information gathered between 2007 and 2013 on the study area was used. Most of the species were included in functional groups sharing similar trophic roles. Only those of particular interest were kept as individual groups: wild gilthead seabream and wild european seabass, escaped gilthead seabream, karamote prawn and farmed fish, given their commercial and/or ecological interest; several groups of invertebrates, juvenile and adult fish species. The artificial food pellets used to nourish the caged fish were considered just like a group of detritus, as well as the terrigenous sediment arriving from the land and discards from fishing activities. The microbial food web was not directly considered in the model, but it was indirectly considered within the zooplankton diet composition and detritus dynamics (Calbet et al., 2002). Biomass was compiled from either own studies or published studies, and was calculated with the swept area method (Pauly, 1984) that is based on the densities of organisms (i.e., the weight of the fish caught per unit area covered by an experimental sampling method), from which the potential yield can be obtained. For non-commercial groups, P/B corresponded to the instantaneous rate of natural mortality (M), and was estimated from data in FishBase (Froese and Pauly, 2015) for fish species, using the empirical equation of Pauly (1980). For commercial species fishing mortality from literature was added to M from FishBase. We used mortality values reported in the literature for the remaining functional groups. Q/B values for fish groups were computed following Palomares and Pauly (1989), which considers environmental temperature, fish weight and size, and caudal fin morphology. For the rest of the functional groups, Q/B was taken from the literature. A predator–prey matrix was developed from own data and reports of stomach contents for the different functional groups, using reports for similar species or groups when no data were available. On the other hand, fishing fleets and catches (Y_i) of important species were included in the model for both commercial and recreational fishing, correcting them by considering discard information from own data.

2.4. Temporal simulations and data analysis

EE > 1 was used as the primary criterion to balance the model, obtaining it by modifying the initial diet values for each prey and producing small changes (±5% max.) instead of adding or removing prey items in the feeding patterns of ecological groups. The consistency of the model was verified by checking that respiration to assimilation and production to respiration ratios were less than 1, and comparing trends in the respiration to biomass ratio which must be higher for active species than for sedentary groups.

We simulated three scenarios based on the three currently situations that can occur in fish farming related to escapes (Prevent Escape Project – 7th Research Framework Program – http://preventescape.eu) by means of a forcing function applying multipliers to both vulnerability v_{ij} and foraging arena biomass flow rate a_{ij}: the baseline ordinary operational level of escapes (×1) evaluated in 5000 fish year^{-1} fish farm^{-1} (1.31 t year^{-1} in overall); the situation when a cage broke and release about 3×10^5 fish (91-fold the baseline ordinary level of escapes; ×91), and the catastrophic event when the entire fish farm were destroyed (1800-fold the baseline ordinary levels of escapes; ×1800). For each scenario we run four simulations increasing ×1 (the baseline fishing effort for the Ecopath model corresponding to twelve fishing vessels devoted to Sepia trammel net for the entire study area), and ×2, ×5 and ×10 multipliers of the ordinary fishing effort.

Empirical observations evidenced an increase of 350-fold the catches after an escape event; so, we assigned this value for the density-dependent catchability factor of the escaped seabreams. Changes over five years in escaped seabream biomass and yield of Sepia (*Sepia officinalis*) trammel-net were simulated to determine how long and how many escaped individuals could remain in the environment. Considering an average market value of 4.67 euros kg^{-1} for gilthead seabream, we calculated the cumulative revenue obtained from the recaptured biomass of escaped seabreams, and the total cumulative costs of the recapture operations considering that each fishing vessel is worth 300 euros per day trip.

3. Results

3.1. The Ecopath model

Input data values are listed in Table 1. The model comprehends 32 ecological groups, including the main trophic components of the ecosystem, some of them with commercial targeted value, and four detritus groups (artificial food pellets, terrestrial inputs, discards and detritus). Trophic level of ecological groups ranged within three integers with the highest values corresponding to pelagic large fishes, wild european seabass and demersal large fishes. The remaining ecological groups were classified between 3.31 and 2 for the most fish species (including the farmed fish) and invertebrates, and 1.0 for primary producers and all the detritus groups. Fish groups exhibited a TL slightly lower than those reported in the FishBase database (Froese and Pauly, 2015). Low EE values were obtained for some groups (e.g., birds, marine mammals) probably because they are not fully dependent of the ecosystem. High EE resulted for escaped seabream, mollusks, sea urchins, polychaetes, farmed fishes, artificial food pellets and discards. Table 2 shows the adjusted predator–prey matrix.

Commercial landings originated from Guardamar fleet (10 métiers) and Santa Pola fleet (10 métiers) (Table 3), reaching a total of 9.41×10^{-1} t km^{-2} year^{-1}. Cuttlefish trammel net, caramote prawn trammel net and flatfish trammel net in Guardamar, and otter trawling, red mullet trammel net and cuttlefish trammel net in Santa Pola were the métiers contributing the most to total commercial landings in the studied area. Recreational fishing included angling from land and from boats, and spearfishing, summing a total catch of 1.16×10^{-2} t km^{-2} year^{-1}. Fish farming produced 3.59 t km^{-2} year^{-1}. Farmed fishes aside, demersal small fishes, cephalopods and demersal large fishes were the most caught groups for the whole studied area (Table 4).

3.2. Temporal simulations of the escapes biomass and recaptures

Empirical data from a post escape event based on landings data obtained after a cage breakage due to a storm in a nearby fish farm exhibited an average catch (±SE) of 3338 ± 810 kg boat^{-1} (13,603–154 landed kg boat^{-1}; 18 boats) along the first month after the escape, while landings dropped to 898 ± 225 kg boat^{-1} (2789–21 kg boat^{-1}; 17 boats) and 36 ± 9 kg boat^{-1} (129–5 kg boat^{-1}; 13 boats) along the next two months, respectively. The artisanal fishing fleet operating in the area was composed of 20 trammel netters.

The ordinary simulation (Escapees ×1, Fishing effort ×1) (Fig. 2) highlighted the increase of escaped fishes biomass till reaching a constant value of about 4.65 t for the whole studied area, yielding about 0.82 t over all the simulated period and for the whole studied area, with a maximum relative yield of 1.07-fold the initial value. The same pattern resulted when fishing effort was ×2 effort but exhibiting lower values of maximum total biomass (3.9 t) and greater values of maximum yield (1.65 t; maximum relative yield of 2.07-fold the ordinary value). Escaped fishes only become extinct in the studied area 43 months after increasing the fishing effort ×5, disappearing earlier (7th months after the escape event) when fishing effort is increased ×10, obtaining maximum relative yields of 4.96 and 8.4-fold the initial value, respectively.

In the scenario for escape ×91, the resulted pattern in terms of total biomass was similar than in escape ×1 when fishing effort was ×1 and ×2 but relative total yield increased till 1.18 and 2.3-fold the ordinary values, respectively. Fishing effort ×5 and ×10 caused a similar pattern than in escape ×1 scenario in terms of total biomass and eradication time (43 and 7 months) but with slightly greater relative maximum yields (5.25 and 8.69-fold the initial value, respectively, both during the second month after the escape).

After a marked drop of the biomass escapees due to an increase of intraspecific competence for preys, the ×1 fishing effort scenario with ×1800 escapees exhibited a strong increase of total biomass values maintained till the end of the simulation, with a relative maximum total yield of 1.17-fold during the 15th month and values close to 1-fold during the rest of the period simulated. The increase of fishing effort favored the eradication of escapees as soon as greater is the increase of fishing effort (31 months for ×2 fishing effort; 9 months for ×5 and 5 months for ×10). The relative maximum total yield was 1.97-fold in the 13th month for ×2 fishing effort, 4.27-fold during the 1st month for ×5 fishing effort and 7.51-fold in the 1st month for ×10 fishing effort. Notably, the captures of escapees were limited to the 4–8 initial months at higher values of fishing effort.

3.3. Expenses–revenue analysis of recaptures

In general, simulations resulted in higher costs than revenues for every scenario (Fig. 3). However, differences between revenues and expenses increased as fishing effort, and hence cost,

Table 2
Adjusted diet matrix for the Ecopath model.

	Prey	Predator						
		1	2	3	4	5	6	7
1	Pelagic large fishes	1.45E – 03				1.33E – 02		
2	Wild european seabass	7.25E – 03	5.23E – 03	1.43E – 04	9.99E – 05	2.66E – 03		
3	Demersal large fishes	9.99E – 05	1.00E – 05	0.00E + 00	0.00E + 00	1.00E – 05		
4	Birds							
5	Marine mammals							
6	Demersal small fishes	2.00E – 02	1.00E – 03	3.00E – 02	2.00E – 02	1.00E – 04	1.00E – 04	
7	Pelagic small piscivorius fishes	4.99E – 02	2.00E – 04	1.00E – 04	6.99E – 02	7.00E – 03		
8	Caramote prawn	1.45E – 07	5.23E – 07	1.00E – 01		1.33E – 08	1.00E – 01	9.57E – 05
9	Sea turtles							
10	Wild gilthead seabream	7.25E – 03	5.23E – 03	1.43E – 04	9.99E – 05	2.66E – 03		
11	Rays	1.45E – 03	5.23E – 03	1.74E – 03		1.33E – 02	9.66E – 04	
12	Juvenile demersal small fishes		1.00E – 05		4.99E – 04	5.58E – 04		
13	Cephalopods	9.99E – 07		7.00E – 05		1.00E – 08	1.00E – 04	9.57E – 04
14	Juvenile pelagic small piscivorous fishes	1.45E – 03	1.05E – 03		4.99E – 03	2.00E – 04		3.83E – 04
15	Juvenile pelagic small planktivorous fishes	9.99E – 05	1.05E – 03		4.99E – 03	6.64E – 03		3.83E – 04
16	Jellyfish	1.45E – 03					4.82E – 02	9.57E – 04
17	Pelagic small planktivorous fishes	4.35E – 01	2.50E – 01	1.30E – 02	4.99E – 01	1.33E – 02		7.87E – 02
18	Escaped gilthead seabream	7.25E – 04	5.23E – 05	1.43E – 05	9.99E – 04	2.66E – 05		
19	Molluscs	1.45E – 04		5.00E – 03		1.33E – 03	2.00E – 03	
20	Crustaceans	2.90E – 02	3.14E – 01	5.81E – 01		1.33E – 02	2.43E – 01	5.74E – 02
21	Sea urchins			7.19E – 02			1.04E – 02	0.00E + 00
22	Zooplankton	2.90E – 03	1.13E – 01			2.66E – 01	2.89E – 02	7.79E – 01
23	Polychaetes	1.45E – 04		1.30E – 02		1.33E – 02	2.89E – 01	4.79E – 03
24	Meiobenthos	1.45E – 04	5.23E – 02	1.44E – 03			1.45E – 01	
25	Sea cucumber			1.43E – 04			9.66E – 04	
26	Farmed fish	4.99E – 05			2.00E – 05	5.00E – 05		
27	Algae						9.65E – 03	0.00E + 00
28	Phytoplankton							1.91E – 02
29	Artificial food pellets	9.99E – 08	1.00E – 07	1.00E – 07			1.00E – 07	1.00E – 07
30	Terrestrial inputs							
31	Discards	1.45E – 03		2.99E – 04	2.99E – 01	1.33E – 04	5.00E – 02	
32	Detritus			5.05E – 06			1.46E – 06	

	Prey	Predator						
		8	9	10	11	12	13	14
1	Pelagic large fishes							
2	Wild european seabass							
3	Demersal large fishes							
4	Birds							
5	Marine mammals							
6	Demersal small fishes			2.00E – 02	1.00E – 03		2.00E – 02	
7	Pelagic small piscivorius fishes						2.00E – 05	
8	Caramote prawn	1.01E – 06		1.10E – 05	5.13E – 05	1.00E – 07	2.57E – 05	
9	Sea turtles							
10	Wild gilthead seabream							
11	Rays			1.15E – 02			1.28E – 03	
12	Juvenile demersal small fishes	1.01E – 05			1.02E – 05		5.00E – 04	
13	Cephalopods		1.00E – 08	1.00E – 05	5.13E – 06	1.00E – 06	5.00E – 05	
14	Juvenile pelagic small piscivorous fishes			1.00E – 04		1.00E – 03	1.00E – 04	1.00E – 03
15	Juvenile pelagic small planktivorous fishes			1.04E – 03		1.00E – 03	1.28E – 03	1.00E – 03
16	Jellyfish		2.35E – 02	5.76E – 03				
17	Pelagic small planktivorous fishes			4.69E – 02			1.28E – 03	
18	Escaped gilthead seabream							
19	Molluscs	1.01E – 02	1.18E – 03	5.06E – 03	3.00E – 03	7.01E – 02	2.50E – 03	1.00E – 04
20	Crustaceans	4.55E – 01	1.18E – 01	1.73E – 01	3.08E – 01	2.00E – 01	6.41E – 01	7.25E – 02
21	Sea urchins		1.18E – 01	1.15E – 02	5.13E – 02	1.00E – 03	5.90E – 02	
22	Zooplankton	5.06E – 02	4.71E – 02	2.12E – 02		1.00E – 02		8.02E – 01
23	Polychaetes	1.72E – 01	1.18E – 01	1.85E – 01	3.59E – 01	7.01E – 02	1.28E – 01	3.75E – 02
24	Meiobenthos	3.03E – 01	1.18E – 01	1.15E – 02	1.03E – 01	6.01E – 01	1.28E – 03	
25	Sea cucumber		2.35E – 02	1.15E – 02	1.03E – 03	1.00E – 03		
26	Farmed fish							
27	Algae			3.45E – 03	1.03E – 03			
28	Phytoplankton							
29	Artificial food pellets	1.00E – 07		1.00E – 07	1.00E – 07			
30	Terrestrial inputs	1.00E – 04						
31	Discards	1.11E – 05	6.82E – 04	1.15E – 04	1.87E – 05		1.05E – 01	
32	Detritus	5.76E – 05		6.91E – 02				

Table 2 (*Continued*)

	Prey	Predator						
		15	16	17	18	19	20	21
1	Pelagic large fishes							
2	Wild european seabass							
3	Demersal large fishes							
4	Birds							
5	Marine mammals							
6	Demersal small fishes				2.09E – 03		1.00E – 06	
7	Pelagic small piscivorius fishes		1.00E – 04					
8	Caramote prawn				1.15E – 05		9.94E – 09	
9	Sea turtles							
10	Wild gilthead seabream							
11	Rays				1.21E – 03			
12	Juvenile demersal small fishes				5.24E – 04		1.00E – 05	
13	Cephalopods				1.05E – 05			
14	Juvenile pelagic small piscivorous fishes		5.00E – 04		1.05E – 04			
15	Juvenile pelagic small planktivorous fishes		1.10E – 04		5.24E – 04			
16	Jellyfish		5.00E – 03	9.91E – 04	6.03E – 03			
17	Pelagic small planktivorous fishes		8.00E – 06	0.00E + 00	4.91E – 03			
18	Escaped gilthead seabream							
19	Molluscs				4.61E – 01	1.20E – 02	9.14E – 06	3.02E – 04
20	Crustaceans	2.00E – 02			1.15E – 01	1.00E – 03	7.22E – 02	3.02E – 02
21	Sea urchins				5.24E – 02	1.00E – 04	4.00E – 03	2.31E – 02
22	Zooplankton	9.18E – 01	6.00E – 01	7.93E – 01	2.22E – 02	2.00E – 01	6.39E – 02	
23	Polychaetes				1.57E – 02	1.00E – 03	1.80E – 02	
24	Meiobenthos				1.21E – 02	1.40E – 01	2.85E – 02	1.01E – 02
25	Sea cucumber				1.21E – 02			1.01E – 02
26	Farmed fish							
27	Algae				1.05E – 02	1.76E – 01		6.30E – 01
28	Phytoplankton	1.00E – 02	7.68E – 03	1.14E – 01		3.60E – 01	2.18E – 03	
29	Artificial food pellets			1.00E – 07	1.88E – 01	1.00E – 07	1.00E – 07	1.00E – 07
30	Terrestrial inputs		5.00E – 04			4.00E – 03	1.00E – 05	1.00E – 04
31	Discards				1.21E – 04	1.00E – 02	3.09E – 04	1.01E – 04
32	Detritus		7.63E – 02		9.42E – 02	9.60E – 02	6.06E – 01	2.95E – 01

	Prey	Predator				
		22	23	24	25	26
1	Pelagic large fishes					
2	Wild european seabass					
3	Demersal large fishes					
4	Birds					
5	Marine mammals					
6	Demersal small fishes					
7	Pelagic small piscivorius fishes					
8	Caramote prawn					
9	Sea turtles					
10	Wild gilthead seabream					
11	Rays					
12	Juvenile demersal small fishes					
13	Cephalopods					
14	Juvenile pelagic small piscivorous fishes					
15	Juvenile pelagic small planktivorous fishes					
16	Jellyfish	5.00E – 03				
17	Pelagic small planktivorous fishes					
18	Escaped gilthead seabream					
19	Molluscs		1.00E – 04			
20	Crustaceans		2.00E – 02			
21	Sea urchins					
22	Zooplankton	5.00E – 02		2.04E – 02		
23	Polychaetes		2.10E – 02			
24	Meiobenthos					
25	Sea cucumber					
26	Farmed fish					
27	Algae		1.00E – 03			
28	Phytoplankton	6.95E – 01	0.00E + 00	2.04E – 02		
29	Artificial food pellets	1.00E – 07	1.00E – 07	1.00E – 07	1.00E – 07	1.00E + 00
30	Terrestrial inputs	2.00E – 05	3.00E – 04	1.00E – 04	1.00E – 03	
31	Discards			1.02E – 06		
32	Detritus	2.41E – 01	9.49E – 01	9.59E – 01	9.99E – 01	0.00E + 00

increased. When fishing effort is ×1, differences between revenues and expenses were less accentuated because the escaped population remain naturalized in the wild and sustain a continuous yield over the simulated period. In this case, revenues from recaptures reach about 469,000 euros for the three escape scenarios, with an accumulated cost of 726,000 euros in each one, along all the simulated period but without eradicating the escapees. Something similar occurs when fishing effort was ×2 in escape

Table 3
Landings from the different harbours and metiers.

ID	Group name	Guardamar fleets Caramote trammelnet	Cuttlefish trammelnet	Barrier trap	Sparid gillnet	Sparid longline	Octopus pots	Red mullet trammelnet	Bonito gillnet	Flatfish trammelnet	Hake gillnet
	Pelagic large fishes	7.06E – 004	7.90E – 004	6.89E – 004	6.19E – 004	3.09E – 006			5.50E – 004	7.54E – 003	6.19E – 005
2	Wild european seabass		1.54E – 004	5.66E – 005	1.70E – 005			7.55E – 006	3.61E – 005		
3	Demersal large fishes	1.72E – 004	1.13E – 003	6.21E – 004	1.51E – 003	2.49E – 004		5.69E – 005	1.94E – 004	3.43E – 004	1.14E – 003
4	Birds										
5	Marine mammals										
6	Demersal small fishes	1.70E – 002	8.48E – 003	1.51E – 004	1.16E – 003	7.73E – 005		1.70E – 003	3.58E – 005	1.30E – 002	5.55E – 004
7	Pelagic small piscivorius fishes	9.68E – 004	9.00E – 004	5.20E – 004	5.00E – 005			4.00E – 006	1.00E – 003		6.00E – 005
8	Caramote prawn	1.12E – 002		4.72E – 005							
9	Sea turtles										
10	Wild gilthead seabream	5.27E – 004	1.85E – 003	1.73E – 004	7.18E – 005	1.00E – 006			5.08E – 004	8.52E – 004	7.72E – 005
11	Rays					1.57E – 005					
12	Juvenile demersal small fishes										
13	Cephalopods	4.84E – 003	2.40E – 002	3.20E – 004		7.42E – 006	1.89E – 002	1.55E – 004	1.16E – 005	1.86E – 003	2.07E – 005
14	Juvenile pelagic small piscivorous fishes										
15	Juvenile pelagic small planktivorous fishes										
16	Jellyfish										
17	Pelagic small planktivorous fishes	2.54E – 004	1.36E – 005	8.54E – 005	1.03E – 006				4.80E – 006		
18	Escaped gilthead seabream	5.27E – 007	1.85E – 004	1.73E – 005	7.18E – 006	1.00E – 008			5.08E – 006	8.52E – 009	7.72E – 008
19	Molluscs										
20	Crustaceans	1.84E – 003			1.93E – 006						
21	Sea urchins										
22	Zooplankton										
23	Polychaetes										
24	Meiobenthos										
25	Sea cucumber										
26	Farmed fish										
27	Algae										
28	Phytoplankton										
29	Artificial food pellets										
30	Terrestrial inputs										
31	Discards										
32	Detritus										
	Totals	3.75E – 002	3.75E – 002	2.68E – 003	3.44E – 003	3.54E – 004	1.89E – 002	1.93E – 003	2.34E – 003	2.36E – 002	1.91E – 003

ID	Group name	Santa Pola fleets Cuttlefish trammelnet	Sparid longline	Octopus pots	Red mullet trammelnet	Sparid gillnet	Bonito gillnet	Flatfish trammelnet	Lobster trammelnet	Hake gillnet	Otter trawling
1	Pelagic large fishes	3.16E – 003	1.27E – 004			7.61E – 003	5.63E – 003	1.47E – 003	1.12E – 002	8.20E – 004	9.46E – 003
2	Wild european seabass	6.14E – 004			5.98E – 004	2.03E – 004	3.70E – 004				4.04E – 003
3	Demersal large fishes	4.50E – 003	1.03E – 002		4.50E – 003	1.80E – 002	1.98E – 004	6.70E – 006	7.23E – 003	1.51E – 002	1.77E – 002
4	Birds										
5	Marine mammals										
6	Demersal small fishes	3.39E – 002	3.18E – 003		1.35E – 001	1.43E – 002	3.67E – 004	2.53E – 003	1.93E – 002	7.35E – 003	9.22E – 002
7	Pelagic small piscivorius fishes	4.00E – 003			4.00E – 005	6.00E – 004	1.10E – 002			8.00E – 004	5.00E – 002
8	Caramote prawn										
9	Sea turtles										
10	Wild gilthead seabream	7.41E – 003	1.00E – 006			8.59E – 004	5.20E – 003	1.66E – 004		1.02E – 003	5.46E – 003
11	Rays		6.49E – 004						4.82E – 003		2.34E – 004
12	Juvenile demersal small fishes										
13	Cephalopods	9.57E – 002	3.06E – 004	7.54E – 002	1.23E – 002		1.19E – 004	3.63E – 004		2.70E – 004	6.18E – 002
14	Juvenile pelagic small piscivorous fishes										
15	Juvenile pelagic small planktivorous fishes										

Table 3 (*Continued*)

ID	Group name	Santa Pola fleets									
		Cuttlefish trammelnet	Sparid longline	Octopus pots	Red mullet trammelnet	Sparid gillnet	Bonito gillnet	Flatfish trammelnet	Lobster trammelnet	Hake gillnet	Otter trawling
16	Jellyfish										
17	Pelagic small planktivorous fishes	5.43E – 005				1.27E – 005	4.92E – 005				2.27E – 002
18	Escaped gilthead seabream	7.41E – 004	1.00E – 007			4.25E – 005	5.20E – 005	1.66E – 009		1.02E – 008	5.46E – 007
19	Molluscs										
20	Crustaceans					2.37E – 005			1.12E – 002		6.55E – 003
21	Sea urchins										
22	Zooplankton										
23	Polychaetes										
24	Meiobenthos										
25	Sea cucumber										
26	Farmed fish										
27	Algae										
28	Phytoplankton										
29	Artificial food pellets										
30	Terrestrial inputs										
31	Discards										
32	Detritus										
	Totals	1.50E – 001	1.45E – 002	7.54E – 002	1.52E – 001	4.16E – 002	2.30E – 002	4.54E – 003	5.38E – 002	2.53E – 002	2.70E – 001

ID	Group name	Fleets for the whole studied area			
		Fish farming	Angling from land	Angling from boats	Spearfishing
1	Pelagic large fishes			3.36E – 003	1.22E – 004
2	Wild european seabass		8.16E – 005	6.49E – 005	7.23E – 005
3	Demersal large fishes		1.17E – 004	4.85E – 004	4.81E – 004
4	Birds				
5	Marine mammals				
6	Demersal small fishes		3.79E – 004	4.12E – 003	1.41E – 003
7	Pelagic small piscivorius fishes				
8	Caramote prawn				
9	Sea turtles				
10	Wild gilthead seabream		5.18E – 005	1.90E – 004	3.50E – 005
11	Rays				
12	Juvenile demersal small fishes				
13	Cephalopods			2.48E – 004	3.24E – 005
14	Juvenile pelagic small piscivorous fishes				
15	Juvenile pelagic small planktivorous fishes				
16	Jellyfish				
17	Pelagic small planktivorous fishes		3.31E – 005	2.82E – 004	1.90E – 006
18	Escaped gilthead seabream		5.18E – 006	1.90E – 006	3.50E – 007
19	Molluscs				
20	Crustaceans				
21	Sea urchins				
22	Zooplankton				
23	Polychaetes				
24	Meiobenthos				
25	Sea cucumber				
26	Farmed fish	3.59E + 000			
27	Algae				
28	Phytoplankton				
29	Artificial food pellets				
30	Terrestrial inputs				
31	Discards				
32	Detritus				
	Totals	3.59E + 000	6.67E – 004	8.76E – 003	2.15E – 003

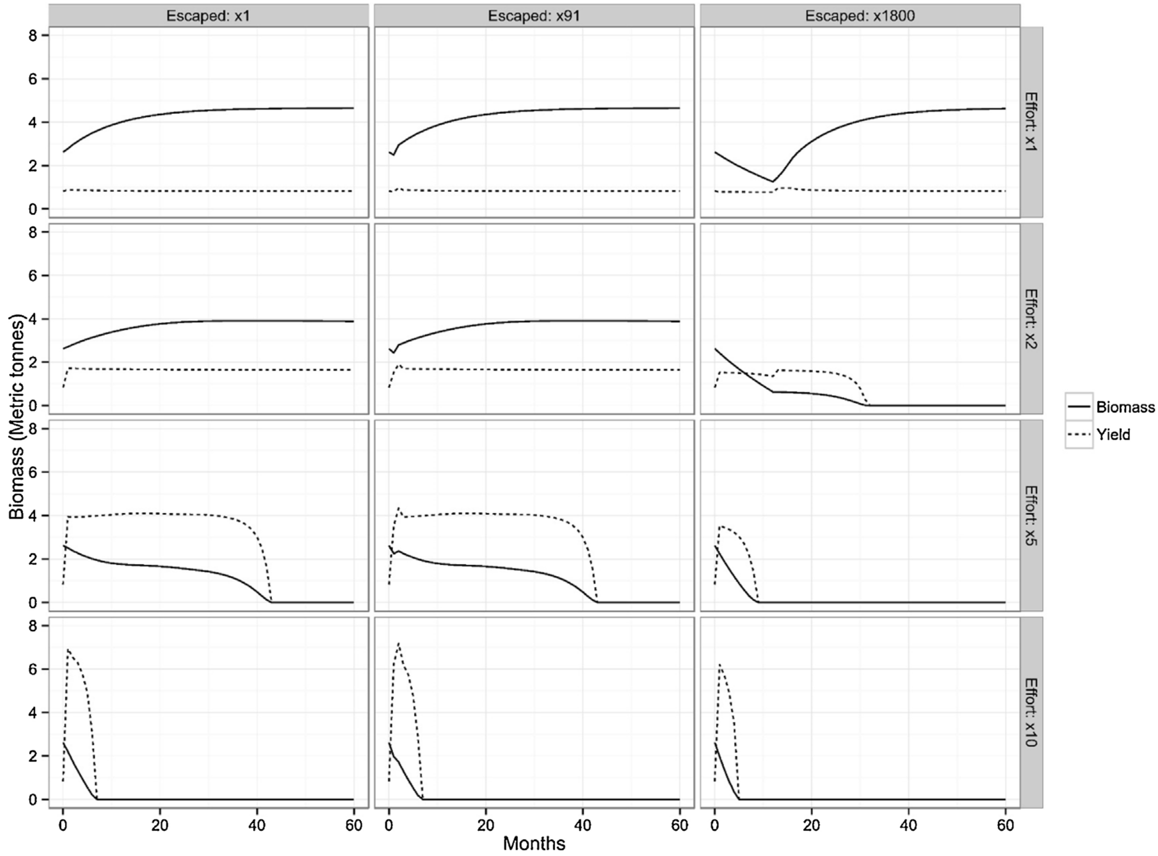

Fig. 2. Trends of biomass and yield of escapees for all the considered scenarios.

Table 4
Expenses, revenues and balance values (in thousands of euros) for each combination of effort and escaped level.

		Escaped level		
Effort	Item	×1	×91	×1800
×1	Expense	360	360	360
	Revenue	237	237	237
	Balance	−123	−123	−123
	Time of erradication (months)	Never	Never	Never
×2	Expense	720	720	372
	Revenue	469	469	210
	Balance	−251	−251	−162
	Time of erradication (months)	Never	Never	31
×5	Expense	1260	1290	270
	Revenue	761	760	111
	Balance	−499	−500	−129
	Time of erradication (months)	42	42	8
×10	Expense	360	360	240
	Revenue	160	157	98
	Balance	−200	−203	−142
	Time of erradication (months)	6	6	4

scenarios ×1 and × 91, but neither with greater costs (1,452,000 euros) nor revenues (about 932,000 euros), and a greater negative balance between them (about 519,000 euros). The escape scenario ×1800 resulted in fewer revenues (about 210,000 euros) as the escapees were eradicated in 31 months and hence less expenses for their recapture (384,000 euros), with a negative balance of 173,000 euros. Fishing effort ×5 resulted in high expenses (1,290,000 euros) and revenues (761,000 euros), with a negative balance of 528,000 euros, during 42 months, for escape scenarios ×1 and ×91, but decreasing significantly for escape scenario ×1800 with 270,000 euros of expenses, 111,000 euros of revenues from recaptures (balance, −158,000 euros) within 8 months from the escape. This pattern accentuates for fishing effort ×10 as the escape level increases, ranging from about 160,000 euros of revenues and 420,000 euros of costs (balance, −259,000 euros) for escape scenarios ×1 an ×91, in 6 months, to 98,500 euros of revenues and 300,000 euros of expenses (balance, −201,000 euros) in scenario ×1800, within 4 months from the escape.

4. Discussion

The empirical data showed that the magnitude of the escape drives the recapture success by trammel netters as the remaining biomass in the wild decreased. Therefore, in real life, the recapture success responds to a density-dependent process related to the escaped biomass and the potential revenue obtained for the catch. The latter, rather than due to just an increase of the probability to capture escaped fish, it is also due to an effect on the spatial dynamics of the fishing fleet. The fishing effort distribution concentrates in areas near farms and a métier change takes place to target specifically the escaped fish. The latter only results cost-effective if high biomasses of fish are captured after massive escapes rather than after events of smaller magnitudes or “leaking”, when fishermen keep targeting traditional seasonal species which report higher revenues. Therefore, only a certain value of escaped biomass would trigger changes in fishing effort distribution and métier usage of artisanal fishing fleets. Thus, fish escaped through “leaking” or small magnitude escape events could have higher chances to survive rather than after massive escapes since fishing effort will not focus on its capture. The pattern of these empirical observations is consistent with the results obtained from the simulations of the model, although more research should be addressed.

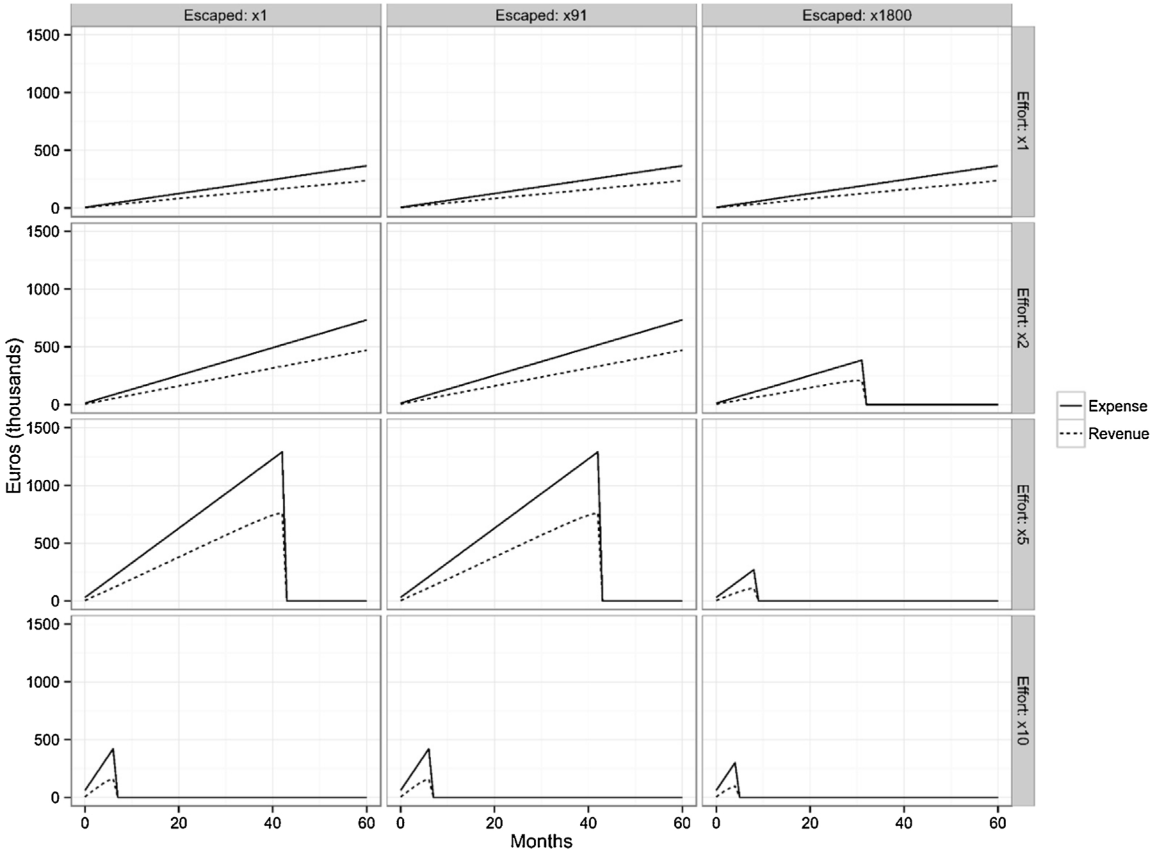

Fig. 3. Trends of revenues and expenses from the recapture for all the considered scenarios.

Consequently, “leaks” and small magnitude escapes may exert higher impact on the ecosystem compared to punctual massive escapes which would trigger artisanal fisheries recapture mechanism *per se*. As with escaped fish biomass, addressing fishing effort targeting escaped fish would only result cost-effective by increasing the fishing effort, especially after a massive escape event, when larger catches yield higher revenues.

The influence of a massive escape on local fisheries catch was empirically described by Toledo-Guedes et al. (2014), with the recapture of escaped fish spanning over 12 months after the escape event. The latter is consistent with the outputs for high values of fishing effort and escaped biomass scenarios of the present model. Initially, fishermen captured escaped fish but it was not after few months later when they both enhanced and re-addressed the fishing effort towards escapees as other commercial species were preyed upon (Toledo-Guedes et al., 2009). The latter reinforces the obtained outputs for the ordinary fishing effort scenarios of our model, where, even at the highest levels of escape, the biomass could remain in the wild even after 60 months. Several experimental escape simulations have resulted in low recapture success (0.6–7.25%) (Hansen and Youngson, 2010; Arechavala-Lopez et al., 2012) most likely due to the low “escaped” fish biomass ($n = 597–2191$), reinforcing the fact that the escaped fish biomass determines the success of the recapture process.

In terms of the cost–benefit ratios arising from the recapture of escaped fish, expenses showed higher than revenues in all scenarios. Ecopath could not mirror the increased catches taking place immediately after the escape event since the model is based on the produced biomass over time. However, if aiming the recapture of escaped fish, an increase of fishing effort enhancing the capture per unit of effort of the fleet (cpue) is suggested, since minimized net expenses were shown in all scenarios of escaped biomass. Consistently, existing legal frameworks constraint the time span when the recapture actions are allowed, ranging from 72 h in Australia until 14 days in Norway (all links to regulations at Izquierdo-Gomez et al., 2014). The latter is based either on the dispersal ability of the escaped species or the potential hazard for the ecosystem. The lack of cost-effective recapture scenarios, can be due to a low density dependent catchability factor applied in this model (350-fold), as it may not be based on recaptures rates after a massive escape but after a middle size escape event. Therefore, it may occur that recapture cost-effectiveness could only be achieved after massive escapes events. The latter should be further investigated through quality data of fish escapes, but first, the declaration of escape events must be stablished as mandatory at a Mediterranean scale since, so far, escape events are not monitored/registered in any Mediterranean country. Consequently, it is difficult to obtain fisheries data-sets corresponding to escape events to unveil denso-dependent mechanisms of recapture. Additionally, fisheries data sets acquisition require a titanic effort, being not always suitable for statistical analysis.

Regarding stock management, low fishing effort resulted in a constant biomass of escaped fish being available over time, meaning that the escapees represent a continuous source of additional income for local trammel-netters. The same have been reported for Atlantic salmon escapees, representing between 11% and 35% of the “wild” spawning biomass in Norway, with some populations exceeding 80% (Fiske et al., 2001). In the Mediterranean Sea, despite the fact that fish escapes occur extensively (Jackson et al., 2015) as marine cage aquaculture is widely spread along both basins (Trujillo et al., 2012) – there is a lack of site specific research. Arising from this study, it is clear that escaped fish can be recaptured by artisanal fisheries, which, if properly managed, would probably show more effective when needed. In addition to fisheries, piscivorous predators have been widely observed around farms (Pemberton and Shaughnessy, 1993; Wiirsig and Gailey, 2002; Güçlüsoy and Savas, 2003; Sepúlveda and Oliva, 2005; Sanchez-Jerez et al., 2008; Uglem et al., 2009; Arechavala-Lopez et al., 2013, 2015) and may contribute to mitigate the negative influence of escapees on the ecosystem, however, the quantitative extent still remains unknown. The latter should be further investigated to better assess the use of local fisheries to recapture escapees, since its efectiveness may be underestimated.

From a management perspective, local fisheries take an economic benefit out of capturing escapees while contributing at the same time to mitigate the impact of fish farming in the ecosystem, which is positive for fish farmers and the ecosystem (Arechavala-Lopez et al., 2012). However, the scenario may be different after a massive escape. Thus, the high numbers of escapees might hinder the normal functioning of local fisheries by collapsing the nets (not providing the species demanded by the market). Additionally, farmers may not be able to cope with economic losses and/or social conflicts may arise from high densities of fishermen/anglers due the presence of escapees in touristic coastal zones. The latter should be further managed since it may derive in a non-sustainable integration of sea cage aquaculture in coastal areas and antagonist effects arising from the coexistence with other coastal users. Sea cage aquaculture is already widely distributed in Mediterranean coastal areas together with traditional users of coastal zones (i.e. local fisheries and tourism). Thus, it is clear that the design of management strategies based on detecting the synergies and the antagonisms among them, is the only way to achieve its sustainability. Therefore, the proposed model comes into force, as it can simulate potential scenarios to predict interactions between escapees, coastal users and the ecosystem, from the perspective of an adaptive integrated management of the coastal zone (IMCZ) suggested by the European Union (COM, 2013). Since legal regulations for escape events are inexistent in the Mediterranean Sea, the optimization of recapture methodologies through research on different fishing gears and the design of a legal framework to regulate escape events in Mediterranean countries is highly encouraged, as so far, the recapture of escapees is accidental and just based on fishermen knowledge. In this regard, this model could be used as a powerful management tool for a legal framework development to regulate fish escapes in a future to come. For instance, the model will help managers to identify temporal thresholds to optimize cost-effectiveness of the recapture actions as well as maximum biomass yields. Additionally it can be used to identify negative effects of fish escapes during site-selection procedures prior to the establishment of the fish farm, thus preventing or minimizing risks for other coastal users (e.g. fisheries and tourism). In areas where fish farming is already present, the ability to predict the fisheries efficiency to recapture escapees will help coastal managers to design contingency plans tailored for the affected areas, from a tourism, fisheries, and/or ecosystemic perspective. The latter should be reinforced with the declaration of the escape events as mandatory, since the lack of information (i.e. date, species, escaped biomass, fish size, etc. . .) hinders either the recapture success of contingency plans, its assessment or, eventually, the ability of the model to predict negative interactions of escapees with coastal users. Monitoring the presence of escapees in the wild is also suggested, as the lack of recaptures may not necessarily indicate failure of recapture actions since it may be due to migration or predator pressure. The outcomes of models are generally dependent on the quality of the data. Therefore, given the lack of studies on fish escapes from a fisheries perspective within the Mediterranean Sea, further research should be carried out to obtain more detailed landings data in terms of spatial and temporal yields, including massive escape event periods, when high densities of escapees are available.

Concluding, this study is the first contribution to shed light on the population dynamic of escapees in the wild and on the fishing effort and escaped biomass effects on its recapture by a local fishery in the Mediterranean. Despite the model predicted negative balances of cost-effectiveness regarding the recapture of escapees, the obtained data in this study increases the knowledge of the long term influence of escaped fish on the ecosystem. Particularly, this research helps to better understand how fishing mortality shapes the escaped fish population. In addition, it provides fisheries managers with useful outputs as the worthwhile fishing effort needed to recover a given proportion of escaped fish. Moreover, the derived effects of fish escapes on other coastal users as tourism can also be explored. For the future to come, more research should be conducted to improve the power of the model through the implementation of landing's data corresponding to different magnitudes of escape events. Additionally, management measures as a rapid increase of the fishing effort addressing escapees are suggested, as well as to develop more strict handling protocols at farms to minimize "leaking", as these type of escapees may have higher chances of survival than fish escaping after massive escapes based on a density-dependent fisheries mortality of escapees. Either fishermen or fish farmers' guilds together with the administration and the scientific community should work together in the same direction to achieve a sustainable use of the coastal zones.

Acknowledgements

JTBS thanks to Conselleria d'Educació, Generalitat Valenciana, for financing the visits to CICIMAR-IPN during 2012. FAS also acknowledges both to University of Alicante and CONACyT for supporting the visits to University of Alicante during 2014 and 2015. An important load of data utilized in this research was provided by the project FATFISH (CTM2009-14362-C02-01), financed by the Ministry of Science and Innovation of Spain.

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