Title:

Systems approach modelling of the interactive effects of fisheries, jellyfish and tourism in the Catalan coast.

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Abstract:

Despite the large fluctuation in annual recordings of gelatinous plankton along the Catalan coast in the north western Mediterranean and the lack of long term data sets, there is a general perception that jellyfish abundances are increasing. Local authorities are concerned about the stranding events and arrivals of jellyfish to beaches and believe it could reduce the recreational appeal of the beaches - a valuable ecosystem service for the regional tourist industry. Previous studies also demonstrate the predation of jellyfish (*Pelagia noctiluca* ephyrae) upon some small pelagic fish larvae (*Engraulis encrasicolus*). Small pelagics are the principal source of revenue for the local fisheries. A social-ecological model was created in order to capture the effects of changes in abundance of *Pelagia noctiluca* upon the local fisheries, the tourist industry and the wider economy. The following sub-models were constructed and connected following the systems approach framework methodology: an

age-class based fisheries model; a jellyfish population matrix model; a jellyfish stranding model; a study on the impact of jellyfish strandings on beach users; and an economic input-output matrix. Various future scenarios for different abundances of jellyfish blooms were run. The “Expected blooms” scenario is similar to the quantity and size of blooms for 2000-2010. For a hypothetical “No blooms” scenario (standard background level of jellyfish but without any blooms) landings would increase by around 294 tonnes (5.1%) per year (averaged over 10 years) or approximately 0.19 M€ in profits per year (4.5 %), and strandings would decrease by 49%. In a “Frequent blooms” scenario, landings would decrease by around 147 tonnes per year (2.5%) and decrease profits by 0.10 M€ per year (2.3%), and strandings would increase by 32%. Given the changes that these scenarios would cause on the regional gross domestic product and employment, this study concludes that the overall impact of either of these scenarios on the economy would not be significant at the regional scale.

Graphical Abstract:

Highlights:

We model the economic impacts of *Pelagia noctiluca* on small pelagic fisheries and beach users

The impact of an increase in *Pelagia noctiluca* on small pelagic fisheries in Catalonia is low

The impact of an increase in *Pelagia noctiluca* on tourism in Catalonia is low

The impact of an increase in *Pelagia noctiluca* would not be significant at the regional scale

Keywords:

Pelagia noctiluca; Anchovy; Sardine; Small pelagic fisheries; Social-ecosystem model; Jellyfish strandings

Regional terms: Mediterranean, Spain, Catalonia

1 Introduction

Jellyfish occur naturally in the coastal waters of Catalonia in the North Western Mediterranean Sea (Calvo et al., 2011; Condon et al., 2012; Gili et al., 1988; Goy et al., 1989). Despite the widespread perception that their numbers are increasing (Canepa et al., 2013), there is a lack of long term observations to confirm this hypothesis (Pauly et al., 2009; Purcell et al., 2007). Speculation regarding this possible long term increase has been attributed to climate change, over-fishing of predators and competitors, eutrophication, habitat modification (creating more habitats for polyps), and introduction of non-native species (translocation via ballast water or ship hulls) (Canepa et al., 2013; Duarte et al., 2013; Purcell et al., 2007; Richardson et al., 2009).

There is concern among academics, managers and the general public (Canepa et al., 2013) that an increase in jellyfish bloom frequency will have a detrimental effect on a number of economic sectors, including but not limited to, fisheries and tourism. In many cases around the world, stranding events of jellyfish reduce the recreational appeal of beaches and bathing waters for beach users being detrimental for the local tourist industry (Purcell et al., 2007; Richardson et al., 2009). In this context, jellyfish outbreaks can be conceived of as an event that potentially diminish the benefit humans receive from marine and coastal ecosystem services (Daily, 2003; Hassan et al., 2005; Hattam et al., 2015), particularly cultural services (e.g. tourism and recreation) (De Donno et al., 2014; Ghermandi et al., 2015; Kontogianni and Emmanouilides, 2014; Nunes et al., 2015; Palmieri et al., 2015) and provisioning services (e.g. seafood) (Angel et al., 2014; Conley and Sutherland, 2015; Graham et al., 2003; Nastav et al., 2013; Palmieri et al., 2014).

Cultural and provisioning services valuation is already robustly backed up in theoretical and empirical terms, by a large number of case studies around the world (Brenner et al., 2010; de Groot et al., 2002; Farber et al., 2002; Heal, 2000). There is a lack of studies regarding changes in the delivery of ecosystem services both in the presence and absence of jellyfish outbreaks though. Our work proposes to assess the impact of these changes, specifically on the tourism and seafood producing industries in Catalonia, under different future scenarios of jellyfish outbreaks, with models parameterized based on data corresponding to the past 15 years.

In Catalonia, beach-based, sun-and-sand tourism and fisheries are the main uses of the coastal zone (Sardá et al., 2005). For instance, tourism revenues are increasing and are currently around €14 billion per year with around 16 million visitors (IDESCAT, 2010), with the majority resulting from “sun and beach” tourism (Ariza et al., 2008). Increasing jellyfish blooms result in beach strandings that may be visually unpleasing to beach users or actually detrimental to human health (Ghermandi et al., 2015).

The contribution of fisheries to the coastal economic is much lower and declining, with a production value (at first sale) of ca. €110 million per year (IDESCAT, 2010). Jellyfish are thought to impact fisheries by feeding on fish larvae (Purcell et al., 2014, 1994; Purcell and Arai, 2001; Sabatés et al., 2010) as well as competing with adults for food (Purcell and Arai, 2001; Purcell and Grover, 1990). Fisheries along the Catalan coast largely consist of semi-industrial and artisanal fleets with the main contributors to landings being the small pelagics sardine (*Sardina pilchardus*) and anchovy (*Engraulis encrasicolus*), which account for around 50% of total annual landings in weight and 25% in economic value (IDESCAT, 2010; Lleonart and Maynou, 2003; Palomera et al., 2007).

This study proposes an integrated approach to the analysis of the impact of jellyfish blooms on the key sectors of tourism and fisheries. The modelling dimension of the Systems Approach Framework (Hopkins et al., 2011; Tomlinson et al., 2011) was undertaken in which the ecological and socio-economic components are defined, modelled and linked together. Future possible scenarios were run

for various intensities of jellyfish blooms, and the impact that they would have on the local tourism and fisheries economy was estimated, in order to contribute to a partial evaluation of the consumer surplus of marine ecosystems free of abnormally high jellyfish outbreaks.

2 Material and methods

A model was constructed using the software ExtendSim. Various sub-models were constructed using different techniques and methodologies as outlined below. A simplified approximation of the overall model is shown in Figure 1, indicating how each sub-model is connected within it. Spatially, the model is divided into three zones representing approximately equal areas of the Catalan Sea. Each zone extends from the coastline to the shelf break - the area where most of the small-pelagic fishing activity and jellyfish occur. The zones cover the area heading south from Cap de Creus to the Ebro Delta and are named after the adjacent provinces: Girona; Barcelona; and Tarragona (Figure 2). Cap de Creus and Ebro Delta are not included in the study area due to the differing fisheries practiced there. In this study, we refer to all three zones together as “Catalonia” but it should be remembered that this does not include the entire administrative region of Catalonia.

[Figure 1: Conceptual model]

[Figure 2: Location of the three study zones]

The model examines the impact of one species of jellyfish, *Pelagia noctiluca*, because it is one of the most abundant in the study zone, has a powerful sting (affecting beach users), and is relatively well studied and documented (Canepa et al., 2014), particularly its predation effects on small pelagic larvae (Purcell et al., 2014; Sabatés et al., 2010). Although many other species of scyphomedusae have been found in the study zone, there is no evidence to suggest that they prey upon fish larvae and so have been excluded from the model.

2.1 Fisheries sub-model

The fisheries sub-model was based on a simplified and adapted version of the MEFISTO model. MEFISTO (Mediterranean Fisheries Simulation TOol) is an age-structured bio-economic model which is multi-species, multi-fleet, within a single predefined zone, where the central management lever is effort limitation. The MEFISTO model has been applied in various analyses including red

shrimp, hake, anchovy and sardine fisheries within the Mediterranean and is fully documented and available to download and use (Lleonart et al., 2003, 1998; Maynou et al., 2006).

For this analysis, the model was adapted in order to capture the predation of jellyfish upon the small pelagics larvae. The MEFISTO model runs at a time-step of one year so all the forecasts of fish mortality, growth, biomass, catches and recruitment are aggregated over the year. Given that anchovy and sardine larvae only occur in the plankton at specific times of the year (summer and winter respectively), in order to ascertain the impact of *Pelagia noctiluca* predation upon these fisheries, the resolution of the model was increased to a time-step of one month, in order to capture this temporally specific interaction. The forecast was run for a period of 120 months (10 years).

The MEFISTO model aggregates the fisheries dynamics over one spatial zone, but in order to capture the various degrees of jellyfish strandings upon different Catalan beaches, a greater spatial resolution was needed. Previous information has shown that the degree of jellyfish strandings can largely be divided into three zones, where the north of Catalonia (Girona) receives a high number of strandings, central Catalonia (Barcelona) receives low strandings, and south Catalonia (Tarragona) receives a medium level (Canepa et al., 2014). Therefore, the spatial resolution was adapted to reflect this, and three zones were used.

Given that principal objective of the analysis is to capture the interaction of jellyfish with small pelagics and not the dynamics of resource allocation within the fisheries themselves, a number of the MEFISTO model elements were simplified: Effort and catchability were fixed; there were no bycatches or discards; all stochastic elements were removed; the market and fishermen components (described as “boxes” in (Lleonart et al., 2003)) were left static (i.e. fish prices are fixed and there is no reinvestment in vessels or bank loans).

The majority of the equations for the biological sub-model are typical to all age-structured models and have been fully documented elsewhere so they are not reproduced here (Lleonart et al., 2003, 1998).

An exception to this is the recruitment sub-model. In MEFISTO and other age-structured models, recruits are generally calculated by using one of three equations: constant recruitment, Beverton and Holt's model; or Ricker's model. This calculates the number of recruits to the following year's cohort at age 0. For our analysis, this is not sufficient because we want to analyze the impact of *Pelagia noctiluca* when it preys upon the larvae of the small pelagics. In our age-structured model, the fish are assumed to be larvae only during their "Age 0" time-step (i.e. for the first month of their life (Palomera et al., 2007)), after which they become classed as "juveniles". After 6 months or older, they then become susceptible to fishing mortality. Incorporation of larvae to fish population is therefore calculated using the fecundity rate of anchovy (Mantzouni et al., 2007) and sardine (Froese and Pauly, 2014) for a given age (in years), multiplied by a monthly spawning factor. The monthly spawning factor elicited from previous studies (García and Palomera, 1996; Olivar et al., 2003; Palomera, 1992) ensures that each species only spawns in the relevant months (winter for sardine, summer for anchovy). This function of larvae recruitment to the environment was then adjusted to data specific to the study zone (García and Palomera, 1996; Martín et al., 2008; Olivar et al., 2003; Palomera, 1992; Sabatés et al., 2013, 2007).

Fish growth parameters were calculated as an average from 2002-2009 for the Northern Spain geographical sub-area (GSA06) (Cardinale et al., 2010). Maturity, natural mortality and fishing mortality rates (also for GSA06) were extrapolated from an annual to monthly value (Cardinale et al., 2010) with the following exceptions: There is zero fishing mortality for the first six months for both anchovy and sardine; and the natural mortality of larvae (Age 0) was taken from the literature (Mantzouni et al., 2007; Palomera and Lleonart, 1989; Pertierra et al., 1997; Romanelli et al., 2002). Initial population levels for each species for each zone were calculated from extracting landings data for each zone (IDESCAT, 2010) from the entire GSA06 (Cardinale et al., 2010) for 2002-2009. Fleet, vessel and market parameters were taken for 2010 and specific to each zone (Anderson and Carvalho, 2013; Cardinale et al., 2010).

2.2 *Pelagia noctiluca* sub-model

In order to model the dynamics of *Pelagia noctiluca*, a matrix population model was constructed using the inverse method for time series and the parameters were estimated using multiple regression (Caswell, 2006). Previous attempts to construct *Pelagia noctiluca* matrix population models were based on size classes, rather than age classes, using a modified Leslie matrix and a time series for data from the Adriatic Sea (Malej and Malej Jr., 2004; Malej and Malej, 1992), with a time-step of one month. Their matrix model consisted of five size classes, the smallest of which was for both ephyra and early development stages (including the egg / planula larvae stage). For our analysis, it was necessary to separate between ephyra and other stages as this is the predominant stage which feeds on fish larvae, so a different matrix was constructed using four classes as shown graphically in Figure 3, and mathematically in Figure 4.

[Figure 3: Graphical presentation of the *Pelagia noctiluca* matrix population model]

[Figure 4: Projection Matrix of the *Pelagia noctiluca* matrix population model]

$$M \times n_t = n_{t+1}$$

$$\begin{bmatrix} L_1 & 0 & 0 & R_4 \\ G_1 & L_2 & 0 & 0 \\ 0 & G_2 & L_3 & 0 \\ 0 & 0 & G_3 & L_4 \end{bmatrix} \begin{bmatrix} n_{1t} \\ n_{2t} \\ n_{3t} \\ n_{4t} \end{bmatrix} = \begin{bmatrix} n_{1t+1} \\ n_{2t+1} \\ n_{3t+1} \\ n_{4t+1} \end{bmatrix}$$

Construction of matrix population models using time series is data intensive, requiring size-frequency distributions throughout (at least) a year. This high resolution data does not exist for the study zone so data was sought from an area with similar conditions. Size frequency distributions data were taken from a study from the Straits of Messina (Central Mediterranean) collected monthly from January 2008 until August 2011 (Rosa et al., 2013), and the matrix was constructed using least squares regression to estimate all the parameters except for reproduction (R_4 in Figure 4) as described by Caswell (2006). *Pelagia noctiluca* can reproduce throughout the year, producing oocytes in different development stages with peaks in spring and autumn (Rottini-Sandrini and Avian, 1991), although gonad maturation and spawning generally occur during the winter and spring (Malej and Malej Jr., 2004). In our model, the eggs/planulae class is a dummy variable class, and should not be considered as the actual population of either eggs or planulae. It is used as a placeholder between the mature adults and ephyrae. So for our model, reproduction (R_4) of class 4 (n_4) to class 1 (n_1) occurs only during the winter season, from October until January. These temporal distinctions were reflected by alternating matrices depending on the month. R_4 was calculated using an optimization algorithm to create a stable cyclical dynamic population. The final population matrices are shown in Figure 5.

[Figure 5: Projection Matrix with parameters]

$$\begin{array}{l} \text{February – September:} \\ \begin{bmatrix} 0.350 & 0 & 0 & 0 \\ 0.298 & 0.650 & 0 & 0 \\ 0 & 0.003 & 0.201 & 0 \\ 0 & 0 & 0.498 & 0.418 \end{bmatrix} \\ \\ \text{October – January:} \\ \begin{bmatrix} 0.350 & 0 & 0 & 2436 \\ 0.298 & 0.650 & 0 & 0 \\ 0 & 0.003 & 0.201 & 0 \\ 0 & 0 & 0.498 & 0.418 \end{bmatrix} \end{array}$$

The model simulation begins in January when there is a lack of *Pelagia noctiluca* population data in the study zone. Therefore in order to initialize the population of the jellyfish matrix, values were chosen for class 1 (dummy) and class 2 (ephyrae) that would reproduce values approximately

equivalent to the available data in June-July for classes 2 (ephyrae), 3 (immature adults) and 4 (mature adults), for each of the study zones (Sabatés et al., 2010).

There have long been strong fluctuations in the inter-annual population of *Pelagia noctiluca* in the Western Mediterranean (Bernard et al., 2011; Brotz and Pauly, 2012; Goy et al., 1989) which are notoriously difficult to predict (Brotz and Pauly, 2012; Rosa et al., 2013). Given the uncertainties involved in the underlying causes of these fluctuations, the model produces a “background” level of *Pelagia noctiluca*, which is based on the minimum populations that usually occur. The model user has the capability to create proliferation events or blooms as a specific event for a given time and given magnitude. This would allow the model to run various scenarios based on blooms with various frequencies and magnitudes, and examine the effect this would have on fisheries and tourism.

Dietary analysis of *P. noctiluca* ephyrae collected in the shelf-slope region of the Catalan Sea in June, when both the abundance of anchovy larvae and *P. noctiluca* is high revealed that from 4400 ephyrae examined there were 26 incidences of recently consumed fish larvae representing up to 12% of the total prey captured by young jellyfish (Sabatés et al., 2010). Given a 3 hour larval digestion time (Purcell et al., 2014) and taking into account that the highest level of predation on fish larvae takes place during the night (Sabatés et al., 2010), a period of 12 hours per day was considered for calculations. This equates to a feeding rate of *P. noctiluca* on fish larvae of 0.709 per month. 38% of the fish larvae consumed were *Engraulis encrasicolus*, so a best estimate (used in the model) of the consumption rate of anchovy larvae by an individual *P. noctiluca* ephyra per month is 0.269. There is no data available regarding the predation rate of *P. noctiluca* (or other jellyfish) on sardine.

2.3 Stranding model

The arrival of jellyfish to the coastal beaches of Catalonia is a complex process which depends on many factors including the offshore production of blooms typically caused by mild winters, low rainfall and high temperatures. Oceanographic structures such as fronts can reduce the likelihood of

jellyfish arriving to the beaches, but when they are weakened, southeast winds can force the jellyfish towards the coast and become present in the bathing waters and strand on the beaches (Canepa et al., 2014). The prediction of such events is therefore complex given the multiple factors that can influence such conditions.

The timestep of the model is monthly which is unable to capture the sporadic daily conditions that influence the weakening of the front and necessary wind forcing which could improve prediction of strandings. Therefore it was decided that an overall estimate of strandings should be based on a comparison of historic stranding events compared to jellyfish population in the coastal waters. A more robust model should include the possibility of including the previously mentioned meteorological factors but there is currently insufficient data available.

Data for strandings of *Pelagia noctiluca* was made available by a cooperation between the Marine Science Institute (CSIC), Barcelona and the regional water authority (Agència Catalana de l'Aigua) for the years 2007-2010 during the summer months (May to September). Girona has the most number of stranding events, with the majority occurring (in all zones) in June. A “stranding event” is defined as where one of the beaches within the zone has at least one stranding. This data was compared with the expected number of *P. noctiluca* adults (immature and mature) within the coastal water to create an average stranding rate per month, averaged over all zones.

There are three types of stranding events depending on the density of the jellyfish. “Type 1” has less than ten individuals per beach. “Type 2” has between 10 individuals per beach and less than 1 individual m^{-2} , and “Type 3” has a density greater than 1 m^{-2} (Canepa et al., 2014).

Research undertaken by Nunes et al. (2015) was used to assess the impact of jellyfish strandings on beach users in Catalonia. They used a stated-choice questionnaire and a Random Utility Model to estimate the quantified tourism losses caused by the presence of jellyfish at the beach. During the summer of 2012, 644 questionnaires were completed by beach users in eight Catalan beaches to elicit

preferences regarding the following attributes of a given beach: (1) risk of presence of jellyfish, (2) beach water quality, (3) infrastructure and amenities, (4) additional travel time to reach the beach being considered (Nunes et al., 2015). Nunes et al. (2015) calculated the consumptive value of travel time using a random parameters model as approximately 25 minutes. Respondents were found to be willing to travel an additional 3.81 minutes more per trip to go to a beach with a jellyfish presence of less than two days a week rather than one with more than five days a week (the 95% confidence interval is between 2.066 and 5.553 minutes). Taking into account only the subsample of those that made a trade-off between various beach attributes (approximately 50% of respondents), and given the average household income per hour was €19.23 for 2012, individuals are willing to pay on average €3.20 to visit a beach with lower risk of jellyfish presence (Nunes et al., 2015).

2.4 Input-Output model

Increases in *P. noctiluca* blooms have a direct economic impact on both fisheries and tourism. However there will also be indirect economic impacts on the wider regional economy through inter-industry relationships which can be calculated using input-output matrix analysis. This is a standard econometric technique which uses certain assumptions to define a matrix of inter-industry transactions and calculate the quantity purchased by a given industry from all other industries (Common and Stagl, 2005; Perman et al., 2011), and is published by most developed countries as part of their national accounts. Although there exists a range of possible methodologies to measure the economic impact of a specific industry on the whole economy (simplistic economic models, complex general equilibrium models), an input-output analysis is computationally less complicated once the data has been collected and the tables have been constructed (Nastav et al., 2013). The input-output matrix is an accurate reflection of the year in which it was produced, and therefore any predictions using the multipliers are relevant only for the short term.

Input-output tables with 65 branches (or sectors), the (type I) inverse matrix and multipliers for Catalonia in 2005 published by the Institute of Statistics of Catalonia (IDESCAT, 2010) were used

for this analysis, which used the methodological standard set by the *System of National Accounts* (EC et al., 2009). According to their analysis, the “Production value” of fisheries for Catalonia is 1.348 which means for every 1 euro change in revenue, there will be a change in related industries of €1.348. The “Employment value” is 19.07 which means for a change in revenues of a million euros, employment would change by 19.07 people. “Production values” for tourism related sectors are higher (1.51 for hotels and other accommodation; 1.48 for restaurants), but have a lower “Employment value” (16.54 for hotels and other accommodation; 13.92 for restaurants) than for fisheries. This means that for a given change in revenues for fisheries, the same change in revenues for sectors related to tourism (hotels and restaurants) will have a greater effect on the regional GDP, but will have less of an effect on regional employment.

3 Results

Three ten-year forecast scenarios were run for varying levels of *P. noctiluca* blooms as shown in Figure 6. The “No blooms” scenario is the minimum level of *P. noctiluca* that will always be present in the coastal waters. The “Expected blooms” scenario is based on historical jellyfish observations from 2000-2010.

[Figure 6: Concentration of *P. noctiluca* in Catalonia for various scenarios]

The maximum observed value from this ten-year historic data set was then applied every year as shown in the “Frequent blooms” scenario. The blooms are applied equally over each study zone. It

should be noted that both immature and mature *P. noctiluca* both contribute towards strandings, negatively affecting the recreational appeal of the beaches, whereas ephyrae do not.

3.1 Fisheries

Figure 7 shows the effect on anchovy catches over the 10 year forecast period under the three scenario conditions. As expected, increases in *P. noctiluca* blooms causes a reduction in catches. Comparing the *Expected blooms* scenario to the *No Blooms* scenario reveals there could be up to a 5.1 % increase in catches per year for Catalonia if there were fewer years with blooms. Conversely, an increase in blooms (under the *Frequent blooms* scenario) could decrease the catches by 2.6 % per year (Table 1). It can also be seen that this trend would continue to increase if a given scenario continued beyond the ten year forecast period, as indicated by comparing the average change over ten years with just the final year of the forecast period. The Barcelona zone appears to be the most influenced by changes in *P. noctiluca* blooms although the difference is minimal.

[Figure 7: Monthly catches of anchovy for Catalonia]

[Table 1: Change in yearly anchovy catches (T), comparing *Expected blooms* to other scenarios]

	No blooms		Frequent blooms	
	10 year average	Last year	10 year average	Last year
Tarragona	71 (4.2 %)	147 (8.8 %)	-35 (-2.1 %)	-80 (-4.8 %)
Barcelona	84 (5.7 %)	172 (12.2 %)	-42 (-2.9 %)	-94 (-6.7 %)
Girona	140 (5.3 %)	287 (11.3 %)	-70 (-2.7 %)	-157 (-6.2 %)
Catalonia (Total)	294 (5.1 %)	608 (10.8 %)	-147 (-2.6 %)	- 332 (-5.6 %)

Given the lack of data regarding the predation of *P. noctiluca* upon sardine larvae, the model produces no difference in the landing totals for sardine under the three scenarios. The impact that changes in anchovy landings have upon the small pelagic fisheries profits is shown in Figure 8. A comparison of *Expected blooms* and *No blooms* shows that profits could increase by 4.5% per year given fewer *P. noctiluca* blooms. Under the *Frequent blooms* scenario, there could be a loss in profits of around 2.3 % per year.

[Figure 8: Yearly profits of small pelagic fisheries for Catalonia]

3.2 Jellyfish stranding events

Table 2 shows a summary of the average yearly *P. noctiluca* stranding events for a 10 year forecast period. As expected, higher occurrences of blooms results in an increase in frequency and density of stranding events. There is a 49% decrease of stranding events for Catalonia comparing the *Expected blooms* scenario to the *No blooms* scenario. Conversely, there is a 33% increase in stranding events when the blooms increase from the *Expected blooms* to *Frequent blooms* scenario.

[Table 2: Average stranding events per year of *P. noctiluca* for each scenario over 10 year forecast period]

Zone	No blooms			Expected blooms			Frequent blooms		
	Type 1 < 10 per beach	Type 2 < 1 m ⁻²	Type 3 > 1 m ⁻²	Type 1 < 10 per beach	Type 2 < 1 m ⁻²	Type 3 > 1 m ⁻²	Type 1 < 10 per beach	Type 2 < 1 m ⁻²	Type 3 > 1 m ⁻²
Tarragona	24	3	1	47	6	2	63	8	3
Barcelona	29	4	1	57	7	3	75	9	4
Girona	48	6	2	95	12	5	125	16	6
Catalonia	102	13	5	199	25	10	263	33	13

Despite the potential increases in *P. noctiluca* stranding events, they still do not meet the threshold in which beach users would choose to travel further to avoid the stranded jellyfish. Nunes et al. (2015) conclude that beach users are willing to each pay €3.20 more per visit to travel from a beach which has more than five stranding events per week to one which has just one or two events. The maximum number of stranding events per month is 55 in the Girona zone in June during the *Frequent blooms* scenario. Given that there are 71 beaches in this zone, this averages less than 0.2 stranding events per beach per week, far from the threshold which would induce beach users to avoid such a beach. Therefore according to these results, the impact of *P. noctiluca* stranding events on tourism under all scenarios is zero.

3.3 Regional economy – Gross domestic product (GDP) and employment

Changes in revenues, whether it is in tourism, fisheries or any other industry will have a knock-on effect on other sectors whereby more or less demand is created for goods or services for that industry.

The overall effect on the regional economy of the various scenarios for changes in the small-pelagic fisheries revenues is shown in Table 3. Given that the threshold for *P. noctiluca* strandings is not reached, the overall impact on tourism and the regional economy is zero and not included in this table. When compared to the *Expected blooms* scenario, the impact of changes in blooms to the regional economy is relatively insignificant when compared to the regional GDP and employment.

[Table 3: Changes to regional economy with comparison to regional economy]

Scenario	Average yearly revenue (10 year forecast period) (€)	Change in revenue* (€)	Change in regional economy* (€)	Change in regional employment* (individuals)
Expected blooms	20,674,929	-	-	-
No blooms	21,150,777	475,848 (102%*)	641,444 (<0.001% of reg. GDP)	12 (0.3% fishing sector)
Frequent blooms	20,436,377	-238,552 (99%*)	-321,568 (<0.001% of reg. GDP)	-6 (-0.1% fishing sector)

2010 GDP of regional economy €143,000 million.
2010 Employment in fishing sector is 4183

*compared to "Expected blooms"

4. Discussion

Before discussing the overall impact of changes in *Pelagia noctiluca* blooms on fisheries, tourism and the regional economy in Catalonia, we should acknowledge the limitations in both the scarcity of available data and knowledge as well as the drawbacks to the modelling methodology used.

The predation rate used in the model of *P. noctiluca* on anchovy was taken from a research cruise conducted in June 1995 and examined only ephyrae and not adults (Sabatés et al., 2010), while there is no information on predation for sardine. Previous studies suggest that *P. noctiluca* is an opportunistic non-selective predator that prey on what it encounters rather than actively hunt target species (Malej, 1989). A problem of large aggregated zones such as those used in the model, limit the ability to predict the consequences when dense quantities of predator and prey coincide temporally and spatially. Other studies have suggested that the effects could be greater than the results of our

model (Purcell et al., 2014). Given that *P. noctiluca* may prey on larvae of different fish species, not only anchovy larvae, an exploratory scenario was run where the same predation rate for anchovy was used for sardine. However, within the model, this decimates the sardine population within a few years so clearly the predation rate has to be less. This could be due to a number of factors such as greater availability of other planktonic prey, or that they do not coincide spatially. It is important to note that sardine larvae are found in the plankton in winter, when the abundance of *P. noctiluca* is much lower than in summer but that of other planktonic organisms, such as copepods, is higher (Fernández de Puelles et al., 2007).

There are many physical, physicochemical, biological and climatic forcings which influence changes in population and migration of *P. noctiluca* (Canepa et al., 2014) which are omitted from this model due to incomplete data and knowledge. Once these data gaps have been completed and these interactions better understood they can be incorporated into this model, until then there have been many simplifications. The initial population value within the jellyfish population matrix dictates the population for its following growth, death and reproduction cycle, therefore it is crucial that an accurate value is used. However, given that the sampled populations of *P. noctiluca* vary by many orders of magnitude, it is difficult to estimate an average value for a given time and zone. The various bloom scenarios (based on all species of jellyfish sightings) try to capture some of this uncertainty where sightings change by up to a factor of five year-on-year, however these changes are small when compared to the variance in initial conditions which is based on recorded samples. Due to a scarcity of data, modelled blooms occur proportionally equally to each zone, however it is likely that this is not the real situation. Further data could improve this simplification. Although the model permits migration of jellyfish from one zone to another and is thought to occur, the data is limited and therefore omitted from the current scenario analysis.

As previously described, the jellyfish stranding model is based on historic aggregated data and cannot model the complex factors involved in accurately predicting such events at the required temporal and spatial resolution. As knowledge further develops towards understanding these processes, this sub-

model should be updated to include and improve upon its predictive capacity. The effect of strandings on beach users is based on a stated-choice experiment to elicit the willingness to pay to avoid beaches with jellyfish (Nunes et al., 2015). Within the study, the alternative option is to travel to another nearby beach (without jellyfish) and calculate the costs involved. Although the costs to the beach and nearby businesses would be negative, the overall change to the regional economy would be zero. A currently unexplored scenario with potentially greater negative impact to the Catalan economy would be if the jellyfish strandings problem became such a continual problem that beach users chose to visit or stay in other regions or countries. The few studies which have directly investigated public perception conclude that providing information to beach users could increase acceptance of jellyfish in the bathing waters (Baumann and Schernewski, 2012; Vandendriessche et al., 2013).

Given these caveats, the results of the various scenarios show that *P. noctiluca* has a low impact on small pelagic fisheries, tourism and the regional economy in Catalonia. The standard deviation of recorded year-to-year anchovy landings (1329 tonnes over the last 5 years) is larger than the standard deviation of the most contrasting modelled scenarios (311 tonnes when comparing *No blooms* to *Frequent blooms*).

As previously described, the effect of the strandings on the tourists is zero within our analysis but this is partly a result of the aggregated spatial dimension of the model. The model cannot determine if the strandings occur in specific beaches in a given zone. If this were the case, then the number of stranding events could be sufficient to influence a beach user's decision to visit another beach with fewer jellyfish. It should also be remembered that this study models the stranding of *P. noctiluca*. It is possible that *P. noctiluca* will strand with other species of jellyfish and reach the threshold in which the beach users choose to visit a different beach.

The impact on the regional economy is limited with just a small effect on the fisheries industry. The much larger tourism industry has the potential to more severely affect the regional economy given its

relative size compared to fisheries as well as its potential effect on dependent industries (i.e a larger production value from the input-output matrix).

Our model could be seen as a contribution to the partial evaluation of the user's surplus of marine ecosystems free of jellyfish outbreaks. Users (local fishers / tourists) would benefit to some extent from good ecosystem health, because even if the global estimated *relative* impact is low, in absolute terms the impact is estimated at a maximum of €1 million (the difference between the *No blooms* and *Frequent blooms* scenarios). This amount would not justify public investment on information and mitigation campaigns to partially offset the welfare losses from abnormally high jellyfish outbreaks. Despite these results, it should be remembered that this study only reflects the impact of just one species of jellyfish in an area where there exist 12 species of scyphomedusae (Canepa et al., 2014). Many studies suggest that the occurrence of jellyfish blooms is increasing for many species, therefore the combined effect with other jellyfish on predation of small pelagics, beach stranding events and the effect on beach users would have a greater impact than the various scenario results presented here (Nunes et al., 2015).

There are relatively few studies which try to quantify the economic impact of jellyfish on socio-economic systems (Ghermandi et al., 2015; Nastav et al., 2013; Palmieri et al., 2014). Nunes et al. (2015) estimate that beach users are willing to pay an additional €3.20 per trip to visit beaches with fewer jellyfish which is equivalent to €423 million/year for the whole of the Catalonia. Ghermandi et al. (2015) estimate that there could be an annual loss of €1.8-6.2 million due to fewer seaside visits caused by jellyfish outbreaks in Israel. Kontogianni & Emmanouilides (2014) estimate that households in the Gulf of Lion are willing-to-pay on average €66 (single payment) to reduce expected jellyfish outbreaks from 9 years per decade to 1 year per decade. In a survey completed by fishers in Oregon, it was estimated that the economic impact to salmon and pink shrimp fishers was over \$650 000 in 2012 (Conley and Sutherland, 2015). Clogging of shrimp nets in Louisiana by jellyfish was estimated to have cost millions of dollars in economic losses (Graham et al., 2003). Nastav et al. (2013) conclude that jellyfish presence had an impact on Slovenian fisheries, reducing catches,

income and employment but do not quantify the losses. Nastav et al. (2013) also conclude that, similarly to this study, the effect on the regional economy was low.

The potential for welfare losses caused by jellyfish outbreaks are clearly large, but difficult to directly measure. Revealed preference methods have begun to quantify these risks, but further research is needed to ascertain the full economic impact of jellyfish blooms. To our knowledge, this is the first study which attempts to quantify the economic impact of jellyfish on both fisheries (predation of fish larvae) and the tourism industry (strandings), as well as the wider effects on the regional economy. The methodology can be applied to other jellyfish species (in Catalonia) to improve the results for this study zone as well as be applied to other regions or countries. Our minimum realistic model can be complemented with other less-well documented effects that have also an impact on welfare losses from jellyfish outbreaks, such as clogging cooling water intake pipes of power plants and desalination plants, clogging fishing nets or impairing fish production in fish farms (Conley and Sutherland, 2015; Ghermandi et al., 2015; Graham et al., 2003).

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