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Trawling regime influences longline seabird bycatch in the Mediterranean: new insights from a small-scale fishery

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ABSTRACT: Unintended mortality in longlines emerged in the early 1990s as one of the most important threats for pelagic seabirds worldwide. Most of the studies were focused on highly developed industrial fisheries, overlooking bycatch in small-scale artisanal fisheries. However, bycatch in small-scale fisheries might have negative effects similar to those of industrial fisheries when they overlap with hotspot areas of top predators. Moreover, different types of fishing gear coexist in the same oceanographic area, particularly in highly exploited marine ecosystems such as the western Mediterranean. We quantify for the first time the influence of trawling regime on Cory's shearwater *Calonectris diomedea* bycatch in the western Mediterranean longline artisanal fishery. The availability of trawling discards has substantial influence on the foraging and breeding ecology of many seabirds, and trawling inactivity may drive shearwaters to seek alternative food resources, such as baits used in longline fishing. Based on our previous knowledge of the system, we also tested other variables affecting bycatch over 8 yr (1998 to 2005). Within this 2-fishery framework, we found that trawling regime, longline fishing time and breeding stage were key factors explaining shearwater attendance to longline vessels, but mainly trawling regime and fishing time increased the incidental capture of Cory's shearwaters. More specifically, during the pre-breeding and chick-rearing periods, bycatch dramatically increased during sunrise sets in the absence of trawling activity. Importantly, this study indicates the need for an integrated multi-fisheries management approach for the conservation of seabirds and highlights the necessity of banning longline fishing during periods of trawling inactivity.

KEY WORDS: Small-scale fishery · Interactions between fisheries · Multi-fisheries management · Trawling inactivity · Cory's shearwater · Mitigation measures · Western Mediterranean

INTRODUCTION

The current environmental state of the global oceans is rapidly deteriorating due to the negative effect of human activities, and the risk of extinction of marine species, especially marine top predators, is far greater than previously thought (Jackson et al. 2001, Myers & Ottensmeyer 2005). Industrial fisheries are largely responsible for the decline of marine top predators, including 90 % of the large predatory fish species, and

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for an 80% reduction in community biomass, affecting both target and non-target species (Myers & Worm 2003, Lewison et al. 2004b). For instance, many thousands of seabirds (mostly Procellariiformes) are killed annually by longline fisheries, and consequently populations have shown important declines in abundance over the last 3 to 4 decades (Weimerskirch & Jouventin 1987, Gales et al. 1998, Brothers et al. 1999, Nel et al. 2002, Cooper et al. 2003). In fact, one-third of the seabird species accidentally caught are catalogued as globally threatened according to the International Union for Conservation of Nature (IUCN) criteria (Brothers et al. 1999, BirdLife International 2004).

Most studies reporting top predator bycatch have been performed on highly developed industrial fisheries, and it has seldom been considered in small-scale artisanal fisheries (but see D'Agrosa et al. 2000, Peckham et al. 2007, Bugoni et al. 2008b). However, interactions between marine predators and artisanal fisheries can be of great concern, and may have negative effects similar to those of industrial fisheries when they overlap with areas of extensive use by marine predators (Peckham et al. 2007). This might be especially true in the Mediterranean Sea where fisheries are diverse, but primarily artisanal, and the seabird community is characterised by a low diversity and abundance, but a high degree of endemism (Arcos 2001, Arcos et al. 2008, Goñi et al. 2008). Previous studies have reported high bycatch rates of marine top predators in Mediterranean small-scale fisheries, and have stated that this interaction might constitute a real threat for the conservation of these species (Godley et al. 1998, Belda & Sánchez 2001, Cooper et al. 2003, Tudela 2004). For instance, Cory's shearwater *Calonectris diomedea*, the most susceptible species to longline bycatch in the area (Belda & Sánchez 2001, Cooper et al. 2003, Valeiras & Camiñas 2003), exhibits a slow but general population decline in the western Mediterranean (Jenouvrier et al. 2008, Igual et al. 2009). Although none of these studies report data linking bycatch with population decline, some studies (Belda & Sánchez 2001, Igual et al. 2009) suggest that several populations could be in decline due to bycatch in longlines.

The international community has recognised the great impact of bycatch on the conservation of marine species and has adopted bycatch mitigation measures, but focusing primarily on specific fishing methods or only on particular taxa (Baker et al. 2007, Moore et al. 2009). However, a multi-species multi-fisheries management is necessary since species affected by bycatch are diverse and different types of fishing gear coexist in the same oceanographic area, particularly in highly exploited marine ecosystems (Žydelis et al. 2009). This might be occurring in western Mediterranean waters where current levels of both fishing activities and environmental degradation are probably leading to important changes in the whole ecosystem (Tudela 2004). For instance, trawling activity has been identified as the most harmful and least selective fishing method on both target and non-target groups (Coll et al. 2006). In addition, trawling also has substantial effects on the foraging and breeding ecology of some seabird species by providing an abundant additional food resource, affecting their population dynamics in complex ways (Oro 1999, Oro et al. 1999, 2004, Arcos 2001, Arcos & Oro 2002b, Louzao et al. 2006, Arcos et al. 2008, Bartumeus et al. 2010). A trawling moratorium has been in place since 1991 in some areas of the Spanish Mediterranean with the aim of helping fish populations to recover from overexploitation. Trawling activity is prohibited for 2 consecutive months per year which overlap with different stages of the reproductive cycle of local seabirds, strongly affecting their ecology (see review in Oro et al. 1999). Discard experiments performed across the Iberian continental shelf show that an average of 83.9% of the trawler discards are consumed by seabirds (Arcos 2001). This consumption efficiency did not change between areas but slightly differed between seasons (79.4% during breeding season and 89.2% otherwise) (Arcos 2001). In particular, Cory's shearwater is one of the most common local species attending trawlers (Oro & Ruiz 1997, Martínez-Abraín et al. 2002, Louzao 2006) and, therefore, the absence of trawling activity might force birds to seek alternative resources, increasing their attendance to longline fishing vessels. In fact, trawling activity does not only stop during moratoria periods, but also during weekends and calendar holidays, according to Spanish fishing norm. Thus, the presence or absence of trawling activity (i.e. trawling regime) could greatly affect unintended seabird captures in Mediterranean waters.

In the present study, we address seabird bycatch within a 2-fishery framework, assessing for the first time the importance of trawling regime on the probability of Cory's shearwater incidental capture within an artisanal longline fishery in western Mediterranean waters. Based on our previous knowledge of the system, we tested the effect of additional factors (both fishing-related and biological) affecting bycatch, such as fishing time, number of hooks and breeding stage. Fishing time is already known to increase bycatch when longlines are set during sunrise (Belda & Sánchez 2001, Sánchez & Belda 2003). The number of hooks was used as an indicator of fishing effort since (1) it is used as a predictor of seabird bycatch (Bugoni et al. 2008a, Dietrich et al. 2009) and (2) it is extensively used as a measure of fishing effort (Belda & Sánchez 2001, Bugoni et al. 2008b). In addition, we also considered the breeding cycle of the species, since energetic requirements may change over the breeding period, from the pre-breeding to the chick-rearing period (Navarro et al. 2007). Finally, we discussed the conservation implications of our results within the current fisheries management scenario in the western Mediterranean.

MATERIALS AND METHODS

Longline fishery and data collection. Fieldwork was conducted onboard the artisanal bottom longline fleet in the Spanish Mediterranean from 1998 to 2005, including the Comunidad Valenciana (Valencian Community) and Islas Baleares (Balearic Islands) (Fig. 1). The artisanal bottom longline fleet in the study area is characterised by vessels of small size (9 to 15 m) with 2 to 3 crew members. This is a very heterogeneous fleet in relation to vessel characteristics, fishing habits, type of bottom longline and fishing ground location. These characteristics make it difficult to quantify the total size of the fleet. For the Comunidad Valenciana, this is estimated as 13 longliners (Campos Guinot 2007). The remaining vessels use other fishing methods that do not interfere with seabirds foraging behaviour because the type of bait they use and the geographical region in which they carry out their fishing activities are different. In the Islas Baleares, the fleet is estimated as ca. 10 bottom longliners which operate during the whole year. There is also an undefined number of smaller vessels that can use bottom longlines jointly with gillnets but they do not have to report their activity to the administration. Therefore, total numbers for the Islas Baleares are difficult to estimate (Mallol & Goñi 2004).

Bottom longlines differ widely in their characteristics according to the target species, namely hake *Merluccius merluccius*, common sea bream *Pagrus pagrus*, red sea bream *Pagellus bogaraveo*, toothed bream *Dentex dentex*, and dusky grouper *Epinephelus marginatus*. Fishermen changed their target species both seasonally and in response to market conditions. The total length and gape of the hooks varied between 29 and 51 mm and 12 and 19 mm, respectively. The distance between secondary lines in the main line ranged from 5 to 12 m, whereas secondary lines measured from 2 to 5 m. Hooks were manually baited with different species: European pilchard *Sardina pilchardus*, round sardinella *Sardinella aurita* (sized 10 to 15 cm), and occasionally with different taxa of cephalopods and crustaceans. Lines were set at 2 to 5 knots. The number of hooks set per fishing operation ranged between 50 and 2650 (median of 460). Bottom longline setting took place between 02:57 and 21:41 h GMT, and the mean (± SD) duration of the setting process was 38 min ± 24. No seabird mitigation measure was implemented during fishing operations.

Data were collected by experienced observers from 237 setting operations. Observers recorded the number of hooks set and the start and end times of setting and hauling operations. During setting, observers recorded bird species, the number of individuals attending vessels per species, and the number of seabirds caught by longlines every 10 min. When longline sets were performed at night, seabird identification was limited to a maximum distance of 75 m by the lights used for setting (Belda & Sánchez 2001). The number of potential species following vessels to be identified was restricted to a maximum of ca. 8 which could be easily recognised by size and flight. Thus, the numbers of birds captured must be considered as minimum values due to partial observation at night, although it is likely that most of the birds were recovered at hauling. Bycatch was measured as the number of birds accidentally captured at longline setting, i.e. the deployment of a longline (regardless of the number of hooks) (Camiñas et al. 2006). A summary of the sampling effort is shown in Table 1.

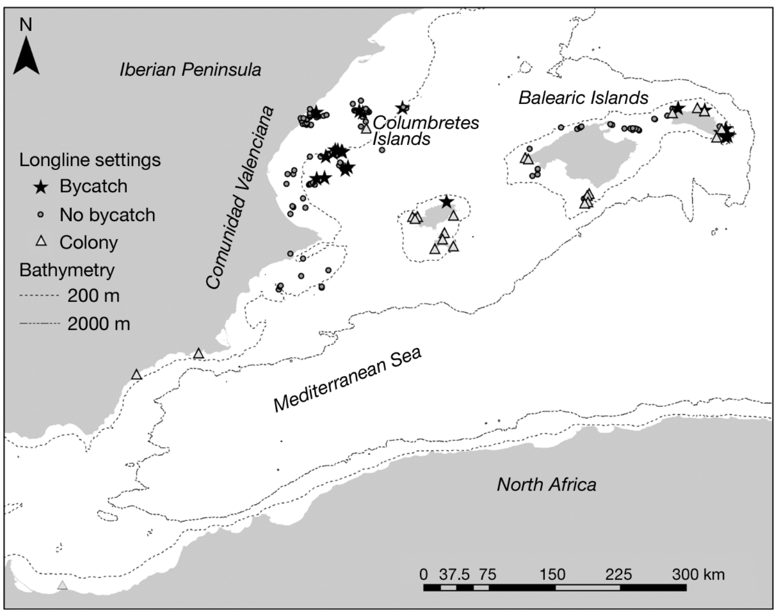

Fig. 1. *Calonectris diomedea.* Study area showing the location of Cory's shearwater bycatch (except 1998 and 1999, which corresponded to the Columbretes Islands area, Belda & Sánchez 2001) and breeding colonies

Modelling bycatch. ***Explanatory variables:*** We assessed the influence of 4 explanatory variables in shearwater bycatch: trawling regime, initial setting time (GMT) (i.e. fishing time), fishing

Table 1. Sampling effort on the artisanal longline fishery in the western Mediterranean (1998–2005) represented by number of longline settings monitored by year during the breeding cycle of Cory's shearwater *Calonectris diomedea* (pre-breeding, incubation and chick-rearing periods), trawling regime (trawling activity and moratoria) and fishing time (sunrise, day and night). The number of hooks and boats are shown by year. The last column indicates the capture rate as the number of birds captured per 1000 hooks

Year	Number of settings								No. of	No. of	Capture
	Pre-breeding	Incubation	Chick-rearing	Trawling moratoria	Trawling activity	Sunrise	Day	Night	hooks (yr^{-1})	boats (yr^{-1})	rate
1998	0	0	26	5	21	9	7	10	18950	6	0.63
1999	0	53	23	49	27	29	30	17	32086	8	0.03
2000	2	0	16	8	10	5	3	10	14000	3	0.13
2001	0	11	7	8	10	18	0	0	27966	2	0.71
2003	11	0	0	0	11	4	2	5	4700	2	1.07
2004	29	30	21	13	67	30	31	19	52966	14	0.15
2005	8	0	0	0	8	3	4	1	2242	2	0
Total	**50**	**94**	**93**	**83**	**154**	**98**	**77**	**62**	**152 910**	**37**	

effort and breeding stage. Within a 2-fishery approach, we explored the effect of a new variable, such as the trawling regime, recording the presence or absence (i.e. during moratorium periods, weekends and calendar holidays when trawlers never operate) of trawling activities. Set fishing time was coded in 3 time intervals: sunrise (1 h before sunrise to 1 h after sunrise), daytime (1 h after sunrise to 1 h before sunset), and night time (1 h after sunset to 1 h before sunrise). Sunset settings (1 h before sunset to 1 h after sunset) were not taken into account because sampling effort was very low in this period (8 sets, 5 of them in the pre-breeding season and no birds captured) and the increase in model complexity (by adding an extra category) was not justified by the consideration of these data. Fishing effort was measured as the number of hooks set in each longline setting.

Similarly, the breeding stage of Cory's shearwaters was also considered since their energetic requirements change over the breeding cycle, influencing their foraging ecology (including foraging effort) and nutritional physiology (Navarro et al. 2007). We therefore hypothesised that, during periods of high energy demand (e.g. chick-rearing period), birds might search for alternative food resources, such as longline baits and fishing discards, increasing bycatch probability (Oro & Ruiz 1997, Martínez-Abraín et al. 2002). We considered 3 breeding periods: pre-breeding (March to mid-May), incubation (mid-May to mid-July) and chick-rearing (mid-July to mid-October). During these periods, Mediterranean Cory's shearwaters forage at highly predictable and productive marine areas along the Iberian continental shelf (Louzao et al. 2009) and we did not expect shifts in the spatial location of their foraging grounds over these stages. From November to February, Cory's shearwaters leave the Mediterranean for their wintering quarters in the central and southern Atlantic (González-Solís et al. 2007), and therefore data from these months were disregarded. Other potentially important factors such as soak time (Ward et al. 2004) and distance to the colony were indirectly considered through the inclusion of intercepts in the models due to the lack of this information.

The zero-inflated Poisson model: Bycatch data are commonly characterised by the occurrence of a high number of zeros (i.e. no bycatch events), but also by large values when aggregations of animals are captured (Hilborn & Mangel 1997, Minami et al. 2007). Thus, zero-inflated Poisson (ZIP) models are good candidates to model bycatch probability and they are currently a standard approach in bycatch studies (Minami et al. 2007, Gardner et al. 2008). With a ZIP distribution, the bycatch process is modelled as a mixed process composed of binary and Poisson distributions (Lambert 1992, Martin et al. 2005). The binary process accounts for the probability of birds 'attending' or 'not attending' vessels, whereas the Poisson distribution models the average number of shearwaters that get accidentally entangled in longlines once birds are attracted to vessels.

Our ZIP model was based on the following equations, where Y events are defined as the number of shearwaters captured per longline set:

$$P(Y=0) = \Phi(x_i) + (1-\Phi(x_i))e^{-\lambda(z_i)}$$
$$P(Y=y>0) = (1-\Phi(x_i))\frac{e^{-\lambda(z_i)}(\lambda(z_i))^y}{y!} \quad \text{for } y = 1,2,3\ldots n \tag{1}$$

using the following link functions:

$$\text{logit}(\Phi(x_i)) = \alpha_0 + \sum_{i=1}^{5} \beta_{0i}\, x_i \tag{1a}$$

$$\log(\lambda(z_i)) = \alpha_1 + \sum_{i=1}^{5} \beta_{1i}\, z_i \tag{1b}$$

where i refers to each explanatory variable, x_i and z_i are explanatory variables, and z_i does not necessarily have to represent the same set of covariates as those represented by x_i. The α_0 and α_1 coefficients represent the intercepts, while β_{0i} and β_{1i} are the coefficients estimated for each explanatory variable included in the model.

According to the ZIP model, $(1 - \Phi)$ is the probability of birds attending vessels while $\lambda(z_i)$ represents the mean number of shearwaters captured during a longline set. The first term of Eq. (1) for zero captures describes the probability Φ that birds are not captured simply because they are not present at the fishing site, while the second term of Eq. (1) accounts for the birds that are not captured even if there are birds in the fishing area. For the case $Y > 1$ in Eq. (1), the Poisson distribution describes the capture of 1 or more birds and is affected by the probability $(1 - \Phi)$ of having birds flying around the vessels.

In this way, we implicitly included the number of birds attending vessels through the ZIP model, assuming that the probability of presence/absence of birds in the region of bycatch is linearly related with our explanatory variables. According to Eq. (1a), $(1 - \Phi)$ is the probability of presence of seabirds in the region of bycatch. A plot of $(1 - \Phi)$ versus the number of shearwaters attending vessels indicates that a linear model gives a good fit (see Fig. S3 in the supplement at www.int-res.com/articles/suppl/m420p241_supp.pdf). We could therefore consider that the probability of presence of birds at vessels is a linear function of the number of birds attending vessels and therefore a linear function of our explanatory variables.

Multiple biological hypotheses and model selection: Prior to modelling, we performed a preliminary screening of explanatory variables in order to check for colinearity by estimating pair-wise correlations between all explanatory variables, which showed very weak associations. For instance, the maximum Pearson correlation coefficient was 0.14 (95% confidence interval, CI.: 0.016 to 0.26) between trawling regime and fishing time. Our dataset presented unbalanced sampling due to constraints inherent to small-scale fisheries (i.e. weather conditions and vessel availability; Table 1) and therefore no interaction terms were considered. Moreover, ZIP models including the number of hooks as an explanatory variable yielded estimated coefficients close to zero for this variable, indicating that the number of hooks did not play an important role in explaining bycatch probability in our particular case (results are shown in the supplement at www.int-res.com/articles/suppl/m420p241_supp.pdf). However, the number of hooks was included as offset in the models (i.e. forcing its coefficient to be 1) since it is extensively used as a measure of fishing effort and to be consistent with previous studies (Belda & Sánchez 2001, Bugoni et al. 2008a,b, Dietrich et al. 2009).

Within the theoretical information framework, we tested all the biologically plausible combinations of the final 3 explanatory variables to assemble candidate ZIP models, including an intercept in both the Poisson and binary part of all models considered ($2^3 \times 2^3 + 1 = 65$ models). Data overdispersion was already considered through the ZIP distribution. ZIP modelling for all the Generalized Linear Models (GLMs) was performed with the Stata software (StataCorp). Models were ranked based on their Akaike's information criteria value corrected for small sample size (AIC_c) (Buckland et al. 1997). The Akaike weights (w_i) were also calculated, which represent the relative probability of the candidate model being the best one (see supplement and Buckland et al. 1997, Burnham & Anderson 2002, 2004). Additionally, a model averaging procedure was applied to account for parameter uncertainty (Burnham & Anderson 2002, Burnham & Anderson 2004). We built our subset of 'best' models based on the distribution of Akaike weights to assess weighted average estimates $\hat{\theta}_a$ for the coefficients $\hat{\theta}_i$ that multiply each explanatory variable (Burnham & Anderson 2002, 2004):

$$\hat{\theta}_a = \sum_{i=1}^{R} w_i \, \hat{\theta}_i \qquad (2)$$

where w_i is the Akaike weight of model i within the 'best' subset. The unconditional variance was calculated as:

$$\text{var}(\hat{\theta}_a) = \left[\sum_{i=1}^{R} w_i \sqrt{\text{var}(\hat{\theta}_i \mid M_i) + (\hat{\theta}_i - \hat{\theta}_a)^2} \right]^2 \qquad (3)$$

where $\hat{\theta}_a$ is the average defined in Eq. (2), and M_i refers to each model within the 'best' subset. More details can be found in Buckland et al. (1997).

Finally, we calculated the relative importance (in %) for each variable included within the best subset of models by summing up the rescaled Akaike weights for all models containing that variable (McAlpine et al. 2008).

RESULTS

A total of 1860 birds of 11 species attended the vessels during 237 artisanal bottom longline settings, and 46 individuals of 4 different species were entangled on longlines (91% of them were recovered dead): Cory's (88% dead) and Balearic shearwaters *Puffinus mauretanicus* (100% dead), Audouin's *Larus audouinii* (100% dead) and yellow-legged gulls *Larus michahellis* (100% dead) (Table 2). Most events corresponded to Cory's shearwater (74% of the captures).

Table 2. Seabird species attending the bottom longline fishery in the western Mediterranean (n = 237 settings) represented by the number of individuals (and percentage between brackets) attending vessels and captured. Species are ordered relative to their abundance when attending longline operations

Species	No. attending vessels (%)	No. captured (%)
Cory's shearwater *Calonectris diomedea*	1088 (58.6)	34 (73.9)
Audouin's gull *Larus audouinii*	375 (20.2)	6 (13.1)
Yellow-legged gull *Larus michahellis*	263 (14.1)	3 (6.5)
Balearic shearwater *Puffinus mauretanicus*	79 (4.2)	3 (6.5)
Mediterranean gull *Larus melanocephalus*	15 (0.8)	0 (0)
Common tern *Sterna hirundo*	15 (0.8)	0 (0)
Black-legged kittiwake *Rissa trydactila*	12 (0.6)	0 (0)
European storm-petrel *Hydrobates pelagicus*	5 (0.3)	0 (0)
Northern gannet *Morus bassanus*	4 (0.2)	0 (0)
Black-backed gull *Larus fuscus*	2 (0.1)	0 (0)
Sandwich tern *Sterna sandvicensis*	2 (0.1)	0 (0)
Total	1860 (100)	46 (100)

Regarding Cory's shearwater, the frequency of bycatch events followed a ZIP distribution (89% were zero counts; Fig. 2). Shearwater bycatch was higher in 3 situations: (1) when longlines were set during sunrise, (2) when trawlers did not operate, and (3) during both the pre-breeding and chick-rearing periods (Fig. 3). Maximum bycatch was observed during sunrise setting in the absence of trawling activity and during the chick-rearing period (see Fig. 3 bottom right panel). We did not monitor any longline setting in the absence of trawling activity during the pre-breeding period at day and night (Fig. 3 top right panel).

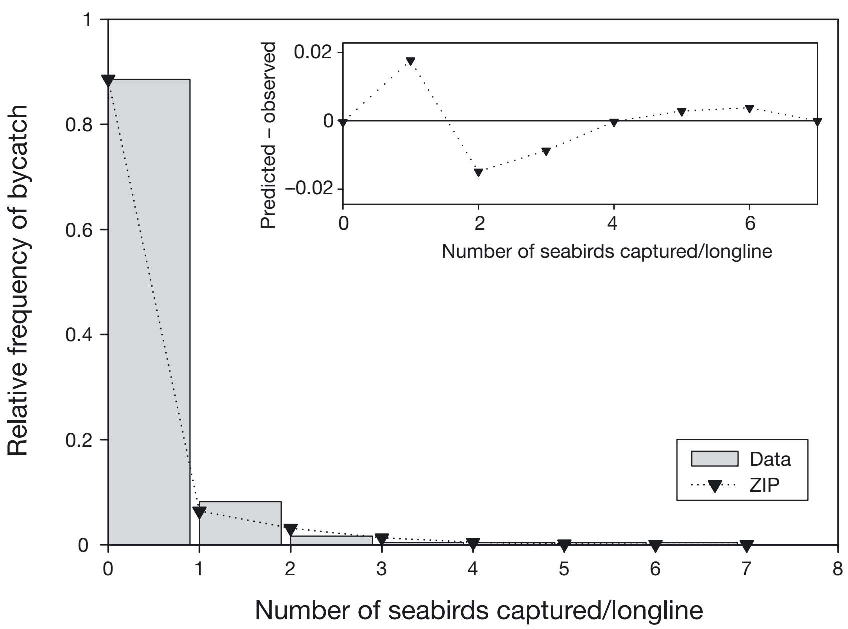

Fig. 2. *Calonectris diomedea.* Frequency of bycatch events for Cory's shearwaters. The inset shows the difference between the number of observed captures and the predicted values with a zero-inflated Poisson (ZIP) model. Bars represent experimental bycatch and triangles represent ZIP model values

We observed a strong positive linear correlation between the number of shearwaters captured and attending vessels (Pearson correlation = 0.6; 95% CI: 0.49 to 0.66). However, given the high dispersion in the data (see Fig. S2 and corresponding section 'Attendance and bycatch' in the supplement at www.int-res.com/articles/suppl/m420p241_supp.pdf) we cannot establish a simple linear relationship between bycatch and shearwaters attendance to vessels.

Concerning ZIP modelling, the most parsimonious model (Table 3, $AIC_c = 196.9$) had an Akaike weight of 0.17, indicating substantial model uncertainty and suggesting the need for a model averaging approach. We built our subset of 'best' models based on the distribution of Akaike weights, choosing models with values higher than 0.03, summing upto 0.55 of the total weight (Table 3, see Fig. S1 in the supplement at www.int-res.com/articles/suppl/m420p241_supp.pdf). Based on the selected subset of models, trawling regime, fishing time and breeding stage affected the probability of birds being attracted to artisanal vessels (the binary process), whereas mainly trawling regime and fishing time increased the expected number of shearwater captures once birds attended vessels (Poisson process, see Table 3). Overall, the relative importance of individual variables was: fishing time > trawling regime > breeding stage (see Fig. S4 in the supplement at www.int-res.com/articles/suppl/m420p241_supp.pdf).

Finally, we estimated the expected average number of incidental captures per set (Fig. 4 right panels) based on the averaged estimated coefficients (Table 4), i.e. computing $\lambda(1 - \Phi)$ (see Eqs. 1a & 1b). Estimations reproduced similar observed

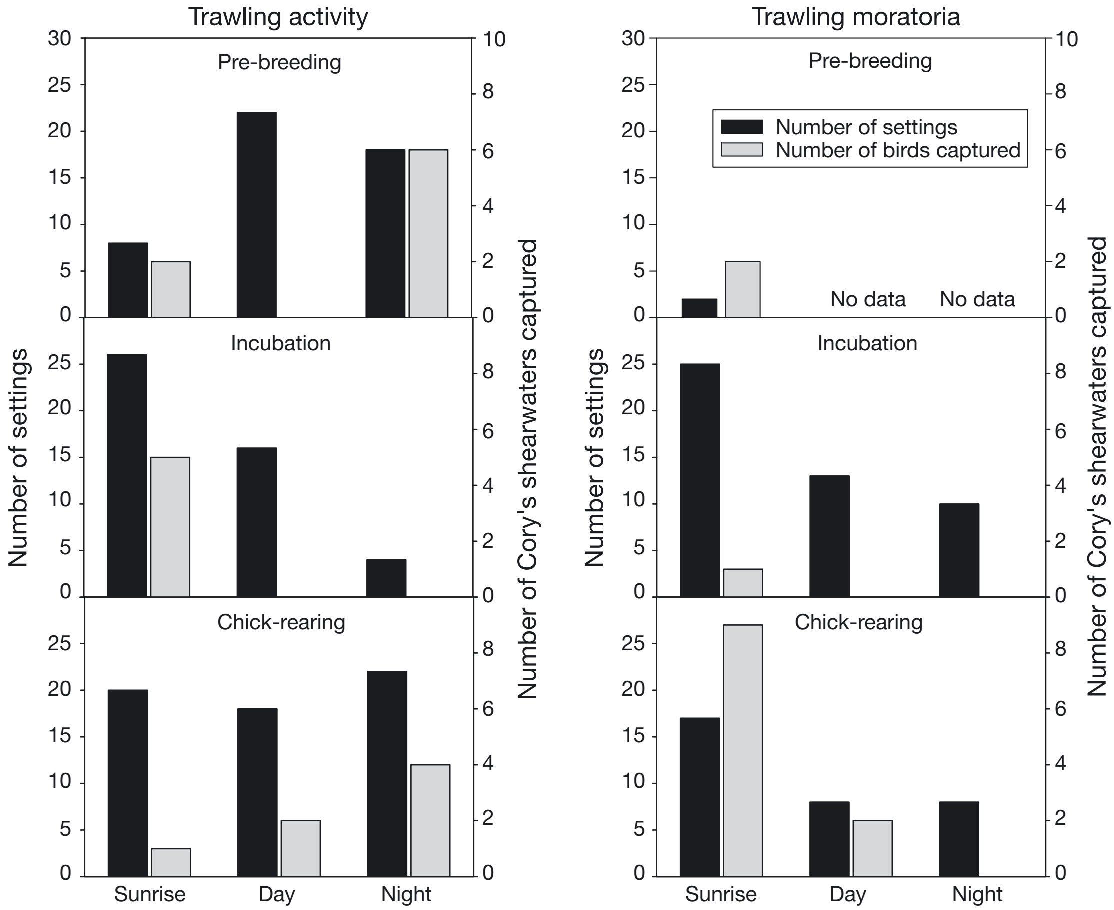

Fig. 3. *Calonectris diomedea.* Number of longline settings and Cory's shearwaters captured for the complete data set. All the possible situations defined by the combination of the explanatory variables (fishing time, trawling regime and breeding stage) are represented. The trawling moratoria category also includes weekends and calendar holidays

bycatch patterns (Fig. 4 left panels), computed as the number of seabirds captured per longline set. Importantly, model predictions allowed the assessment of unobserved bycatch (i.e. 0.22 and 0.04 captures per setting during the pre-breeding period in the absence of trawling activity at day and night, respectively).

DISCUSSION

Modelling bycatch in the western Mediterranean

Within a multi-fisheries framework, this is the first study to suggest a link between trawling fishing activity and seabird bycatch on bottom longlines for small-scale fisheries in Mediterranean waters. When trawling discards were not available, Cory's shearwaters were presumably more attracted to the bottom longline fishery, searching for alternative opportunistic food (Oro & Ruiz 1997). According to ZIP models, trawling regime, fishing time and breeding stage were key factors

Table 3. Results of the zero-inflated Poisson (ZIP) modelling for the Cory's shearwater bycatch data, showing the best set of models. Explanatory variables are: TR: trawling regime, FT: fishing time, BS: breeding stage. *K:* number of parameters. Akaike's information criteria corrected by sample size (AIC_c) as well as the Akaike weights (w_i) for all the models are also shown. X indicates which variables were included in each of the models

Model	Binary			Poisson			K	Deviance	AIC_c	w_i
	TR	FT	BS	TR	FT	BS				
1	X	X	X	X	X	X	11	176	196.9	0.17
2			X		X		6	185	197.7	0.11
3			X	X	X		8	184	198.2	0.08
4					X	X	7	186	198.9	0.06
5	X		X		X		8	185	199.8	0.04
6	X		X	X	X		9	183	200.0	0.03
7		X	X	X	X		10	181	200.1	0.03

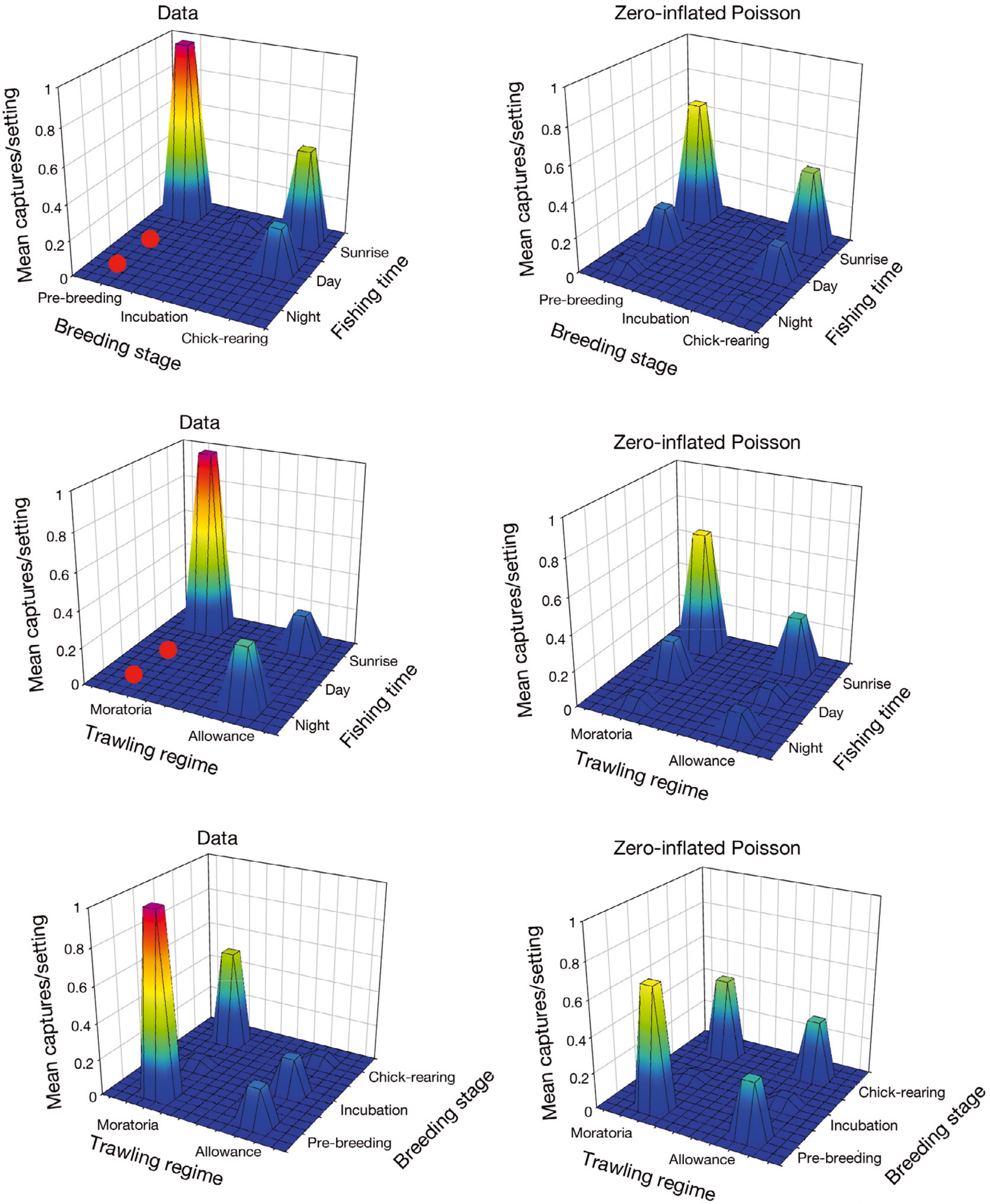

Fig. 4. *Calonectris diomedea.* Mean number of captures per set based on experimental data (left panels) and zero-inflated Poisson (ZIP) model (right panels) during trawling moratoria, pre-breeding and sunrise sets (first, second and third rows, respectively). ZIP bycatch values were assessed from coefficients in Table 3 using Eqs. (1a) & (1b). Red dots indicate no data available

Table 4. Averaged parameters and unconditional standard errors (SE) of the ZIP modelling (listed in Table 3) calculated using Eqs. (2) & (3), respectively. The parameters α_0 and α_1 represent constant terms, and β_{0i} and β_{1i} are vectors whose components are the coefficients of each explanatory variable as quoted in Eqs. (1a) & (1b). Sunrise, trawling moratoria and pre-breeding period were taken as a reference with zero value for the estimation of the coefficient of other categories. The number of hooks was included as an offset of the model

Variables	Coefficient (±SE)	
	β_{0i} for Binary	β_{1i} for Poisson
Day	−1.1 ± 1.7	−1.6 ± 0.7
Night	3.7 ± 2.1	0.2 ± 0.6
Trawling activity	−2.8 ± 1.9	−1.4 ± 0.5
Incubation	2.5 ± 1.0	−1.1 ± 0.6
Chick-rearing	0.6 ± 0.8	0.2 ± 0.5
Constant (α_1)	0.01 ± 0.8	0.3 ± 0.3

explaining shearwater probability of being attracted to longline vessels, but mainly trawling regime and fishing time increased the chances of the incidental capture of Cory's shearwaters. For instance, during the pre-breeding and chick-rearing periods, shearwater attendance to longline vessels increases (Belda & Sánchez 2001), as well as that to trawlers (Arcos 2001, Martínez-Abraín et al. 2002, Louzao 2006), presumably due to the higher energy demand associated with egg formation and chick rearing (Navarro et al. 2007). During both breeding periods, bycatch dramatically increased during sunrise settings (Belda & Sánchez 2001, Sánchez & Belda 2003), since it is the most active period for seabirds (e.g. Péron et al. 2010), in the absence of trawling activity (moratoria, weekends and calendar holidays).

It is worth noticing that in our case the number of hooks per set was unimportant as an explanatory variable, although it has been suggested as a predictor variable (Dietrich et al. 2009) and is widely used as a measure of fishing effort (Belda & Sánchez 2001, Bugoni et al. 2008a). This is in agreement with Véran et al. (2007), who suggested that the relationship between number of hooks per set and fish caught is not always straightforward (but see Báez et al. 2007). This mismatch could be due to the high variability in catch-per-hook rates relative to weather conditions, set time and type of hook (Brothers et al. 1999). Therefore, rather than only consider hook number, a reliable metric of fishing effort should integrate heterogeneous effort measures (Camiñas et al. 2006, Véran et al. 2007). Unfortunately, due to the numerous difficulties in documenting bycatch in small-scale fisheries and the relative small sample sizes, other measurements of fishing effort could not be tested and more data would be needed to test these factors.

Regarding bycatch data collection in the Spanish Mediterranean, data are only available from specific studies performed by independent researchers in the case of bottom longline. Regarding pelagic longline, the Spanish Institute of Oceanography runs an observer programme to register marine top predator bycatch since 1998, as well as specific projects (e.g. García-Barcelona et al. in press). Several nations implement observer programmes to monitor bycatch since they provide high quality data, even though they require well-trained observers and, therefore, observer effort is low relative to total fishing effort (Lewison et al. 2004b). Most information is obtained from regulated fisheries and there is a lack of knowledge of non-regulated fisheries bycatch (Brothers et al. 1999), although their impact could be higher. Hence, it is important to accurately model bycatch to provide additional interpretation when information is scarce.

Management and conservation

Our study highlights the importance of specific regulations to avoid severe seabird incidental bycatch (Dunn 2007). Given that trawlers never operate during weekends and calendar holidays when bycatch dramatically increases, one easy to implement measure that might benefit all the species would be to ban longline fishing during those periods of trawling inactivity. Moreover, the implementation of trawling moratoria could be shifted to other non-critical periods for seabird reproduction in order to reduce seabird bycatch. Additionally, we recommend the regulation of longline set time, enforcing day- and/or night-time setting (Belda & Sánchez 2001, Sánchez & Belda 2003, Delord et al. 2005). Interestingly, in our study area, bait losses during night or day sets were 80% lower than during both sunrise and sunset sets, and in fact, some fishermen have voluntarily started to apply this mitigation measure in the western Mediterranean (Belda & Sánchez 2001). However, the effectiveness of night setting might depend on the species, given that some seabirds are active feeders at night, e.g. Audouin's gull (Arcos & Oro 2002b). Other mitigation measures, such as bird-scaring devices, have been experimentally assessed in the study area with excellent results (a decrease of 90% in bait predation attempts and no bycatch), but they were carried out in a reduced number of sets and results cannot be considered as conclusive (Guallart 2004). Additionally, bird-scaring devices could be potentially entangled with longlines. Given the reduced number of crew members required to manage both lines and the low average frequency of seabird bycatch, fishermen chose not to use bird-scaring devices and alternatively advance fishing time to before dawn (Guallart 2004). Ultimately, reducing gear soak time and setting the fishing gear under the sea surface might help to reduce bycatch. These measures have to be adapted to the small dimensions of the vessels and the type of longlines.

Cory's shearwater is the most frequently captured seabird species in the artisanal bottom longline fishery in the western Mediterranean, where the natural foraging range of the species overlap with fishing grounds over the continental shelf and slope (Karpouzi et al. 2007, ICES 2008, Louzao et al. 2009). However, it is difficult to assess bycatch impact on the population of Cory's shearwaters due to the complexity of estimating the amount of birds killed annually, the age structure and overall population sizes (Véran et al. 2007). Bycatch consequences could be particularly harmful for small populations which are most sensitive to the effects of environmental and/or demographic stochasticity (Igual et al. 2009). For instance, Belda & Sánchez (2001) detected a population decline of 45% in the Columbretes Islands (ca. 50 breeding pairs) over a short period (1998 to 1999) and estimated that a minimum of 4 to 6% of the breeders in that colony were killed annually by longline fisheries. Under such a scenario, the species could be seriously threatened in the Mediterranean in the near future (Cooper et al. 2003), especially considering the synergistic effects of other threats, such as introduced species at their breeding colonies (Igual et al. 2007, 2009).

Currently, there are few guidelines for bycatch mitigation in Europe (Carboneras 2009), and European fishing policies are pushing for longer trawling moratorium periods and the reduction of trawling discards to decrease the dramatic ecological impacts of trawling (Demestre et al. 2008). However, this regulation should be applied within a multi-fisheries framework, considering the joint effect of trawling management and local factors such as bycatch mortality, in particular for threatened populations. Even more important is the consideration of a multi-species bycatch perspective in order to find solutions that benefit multiple taxa (e.g. sea turtles), instead of shifting problems from one species to another. Beyond fishery regulations, ecosystem restoration via the recovery of natural prey populations should be the most beneficial solution for reducing bycatch in the long run. Fishing activities are of high concern for the conservation of marine top predators in general (Arcos & Oro 2002a,b, Mínguez et al. 2003, Arcos et al. 2008, Bartumeus et al. 2010). Fisheries management requires a wide (ecosystem) perspective that handles the unwanted and unexpected negative effects of trawling moratoria on seabird mortality. Populations under severe adult mortality can decline through bycatch over short timescales (i.e. decades), often without detection (Weimerskirch 2002, Lewison et al. 2004a).

We have dealt with conservation issues affecting Cory's shearwaters preservation in the western Mediterranean, but this species travels hundreds of kilometres across oceans during their post-breeding dispersal and could interact with different longline fishing fleets (both industrial and artisanal; González-Solís et al. 2007). Hence, additional bycatch events could be affecting Cory's shearwater populations in their Atlantic wintering quarters (Bugoni et al. 2008b, Jenouvrier et al. 2009). Thus, a global evidence-based approach is required to accurately characterise the magnitude and extent of bycatch effects on the population dynamics of Mediterranean marine top predators, and to implement protective measures throughout their life cycles.

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