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Temporal variability in predator presence around a fin fish farm in the Northwestern Mediterranean Sea

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Abstract

Recently, aquaculture has generated worldwide interest as a result of the over-exploitation of wild stocks combined with a growing international demand for fish and seafood products. Wild fish attracted to the marine fish farms, together with the presence of the farmed fish, are powerful attractants to predators that normally feed on similar or identical fish stocks in nature. This 9-year study describes for the first time in Mediterranean waters the temporal variability of mammalian and avian predators in a coastal fin fish farm. In all, 99 months (1062 days during 36 consecutive seasons) were spent in the field. By examining the results of this study, it is clear that species as seagulls, shags, bottlenose dolphins and grey herons (considered to cause economic loss in aquaculture owing to direct predation) interact regularly with the fish farm. Although bottlenose dolphins and grey herons were not the most important of all predator species, predatory interactions with the fish farm occurred with what seems to be increasing regularity. Another result observed is the possible bottlenose dolphins' attraction caused by the harvesting operations in the fish farm. The fish farm offers an alternative food source for predators; hunting at fish farms usually requires less effort on the part of the predator, and becomes a more attractive option than hunting wild fish over wide ranges. During the period of this study, individually identified dolphins feeding were regularly observed feeding on discarded fish from fish farm workers during harvesting operations, supporting the possibility that some individuals are habituated to this food supply. Based on the evidence presented in this paper, it is recommended that strategies for the management of both the aquaculture industry and marine mammal populations should take the results of this study into consideration.

Introduction

The worldwide decline in ocean fisheries stocks has provided an impetus for rapid growth in fish and shellfish farming, or aquaculture (FAO 2007). Intensive fin fish farming is amongst the most rapidly growing segments of aquaculture (Naylor *et al.* 2000) and has recently greatly expanded in Mediterranean waters (UNEP/MAP/MED POL, 2004; Barazi-Yeroulanos 2010).

As intensive fin fish farming continues to increase and intensify, both its reliance and its impact on marine ecosystems are likely to expand even further (Pillay 2004).As a consequence of the creation of new habitats through the supplement of nutrients, a bottom-up effect has been created through the marine food web. This has resulted in wild fish species becoming concentrated in the vicinity of coastal sea-caged fish farms (Dempster *et al.* 2004). Owing to the presence of the cultivated fish and the wild fish aggregated around the cages, predators are attracted to fish farms, in some circumstances leading to economic consequences for farmers (Nash *et al.* 2000). Consequently, the number of conflicts related to fish-eating predators/aquaculture interactions has increased over the years (Quick *et al.* 2004).

Coastal marine fin fish farms attract a large range of species, including harbour seals (*Phoca vitulina*), grey seals (*Halichoerus grypus*), common bottlenose dolphins (*Tursiops truncatus*), cormorants (*Phalacrocorax carbo*), shags (*Phalacrocorax aristotelis*), grey herons (*Ardea cinerea*), gulls (*Larus* spp.), pelicans (Pelecanus spp.), grebes (Podiceps spp.), otters (*Lutra lutra*) and minks (*Mustela vison*) (EIFAC 1988; Ross 1988; Rueggeberg & Booth 1989; Pemberton & Shaughnessy 1993; Carss 1994; Morris 1996; Beveridge 1996; Kemper *et al.* 2003; Díaz López *et al.* 2005; Diaz Lopez *et al.* 2013; ; Díaz López & Shirai 2007; Díaz López 2012). Marine top predators take fin fish from pens, decimate the pens, and sometimes cause scarring of the farmed fish, increasing fish susceptibility to disease and/or decreasing fish growth because of stress (Westers 1983; Price & Nickum 1995; Morris 1996; Díaz López 2006). Conversely several potential direct hazards to top predators can be readily identified, such a risk of entanglement (Würsig & Gailey 2002; Díaz López & Shirai 2007), habitat exclusion as a result of physical structures (Watson-Capps and Mann, 2005), aversive acoustic devices (Olesiuk *et al.* 2002; Fjälling *et al.* 2006; Díaz López & Mariño 2011), habitat degradation from effluent, alteration of natural behaviour patterns (Díaz López, 2009) and intentional, retaliatory killing of predators (Carss 1994). These hazards can cause significant problems in cases where top predator populations are limited or endangered.

Along the Mediterranean coast, marine mammals and birds occur in relatively low numbers around coastal fish farms as natural and human induced disturbances have greatly reduced their populations (Bearzi *et al.* 2008; Sanchez-Jerez *et al.* 2008). However, in spite of this reduced abundance compared with other geographical areas, predatory interactions with fish farms occur with what seems to be increasing regularity. For example, marine mammals, with their large size (and therefore requiring a great deal of food), have become a culprit for the problems that coastal fish farms face in the Mediterranean Sea. Monk seals (*Monachus monachus*) have attacked fish at several marine fish farms in the Turkish Aegean Sea (Güçlüsoy & Savas 2003). Bottlenose dolphins interact with fish farms along both the northeastern and northwestern coasts of Sardinia, Italy (Díaz López & Shirai 2007; Díaz López 2012; Diaz Lopez *et al.* 2013), around Lampedusa Island, Italy (Pace *et al.* 2012) and in the Northern Evoikos Gulf, Greece (Bonizzoni *et al.* 2014).

To date, interactions by both mammalian and avian predator species with sea-cage fin fish aquaculture have not been documented on a long temporal scale in Mediterranean waters, despite awareness of specific aggregations of bottlenose dolphins in Sardinia, Italy. In this area the presence of a marine fin fish farm since 1995 has been linked with changes in the distribution and behaviour of the dolphins in the area (Díaz López 2012), but no study has yet investigated on a long-term scale the temporal variability of both mammalian and avian predator assemblages around fin fish cages.

In this context, the aims of this paper were (i) to analyse patterns in the occurrence, abundance and diversity of mammalian and avian predators associated with a coastal sea-caged fin fish farm in Sardinia over a period of nine consecutive years; and (ii) to evaluate the factors that induced changes in the occurrence of predators.

Methods

Study location

The present study was carried out at a sea bream (*Sparus auratus*) and sea-bass (*Dicentrarchus labrax*) farm on the northeastern coast of Sardinia, Italy (40°59.98′ N, 9°37.09′ E; Fig. 1), from November 2004 to November 2013. The fish farm is located at a depth of 18–26 m over a bottom characterized by mostly mud with scattered areas of rock and sand. During the study 21 floating cages of 22-m diameter were in use. The total surface are occupied by the complex was 24,000 m^2. The farm has operated since 1995. The farm used anti-predator top nets during the full study period and underwater barrier nets during a 4-month period (between November 2004 and February 2005).

Direct observation procedures

Boat-based observations were undertaken year-round in the fin fish farm area using a 5-m research vessel powered with a 40-hp outboard motor. To minimize the effect of the observers' presence on top predator activity and presence, data were collected when the boat engine was off. The fish farm area was surveyed during daylight with at least three experienced observers scanning the sea surface in search of mammalian and avian predators, either with the naked eye or with 10 × 42 and 10 × 50 magnification binoculars.

To record whether or not top predators were currently present in the fish farm area instantaneous sampling (Altmann 1974), at 20-min sample point, was used. At the beginning of each instantaneous sample all top predators within the fish farm area were identified and counted. Animal aggregations were estimated based on the initial count of individuals of the same species observed at one time in the fish farm area. The observers also recorded potentially confounding variables that were beyond the control of the observers but which may have influenced the presence,

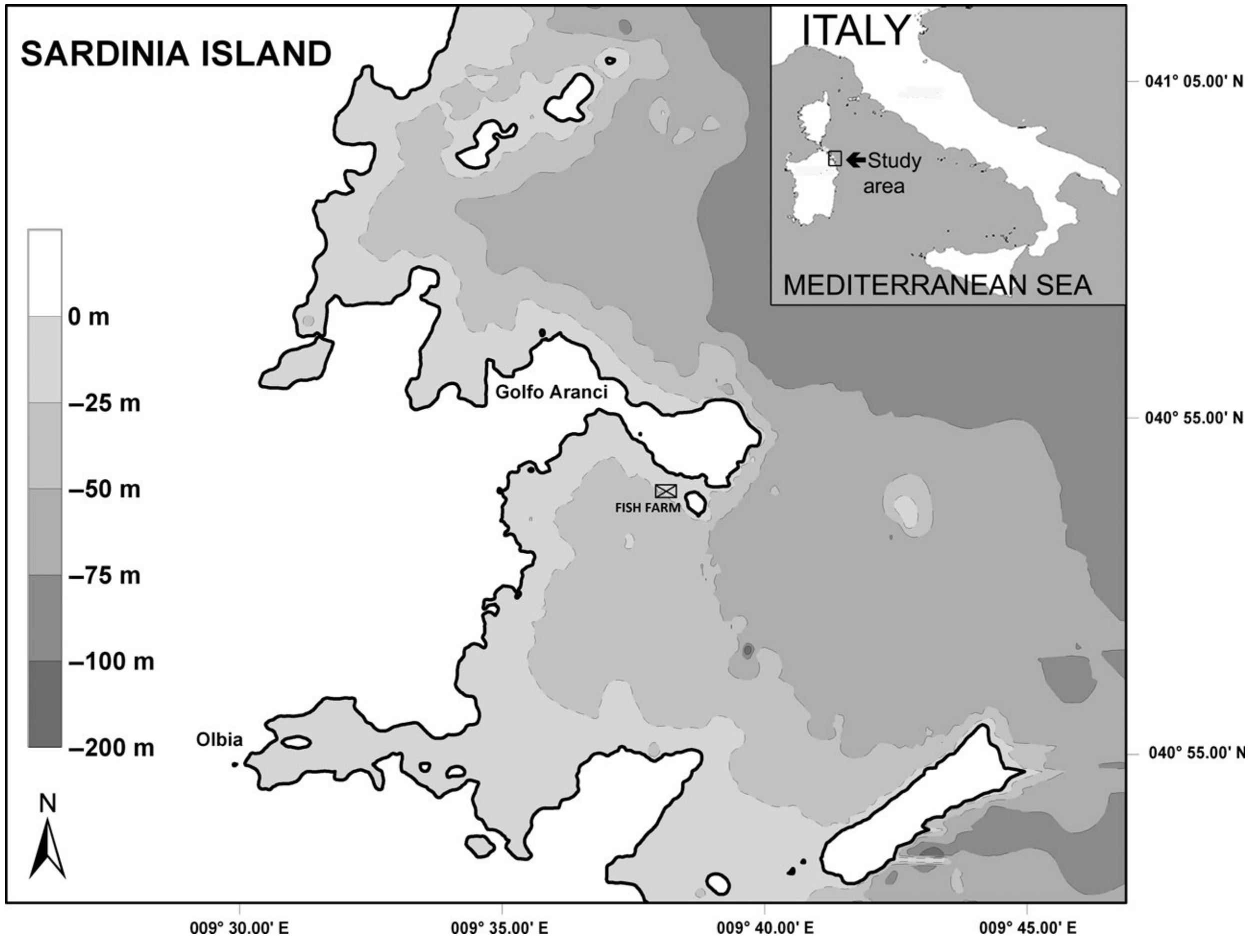

Fig. 1. Map of the northeastern coast of Sardinia (Italy) showing the location of the marine fin fish farm.

relative abundance or sightability of the predators. The variables that were taken in consideration in the 20-min sample sets were both environmental (wind speed, sea state, water temperature, and visibility) and anthropogenic (harvesting operations in the fish farm). Twenty-min sample sets were considered satisfactory when the visibility was not reduced by rain or fog, and sea conditions were <4 on the Douglas sea force scale (approximately equivalent to the Beaufort wind force scale).

In order to analyse the seasonality of top predators in the study area, four seasons were defined: winter (January to March); spring (April to June); summer (July to September); and autumn (October to December). Furthermore, to analyse circadian fluctuations in the presence of predators, each day was divided into three different time periods of the same duration based on the total daylight hours of the month (morning, afternoon and evening hours). Local time was converted to solar time when appropriate, to account for clock changes for daylight saving.

Photo-identification of bottlenose dolphins

During each bottlenose dolphin encounter attempts were made to photograph all individuals present in the fish farm area. This was done in order to determine individual identification by using photographs of their dorsal fins and surrounding area as unique natural markers (Würsig & Jefferson 1990). Digital photographs were taken using digital single-lens reflex cameras equipped with telephoto zoom lens. Only photographs in focus, with the dorsal fin perpendicular to the plane of the photograph and with the dorsal fin large enough to identify small notches were used for subsequent analyses. Individual dolphins were identified from photographs based primarily on the size, location and pattern of notches on the trailing edge of the dorsal fin and on the back, directly behind the dorsal fin. Features such as body and dorsal fin scars, lesions and tooth-rakings were used as secondary characteristics, thereby reducing the possibility of false positives (Wilson *et al.* 1999). Thus, a marked individual was considered one that is recognized not by a single feature, but by a matrix of marks that form a distinctive 'face' for the individual (Díaz López 2012). Although bottlenose dolphins may acquire new marks as they get older, the year-round nature of the present study allowed the observers to monitor small and gradual changes in these distinctive marks. 'Poor' quality photographs or unmarked individuals were excluded from the analysis to minimize the bias from possible misidentification.

Statistical analysis

By selecting data at random the lack of independence arising from consecutive samplings was limited, avoiding the influence of variations in the observation effort, and limiting any pseudoreplication problems. The target sample size was arbitrarily set at 100 randomly selected instantaneous 20-min sets for each season for each year for all 9 years of the research. Thus, in order to limit the lack of independence arising from consecutive 20-min instantaneous set sampling and to control for seasonal variation, a total of 3600 (47% of the collected 20-min instantaneous sets) randomly selected samples was used.

The relative frequency of occurrence of the various species (from now on described as encounter ratio, ER) was computed for each predator species observed as ER = Ns/St (h), where St is the number of 20-min sets spent in the fish farm area and Ns is the total number of 20-min sets for which the species in question was present in the fish farm area.

Detection of inter-annual trends in presence and numbers of predators in the fish farm area was one of the objectives of the analysis. Two tests were applied to the 9 years of data in this study to detect statistically significant annual trends: (i) the rank-based non-parametric Mann–Kendall test (Kendall 1975) for a monotonic downward or upward trend, complemented by the Theil slopes of the linear trend line and (ii) a test based on the non-linear locally weighted polynomial regression (LOESS smoother). In these tests, the null hypothesis (H_0) was that there has been no annual trend in ER over time; the alternative hypothesis (H_1) was that there has been a trend (increasing or decreasing) over time. The Mann–Kendall test is efficient and outlier-resistant in the case of a linear trend, but cannot be applied for assessing non-monotonic or highly non-linear trends. The test based on the LOESS smoother (Fryer & Nicholson 1999; Uhlig 2001) can also be applied for non-linear and non-monotonic trends, but is not outlier-resistant and the corresponding test examines the underlying linear trend component only. The test statistic is derived from the estimate of the linear trend component and the residual variance of the LOESS smoother (Hastie & Tibshirani 1990).

As the shapes of relationships with explanatory variables were unknown, generalized additive models (GAMs) were used. Explanatory variables were measures of weather (wind speed and sea force state), sea surface temperature, season of the year and the time period within each day at which observations were carried out.

We initially attempted to model presence-absence of predators as a binomial GAM with a logistic link function. For numbers of animals seen, quasi-Poisson models were used, *i.e.* assuming a Poisson distribution with an additional parameter to allow for over-dispersion (Pierce *et al.* 2010). The GAMs were implemented from the library mgcv (Wood 2006) in v. 1.8.1. of the computer package R (R Development Core Team 2005).

Models were constructed by a combination of forwards and backwards selection. We conservatively removed a variable in the model if it was clearly non-significant ($P \gg 0.05$). To assist with the selection process we used the 'basis = cs' option for fitting smoothers, which allows degrees of freedom for individual smoothers to fall to zero (a good indication of non-significance). If the final value for degrees of freedom of a smoother was around 1.0, *i.e.* the fit was approximately linear, we replaced the smoother with a linear term (Pierce *et al.* 2010).

The final model was the model with the lowest Akaike information criterion value given that the effects of all explanatory variables retained in the model were statistically significant and that there were no clear patterns in the residuals.

Results

Survey effort and presence of predators

The field effort in the marine fin fish farm entailed nine consecutive years of fieldwork from November 2004 to November 2013. Overall, 99 months (1062 days during 36 consecutive seasons) were spent in the field. A total of 2534 h was spent in satisfactory conditions (corresponding to 7602 instantaneous 20-min sets). On average 118 ± 4.6 days per year (281 ± 42 h, corresponding to 845 ± 126 instantaneous 20 min sets) were spent conducting observations in the fish farm area.

The most frequently sighted species, the yellow-legged seagull (*Larus michahellis*), was seen during 84% of observation periods as compared with 74% for the next most common, the shag (*Phalacrocorax aristotelis*). Common bottlenose dolphins (*Tursiops truncatus*) were seen during 57% of observations whereas grey herons (*Ardea cinerea*) were seen during 6% of observation periods. Other species, such as common terns (*Sterna hirundo*), Adouuins gull (*Ichtyaetus adouinii*), cormorants (*Phalacrocorax carbo*), and hooded crows (*Corvus cornix*), were observed sporadically and at low densities.

The relative frequency of occurrence (ER) of the predator species in relation to the different temporal variables (year, season and time period of the day) and harvesting operations are summarized in Tables 1–4 , respectively. Uncorrected data on frequency (ER) suggested an increase in occurrence of bottlenose dolphins and grey herons over time. No clear trends were evident for the other species.

The aggregation sizes of marine birds varied between one and 350 individuals. Bottlenose dolphin aggregations ranged from one to 16 individuals. The numbers of different predators observed at one time at the fish farm in relation to the different temporal variables (year, season and time period of the day) are summarized in Tables 5–7, respectively.

Annual trends in presence of mammalian and avian predators

Trend analysis revealed significant upward annual trends in the presence of bottlenose dolphins and herons ($P \ll 0.01$). For the remaining species (yellow-legged seagulls and shags), annual trends were not significant ($P > 0.05$).

Fluctuations in predators' presence in the fish farm area

The final models for the presence of the most frequently seen predator species are summarized in Table 8. The final GAMs for presence of predators indicated that the effects of wind strength and sea force state (weather conditions) were not significant.

Once these results were taken into account, in the final model for bottlenose dolphins there was a tendency for increased sightings during the later years of the project compared with the first year. There was also a peak of sightings during harvesting operations in the fish farm, rather than in absence of operations of this type. Moreover, sightings occurred most frequently during the periods with lower sea surface temperature (Fig. 2a). Likewise, there was a significant trend for fewer sightings to take place during the spring and summer months. There was no significant diurnal variation in the incidence of sightings. The model explained 21% of the deviance in bottlenose dolphin presence and is thus relatively good.

The final models for the presence of avian predators indicated that sightings of yellow-legged seagulls and shags did not change over the 9 years of study. However, trend for increased sightings of grey herons during the later years of research compared with the first year was observed. Whereas the frequency of sightings of shags was lowest during periods with lower sea surface temperature (Fig. 2b), there was a peak of sightings of grey

Table 1. The observation effort, random subset of data and observed encounter ratio (ER) for each of the 9 years of research.

Year	No. 20-min instantaneous sets	Random subset of data	Bottlenose dolphin ER	Seagull ER	Shag ER	Heron ER
1st year	1079	400	0.35	0.83	0.75	0
2nd year	1030	400	0.29	0.78	0.76	0.005
3rd year	1049	400	0.53	0.88	0.81	0.0175
4th year	1033	400	0.59	0.81	0.75	0.005
5th year	912	400	0.69	0.93	0.87	0.08
6th year	695	400	0.77	0.79	0.60	0.1475
7th year	579	400	0.64	0.91	0.71	0.2475
8th year	620	400	0.65	0.90	0.77	0.2875
9th year	605	400	0.66	0.77	0.64	0.31
Total	7602	3600	0.57	0.84	0.74	0.06

Season	No. 20-min instantaneous sets	Random subset of data	Bottlenose dolphin ER	Seagull ER	Shag ER	Heron ER
Winter	1474	900	0.62	0.83	0.69	0.12
Spring	2274	900	0.47	0.85	0.78	0.01
Summer	2671	900	0.52	0.73	0.76	0.03
Autumn	1183	900	0.64	0.76	0.71	0.13

Table 2. The observation effort, random subset of data and observed encounter ratio (ER) with respect to season.

Time period	No. 20-min instantaneous sets	Random subset of data	Bottlenose dolphin ER	Seagull ER	Shag ER	Heron ER
Morning	2725	1200	0.56	0.72	0.62	0.03
Afternoon	3009	1200	0.59	0.66	0.57	0.05
Evening	1868	1200	0.56	0.60	0.50	0.11

Table 3. The observation effort, random subset of data and observed encounter ratio (ER) with respect to daily time period.

Table 4. The observation effort data and observed encounter ratio (ER) with respect to whether or not harvesting operations were taking place in the fish farm.

Harvesting operations	No. 20-min instantaneous sets	Bottlenose dolphin ER	Seagull ER	Shag ER	Heron ER
Yes	1390	0.62	0.71	0.62	0.03
No	5810	0.48	0.69	0.59	0.05

herons in periods with lower sea surface temperature conditions (Fig. 2c). Yellow-legged seagulls were seen more often during the evening whereas shags were seen less often during this time of day. There was a significant diurnal variation in the incidence of sightings of grey herons, with more sightings in the afternoon and evening, and fewest in the morning. In all of the latter three cases, the % deviance explained was over 20% and so the models can be considered satisfactory.

Temporal trends in numbers of predators seen

The GAM results for the number of individuals of the same species sighted at the same time are summarized in Table 9. Like in the models for the presence of predators, in these models relationships with weather conditions (wind strength and sea force state) were not significant.

The numbers of bottlenose dolphins visiting the fish farm at the same time tended to be higher during the later years of research compared with the first year. The aggregations were bigger during autumn and there was a lower number of individuals during the morning. The model explained 16.9% of the deviance in numbers of bottlenose dolphins and is thus relatively weak.

The numbers of yellow-legged seagulls showed peaks during spring and in the evenings. The sizes of aggregations of shags and grey herons showed variations depending on the sea surface temperature, with a negative effect on the number of individuals for grey herons and a positive effect for shags (Fig. 3). Likewise, peaks in the

Table 5. Mean±SE, and minimum and maximum number (below) of the different predators observed at one time at the fish farm during each year of research.

Year	Bottlenose dolphin	Seagull	Shag	Heron
1st year	3.6 ± 0.2	23.3 ± 0.9	5.7 ± 0.2	
	1–13	1–140	1–32	0
2nd year	3.2 ± 0.2	24.1 ± 1	5.8 ± 0.1	
	1–16	1–120	1–30	0
3rd year	3.0 ± 0.1	23.8 ± 1	5.9 ± 0.2	1.6 ± 0.3
	1–10	2–140	1–33	1–3
4th year	3.8 ± 0.2	19.1 ± 0.7	6.6 ± 0.5	5 ± 4
	1–13	1–100	1–75	1–9
5th year	3.9 ± 0.2	20.1 ± 0.7	3.7 ± 0.2	2.8 ± 0.4
	1–12	1–112	1–22	1–10
6th year	5.1 ± 0.2	52.1 ± 2.1	5.6 ± 0.3	3.9 ± 0.6
	1–16	1–258	1–40	1–18
7th year	4.8 ± 0.2	50.2 ± 1.6	6.9 ± 0.4	3.4 ± 1
	1–14	2–164	1–47	1–15
8th year	4.0 ± 0.2	40.9 ± 1.6	6.5 ± 0.5	4.1 ± 1
	1–16	1–220	1–56	1–34
9th year	4.8 ± 0.2	51.0 ± 1.7	6.5 ± 0.5	8 ± 1.8
	1–12	2–220	1–56	1–60
Total	4.0 ± 0.1	36.5 ± 0.6	5.9 ± 0.1	4.5 ± 0.5
	1–16	1–258	1–75	1–60

Table 6. Mean±SE, and minimum and maximum number (below) of the different predators observed at one time at the fish farm in each season.

Species	Spring	Summer	Autumn	Winter	Total
Bottlenose dolphin	4.2 ± 0.1	3.9 ± 0.1	4.5 ± 0.2	3.5 ± 0.1	4 ± 0.1
	1–16	1–16	1–16	1–12	1–16
Seagull	34.8 ± 0.8	29.5 ± 0.7	33.4 ± 0.9	27.9 ± 0.7	31.3 ± 0.4
	1–258	1–350	1–140	1–161	1–350
Shag	5.3 ± 0.1	7.5 ± 0.1	4.1 ± 0.2	5.6 ± 1.1	6.6 ± 0.1
	1–27	1–40	1–20	1–94	1–94
Heron	1 ± 0	4.6 ± 1.3	5.1 ± 0.6	4.2 ± 0.7	4.5 ± 0.4
	1	1–60	1–34	1–38	1–60

Table 7. Mean±SE, and minimum and maximum number of the different predators observed at one time at the fish farm in different daily time periods.

Species	Morning	Afternoon	Evening
Bottlenose dolphin	3.8 ± 0.1	4.3 ± 0.1	4.0 ± 0.1
	1–16	1–16	1–16
Seagull	26.8 ± 0.6	28.2 ± 0.5	29.2 ± 0.7
	1–258	1–258	1–140
Shag	4.5 ± 0.1	6.4 ± 0.1	5.8 ± 0.1
	1–43	1–19	1–18
Heron	3.5 ± 0.1	4.75 ± 1.0	4.76 ± 0.5
	1–38	1–60	1–34

number of individuals were observed during summer for shags and the lowest number of herons occurred during spring. There were effects of the time period of the day, with the smallest aggregations of shags occurring during the morning and a higher number of herons during the evening. In all of the latter three cases, the % deviance explained was over 20% and so the models can be considered satisfactory.

Recognizable bottlenose dolphins and preferences for the fish farm area

Overall, 27,978 ‘good’ quality photographs were obtained from 801 independent dolphin aggregations (accounting for 55% of all encounters). A total of 121 identified individuals visited the fish farm area between November 2004 and November 2013.

The average number of photographic recaptures per individual was 41.3 ± 8.9 (from 1–564, n = 121), with 22 individuals (18.8%) re-sighted over 50 times. In particular, 16 common bottlenose dolphins, accounting for 13% of all identified individuals, were identified more than 100 times throughout the study period (corresponding to 76% of observations). However, 26 common bottlenose dolphins (21%) were identified only once throughout the study period. This shows that some individuals interacted with the marine fin fish farm on a regular basis, whereas others were present occasionally.

Discussion

The interaction between predators and aquaculture, and the consequences of this interaction, are of great importance for coastal and aquaculture management. This long-term study describes for the first time in Mediterranean waters the temporal variability of mammalian and avian predators’ presence at a coastal fin fish farm.

During this long-term study four different species of top predators were seen interacting with the marine fin fish farm. Common bottlenose dolphins (*Tursiops truncatus*), yellow-legged seagulls (*Larus michahellis*), shags (*Phalacrocorax aristotelis*) and grey herons (*Ardea cinerea*) were observed regularly feeding in the fish farm area. Although other species such as common terns (*Sterna hirundo*), Adouuins gull (*Ichtyaetus adouinii*), cormorants (*Phalacrocorax carbo*) and hooded crows (*Corvus cornix*) visited or passed close to the fish farm area at low densities, apparently none preyed on the stock. By examining the results of this study, it is clear that the presence of the four top predator species mentioned above (considered to cause economic loss to the fish farm owing to direct predation) is reasonable. Moreover, the results suggest an increasing annual trend in the presence and numbers of bottlenose dolphins and herons from the first year of research.

Avian predators

The bird species considered to cause economic loss in the fish farm owing to direct predation were similar to species causing problems in other geographical locations. Surveys of Scottish fin fish farms showed that gulls, shags and grey herons were the most commonly reported bird predators at the fish farms (Mills 1980; Ross 1988). Of these three species of marine birds, aquaculturists are most concerned about shags. Shags are almost entirely piscivorous and feed exclusively during daylight hours

Table 8. Summary of generalized additive models for temporal patterns in presence of all predator species: bottlenose dolphins, yellow-legged seagulls, shags and grey herons. For categorical explanatory variables, the effect given for each level is relative to a reference level (*e.g.* for sea force state, all comparisons are in relation to observation periods with level zero for the sea force state). For each model, all significant explanatory variables are listed with their associated probability (P) value, along with the overall % deviance explained by the model and sample size (number of observation periods, n). For categorical and linear explanatory variables, the direction of the effect is indicated as + or –; for smoothers (s), the degrees of freedom are indicated in parentheses. Not significant P > 0.05 values are represented by empty fields -.

Variables	Bottlenose dolphin	Seagull	Shag	Heron
wind strength	–	–	–	–
Sea force state 1	–	–	–	–
Sea force state 2	–	–	–	–
Sea force state 3	–	–	–	–
Sea surface temperature	s(6.0), $P < 0.0001$	–	s(2.8), $P = 0.0302$	S(3.64), $P = 0.0003$
Project year 2	–, $P = 0.0018$	–	–	$P > 0.05$
Project year 3	+, $P = 0.0002$	–	–	$P > 0.05$
Project year 4	+, $P < 0.0001$	-	–	$P > 0.05$
Project year 5	+, $P < 0.0001$		–	+, $P < 0.0001$
Project year 6	+, $P < 0.0001$	–	–	+, $P < 0.0001$
Project year 7	$P > 0.05$	–	–	$P > 0.05$
Project year 8	+, $P = 0.035$	–	–	+, $P = 0.0450$
Project year 9	+, $P < 0.0001$	–	–	+, $P = 0.0020$
Morning	–	+, $P = 0.0335$	$P > 0.05$	–, $P = 0.0452$
Evening	–	$P > 0.05$	–, $P = 0.0256$	+, $P < 0.0001$
Season 2 (winter)	$P > 0.05$	–	–	–, $P = 0.0036$
Season 3 (spring)	–, $P < 0.0001$	–	–	–, $P < 0.0001$
Season 4 (summer)	–, $P < 0.0001$	–	–	–, $P = 0.013$
% deviance explained	17.6	24	73.8	42.1
n	1966	237	170	1096

(Cramp & Simmons 1977). In the present study, sightings of shags occurred most frequently during periods with higher sea surface temperature and less often during evening hours. Their numbers also increased during summer months. They were often persecuted as the workers discovered that they are capable of extracting large quantities of fish from inside the cages. Observations during this study agree with observations made in Scotland, where shags mostly attacked fish through the netting, instead of taking them from the inside of the cages (Carss 1993). Thus, in both studies most of the fish eaten by the shags near the farm were wild and concentrated on the outside of the cages.

Yellow-legged gulls were present frequently in the fish farm. This predator was moreover the most abundant. The gulls interfered frequently with farmed fish feeding operations, causing the stressed fish to stop eating. The interference was due to their interest in both the fish being fed and the food itself.

In this study, the occurrence of grey herons in the fish farm increased from the first year of research. Herons usually fed by standing on the anti-predator top nets and pulling fish through the mesh. They were attracted to the fish farm, but owing to the low number of individuals present at any one time it is believed that the resulting economic losses were low. This differs from other areas where the interaction between herons and fish farms produced major economic losses (*e.g.* Draulans & van Vessem 1985). The occurrence of grey herons in the study area decreased during warmer periods, for migratory reasons. In addition, the presence and numbers of herons in the fish farm increased during the evening. This increase could be explained by the nocturnal behaviour of the herons and lower anthropogenic disturbance during evening hours. Hence, it is possible to expect a higher number of herons throughout the night than during daylight hours. A similar circadian distribution was observed in a fish farm in the north of Belgium (Draulans & van Vessem 1985).

Mammalian predators

Although the bottlenose dolphin was not the most important of all predator species observed here, predatory interactions with the fish farm occurred with what seemed to be increasing regularity over the study period. Annual increases in the levels of occurrence and numbers of bottlenose dolphins were observed from the first year of research onwards. Another factor to take into consideration is the possible attraction caused by the harvesting operations in the fish farm. Our data indicate that

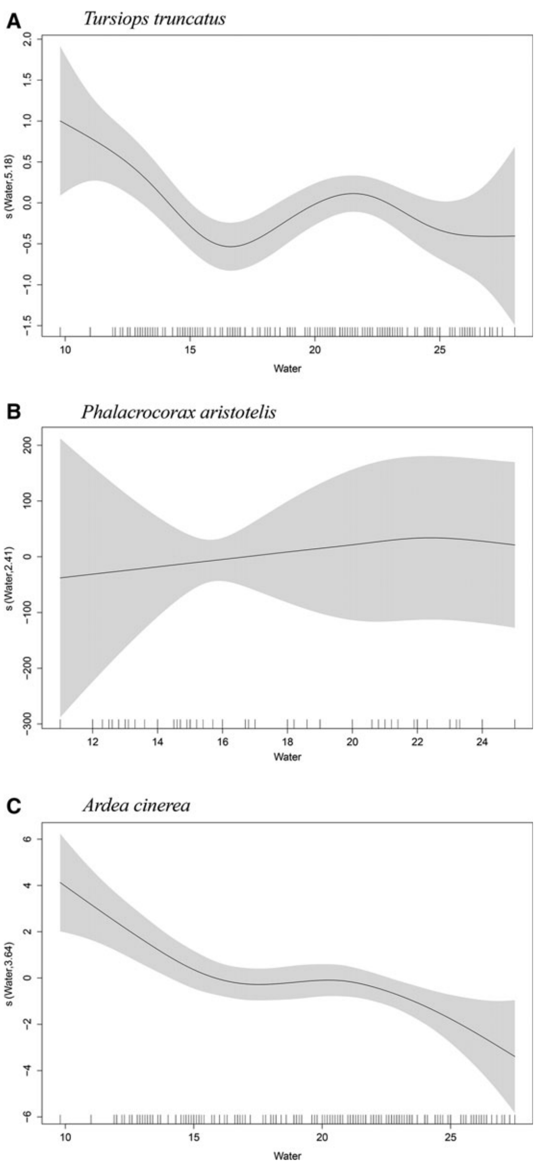

Fig. 2. Smoothers for generalized additive models showing significant effects of sea surface temperature on bottlenose dolphin (*Tursiops truncatus*) (a), shag (*Phalacrocorax aristotelis*) (b) and grey heron (*Ardea cinerea*) (c) presence.

bottlenose dolphins were more often seen in the fish farm area when harvesting operations were taking place. This is in accordance with observations of bottlenose dolphins predating on the fish that sometimes escape or are discarded during the harvesting procedure. Owing to this predatory interaction and their regular presence, bottlenose dolphins have become the main culprit for the problems that the fish farm faces (*i.e.* farmed fish mortality as a result of stress, C. Graziano personal communication).

The observed seasonal patterns in occurrence and group size seem to be related to both changes in feeding opportunities and seasonal fluctuations in metabolic needs. In a different fish farm along the northwestern coast of Sardinia bottlenose dolphins showed a similar seasonal pattern during spring and summer (seasons in which sea surface temperatures peak and dolphin occurrence is lowest) in response to increased feeding opportunities in the surrounding area (Diaz Lopez *et al.* 2013). Fish farms offer an alternative food source for dolphins during periods with low prey abundance (*i.e.* autumn and winter months); thus, hunting at fish farms usually requires less effort on the part of the predator, and becomes a more attractive option than hunting wild fish over wide ranges at these times.

During the period of this study, a low percentage of bottlenose dolphins (13%) exhibited high site fidelity to the marine fin fish farm. They visited the fish farm frequently in aggregations containing low numbers of individuals (between one and 16). The proportion of bottlenose dolphins regularly observed in the study area indicates that there are few individuals that should be considered as direct predators in the fish farm. The observed long-term interaction leads to individuals possessing intimate knowledge of the fish farm, and therefore knowledge about where food resources are most likely to be found and how to obtain them. This type of interaction may also influence the extent of home ranges for these specialized individuals (Eifler 1996). In a similar way, Boutin (1990) for example, conducted a review of deliberate supplemental feeding of terrestrial vertebrates and found that in most cases (where home range size was examined) a reduced home range was observed.

Consequences of the observed predatory interactions

The current risks of the top predators observed here to the aquaculture industry are both market-related, as they affect the quality of the product, and production-related, as they affect daily operations. Production loss was observed in several ways in the present study and varied with the predator species. First, there was direct predation, which was clearly observable for marine birds but more difficult to estimate with bottlenose dolphins. Moreover, the presence of mammalian and avian predators may also worsen a disease outbreak by increasing the stress levels of the fish (Westers 1983; Price & Nickum 1995). Birds also carry bacterial pathogens in their gut and on their feet (Taylor 1992), and are intermediate or definitive hosts to numerous cestodes, nematodes, trematodes and other parasites (European Inland Fisheries Advisory Commission (EIFAC) 1988).

Table 9. Summary of generalized additive models for temporal patterns in numbers of animals seen for *Tursiops truncatus*, *Larus michahellis*, *Phalacrocorax aristotelis* and *Ardea cinerea*. For categorical explanatory variables, the effect given for each level is relative to a reference level (*e.g.* for sea force state, all comparisons are in relation to observation periods with level zero for the sea force state). For each model, all significant explanatory variables are listed with their associated probability (P) value, along with the overall % deviance explained by the model and sample size (number of observation periods, n). For categorical and linear explanatory variables, the direction of the effect is indicated as + or –; for smoothers (s), the degrees of freedom are indicated in parentheses. Not significant P > 0.05 values are represented by empty fields -.

Variables	*Tursiops truncatus*	*Larus michahellis*	*Phalacrocorax aristotelis*	*Ardea cinerea*
Wind strength	–	–	–	–
Sea force state 1	–	–	–	–
Sea force state 2	–	–	–	–
Sea force state 3	–	–	–	–
Sea surface temperature	–	–	s(7.9), P < 0.0001	s(8.67), P < 0.0001
Project year 2	P > 0.05	–	P > 0.05	P > 0.05
Project year 3	P > 0.05	–	P > 0.05	P > 0.05
Project year 4	P > 0.05	-	P > 0.05	P > 0.05
Project year 5	+, P = 0.0453		P > 0.05	+, P = 0.0426
Project year 6	+, P < 0.0001	–	–, P < 0.0001	+, P < 0.0453
Project year 7	+, P = 0.0016	–	P > 0.05	P > 0.05
Project year 8	+, P = 0.0432	–	+, P = 0.0186	P > 0.05
Project year 9	+,P = 0.0039	–	+, P = 0.0436	+, P = 0.0015
Morning	–, P = 0.0011	P > 0.05	–, P < 0.0001	–, P = 0.0016
Evening	P > 0.05	–, P = 0.0318	+, P = 0.0037	+, P < 0.0001
Season 2 (winter)	–, P < 0.0001	P > 0.05	+, P < 0.0001	–, P < 0.0001
Season 3 (spring)	–, P = 0.0134	+, P < 0.0001	+, P < 0.0001	–, P < 0.0001
Season 4 (summer)	–, P = 0.0048	–, P = 0.0009	+, P < 0.0001	–, P = 0.0269
% deviance explained	16.9	40.1	26.5	56.8
n	1491	1098	1098	1096

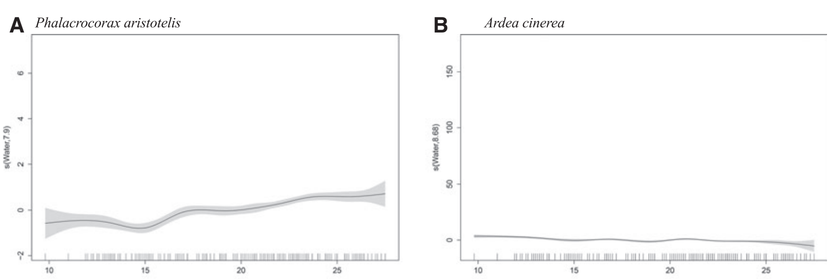

Fig. 3. Smoothers for generalized additive models showing significant effects of sea surface temperature on shag (*Phalacrocorax aristotelis*) (a) and grey heron *(Ardea cinerea)* (b) numbers.

Anti-predator measures used to protect the fish farm from 2004 to 2013 included human presence, top and underwater barrier nets, overhead lines and the use of acoustic harassment devices (Díaz López & Shirai 2007; Díaz López & Mariño 2011). Fish farm workers perceived problems with birds to be smaller in cages with top nets than those without (‘unprotected’; C. Graziano, personal communication). Avian predators were often caught incidentally in top netting at cage farms and incidental captures of bottlenose dolphins in barrier nets were also observed in this area (Díaz López & Shirai 2007; Díaz López 2012).

When attempting to curb predation, the marine fin fish farm did not take into consideration human activities that were attracting the predators. The frequent and increasing number of observations of dolphins being fed discarded fish by fish farm workers during harvesting operations supports the theory that some individuals were becoming habituated in response to this food supply.

This ‘deliberate feeding’ activity increased yearly (Dr Graziano, personal communication) and had a variety of impacts on the dolphins. Deliberate and long-term provision of food to marine mammals has been shown to alter natural behaviour patterns and population levels (Orams 1995). It has also resulted in the dependency of animals on the human-provided food and in their habituation to human contact. Bottlenose dolphins’ offspring learn the skills for obtaining food from mothers and other adults (Gibson & Mann 2008). If the adults are dependent on humans, the offspring may never acquire the skills that they need to feed for themselves (Mann & Sargeant 2003).

The current risks of the observed feeding activity for the industry affected daily operations. In several cases fish farm divers were disturbed in their operations because an animal detected food but was denied it, or was teased with it (B. Díaz López, personal observation). Similarly, illegal feeding of dolphins in the Southeastern USA has resulted in ‘‘people being bitten, swimmers being pulled under the water, and injuries severe enough to require stitches and hospitalization’ (Orams 2002). In Brazil, a man who was harassing a wild dolphin was killed when the dolphin rammed him in the chest (Orams 2002). Orams *et al.* (1996) also reported on the risks of dolphins becoming aggressive as a result of regular provisioning.

Based on the results presented in this paper, it is recommended that strategies for the management of the aquaculture industry and the protection for animal species, some of this predator species are listed in Annex IV (a) in the European Habitats Directive (art. 12) (Office for Official Publications of the European Communities 2000), should take this study in consideration.

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