Original Article

Risso’s dolphin depredation in the Azorean hand-jig squid fishery: assessing the impacts and evaluating effectiveness of acoustic deterrents

Maria João Cruz1*, Vera Leal Jordão1, João Gil Pereira1, Ricardo Serrão Santos1, and Mónica A. Silva1,2

1Departamento de Oceanografia e Pescas, IMAR and LARSyS Associated Laboratory, Universidade dos Açores, 9901-862 Horta, Portugal
2Biology Department, Woods Hole Oceanographic Institution, Woods Hole, MA 02543, USA

*Corresponding author: tel: +351 292 207 800; fax: +351 292 207 811; e-mail: mjoaocruz@uac.pt


Depredation rate was calculated at 3% yielding an estimate of 8–12 t of squid lost to dolphins per year and an annual economic loss of €50 000 for the squid fishery of S. Miguel. The use of pingers had no significant effect on the catch per unit effort of squids. Depredation rates were similar for the control (0.20), inactive (0.19), and active (0.19) pinger conditions. Models indicated no significant effect of pinger brand and condition on cetacean depredation. This study is the first attempt to monitor depredation by Risso’s dolphins on a hand-jig squid fishery providing a scientific basis for future management of interactions between cetaceans and fisheries.

Keywords: acoustic deterrents, depredation, Risso’s dolphin, squid fishery.

Introduction

Interactions between marine mammals and fisheries occur worldwide, involving nearly all fisheries and species, and are a growing economic, ecological, and social issue. Marine mammals may interact directly with the fisheries (operational interactions), becoming entangled, damaging the fishing gear, interfering with fishing operations, and reducing the catch, and indirectly (ecological interactions), by competing for the same resources (Trites et al., 1997; Kaschner et al., 2001; Read, 2008). Cetacean depredation, i.e. damage or removal of captured fish from fishing gear, can result in catch loss or a decrease in its economic value, and often in damages to the fishing gear. Depredation is responsible for substantial economic losses in some fisheries (Hucke-Gaete et al., 2004; Zollet and Read, 2006; Roche and Guinet, 2007; Brotons et al., 2008a, b; Tixier et al., 2010) and often creates hostility in fishers who may attempt to retaliate against cetaceans to protect their catch or gear (Gilman et al., 2006, Read, 2008). Depredation by odontocetes appears to be growing in frequency, geographic extent, and severity (Reeves et al., 2001; Donoghue et al., 2003; Gilman et al., 2006; Brotons et al., 2008a, b; Lauriano et al., 2009). Therefore, the fishing industry is in urgent need of mitigation measures that can reduce the frequency and severity of such interactions.
Acoustic alarms, such as pingers, were initially developed to reduce bycatch of small cetaceans in gillnet fisheries (Goodson, 1997; Kraus et al., 1997). Pingers are low-powered sound generators (typically <150 dB re 1 mPa at 1 m) and operate in the mid- to high-frequency range (10–100 kHz). Past experiments to determine whether acoustic alarms could be prevented or deter cetaceans from interacting with fishing gear have provided disparate results. Brotons et al. (2008b) reported that the use of active pingers apparently discouraged bottlenose dolphins (Tursiops truncatus) from interacting with the gillnet fishery in the Balearic Islands. Buscaino et al. (2009) reported that bottom gillnets equipped with pingers contained 28% more fish and were less damaged (31%) by dolphins. In contrast, Cox et al. (2003) observed limited behavioural responses by bottlenose dolphins to gillnets equipped with pingers. They also noted that the pingers used in this experiment did not prevent occasional incidences of depredation. Similar results were observed by Burke (2004) wherein pingers were not effective in dissuading bottlenose dolphins from readily approach the gillnets and engage in depredation in the Spanish mackerel fishery.

Considering the different acoustic properties of these devices, each model should be properly tested since the response to the produced sound is likely to vary between species and even individuals, fishing areas, and fisheries (Dawson et al., 1998; Kastelein et al., 2007; Berrow et al., 2008; Brotons et al., 2008b).

In the Azores, interactions between cetaceans and fisheries are becoming increasingly problematic. There are four main fisheries in the region: a small pelagic fishery targeting young blue horse mackerel (Trachurus picturatus), chub mackerel (Scomber japonicus), and sardine (Sardina pilchardus) with surrounding nets; a pole-and-line fishery for tunas (Tuna spp.); a multispecific demersal fishery that uses handlines and bottom longlines; and a swordfish (Xiphius gladius) fishery with surface longlines (Santos et al., 1995; Morato et al., 2001; Menezes et al., 2002; Carvalho et al., 2011). All these fisheries have experienced interactions with cetaceans, but the nature and impact of the interactions vary with the fishery and cetacean species involved (Silva et al., 2011). In the tuna fishery, common (Delphinus delphis) and spotted dolphins (Stenella frontalis) were responsible for most interference, by scaring the fish and eating the bait, resulting in an increase in the proportion of fishing events with no catches and the time spent in fishing operations (Silva et al., 2002, 2011). In demersal fisheries, bottlenose dolphins were responsible for most depredation events, while in the swordfish fishery, depredation was associated with the presence of killer whales (Orcinus orca). In both cases, the rates of interaction were low but likely underestimated due to low observer coverage (Silva et al., 2011).

More recently, Risso’s dolphins (Grampus griseus) have been reported by the fishers to interact with the Azorean artisanal fishery for veined squids (Loligo forbesi). This fishery is undertaken in daylight (6–7 h of fishing) by small wooden open-deck boats (<10 m length, 2–7 crew), using handlines (Porteiro, 1994). Each fisher handles a single handline with 1–2 plastic jigs and a small weight placed at the end of the line to keep the gear at a fishing depth of 100–180 m. The fishery does not use bait (dead or alive). Although considered a small-scale fishery, with 166 fishing vessels (Porteiro, 1994) and accounting for only 5% of total fisheries revenue (Carvalho, 2011), the squid fishery is the only source of work and income for several local communities.

In an attempt to address the growing complaints caused by dolphin depredation in this fishery, in 2008, the Fishermen’s Association of the islands of S. Miguel and S. Jorge acquired two pingers (“Fumunda Marine” and “AQUAmark300”, see characteristics of the pingers below) and handed them to selected fishing boats, without instructing fishers on their use. These two pingers were used a few times and rapidly put aside, as fishers failed to notice an evident reduction in depredation by Risso’s dolphins. Yet, pinger utilization and effectiveness were never properly assessed. Studies focusing on interactions between Risso’s dolphins and fisheries are scarce. We found but a few reports of Risso’s dolphin bycatch in pelagic drift gillnet and longline fisheries (Notarbartolo di Sciara, 1990; Öztürk et al., 2001; López et al., 2003; Garrison, 2007; Mangel et al., 2010; Bearzi et al., 2011; Carretta and Henríquez, 2012). Mussi et al. (1999) noted the occurrence of interactions between Risso’s dolphins and a squid handline fishery during a general study of cetacean populations in the archipelago Pontino Campano, in which dolphins were attracted to boats to take advantage of squid aggregations.

Understanding the nature and impact of the factors that may drive the interaction of Risso’s dolphins with the hand-jig squid fishery in the Azores is essential to the development of mitigation measures with benefits for both Risso’s dolphin populations and the fishery. The aims of the current study were to (i) characterize how the squid fishery has evolved since 1993, following on from Porteiro (1994), (ii) assess the frequency and severity of dolphin depredation, (iii) estimate catch losses and economic impacts resulting from depredation, (iv) determine which factors influence the frequency and magnitude of depredation, and (v) experimentally test different brands of pingers to determine their efficiency at reducing dolphin depredation.

Methods

Study area

The archipelago of the Azores (Portugal) is a group of nine volcanic islands located between 37° and 41° N and 25° and 31° W in the Atlantic Ocean (Santos et al., 1995). This study was conducted in the islands of S. Miguel, Faial, Pico, S. Jorge, Graciosa, and Terceira (Figure 1).

Data collection

Fishery statistics

Data collected by the National Program for Fisheries Data Collection (NPFDC) were used to characterize the squid fishery in the Azores. The database includes information on the weight and economic value of the species landed by fishing boat per day in each harbour, as well as information on boat characteristics (vessel length and gross tonnage).

Fisher interview surveys

From July 2009 to September 2011, we conducted voluntary surveys to fishers in the islands with the highest contribution to the overall daily squid landings, based on information from the NPFDC. A single fisher was interviewed by boat and the respondent was asked to report on the last fishing trip. The interview survey was restricted to fishing boats dedicated to the squid fishery, as defined by the number of times they landed squid (see the Data analysis—Fishery characterization section). All interviews were conducted in person. The questionnaire requested information on boat and gear characteristics, crew, fishing techniques, location of fishing grounds, fishing hours, catches of target species, presence...
and interaction of dolphins and sharks, identification of interacting species, and dolphin bycatch.

**Fishery observations**

Owing to the fishers’ difficulty in quantifying catch loss, fishery observations were carried out to estimate the number of depredated squid per trip and rates of depredation over time, and to collect data on potential factors driving depredation. Time and logistical constraints limited fishery observations to a single island. We selected the island of S. Miguel because it was the area that contributed most to total squid landings, had the greatest number of vessels dedicated to the squid fishery, and where the fishery was practised year-round.

Between July 2009 and August 2011, two trained observers were separately assigned to and rotated between fishing boats from different harbours of S. Miguel. For each daily fishing trip, observers collected information on duration of fishing activity, location, type of gear, number of fishing lines, presence of other fishing boats, number and size class (small < 1 kg, medium = 1 kg, large > 1 kg) of squids captured, presence of dolphins, and number of depredation events. Dolphins were considered to be present during the fishing activity if at least one individual was seen by naked eye within 500 m from the fishing boat. In this case, the species, number of individuals, behaviour, and impact on fishing activity were noted.

Dolphin depredation events included occasions when fishers felt the hooked squid being taken from the line plus the cases when dolphins partially consumed and damaged the squid.

**Pinger experiment**

We selected the island of S. Miguel (Figure 1) to conduct the trials of pinger effectiveness because this was the area with the highest frequency of depredation recorded during the interview survey. The experiment was carried out between May 2010 and August 2011 aboard five boats from the artisanal squid fishing fleet that offered to collaborate in the experiment. Tests were carried out by the same observers that conducted the interview survey and fishery observations.

The pinger was attached to a rope and deployed from the bow of the fishing boat to a fixed depth of 60 m to prevent entanglement in the fishing gear and avoid contact with the propeller. Three pinger conditions were tested: control (no pinger), active pinger (deployed and transmitting), and inactive pinger (deployed but not transmitting). In addition, we examined the effect of two brands of pingers: Fumunda Marine® (sound level 132 ± 4 dB re 1 μPa at 1 m, frequency 10 kHz, replaceable batteries) designed and produced by Future Oceans (http://www.fumunda.com) and the AQUAmark300® (sound level 132 dB re 1 μPa at 1 m, frequency 10 ± 2 kHz, sealed batteries) designed and produced by AQUATEC (http://www.aquatecgroup.com). Both pingers comply with EC Regulation 812/2004 of 26 April 2004. Before the experimental study, we tested whether the acoustic properties of each pinger were in accordance with the manufacturer specifications. The devices were placed underwater to a depth of 10 m and recordings were made during 10 min using the hydrophone Reson TC4032.

Overall, we tested five treatments resulting from the combination of pinger condition and brand: control (no pinger), Fumunda-active, and interaction of dolphins and sharks, identification of interacting species, and dolphin bycatch.

**Fishery observations**

Owing to the fishers’ difficulty in quantifying catch loss, fishery observations were carried out to estimate the number of depredated squid per trip and rates of depredation over time, and to collect data on potential factors driving depredation. Time and logistical constraints limited fishery observations to a single island. We selected the island of S. Miguel because it was the area that contributed most to total squid landings, had the greatest number of vessels dedicated to the squid fishery, and where the fishery was practised year-round.

Between July 2009 and August 2011, two trained observers were separately assigned to and rotated between fishing boats from different harbours of S. Miguel. For each daily fishing trip, observers collected information on duration of fishing activity, location, type of gear, number of fishing lines, presence of other fishing boats, number and size class (small < 1 kg, medium = 1 kg, large > 1 kg) of squids captured, presence of dolphins, and number of depredation events. Dolphins were considered to be present during the fishing activity if at least one individual was seen by naked eye within 500 m from the fishing boat. In this case, the species, number of individuals, behaviour, and impact on fishing activity were noted.

Dolphin depredation events included occasions when fishers felt the hooked squid being taken from the line plus the cases when dolphins partially consumed and damaged the squid.

**Pinger experiment**

We selected the island of S. Miguel (Figure 1) to conduct the trials of pinger effectiveness because this was the area with the highest frequency of depredation recorded during the interview survey. The experiment was carried out between May 2010 and August 2011 aboard five boats from the artisanal squid fishing fleet that offered to collaborate in the experiment. Tests were carried out by the same observers that conducted the interview survey and fishery observations.

The pinger was attached to a rope and deployed from the bow of the fishing boat to a fixed depth of 60 m to prevent entanglement in the fishing gear and avoid contact with the propeller. Three pinger conditions were tested: control (no pinger), active pinger (deployed and transmitting), and inactive pinger (deployed but not transmitting). In addition, we examined the effect of two brands of pingers: Fumunda Marine® (sound level 132 ± 4 dB re 1 μPa at 1 m, frequency 10 kHz, replaceable batteries) designed and produced by Future Oceans (http://www.fumunda.com) and the AQUAmark300® (sound level 132 dB re 1 μPa at 1 m, frequency 10 ± 2 kHz, sealed batteries) designed and produced by AQUATEC (http://www.aquatecgroup.com). Both pingers comply with EC Regulation 812/2004 of 26 April 2004. Before the experimental study, we tested whether the acoustic properties of each pinger were in accordance with the manufacturer specifications. The devices were placed underwater to a depth of 10 m and recordings were made during 10 min using the hydrophone Reson TC4032.

Overall, we tested five treatments resulting from the combination of pinger condition and brand: control (no pinger), Fumunda-active,
Fumunda-inactive, AQUAmark-active, and AQUAmark-inactive. Five trials with 1 h of duration were carried out in each fishing trip to test all treatments on the same day under similar conditions. The order of trials was randomly selected before each fishing trip. Fishers were unaware of the trial order or whether pingers were active or not, as they were activated by saltwater switches once immersed.

For every trial, observers recorded the time, location, number of boats present in the area, number of handlines and jigs used, number and size class of squids caught, presence and behaviour of dolphins, and number of squids depredated. Observers also noted dolphin reaction to the pingers (active and inactive) as: 0, no reaction; 1, avoidance, direction change by 90°, longer dives, tightening of group formation or increase in swimming speed; 2, significant behaviour change, rapid change of swimming direction (opposite to the initial), increased travel speed, coordinated behaviour at the surface (Berrow et al., 2008).

Data analysis

Fishery characterization

Fleet composition, fishing effort, and catch per unit effort (cpue) of the hand-jig squid fishery were examined for the period 1993–2011 for the islands of Faial, Pico, São Jorge, and São Miguel. The other islands contributed <2% of the squid landings in Azores and were excluded from the analysis.

Estimating the composition and effort of the hand-jig squid fishery is difficult because small open-deck boats usually practise a multispecies fishery and shift between gears and fisheries depending on the season and availability of target species. Squid can also be captured by different fisheries and gears, so total squid landings are a poor indicator of the squid fishery operations. Thus, using information from the interview survey, we estimated, for each island, the average number of landing events made by boats known to be dedicated to the hand-jig squid fishery. We then reviewed the fishery statistics for the period 1993–2011 obtained by the NPFDC, to identify boats that landed squid as or more often than the estimated average for that island. Boats from Faial were considered to be dedicated to the hand-jig squid fishery if they landed squid ≥5 times a year, boats from S. Jorge and Pico ≥20 times a year, and from S. Miguel ≥30 times year.

Cpue of the hand-jig squid fishery was calculated as kilogrammes of squid landed per fisher per fishing day (kg fisher⁻¹ d⁻¹). The number of fishers on each boat was estimated from the relationship between crew size and boat length calculated using data from the interview survey.

Dolphin depredation

The frequency of dolphin depredation on the squid fishery was assessed for the islands with the highest contribution to the overall daily squid landings through interview surveys. A total of 551 interview surveys were conducted, but we analysed only questionnaires in which the last fishing trip was ≤7 days (n = 506) from the date of the interview. Information about fishing activity and dolphin depredation in the fishery is presented by fishing trip, which is equivalent to one fishing day.

The effect of dolphin depredation on the catch was determined by comparing squid captures (in weight) between fishing trips with and without depredation. Data on squid captures were obtained from the NPFDC database. A two-way analysis of variance using data from the interview surveys was performed to investigate the effect of season and dolphin depredation and of the interaction between the two on cpue (defined as kilogramme of squid caught per fisher per hour). Cpue was calculated per hour to allow comparison with cpue estimated for the pinger experiments (in which each trial lasted 1 h).

Data from on-board observations were also used to assess the frequency and impact of dolphin depredation for the squid fishery in S. Miguel and compare with results from the interview survey.

Generalized additive models (GAMs) were used to evaluate the influence of fishing effort, fishing operations, catch rates, and temporal and environmental variables on the occurrence of dolphin depredation using data from 96 monitored trips in S. Miguel. GAM was used to account for non-linear effects of predictors. Sea surface temperature (SST) and chlorophyll a were obtained from NOAA/NASA AVHRR and MODIS AQUA, respectively, as monthly composites with a resolution of 4 km. Remote-sensed data were retrieved for an area extending to 4 km from the island of S. Miguel to coincide with the squid fishing grounds.

We used generalized linear model (GLM) to examine the effect of fishery-related variables on the number of depredated squid using data from 32 trips with depredation. The GAM predicting the presence/absence of depredation used a binomial error distribution with an identity link function, whereas the GLM predicting the count of depredated squid used a quasipoisson distribution with a log link function. Explanatory variables considered in each model are presented in Table 1. Before fitting the models, pairwise correlations were computed between all variables to check for collinearity and variables with the highest Akaike information criterion (AIC) score were excluded. A backward stepwise selection procedure was employed to identify the best fitting model using the AIC value.

To estimate total catch loss due to depredation by Risso’s dolphins in the hand-jig squid fishery in S. Miguel, we calculated a depletion rate from fishery observer data and multiplied it by the total weight of squid landed in S. Miguel for each year of study. The total weight of depredated squids during the monitored trips was estimated by multiplying the number of squids removed by the average weight of squid captured by fishing trip. Depredation rate was then calculated as the weight of squid depredated by dolphins relative to the weight of squid captured per fishing trip. There was considerable variability in depredation rates and observer coverage between months and years. As a result, a pooled depletion rate was calculated for the whole study period (December 2009–September 2011). The pooled depletion rate was multiplied by the annual weight of squid landed in S. Miguel by the squid fishery fleet to obtain an estimate of the squid depredated by Risso’s dolphins per year. Standard error of the depletion rate and confidence limits for the estimates of depredated squid were calculated using the formula given by Cochran (1977) for ratio estimators.

Effect of pingers on squid catch and dolphin depredation

We investigated the effect of pinger condition (control, active, or inactive) on cpue, the probability of occurrence of depredation, and the proportion (by weight) of depredated squid. In addition, we also tested the effect of the categorical variable pinger brand combined with pinger condition on the same response variables. “Control” was the baseline level for the variable pinger treatment in all the models.

Generalized linear mixed models (GLMM) and linear mixed-effects models were used to investigate if pinger condition and brand had any effect on Risso’s dolphin depredation, using data collected during pinger experiments (n = 154 trials). The data were analysed using mixed models because trials carried out during the
same fishing trip could not be considered independent (Zuur et al., 2007). Therefore, all models included fishing trip as a random effect. Three responses were tested: (i) probability of dolphins depredating, (ii) cpue, and (iii) proportion of depredated squids, i.e. estimated weight of depredated squids divided by estimated weight of squids captured. The probability of depredation was modelled using a GLMM with a binomial error distribution and a logit link function, while cpue and proportion of depredated squids were modelled using linear mixed-effects models.

Results

Fishery characterization

The hand-jig squid fishing fleet of the islands of Faial, Pico, S. Jorge, and S. Miguel consisted of 200 boats, with 59% of the fleet operating in S. Miguel. In S. Miguel, the boats had on average five fishers while in the remaining islands, the average crew consisted of two fishers. Boats with fewer fishers used more jigs per gear and made longer fishing trips. In S. Miguel, the squid-fishery operated year-round, while in the other islands, the fishing started in October (Table 2). In S. Miguel, the boats had on average five fishers while the remaining islands, the average crew consisted of two fishers.

Table 1. Summary of explanatory variables considered for the GAM for predicting the presence/absence of depredation and the GLM for predicting the count of depredated squids.

<table>
<thead>
<tr>
<th>Model</th>
<th>Category</th>
<th>Explanatory variables</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>GAM predicting presence/absence depredation</td>
<td>Temporal variables</td>
<td>Year</td>
<td>Categorical</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Month</td>
<td>Categorical</td>
</tr>
<tr>
<td></td>
<td>Environmental variables</td>
<td>Sea surface temperature</td>
<td>Continuous</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Chlorophyll a</td>
<td>Continuous</td>
</tr>
<tr>
<td></td>
<td>Fishing operations</td>
<td>Depth</td>
<td>Continuous</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Boats in the area</td>
<td>Continuous</td>
</tr>
<tr>
<td></td>
<td>Fishing effort</td>
<td>N. handlines</td>
<td>Continuous</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fishing time</td>
<td>Continuous</td>
</tr>
<tr>
<td></td>
<td>Catch</td>
<td>Captured squid weight (kg)</td>
<td>Continuous</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Total squid landings S. Miguel fleet (kg)</td>
<td>Continuous</td>
</tr>
<tr>
<td></td>
<td></td>
<td>N. trips S. Miguel fleet</td>
<td>Continuous</td>
</tr>
<tr>
<td>GLM predicting the count of depredated squid</td>
<td>Fishing operations</td>
<td>Boats in the area</td>
<td>Continuous</td>
</tr>
<tr>
<td></td>
<td>Fishing effort</td>
<td>N. handlines</td>
<td>Continuous</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fishing time</td>
<td>Continuous</td>
</tr>
<tr>
<td></td>
<td>Catch</td>
<td>Captured squid weight (kg)</td>
<td>Continuous</td>
</tr>
</tbody>
</table>

Table 2. Azorean squid hand-jig fishery characteristics from four islands (Faial, Pico, S. Jorge, S. Miguel) that accounted for most squid landings, from 2009 to 2011.

<table>
<thead>
<tr>
<th>Island</th>
<th>Fleet size (N)</th>
<th>BOL (m)</th>
<th>Crew</th>
<th>Jigs</th>
<th>S</th>
<th>L</th>
<th>NT</th>
<th>H</th>
</tr>
</thead>
<tbody>
<tr>
<td>S. Miguel</td>
<td>118</td>
<td>8.7 (2.1)</td>
<td>5.0 (2.4)</td>
<td>2</td>
<td>January</td>
<td>12</td>
<td>7.8 (5.3)</td>
<td>5.1 (2.2)</td>
</tr>
<tr>
<td>S. Jorge</td>
<td>23</td>
<td>6.5 (1.0)</td>
<td>2.3 (1.1)</td>
<td>5</td>
<td>November</td>
<td>9</td>
<td>5.2 (4.1)</td>
<td>9.2 (2.1)</td>
</tr>
<tr>
<td>Pico</td>
<td>44</td>
<td>6.2 (1.1)</td>
<td>1.9 (0.6)</td>
<td>4</td>
<td>October</td>
<td>6</td>
<td>3.9 (3.2)</td>
<td>5.0 (4.0)</td>
</tr>
<tr>
<td>Faial</td>
<td>15</td>
<td>8.3 (2.0)</td>
<td>2.1 (1.4)</td>
<td>3–4</td>
<td>November</td>
<td>4</td>
<td>2.9 (2.3)</td>
<td>12.3 (9.0)</td>
</tr>
</tbody>
</table>

BOL, boat overall length; S, month starting the fishing season; L, length of the fishing season in months; NT, number of trips per month; H, fishing hours per day. Standard deviation of the mean values given in parentheses.

Frequency and impact of depredation: interview survey

During the study period, 506 fisher interviews were conducted from 122 fishing boats, representing 61% of boats dedicated to the squid fishery from the four islands (Supplementary Table S1).

Fishers reported the presence of dolphins in 61% (n = 308) of the interviews. Depredation was recorded in 83% (n = 255) of the trips in which dolphins were present and in 5% fishers also reported loss of gear. Dolphins removed the mantle of the squid leaving only tentacles and heads. The highest frequency of depredation occurred in S. Miguel (54%) and Pico (57%) followed by Faial (38%) and S. Jorge (8%). The frequency of depredation varied considerably between months but tended to be higher in August–November and March–April (Figure 4).

Risso’s dolphins were reported to be responsible for 92% of depredation events and bottlenose dolphins for 6%. Fishers were unable to identify the species responsible for depredation in 2% of depredation events.

There was no difference in the mean weight of squid landed in trips with (57.0 ± 48.5 kg) and without dolphin depredation (56.8 ± 42.6 kg; t = 0.037, d.f. = 353, p = 0.971). C_pu_e was significantly higher in winter \[ F_{3,356} = 6.899, p < 0.001 \], but the effect of dolphin depredation on cpue was independent from season \[ F_{3,356} = 2.530, p = 0.057 \].

Frequency and impact of depredation in S. Miguel: fishery observer data

We monitored 96 fishing trips on-board 19 commercial fishing boats from S. Miguel (Table 3). Risso’s dolphins were observed in November–January. This seasonal variation was also evident in cpue values (Figure 3).
44% \((n=42)\) of the fishing trips and depredated 33% \((n=32)\) of the trips. In six trips with depredating Risso’s dolphins, blue sharks (*Prionace glauca*) were also observed depredating squids and on another two trips, bottlenose depredation was also documented. Depredation by dolphins was easily distinguished from depredation by sharks or other veined squid because dolphins pull the squid from the jig pins removing it whole or leaving the head and tentacles, whereas sharks make clean cuts and squids cause only superficial damages to the squid flesh. Risso’s dolphins were observed depredating squid \(1.5 \pm 1.6\) h after the fishing activity.
Factors affecting depredation occurrence and rates

The best fitting GAM explained 22% of the deviance and included parametric terms for depth and SST, and a smoother for fishing time (Supplementary Table S2). Depredation probability increased linearly with depth and decreased with SST, being more likely to occur in areas deeper than 165 m and when the water temperature was <18.5 °C (Figure 5). The duration of the fishing trip affected the likelihood of depredation, but the relationship was non-linear. The probability of dolphins depredating squids decreased rapidly with fishing time, reaching the minimum for fishing trips of 5–7 h but increased slightly in longer trips.

We then developed a quasipoisson GLM to investigate which factors influenced the quantity of depredated squid by dolphins. The model included only fishing trips with depredation to eliminate the excess of zeros that are difficult to model when sample size is small. Instead of building a model with all available explanatory variables, we included only a subset of covariates describing two aspects of the fishery—effort and catch—that we expected to be influential on the number of squids depredated. The number of hand-jigs, total catch, and number of fishing boats in the area had no effect on the number of squids depredated and fishing time was the only variable retained in the final model (GLM: $t = 2.470, p < 0.05$).

The model predicted greater catch losses as duration of fishing trips increased, with >5 squids depredated for trips longer than 6 h (Figure 6).

### Estimates of catch loss due to depredation

Depredation rate for the period from 2009 to 2011 was calculated at 0.32 (standard error $= 7.9 \times 10^{-4}$), meaning there was a loss of 3.2% of the total squid catch (in kg) per trip. The highest depredation estimate was in 2010 with over 12 t of squid depredated. Combining data for the 3 years, depredation by dolphins represented a catch loss of 30 t of squid and an economic loss of about €152 000 for the squid fishing community of S. Miguel (Table 4).

### Effect of pingers on squid catch and dolphin depredation

A total of 154 trials were performed during 45 fishing trips to test the effect of pinger condition and brand on the catch and on dolphin depredation (Supplementary Table S3). On several occasions, it was not possible to carry out the five trials during a fishing trip due to degradation of sea state or shifts in fishing area.

An average of 2 ± 1.4 squids fisher$^{-1}$ h$^{-1}$ was captured during the trials. Cpué for the control condition was 2.17 ± 1.37, compared with 2.19 ± 1.49 for pinger-inactive and 1.71 ± 1.19 for pinger-active, with the linear mixed-effects model, suggesting that pinger condition had no effect on cué (Supplementary Table S4). While the Fumunda-active showed some reduction in cué compared with the control and other treatments, changes in cué across pinger treatments were not significant ($p > 0.05$; Figure 7; Supplementary Table S4).

Depredation was recorded in 33% ($n = 15$) of the fishing trips and Risso’s dolphins were responsible for all depredation events. Risso’s dolphins depredated on average 3 squids per trip. About 20% of the control trials and 19% of the trials with pingers present (independently of being active or not) were depredated. Pinger condition and brand had no effect on the probability of dolphins depredating the catch ($p > 0.05$; Figure 8; Supplementary Table S5). The linear mixed-effects model predicting the proportion of depredated squid also did not suggest a significant effect of pinger condition and pinger brand (Supplementary Table S5).

There was no documented change in dolphin behaviour (0, no reaction) relative to the presence of active or inactive pingers.

### Table 3. Monitored fishing trips on-board commercial squid fishing boats from S. Miguel.

<table>
<thead>
<tr>
<th>Year</th>
<th>Month</th>
<th>Monitored trips</th>
<th>No. of boats sampled</th>
<th>Trips with dolphin presence</th>
<th>Trips with dolphin depredation</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009</td>
<td>July</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2009</td>
<td>December</td>
<td>4</td>
<td>3</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>2010</td>
<td>March</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2010</td>
<td>April</td>
<td>9</td>
<td>3</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>2010</td>
<td>May</td>
<td>6</td>
<td>1</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>2010</td>
<td>June</td>
<td>9</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2010</td>
<td>July</td>
<td>6</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2011</td>
<td>March</td>
<td>6</td>
<td>4</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>2011</td>
<td>April</td>
<td>11</td>
<td>4</td>
<td>9</td>
<td>6</td>
</tr>
<tr>
<td>2011</td>
<td>May</td>
<td>9</td>
<td>6</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>2011</td>
<td>June</td>
<td>9</td>
<td>4</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>2011</td>
<td>July</td>
<td>18</td>
<td>3</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>2011</td>
<td>August</td>
<td>7</td>
<td>2</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>96</td>
<td>42</td>
<td>32</td>
<td></td>
</tr>
</tbody>
</table>

Figure 4. Proportion of fishing events depredated by month, calculated from the interview survey conducted from 2009 to 2011. Values at top of the bars represent the number of interviews per month. Error bars represent the standard errors.
Discussion

The artisanal hand-jig squid fishery in the Azores has increased in importance in terms of landings and economic value. In 1993, this fishery landed 80 t of squid with a total landed value of about €165,000, while in 2011, 640 t of squid were landed, representing about €3.3 million. Despite the overall growth of this fishery, squid catches varied considerably from year to year, as previously reported by Porteiro (1994), which likely reflects squid natural abundance in the area. This species is characterized by a short (annual) lifespan, with non-overlapping generations and rapid growth. Annual stock size depends almost entirely on recruitment success that appears to be strongly affected by environmental conditions, including water temperature (Pierce et al., 1998; Pierce and Boyle, 2003). Part of the variability in squid catches may also result from between-year fluctuations in fishing effort, as large increases or decreases in landings from 1 year to the next were often not matched by similar changes in cpue values as would be expected if effort was more or less constant through time. Even fishing boats usually dedicated to the squid-fishery are likely to switch to another type of fishery if it offers better economic prospects in a given year.

Squid landings in the Azores for the period 1993–2011 showed a strong seasonal pattern peaking from November to January and again in April and May (although the latter peak was smaller), in agreement with the pattern found in earlier years (Porteiro, 1994). Little is known about squid distribution and abundance in the Azores, but studies in other areas indicate that the seasonal pattern of L. forbesi is caused by the migration of recruits to coastal waters for spawning during winter (Boyle and Pierce, 1994; Pierce et al., 1998; Hastie et al., 2009). Squids are also known to form spawning aggregations around the islands of the Azores and local fishers certainly learned to exploit the higher concentration of mature squid on these spawning grounds during winter (Porteiro, 1994; Porteiro and Martins, 1994; Pham et al., 2009).

A significant proportion of the annual squid landings in the Azores are caught in S. Miguel, where most of the fishing boats and fishers that dedicate to this fishery are based. In contrast to what happens in other islands, the squid fishery in S. Miguel is not seasonal but is practised year-round. Although the squid does not reach the same market values as other species (e.g. demersal fish or tunas), it represents 14% of the economic worth of the fishing activity for this island.

Dolphin depredation in the hand-jig squid fishery was rare or only occasional in most Azorean islands but relatively common in S. Miguel, occurring in 33% of the observed fishing trips from 2009 to 2011 and reported in 54% of the interview surveys conducted in the same period. Damages to fishing gear were infrequently reported and should not represent a significant problem for this
Table 4. Observed landings (kg), total landings (kg), observation coverage (observed landings/total landings), observed and estimated squid depredated (kg; 95% confidence intervals given in parentheses), and estimated loss (€) in the hand-jig squid fishery fleet from S. Miguel, 2009–2011.

<table>
<thead>
<tr>
<th>Year</th>
<th>Observed landings (kg)</th>
<th>Total landings (kg)</th>
<th>Observer coverage (%)</th>
<th>Observed depredation (kg)</th>
<th>Estimated depredation (kg)</th>
<th>Estimated loss (€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009</td>
<td>380</td>
<td>302 846</td>
<td>0.13</td>
<td>42.56</td>
<td>9 619 (9 659–9 580)</td>
<td>46 075</td>
</tr>
<tr>
<td>2010</td>
<td>1797</td>
<td>389 709</td>
<td>0.46</td>
<td>44.80</td>
<td>12 379 (12 430–12 328)</td>
<td>61 152</td>
</tr>
<tr>
<td>2011</td>
<td>2794</td>
<td>267 561</td>
<td>1.04</td>
<td>70.56</td>
<td>8 499 (8 534–8 464)</td>
<td>44 704</td>
</tr>
<tr>
<td>Total</td>
<td>4971</td>
<td>960 116</td>
<td>0.52</td>
<td>157.92</td>
<td>30 498 (30 624–30 372)</td>
<td>151 932</td>
</tr>
</tbody>
</table>

Depredation rate = total observed depredation/total observed landings.

Figure 7. Cpue for five experimental treatments: control (no pinger), pinger Fumunda active, pinger Fumunda inactive, pinger Aquamark active, and pinger Aquamark inactive.

Figure 8. Interaction rates by pinger experiment: control (no pinger), with pinger Fumunda active, with pinger Fumunda inactive, with pinger Aquamark active, and with pinger Aquamark inactive.

fishery. There were no observations or reports of incidental capture of dolphins and the interaction seems mostly detrimental to fishers. Risso’s dolphins were responsible for most depredation events. This may be explained by the fact that Risso’s dolphin diet consists primarily of cephalopods, with a clear preference for mesopelagic squid (Clarke, 1986; Bearzi et al., 2010). In addition, this species is common in the Azores where it occurs year-round and shows strong site fidelity to some areas (Silva et al., 2003, 2014; Hartman et al., 2008; Pereira, 2008).

Risso’s dolphin interaction and depredation in fisheries has been described elsewhere, although rarely. Risso’s dolphins have been observed foraging around fishing boats using illuminated handlines for squid in the archipelago Pontino Campano, taking advantage of the squids attracted by the gear’s light (Mussi et al., 1999). Garrison (2007) observed Risso’s dolphins stealing squids used as bait in the US longline fishery for swordfish and tuna. To the best of our knowledge, this is the first study documenting depredation by Risso’s dolphins on a hand-jig squid fishery.

SST showed an effect on depredation probability, reflecting the seasonal pattern in dolphin depredation that tended to be higher from late autumn to early spring. As discussed before, spawning squids seem to form dense aggregations in nearshore waters during winter. Both Risso’s dolphins and fisheries are likely attracted by this temporarily abundant resource, leading to a spatio-temporal overlap between the two and thus increasing opportunities for dolphin depredation. The time preceding the first depredation event suggests that Risso’s dolphins were not far from the fishing sites and might have subsequently approached the area attracted by the engines’ noise. Although depredation frequency was not related to the number of boats fishing in the area (see below), perhaps other factors not examined here (e.g. acoustic properties of the engines, factors affecting sound propagation) are more influential in attracting dolphins to fishing areas.

Seasonal changes in depredation occurrence could also be linked to changes in the distribution of Risso’s dolphins. Although we lack detailed knowledge of the movements of Risso’s dolphins around S. Miguel, information from surveys conducted around all the Azorean islands do not indicate seasonal differences in distribution of the species (Silva et al., 2014).

Risso’s dolphin depredation was more likely to occur in deeper waters. There are several possible explanations for the observed pattern. When fishing at greater depths, fishers release more handline into the water, consequently increasing the haulback time, and the opportunity for Risso’s dolphins to detect and remove the captured squids.

Fishing activity was generally concentrated close to coast, with fishers starting their activity at dawn at shallower depths and moving to deeper waters as the day progresses. Perhaps Risso’s dolphins preferentially target deeper hauls to take advantage of the daylight to perceive and remove squids from the gear. Dolphins may also be avoiding shallow and less familiar habitats that may pose increased risk. In addition, the veined squid seems to be more abundant at depths of ~300 m (Roper et al., 1984), which was reflected in our study by higher cpue at depths >150 m.

Except for the duration of fishing events, none of the variables used to represent fishing operations, effort, or squid catches showed a significant relationship with the occurrence of depredation. This is somewhat counterintuitive, but we suspect that it may be related to one or more of the following reasons. Squid fishing boats tended to concentrate within small areas (during this study, there were as many as 20 boats in a few tens of square kilometres) and depredating Risso’s dolphins alternated attacks among boats present. Thus, dolphin depredation in the boats carrying observers could also have been influenced by the operations, effort, catch, and depredation on the neighbouring boats, potential effects that were not accounted for in our models. Some of the variables that were available may also be poor proxies for the effects
examine. This was probably the case of total daily landings and number of trips by the squid fleet of S. Miguel that were selected as "indices" of squid abundance. However, as discussed earlier, other factors besides squid abundance may influence the fishers decision to select to this fishery. Last, sample size may have been insufficient to uncover potential effects of some of the variables.

The duration of fishing events was an important factor affecting depredation probability and intensity. The probability of depredation decreased rapidly as duration of fishing trips increased and seemed to increase slightly on trips longer than 7 h. The initial decrease possibly occurred because the first attack commonly took place in the first 2 h of fishing and fishers often reacted to depredation by interrupting the activity and moving to another fishing area. However, not all fishers aborted the activity after the first depredation event, and in these cases, the cumulative number of squid depredated obviously increased over time. Although the model suggested that depredation probability increased again on trips longer than 7 h, this was certainly influenced by the reduced sample of trips with longer duration. Our models explained a low percentage of variability in the data. We suspect this was mainly caused by lack of information on some important factors driving Risso's dolphin interaction on the squid fishery, including squid abundance and patchiness and Risso's dolphin abundance.

Risso's dolphin depredation was observed in about one-third of the fishing trips monitored in S. Miguel, but it had a moderate impact on the catches. According to the estimates obtained in this study, <5 kg of squid per fishing trip were lost on average to depredating dolphins, corresponding to ~3% of the squid caught. Depredation was not responsible for significant decreases in squid catches or for a significant decrease in cpue. Nevertheless, we estimated that the catch loss of the squid fishery of S. Miguel can amount to 8–12 t a year, which translates into an economic loss estimated 571 t and 4.8 million of Patagonian toothfish were lost due to depredation by killer whales and sperm whales (Nachtigall et al., 2005). Yet, the animals were not deterred by the sound produced by these devices, nor did they change their behaviour in the proximity of fishing gear when pingers were in the water. Fumunda and Aquamark pingers were developed mainly to reduce bycatch by alerting dolphins to the presence of fishing gears and our results suggest that the sound they produce do not dissuade Risso's dolphins from interacting with the hand-jig squid fishery to take advantage of an easily accessible food source. However, the number of trials may have been insufficient to assess a reduction in depredation (especially if pinger effect was weak or only moderate) and we recommend that more trials be conducted in the future. Nevertheless, our results are similar to those observed for other species that also failed to detect a reduction in depredation related to pinger use (Burke, 2004; Lopez and Marinho, 2011).

The absence of response to the pingers used in this study does not mean that Risso's dolphins would not react differently to other types of acoustic deterrent devices. Nonetheless, the use of acoustic deterrents should be carefully considered and its benefit precisely weighted since it implies addition of more noise into the marine environment and may have unclear biological and ecological effects on Risso's dolphins and other non-target species (e.g. other cetaceans, fish, and some invertebrates). Also the presence of dolphins in the fishing area and the potential for depredation could increase with the widespread use of pingers, as the animals may habituate to the sound and associate it with a readily available source of food (known as the "dinner bell effect"; Jefferson and Curry 1996; Dawson et al., 1998; Cox et al., 2001, 2003; Bordino et al., 2002).

Conclusions

Monitoring interactions between dolphins and fisheries is essential to produce accurate estimates of dolphin depredation. In our study, data from interviews to fishers tended to overestimate the frequency of dolphin depredation, reinforcing the importance of observer programmes to assess cetacean–fisheries interaction.

The results presented in this study improved the understanding of interactions between Risso's dolphins and the squid-fishery and identified some of the factors that may influence depredation behaviour. The veined squid is a seasonally abundant patchily distributed resource in the Azores, targeted both by fishers and by Risso's dolphins. Thus, temporal and spatial overlap between the two is inevitable. Our study suggests that depredation occurred where and when fisheries exploited the same resource as Risso's dolphins and does not appear linked to any specific times, areas, boat, or gear characteristics. We also did not find a relationship between depredation and fishing effort or squid captures, although variables used may not have been the best indicators for these effects and sample size may have influenced the outcome of the analysis. Our study suggests that the impact of Risso's dolphin depredation is low and does not cause a significant reduction in the daily catch of squid-fishing boats. Nevertheless, finding a way to reduce the frequency of depredation is of benefit to both fishery participants and the conservation of population of Risso's dolphins, as it prevents potential retaliations against dolphins. Pingers do not seem to be effective in
reducing dolphin depredation. Depredation being highly rewarding should be rapidly learned and transmitted among dolphins. Modification of fishing gear could be a potential solution to decrease the frequency of depredation. As depredation takes place during hauling, the use of a mechanism designed to protect the hooked squid from Risso's dolphins could be beneficial in reducing depredation. Gear modification has proven successful in decreasing depredation by killer whales and sperm whales in Chilean toothfish (Diostichichus eleginoides) longline fishery and by short-finned pilot whales (Globicephala macrocephalus) and false killer whales (Pseudorca crassidentis) in pelagic longline fishing (Moreno et al., 2008; Rabearisoa et al., 2012). Future research should focus on proposing and evaluating the efficiency of gear modifications. This requires the involvement and concerted efforts of the regional administration, local fishers associations (commercial and recreational), along with research organizations.

Supplementary data
Supplementary material is available at the ICESJMS online version of the manuscript.

Acknowledgements
We are grateful to all the fishers and captains that collaborated in this study, by responding to the interview survey, accommodating observers onboard and allowing us to conduct the pinger trials. We wish also to acknowledge the initial talks with Gualberto Rita from the “Cooperativa de Economia Solidária Pescadores da Ribeira Quente”, António Laureno “Associação de Pescadores da Ilha de São Jorge”, and Luis Rodrigues da “Associação Porto de Abrigo” and also to “Associação de Armadores de Pesca Artesanal do Pico”, “Associação de Pescadores da Horta”, “Associação dos Pescadores da Ilha da Graciosa”, “Associação Terceirense de Armadores”. Our thanks to our colleagues Dália Reis, Ângela Canha, Hugo Diogo, Ana Paixão, Inês Machado (NPDC), and Rui Rosa (DOP/UAç) for introducing us to the fishing community and providing much of the fishery data used in this study. We also thank Ruth Higgins for her reviews which helped improve our manuscript, Ricardo Medeiros for providing the map of the Azorean archipelago, and to Rui Prieto for editing the figures. This research was funded by the Regional Secretariat of Fisheries and the Regional Secretariat for Education, Science and Culture, Government of the Azores, FEDER, the Competitiveness Factors Operational (COMPETE), QREN European Social Fund, and Proconvergência Açores Program through research projects CETPESCA (Monitoring interactions of cetaceans and the squid fishery) and MAPCET (M2.1.2/F/012/2011—Integrating cetaceans into marine spatial management in the Azores). We acknowledge funds provided by FCT to LARSysS Associated Laboratory and IMAR-University of the Azores/the Thematic Area E of the Strategic Project (OE and Compete) and by the FRC—Government of the Azores pluriannual funding. MJC was supported by an FRC doctoral grant (M3.1.2/F/008/2009). MAS was supported by an FCT postdoctoral grant (SFHR/BPD/29841/2006) and is currently supported by POPH, QREN European Social Fund, and the Portuguese Ministry for Science and Education, through an FCT Investigator grant.

References


Handling editor: Simon Northridge