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A modified gear design to reduce interactions of sperm whales (*Physeter macrocephalus*) and seabirds with bottom-set longlines for Patagonian toothfish (*Dissostichus eleginoides*) on the High Seas of the Southwest Atlantic

Sabine Goetz, Martín Laporta, Julio Martínez Portela, María Begoña Santos and Graham John Pierce

Abstract

Depredation, i.e. damage or removal, of Patagonian toothfish (*Dissostichus eleginoides*) from longlines by sperm whales (*Physeter macrocephalus*), can cause considerable economic loss for Spanish fishing vessels in southwest Atlantic waters. The fishery is also known to suffer high bycatch rates of seabirds. The main goal of the study was to assess the extent of depredation and seabird bycatch and to test the potential of a modified longline design, including so-called "umbrellas", for minimizing both. Moreover, we investigated the relationships between sperm whale sightings, depredation, catches and environmental variables using Generalised Additive Modelling. Data were collected during 297 hauls on a longliner between November 2007 and April 2008 in international waters of the SW Atlantic. Sperm whales were sighted during 35 % of hauls, always during gear retrieval and their presence was positively related to damage to fish. The overall depredation rate (0.44 % of total catch) was low, but is assumed to be underestimated since sperm whales were suspected to also take fish without leaving visual evidence. The umbrellas were highly effective in preventing bycatch, and appeared to restrict depredation, but significantly reduced catches. Our results demonstrate there is still some way to go to solve the problem of depredation.

Keywords

depredation, longline, sperm whale, umbrella system

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1. Introduction

The large-scale fishery for Patagonian toothfish (*Dissostichus eleginoides*) began in the early 1990s (Lack and Sant, 2001), following the decline in fish stocks in Chilean waters and in many northern hemisphere fisheries. In 1992 the total reported catch of the Patagonian toothfish reached 40 710 t worldwide (FAO, 2003) and since then this fishery has developed into an important and highly valuable fishery with reported annual catches between 28 035 – 44 047 tonnes (1995-2001) (FAO, 2003; Laptikhovsky and Brickle, 2005). In 2007/08 the total landings of toothfish were 12 573 tonnes and 10 291 tonnes within and outside the CCAMLR Convention Area, respectively (STECF, 2009).

Two different longline gears are used in the toothfish fishery around the Falkland Islands: the MUSTAD autoline system, which employs lines made up of 250 m sections, with snoods (short hook lines with baited hooks) connected with crimps and swivels at 1.2–1.4 m intervals and the "Spanish system" that employs two lines, a fishing line and a safety line, and two winches for hauling. The longline fishery takes place all year round at fishing depths of 650 to 2000 m.

The Patagonian toothfish is a long-lived and slow growing notothenid fish, endemic to Antarctic and sub-Antarctic waters (Agnew, 2004), which is distributed on the continental shelf and shelf slope around South America and on a number of sub- Antarctic islands (Agnew *et al.*, 1999). Its distribution in the southwestern (SW) Atlantic Ocean is conditioned by the Falklands/Malvinas Current. In the SW Atlantic Ocean, Patagonian toothfish is found in low natural densities (Prenski and Almeyda, 2000). Toothfish vary in size according to depth, with larger specimens found below 2000 m (Cousseau and Perrotta, 2000).

It is a commercially highly valuable species reaching on average market prices of 14 US$/kg (J.A. Novo, captain of longline FV "Arnela", pers. comm., 2009). Damaged fish are usually discarded since only immaculate specimens can be sold. Cetacean depredation, i.e. the damage and removal of hooked fish and bait from the fishing gear, can therefore lead to considerable economic loss for longline fisheries if it reaches significant levels and has been widely reported for this fishery, primarily involving the sperm whale (*Physeter macrocephalus*) (Ashford *et al.*, 1996; Kock, 2001; Hucke-Gaete, 2004; Purves *et al.*, 2004; Kock *et al.*, 2006; Pin and Rojas, 2007; Roche, 2007; Moreno *et al.*, 2008).

Sperm whales are the largest toothed whales, with mature males recorded as reaching up to 21 m in length (Berzin, 1971). They present a complex social organisation where groups of young males ("bachelor" groups in different stages of sexual maturation) and solitary sexually mature males spend most of the year separated from groups of females and calves, undertaking migrations to higher latitudes in spring/summer and returning to lower latitudes in winter, while females and calves stay in low latitudes all year round (Berzin, 1971).

Sperm whales are found in deep waters of all oceans and results from many studies (originally based on analysis of stomach contents of animals killed commercially and more recently on stranded specimens) indicate a diet mainly based on deep-sea cephalopods of various sizes followed by fishes (for reviews see Kawakami, 1980; Rice, 1989; Santos *et al.*, 1999). Korabelnikov (1959) reports the presence of Patagonian toothfish in the diet in the southern ocean.

Cetaceans seem to be particularly attracted to longlines because large and easily accessible prey is provided (Capdeville, 1997) and the sounds of the engine, electronic equipment and the hauling noise of the longline vessels can be used as a cue to locate food (Thode *et al.*, 2007). When preying on longline catches, sperm whales are thought to rip the fish from the line, leaving only the lips and jaws on the hooks, or to remove the entire fish (Ashford *et al.*, 1996; Purves *et al.*, 2004). Depredation occurs primarily during gear hauling (Nolan *et al.*, 2000; Purves *et al.* 2004), most likely because it is easier for the whales to feed on the catch during hauling than deep-diving to remove the fish during gear soaking (Gilman *et al.*, 2006).

According to Kock (2001) and Purves *et al.* (2004), sperm whale depredation on catches can occasionally reach levels of 80 % or more of total catch per haul. However, the reported overall depredation rate on catches is usually much lower and highly variable, ranging between 0.3 - 1.7 % of total catches (Hucke-Gaete *et al.*, 2004; Moreno *et al.*, 2008; Sigler *et al.*, 2008).

Sperm whales may occasionally become entangled in the longline and cause breakage of the line (Kock *et al.*, 2006) but they are rarely by-caught. Bycatch of seabirds, however, is a much bigger conservation issue in this fishery, mostly affecting albatrosses and petrels (Ashford *et al.*, 1995; Moreno *et al.*, 1996). When the longlines are set, birds are frequently hooked or entangled while feeding on the bait, being dragged underwater and drown as the gear sinks (Gilman *et al.*, 2005). The area in and around the Falkland Islands supports seabird populations of international importance (Woods and Woods, 1997) and several species of albatrosses and petrels have been listed by the United Nations Convention on Migratory Species (CMS) and are therefore subject to conservation agreements. According to Gales (1993), population declines of several albatross species have been linked to longlining fisheries in the Southern Ocean.

There are several approaches to avoid or reduce interactions with sperm whales and seabirds (Gilman *et al.*, 2005; Gilman, 2006). Vessels might, for instance, try to avoid fishing areas where sperm whales and seabirds are concentrated. However, these areas tend usually to be also the richest fishing grounds, and navigating to alternative fishing areas inevitably causes additional costs for fuel and loss of fishing time. Other strategies to keep cetaceans/seabirds away from the longline include the use of specific deterrents or to reduce detectability of the baited hooks, gear and the vessels. This can, for instance, be achieved by dying the bait blue (seabirds) or by using underwater acoustic masking devices (cetaceans).

In the Patagonian toothfish fishery there have been several attempts in recent years to reduce interactions by limiting the cetacean and seabird access to catch and bait using a so-called Mammals and Birds Excluder Device (MBED) or umbrella system (Pin and Rojas, 2007; Moreno *et al.*, 2008). This device consists of a cone-shaped umbrella-like net sleeve that protects the hooked fish from depredation during hauling. In addition, weights are attached to the gear to allow for a higher sinking rate and as a consequence minimize the bycatch of seabirds by reducing the time the bait remains at the surface.

The present study was conducted by the Spanish Institute of Oceanography (IEO) and financed by the European Fisheries Fund (EFF) under the auspices of a pilot project on experimental fisheries in the High Seas of the South West Atlantic (RAI-AP 25/2006), applying an innovative longline design and MBEDs. The main goal of the study was to assess the extent of sperm whale depredation on catches and cetacean/sea bird bycatch in a scientifically largely unexplored fishing area and to test the potential of different longline designs to minimize depredation. Moreover, we investigated how sperm whale sightings, depredation and catch rates are related with each other and to environmental and fishery-related variables.

2. Materials and methods

Data were collected by an experienced fisheries observer (ML) on-board the Spanish commercial longlining vessel “Arnela”, which was mainly targeting Patagonian toothfish between 23 November 2007 and 7 April 2008. Fishing took place in two different areas: area AI46 (extending to the East of the Argentinean Exclusive Economic Zone between 41ºS and 48ºS and up to 56ºW) and area AI54 (bordering with Falkland Island waters to the west and extending between 53ºS and 55ºS and 50ºW). In order to investigate spatial trends, the study area was divided into 25 subareas of 1º x 1º. The fishing effort for each subarea is displayed in Figure 1.

2.1 Longline design and experimental setting

The experimental longline design used during the study derives from the traditional Spanish longline system, applying the following modifications: a) use of MBEDs or "umbrellas" to protect hooked toothfish from sperm whale depredation, b) attachment of stones to increase the sinking speed of baited hooks to reduce entanglement of seabirds during gear setting c) replacement of single monofilament hook line by polypropylene main line with several branch lines to reduce the loss of monofilament and hooks at sea. The distance between branch lines varied between 10 and 20 m (depending on vessel speed during longline setting). Each branch consisted of a polypropylene line (diameter Ø 8 mm) supporting 6 snoods with baited hooks, a stone (approximately 8 kg) to weigh down the branch line and a MBED. The bait used during the study was mostly sardine (*Sardina pilchardus*). Each MBED was composed of an upper and a lower ring (Ø 10 and 80 cm, respectively) supporting a cone-shaped net sleeve that varied between 1.5 and 2 m in length (Figure 2a). The rings and the net had positive buoyancy in the water, allowing the umbrella to float over the baited hooks while the gear was soaking. When the main line is hauled back (during gear retrieval), the net sleeve slides down, covering the hooked toothfish (Figure 2b). Since depredation is believed to occur primarily during gear retrieval it was assumed that this mechanism could protect hooked fish from sperm whale attacks and reduce damage to the catch.

We tested 4 different umbrella designs in the course of the study, modifying the material of the rings and the length of the net sleeve. During fishing operations either all (complete coverage), two thirds, or half (partial coverage) of the branch lines carried umbrellas. This resulted in 8 different experimental longline settings (G1-G8), varying in the proportion of hooks covered by MBEDs and the combination of different umbrella types (Table 1).

2.2 Data collection

During each set the on-board observer recorded the start/end time of gear setting/retrieval, fishing location, Nº of branch lines, experimental longline setting used, amount (kg/Nº individuals) of each species caught, sea surface temperature (SST), sea state (Douglas scale), wind speed, moon phase, cloud cover, sightings of cetaceans (species and Nº of animals observed) and seabirds (species only), depredation on catches (occurrence/Nº of fishes damaged) and accidental bycatch of seabirds and cetaceans (Table 2). In addition, the captain registered toothfish catches and sperm whale sightings for each segment of the longline in a logbook. Each segment comprised 25 branch lines and was marked with coloured plastic tags. After each haul, evidence of depredation was assessed by counting the number of toothfish damaged by sperm whales. A toothfish was considered as having been damaged by a sperm whale if it was missing body parts and displayed crushed tissue with typical blunt tooth marks (Figure 3). The sharp teeth of other potential predators such as sharks would result in cut tissue with well defined borders (Dalla Rosa and Secchi, 2007; Sigler *et al.*, 2008). Photos were taken of damaged fish in order to facilitate identification of bite marks

2.3 Data analysis

Since sightings of sperm whales by both the observer and the captain were opportunistic we combined both datasets for analysis. Catches of toothfish were expressed as cpue (catch per unit effort), one unit of effort corresponding to the mean number of branch lines present during the whole study.

It is highly likely that sperm whales remove an unknown number of fishes entirely from the longline. Consequently, taking into account only fishes damaged may underestimate the real depredation level. We therefore compared the cpue for sets with/without sperm whale presence and evidence of depredation using the non-parametric Mann-Whitney test, assuming that a significant, visually undetectable, removal of fish from the line would be reflected in lower catches. In order to assess if sperm whales really remove whole hooked fish directly from the line during retrieval, we analyzed whether the occurrence of sperm whales close to the vessel has an immediate effect on catches. For this purpose, the sums of fishes caught on the longline segments before and after sperm whale occurrence were compared applying the Mann-Whitney test. The 5 segments before and after sperm whale occurrence were coded as follows:-5, -4, -3, -2, -1, 0, +1, +2, +3, +4, +5, segment 0 representing the segment when the sperm whale was first seen. The number of fishes was then summed up for the 5, 4, 3, 2 and 1 segments before/after the 0 segment and then compared pairwise.

In order to assess how presence of sperm whales, depredation, catch rates, environmental and fishery-related variables are related with each other, we used Generalised Additive Models (GAMs) (Hastie and Tibshirani, 1990; Wood, 2006; Zuur *et al*., 2007). The response and explanatory variables are presented in Table 2. Prior to running the models we explored our data following the protocol of Zuur *et al.* (2007, 2009). We checked all explanatory variables for collinearity and excluded one from every pair of collinear variables from the subsequent analysis. In order to reduce the influence of small numbers of large values, the variables cpue of toothfish and soak time were square root transformed. One sample was dropped from the analysis because of its very extreme values for number of branch lines and duration of retrieval. The variables sea state and cloud cover were treated as continuous variables in our analysis, resulting in better models, i.e. higher percentage of variance explained, than using them as nominal variables. The nominal variable moon phase was coded using dummy variables according to the scheme of Zuur *et al*. (2007) allowing for a stepwise comparison of one moon phase with all other moon phases (Table 3). For the variable gear design we included only a comparison of complete versus partial hook coverage in the model. Response variables followed Gaussian (continuous data), Poisson (count data) or binomial (presence-absence data) distributions. Since our binomial datasets contained more zeros than ones we selected the cloglog as a link function (Zuur et. al, 2009). Continuous explanatory variables were entered into the model as smoothers and the maximum number of degrees of freedom (k) was restricted to 4 in order to avoid over-fitting and selection of biologically unrealistic models. Models were fitted using backwards selection, sequentially excluding individual variables to identify the model which would result in the lowest AIC (Akaike Information Criterion). Having thus removed one variable the process was repeated until all remaining terms were significant or none remained.

We used the Mann-Whitney test to determine which of the four different umbrella designs resulted in the highest catches. For this purpose, the number of fishes caught per set with each umbrella type were standardized for a mean number of branch lines and then averaged.

All GAMs were run in Brodgar 2.6.5 (www.brodgar.com). More information about these techniques can be found in Zuur *et al*. (2007) and Zuur *et al*. (2009). Mann-Whitney tests were performed using Minitab 15.

3. Results

3.1 Fishing effort and catches

A total of 297 hauls was carried out in water depths between 600 and 2200 m ($\bar{x}$ = 1264 ± 283). Each longline carried between 150 - 500 branch lines ($\bar{x}$ = 300.74 ± 85.05) and was left to soak in the water for 3 to 67 hours ($\bar{x}$ = 20.67 ± 11.22 hrs). Fishing effort in zones AI46 and AI54 were 56069 (62.8 %) and 33250 (37.2 %) branch lines, respectively. A total of 61 tonnes of toothfish was caught during the whole study. Sixty-five percent of the toothfish catches were taken in area AI54 confirming the southern distribution of this species. The cpue was quite variable for the different subareas, with highest values in areas 1, 2, 10 and 25 (Figure 4). Highest cpue was obtained in the strata between 800 – 1600 m and 2000 – 2200 m water depth despite the latter being the stratum with the lowest effort (probably due to the stronger currents).

3.2 Cetacean and sea bird sightings

Sperm whales were sighted during 104 of 297 longline sets (35 %) and exclusively during gear retrieval. The proportion of hauls with sperm whale presence was 37.4 % for area AI46 and 32.9 % for area AI54. The number of individual sperm whales sighted per haul ranged between 1 and 6 animals. They were usually swimming alone (72 %), or in groups of 2 (16 %) or 3 (10 %) individuals. The maximum number of animals per group was 5. Sperm whale sightings were most numerous in subareas 2, 5, 8, 14, 19 and 25 (Figure 4). Other cetacean species observed were minke whales (*Balaenoptera acutorostrata*), long-finned pilot whales (*Globicephala melas*), killer whales (*Orcinus orca*), dusky dolphins (*Lagenorhynchus obscurus)* and southern right whale dolphins (*Lissodelphis peronii*). Seabirds sighted comprised several species of albatrosses, petrels and shearwaters (Table 4)

3.3 Sperm whale depredation on catches

Twenty-four longline sets showed evidence of depredation on catches (damage rate = 8 %). Usually only 1 to 2 fishes were damaged, however depredation could reach up to 5 fishes per set. Most of the toothfishes damaged by sperm whales were hauled with only the head or the lips left on the hook or displaying multiple fractures in the cranium. If fishes were covered with umbrellas during hauling, observed evidence of depredation by sperm whale mainly comprised missing body parts and crushed tissue with typical blunt tooth marks. Some fishing hooks were observed to be bent, indicating that bait or hooked fish were torn off the hook by force (Figures 3a-f).

Sperm whales were seen in proximity to the vessel during 71 % (17 sets) of depredation events. In other words, out of the 104 sets where sperm whales were present, 87 sets (84 %) had no evidence of damaged catches.

When evidence of depredation was detected, between 1.5 and 17.2 % ($\bar{x}$ = 6.6 ± 4.4 %; n = 23) of the total toothfish catch was damaged per set. On one occasion the total catch was damaged, but comprised only of a single fish. The overall depredation rate, i.e. the ratio of damaged fish in all the sets to total number of fish caught during the whole study, was 0.44 % (39 out of 8885 toothfishes).

All the pairwise comparisons of the numbers of fishes hooked on the longline segments before and after the 0 segment, i.e. the segment where sperm whales were first sighted, indicated significant differences. The most significant difference was found when we compared the 2 segments ($W = 5180.5$; $p < 0.001$) and 3 segments ($W = 3116$; $p < 0.001$) before and after sperm whale appearance. This suggests that sperm whales take hooked fish entirely from the line and that fish damage is an underestimate of total depredation.

We found no significant difference in cpue when we compared sets with/without evidence of depredation ($W = 40414$; $p = 0.52$) and sets with/without presence of sperm whales ($W = 28\,344$; $p = 0.56$). This suggests, that even if sperm whales remove fish entirely from the line, they do not significantly reduce overall catch rates.

3.4 Factors affecting sperm whale sightings, catch rates and depredation on catches

The GAM revealed that sperm whales were more frequently sighted close to the vessel during the day than during the night and more often during a waxing moon compared to other moon phases (Table 5). Another factor found to influence the frequency of sperm whale sightings was SST, with the lowest sighting frequency in water temperatures around 8 ºC and highest frequency at around 11 ºC (Table 5; Figure 5).

The cpue of toothfish was related to duration of gear retrieval, gear design, SST, the number of sperm whales sighted and depth of gear retrieval (Table 5). It was higher for longer retrieval times and partial coverage of hooks and showed a minimum at SST around 8-9 ºC (Figures 6a,b). The GAM also showed that cpue decreased with increasing numbers of sperm whales around the vessel and increased with water depth until 1200 m, after which it decreased (Figures 6c,d).

GAM results showed that evidence of depredation on catches was highly positively related to the presence of sperm whales (Table 5). Furthermore, depredation was more frequently found when the sea was rough (Figure 7). No relationships were found between depredation and cpue or duration of gear retrieval.

The number of fishes damaged showed a strong relationship with the number of sperm whales sighted around the vessel, first increasing with higher numbers of sperm whales and then being relatively stable if more than 3 sperm whales were around (Figure 8a). There were fewer damaged fish when cpue was high (> 23 kg) (Figure 8b). Moreover, the amount of fish damaged increased with sea state until state 6, and then dropped again in rough sea conditions (Figure 8c).

3.5 Impact of umbrella design and experimental longline setting on catch and depredation rates

The Mann-Whitney test showed that hooks that had no coverage with umbrellas caught more fishes than hooks that were covered. Comparing the different umbrella designs, designs 1, 2 and 4 allowed for higher catches than design 3 but there were no significant differences in catch rates between designs 1, 2 and 4 (Table 6)

When comparing the 8 different experimental longline settings, we found that settings with partial hook coverage had a higher cpue than settings with complete coverage. Among the three settings with complete coverage (G1-G3) no significant differences were found in catch rates. Of the settings with partial coverage, G5 and G8 achieved significantly higher cpue than the other settings (Table 7)

There were no significant differences in the occurrence of depredation between the two levels of hook coverage or between the 8 different longline settings. Depredation was low for longline settings G1, G6 and G8 and there was no depredation at all registered for settings G2 and G4 (Figure 8)**.**

3.6 Bycatch of cetaceans and seabirds

During the whole study only one seabird, a black-browed albatross (*Thalassarche melanophrys*), was caught accidentally on a longline. This happened when some of the stone weights were not correctly attached to the line and consequently became detached and sank, leaving the baited hooks floating at the surface for a while. There was no bycatch of cetaceans.

4. Discussion

4.1 Sightings

All cetacean and seabird species sighted during the survey are common in the cold water marine ecosystem of the SW Atlantic (Northridge, 1984; Moore *et al.* 1999; Crespo, 2002; Croxall and Wood, 2002; White *et al.*, 2002; Gandini and Seco Pon, 2007; Copello and Quintana, 2009).

Sperm whales were, by far, the most frequently sighted cetacean species in the proximity of the vessel. They were mostly seen as solitary individuals, but groups of 2 or 3 animals were also observed. Similar group sizes were reported by Purves *et al.* (2004) and White *et al.* (2002) in SW Atlantic waters. The large-scale distribution of the sperm whales primarily depends on that of their major prey, i.e. cephalopods, and suitable conditions for breeding. In the SW Atlantic they are mainly found in the warm waters of the Brazil current off Brazil and Uruguay where cephalopods are more abundant (Berzin, 1971). Nevertheless, sperm whales are known to follow their prey along warm, deep currents into higher latitudes, concentrating in areas where warm currents reach into colder waters (Kirpichnikov, 1950). Our study area, particularly area AI46, is directly bordering the Brazil-Malvinas Confluence (BMC) zone. This region, recognized as one of the most energetic zones in the world, is characterized by the confluence between the warm saline Brazil current that flows southward and the cold and fresh Malvinas/Falkland current which flows in the opposite direction (Olson *et al*., 1988). This area is a transition zone, inhabited by a mixture of subtropical and sub-Antarctic organisms (Deacon, 1982; Boltovskoy, 1986) and is rich in fishery resources.

Sperm whales are thought to primarily feed on meso- and bathy-pelagic cephalopods, squid being of much greater importance than octopus (Akimushkin, 1955; Rice, 1989; Riedl, 1991). Fish have been found to be important component of the diet in some areas e.g. off Iceland, Roe (1969), Martin & Clarke (1986); Gulf of Alaska and east Bering Sea (Okutani & Nemoto (1964). The most common fish recorded in the diet have been demersal species that in some cases could attain large sizes (1-3 m) (Berzin, 1971). Kawakami (1980) reported 68 species of fish from 49 families in his review on the diet of the species.

Sperm whales show a strong preference for deep waters with steep depth gradients (Davis *et al.,* 1998) and feeding dives are mostly to water depth between 400 and 800 m (Papastavrou *et al.*, 1989; Watkins *et al*., 1993; Amano and Yoshioka, 2003).

According to Huecke-Gaete *et al.* (2004) and Purves *et al.* (2004), sperm whales are likely to be attracted to fishing areas with high catch rates. In our study, we did not find a positive relationship between catch rates and the frequency of sperm whale sightings. Nevertheless, sperm whale sightings and toothfish catches increased towards warmer waters and were concentrated in areas with mean water depths between 1000 and 1600 m in our study. This indicates that sperm whales are likely to be found in areas with high toothfish density. However, if the sperm whales preyed on toothfish directly close to the sea floor on a regular basis they would consequently have to exceed their common diving range considerably. Therefore sperm whale distribution might rather be determined by the distribution of their principal prey, i.e., squid, or they might congregate in areas where toothfish are usually caught, i.e. feeding primarily on hooked fish during longline retrieval.

We also found that sperm whale sightings were more prevalent during the day than during the night, which was also reported by Purves *et al.* (2004). This result may, however, be simply attributed to the fact that sighting probability is much lower during the night due to the lack of light.

Another factor that seems to affect the frequency of sperm whales sightings was moon phase, with most sightings during waxing moon. Many cephalopod species exhibit some level of light-induced diel vertical migration, moving to the surface at night and returning to deeper waters at sunrise (Roper and Young, 1975). Therefore the sperm whales in our study might have foraged closer to the surface during waxing moon, resulting in a higher sighting frequency during that moon phase. However, the lack of any impact of lunar cycle on foraging success during the day, found by Whitehead (1996), does not support this theory.

4.2 Depredation on catches

Since sperm whales were present in proximity to the vessel in almost three-quarters of depredation events, they are assumed to be the main predators on hooked toothfish. They were exclusively sighted during longline hauling and, in addition, the number of fishes caught on the longline was significantly lower immediately after the appearance of sperm whales close to the vessel. It is therefore highly likely that depredation takes place while the gear is being hauled and not while it is soaking on the sea floor. Since longlines were usually set in depths over 1000 m, sperm whales probably prefer to feed on hooked fish close to the surface instead of deep-diving for it. Gear hauling took on average 5.85 hours in our study, and significantly increased in duration (up to 12 hours) when cpue of toothfish was high. Consequently sperm whales would have enough time to feed on catches. The sound of the hydraulics might serve as a cue to the start of hauling. This is consistent with the observations of Ashford *et al.* (1996) and Purves *et al.* (2004), who suggested that sperm whales take fish off the line at low water depth. In addition, Straley *et al.* (2002), reported that some sperm whales showed evidence of depredating on the line, e.g. grooved indentations along the side of the head apparently caused by a line running through their mouth.

The characteristics of damaged fish are similar to those described by Ashford *et al.* (1996), Purves *et al.* (2004) and Pin and Rojas (2007) in previous studies, identifying the sperm whale as the main predator on hooked toothfish. This assumption is also supported by the highly significant positive relationship we found between the occurrence of depredation and the presence of sperm whales around the vessel.

Damage and depredation rates in our study were low. The damage rate (percentage of longline sets with evidence of depredation) was lower than the one reported by Pin and Rojas (2007) for longlines equipped with MBEDs, who calculated that 16 % of sets had suffered depredation. The overall depredation rate (percentage of fish damaged during all longline sets) is similar to the rates found by Moreno *et al.* (2008) with MBEDs and by Sigler *et al*. (2008) without MBEDs. Although we found no significant difference in cpue from sets with/without visual evidence of depredation, we have to consider that cpue decreased with higher numbers of sperm whales around the vessel. This suggests that sperm whales may actually have a negative impact on catch rates, particularly if they attack the longlines in large groups. If we consider that, on the majority of occasions when sperm whales were sighted around the vessel, depredation was not evident by visual observation, this finding supports our hypothesis that a considerable amount of depredation remains undetected. We also discovered that the occurrence of depredation and the number of fishes damaged were positively related to the sea state. Since hauling usually takes longer in rough sea conditions, sperm whales might have more time to prey on the hooked fish than under calm conditions. Sea state 7-9 was only registered in 3 % of all hauls and therefore there were insufficient observations to make a clear statement about depredation levels under very rough sea conditions.

Kock (2001) and Pin and Rojas (2008) mention that sperm whales occasionally take up to 100 % of the catch in a single set. In our study the maximum percentage of fish damaged per set was lower than 20 % (except the set where the whole catch was one fish), indicating that the MBEDs are most likely efficient in preventing the sperm whales from taking large quantities of catch from the longline. However, damage and depredation rates in our study are most likely underestimated since only fish damaged was considered as lost.

4.3 Economic loss due to interactions with sperm whales

Even though the average loss due to damaged fish appears to be small, the financial loss to fishermen may be significant because of the high market value of the toothfish and the likelihood that some depredation goes unrecorded. Moreover, navigating to alternative fishing areas in order to "escape" from the sperm whales causes additional expenses for petrol and loss of fishing time.

4.4 Impact of gear design on catch rates, depredation and bycatch

We found that hooks that were covered with umbrellas caught fewer fish than uncovered hooks and that cpue was higher for longline settings with partial hook coverage than for complete coverage. In contrast, in a comparable study by Moreno *et al.* (2008), the use of MBEDs had no adverse effect on catch rates. In our experimental setting the MBEDs were knotted to the branch lines while Moreno *et al.* (2008) attached them in such a way that the sleeves could slide up and down the branch line during setting and hauling.

Comparing the different umbrella designs, designs 1, 2 and 4 had higher catches than design 3. No depredation was observed for settings G2 (complete coverage) and G4 ($^2/_3$ of hooks covered). However, small sample size is an issue here, since the number of observations for these longline settings was very low compared to the other settings. Among the settings that reduced depredation most efficiently, G8 had the highest catch rates and might therefore be the most appropriate of all settings tested.

The attachment of stone weights to the branch lines proved to be very efficient in minimizing accidental bycatches of seabirds. The fast sink speed of the longline during setting prevented the birds from feeding on the bait, and consequently getting hooked on the line and drowning.

4.5 Feasibility of the new gear design

The new longline design was highly effective in preventing accidental bycatch of seabirds and marine mammals in our study. The effectiveness of MBEDs in reducing sperm whale depredation on catch, however, was not very evident in our study, although some of our results indicate that, given the appropriate umbrella design, they might be useful in preventing the sperm whales from taking large quantities of catch from the longline. Nevertheless, they could not prevent depredation completely. Material costs for the MBEDs are relatively low, and if the fishermen build them themselves, production costs can be reduced to a minimum. They can be used for a long time, and if umbrellas prove to reduce depredation on catches, they are a reasonable investment that will pay off after a while. However, we have to bear in mind that umbrellas reduced catches significantly in our study. So the negative effects of the MBEDs might exceed their benefits. Modifications to the umbrellas, such as allowing the net sleeve to move along the branch line or reducing the visibility of the umbrellas in the water, might help to improve catch rates. Fishermen and longline fishery associations should be encouraged to become active participants in the improvement of existing and the development of new longline designs.

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Figure legends

Figure 1. Study area and fishing effort for subareas.

Figure 2. a) Experimental longline setting and b) umbrella (MBED) design & mechanism.

Figure 3. Evidence of sperm whale depredation on toothfish a) only head or b) lips left on the hook, c) fractured cranium, d) blunt tooth marks, e) missing body parts and crushed tissue, f) bent fishing hooks.

Figure 4. Proportion of hauls (n= 297) with sperm whale sightings (sight), evidence of depredation (deprd) and mean cpue of toothfish for different subareas.

Figure 5. GAM results for sperm whale sightings: smoothing curve for partial effect of SST. Dotted lines indicate 95% confidence bands.

Figure 6. GAM results for cpue of toothfish: smoothing curve for partial effect of a) duration of gear retrieval, b) SST, c) Nº of sperm whales and d) depth of gear retrieval.

Figure 7. GAM results for occurrence of depredation: smoothing curve for partial effect of sea state. Dotted lines indicate 95% confidence bands.

Figure 8. GAM results for Nº of toothfish damaged: smoothing curve for partial effect of a) Nº of sperm whales, b) cpue of toothfish and c) sea state. Dotted lines indicate 95% confidence bands.

Figure 9. Proportion of hauls (n=297) with sperm whale sightings (sight), evidence of depredation (deprd) and mean cpue of toothfish for different gear designs.

Table 1. Experimental longline settings (different umbrella designs used and their arrangement on the longline).

Umbrella designs			
0 No umbrella			
1 base ring: metal / net sleeve length: 1.5m		**2** base ring: rope / net sleeve length: 1.5m	
3 base ring: rope / net sleeve length: 1.7 m		**4** base ring: rope / net sleeve length: 2.0m	
G1	1 – 2 – 1 – 2 – 1 – 2 – 1	all hooks covered	complete hook coverage
G2	2 – 2 – 2 – 2 – 2 – 2 – 2	all hooks covered	complete hook coverage
G3	4 – 4 – 4 – 4 – 4 – 4 – 4	all hooks covered	complete hook coverage
G4	2 – 3 – 0 – 2 – 3 – 0 – 2	$^2/_3$ of hooks covered	partial hook coverage
G5	2 – 0 – 2 – 0 – 2 – 0 – 2	$^1/_2$ of hooks covered	partial hook coverage
G6	2 – 0 – 3 – 0 – 2 – 0 – 3	$^1/_2$ of hooks covered	partial hook coverage
G7	2 – 0 – 4 – 0 – 2 – 0 – 4	$^1/_2$ of hooks covered	partial hook coverage
G8	4 – 0 – 4 – 0 – 4 – 0 – 4		

Table 2. List of variables and their descriptors used for analysis.

	Variables	Descriptor
fishery data	catches of toothfish	cpue Nº of fishes
	Nº of branchlines	
	soak time	in minutes
	duration of gear retrieval	in minutes
	depth of gear retrieval	in m
	gear design used	4 umbrella designs complete / partial hook coverage 8 experimental longline settings G1 – G8
sightings	sightings of sperm whale	presence/absence of sperm whales Nº of sperm whales
depredation	depredation on toothfish	occurrence of depredation Nº of fish damaged
environmental / oceanographic data	sea state (S)	Douglas scale: from 0 - 9
	cloud cover (C)	scale: from 0 - 8
	moon phase (M)	M1: new moon M2: waxing moon M3: full moon M4:waning moon
	sea surface temperature (SST)	in ºC
	time of day	day / night

Table 3. Coding schemes for nominal variables according to Zuur *et al*. (2007): example moon phase.

Moon phase				
	M1	M2	M3	M4
new moon	1	0	0	0
waxing moon	0	1	0	0
full moon	0	0	1	0
waning moon	0	0	0	1

Table 4. Sightings of cetaceans (sighting frequency, species and Nº of individuals sighted) and seabirds (species sighted only).

	Scientific name	Common name	Sighting frequency	Nº of individuals
Cetaceans	**Physteridae**			
	Physeter macrocephalus	sperm whale	104	1 – 6
	Balaenopteridae			
	Balaenoptera acutorostrata	common minke whale	3	1
	Delphinidae			
	Globicephala melas	long-finned pilot whale	2	3 – 15
	Orcinus orca	killer whale	1	4
	Lagenorhynchus obscurus	dusky dolphin	1	> 200
	Lissodelphis peronii	southern right whale dolphin	1	5
Seabirds	**Diomedeidae**			
	Diomedea exulans	wandering albatross		
	Diomedea epomophora	southern Royal albatross		
	Thalassarche chrystostoma	grey-headed albatross		
	Thalassarche melanophris	black-browed albatross		
	Procellariidae			
	Macronectes giganteus	southern giant petrel		
	Macronectes halli	northern giant petrel		
	Daption capense	cape petrel		
	Procellaria aequinoctialis	white-chinned petrel		
	Puffinus puffinus	Manx shearwater		
	Puffinus gravis	great shearwater		
	Hydrobatidae			
	Oceanites oceanicus	Wilson's storm-petrel		
	Fregetta tropica	black-bellied storm-petrel		

Table 5. GAM results (n = 296 sets). The response variables presence/absence of sperm whales and occurrence of depredation both followed a binomial distribution, while Gaussian distribution was appropriate for cpue of toothfish and Poisson distribution for Nº of fishes damaged. Results displayed are as follows: explanatory variables included in the final model, whether they were included as smoothers (S) or nominal variables (N), their significance (based on χ^2, F or t tests, with p-value) and the direction (sign) of the effect (+ or -). Also given are the overall percentage of deviance explained (%dev) and AIC value for the model. For explanatory variables used see list of variables (Table 2). For the variable gear design only the descriptor of complete/partial coverage of hooks was considered in the model.

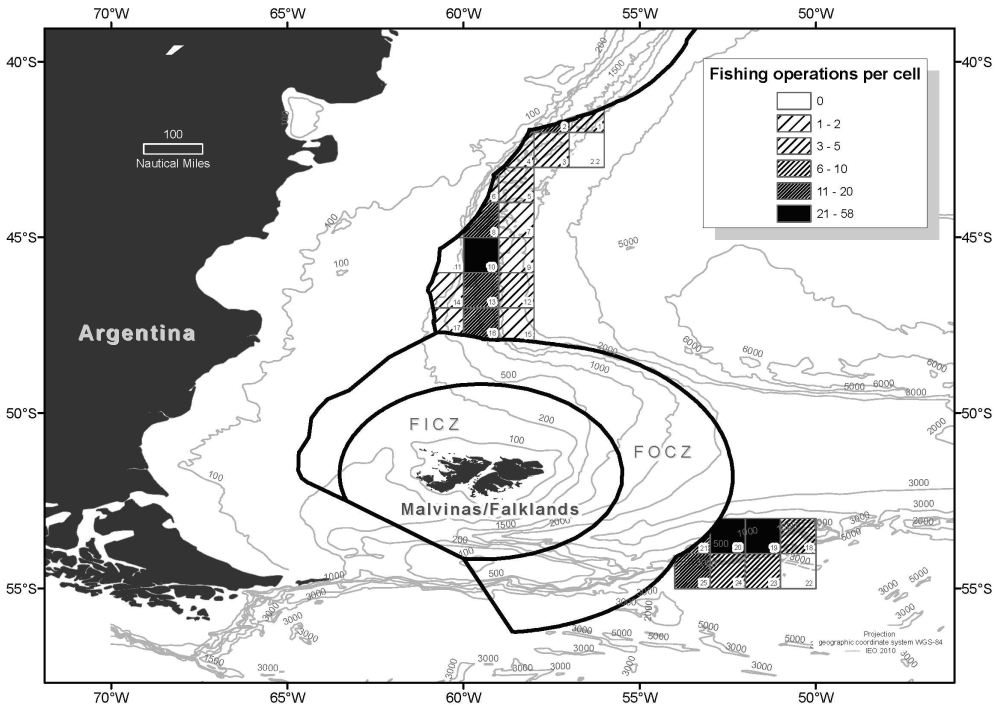
Response variables	Explanatory variables	Type	$z / F / \chi^2$	p	sign	%dev	AIC
presence/absence of sperm whales	day / night	N	3.69	0.0002	+	12.3	341.48
	M1	N	-3.22	0.0013	-		
	M2	N	-2.70	0.0069	-		
	M3	N	-2.70	0.0060	-		
	SST	S	14.64	0.0020			
cpue of toothfish	duration of gear retrieval	S	10.84	0.0011		15.2	1 842.68
	compl./part. hook coverage	N	-2.80	0.0055	-		
	SST	S	5.22	0.0056			
	Nº sperm whales	S	4.86	0.0106			
	depth of gear retrieval	S	3.03	0.0442			
occurrence of depredation	pres./abs. of sperm whales	N	4.79	< 0.0001	+	10.3	155.46
	sea state	S	6.91	0.0086			
Nº of fish damaged	Nº sperm whales	S	26.07	< 0.0001		22.2	233.54
	cpue of toothfish	S	17.75	0.0004			
	sea state	S	17.03	0.0003			

Table 6. Mann-Whitney test comparing catch rates (Nº of fishes caught) for different umbrella designs : 0 = no umbrellas; 1 – 4 = different umbrella designs.

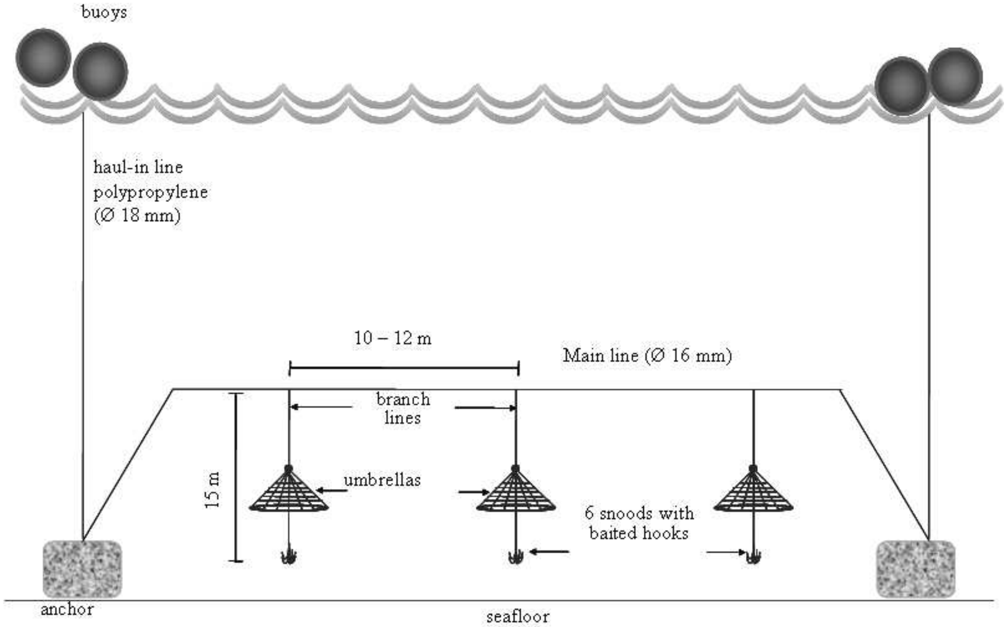
Pairwise comparison of catch rates First sample > second sample Confidence level = 95.00	W	p
0 > 1	34 067	0.0001
0 > 2	63 982	< 0.0001
0 > 3	41 409	< 0.0001
0 > 4	44 849	< 0.0001
1 > 3	3 964	< 0.0001
2 > 3	36 197	0.0008
4 > 3	12 949	< 0.0001

Table 7. GAM results: Relationship between cpue of toothfish and different experimental longline settings.

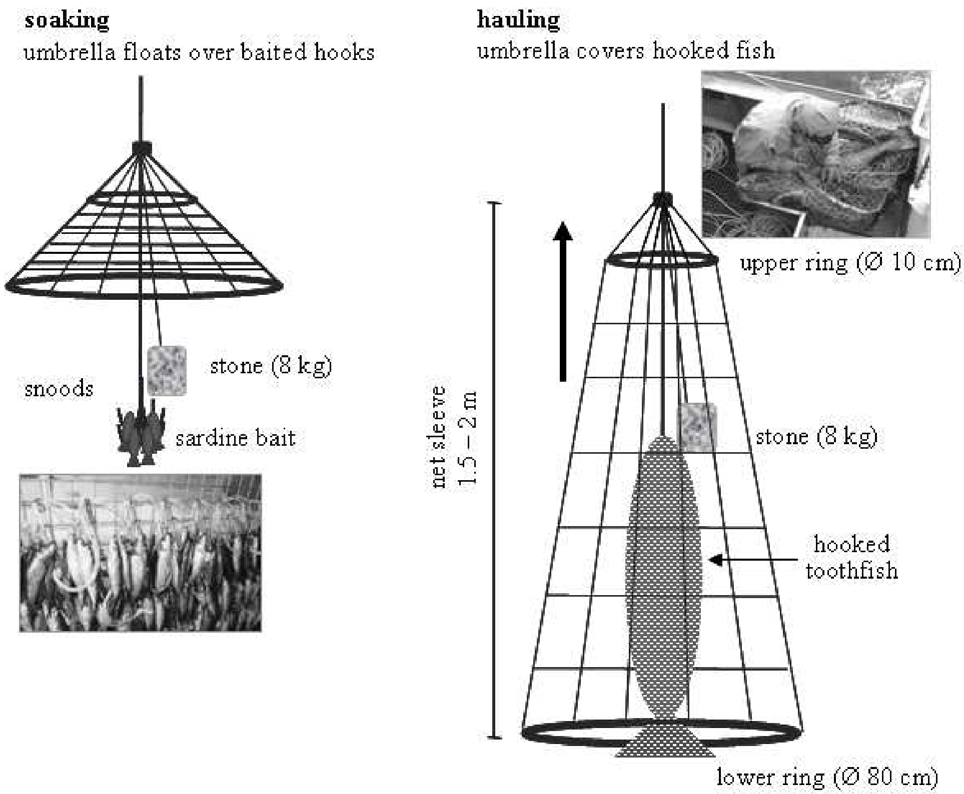
Pairs of settings compared	Type	t	p	sign	%dev	AIC
complete – partial hook coverage	N	-3.04	0.0026	-	13	1 876.1
G5 – G4	N	2.48	0.0134	+	15.3	1 879.1
G5 – G6	N	2.69	0.0076	+		
G5 – G7	N	2.79	0.0056	+		
G8 – G4	N	2.38	0.0178	+		
G8 – G6	N	2.64	0.0088	+		
G8 – G7	N	2.70	0.0073	+		



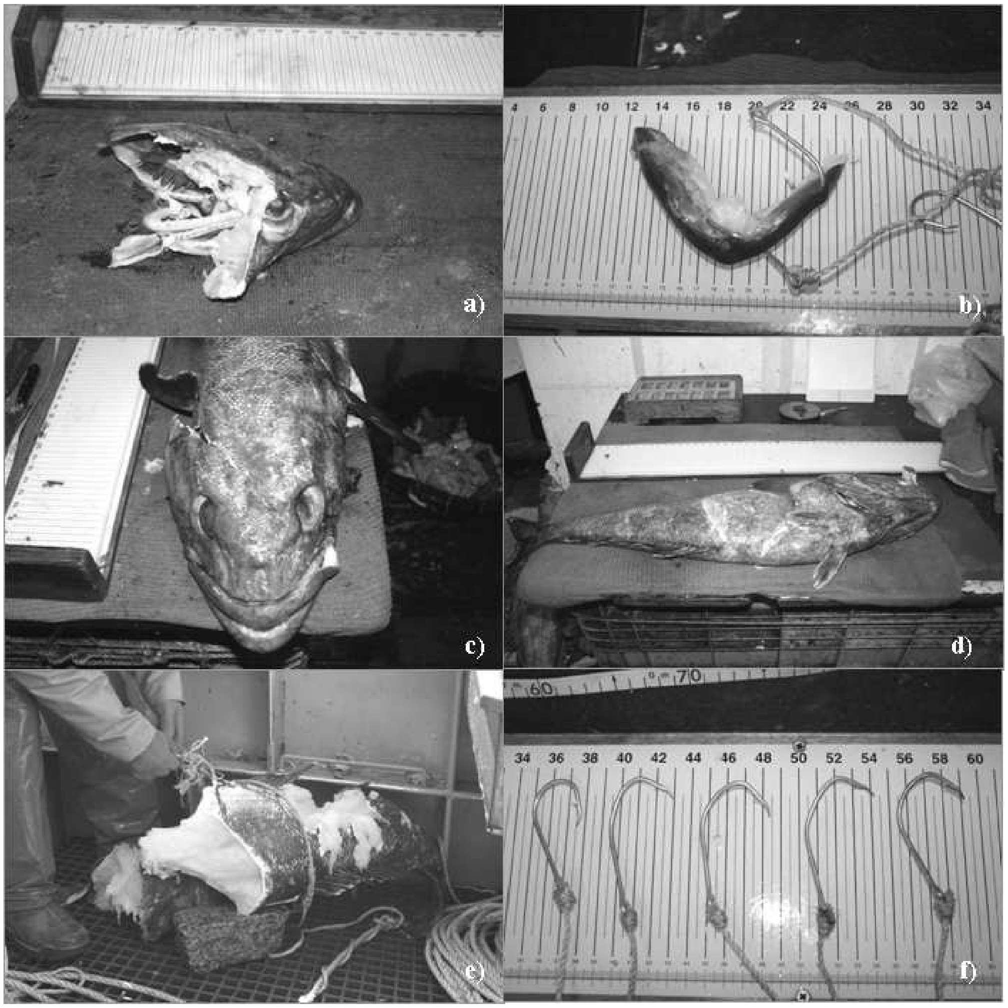
Study area and fishing effort for subareas.
825x583mm (72 x 72 DPI)



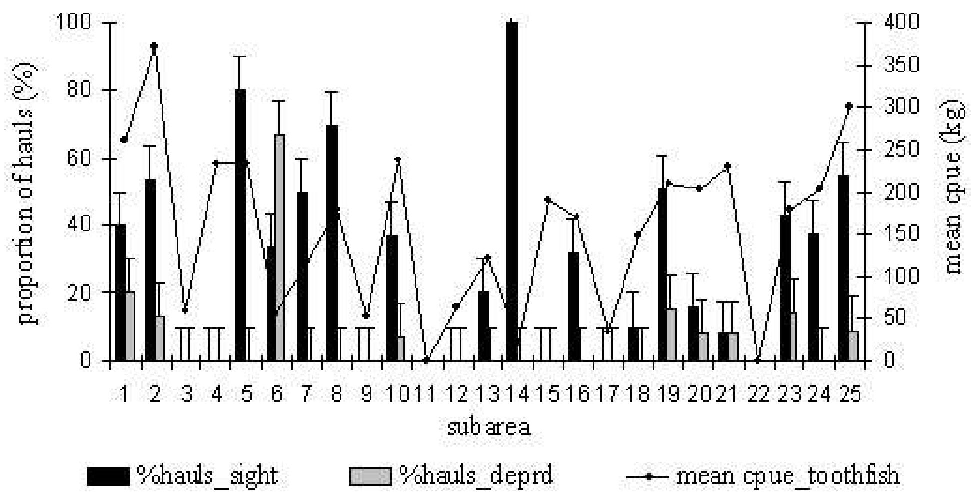
Experimental longline setting.
283x182mm (72 x 72 DPI)



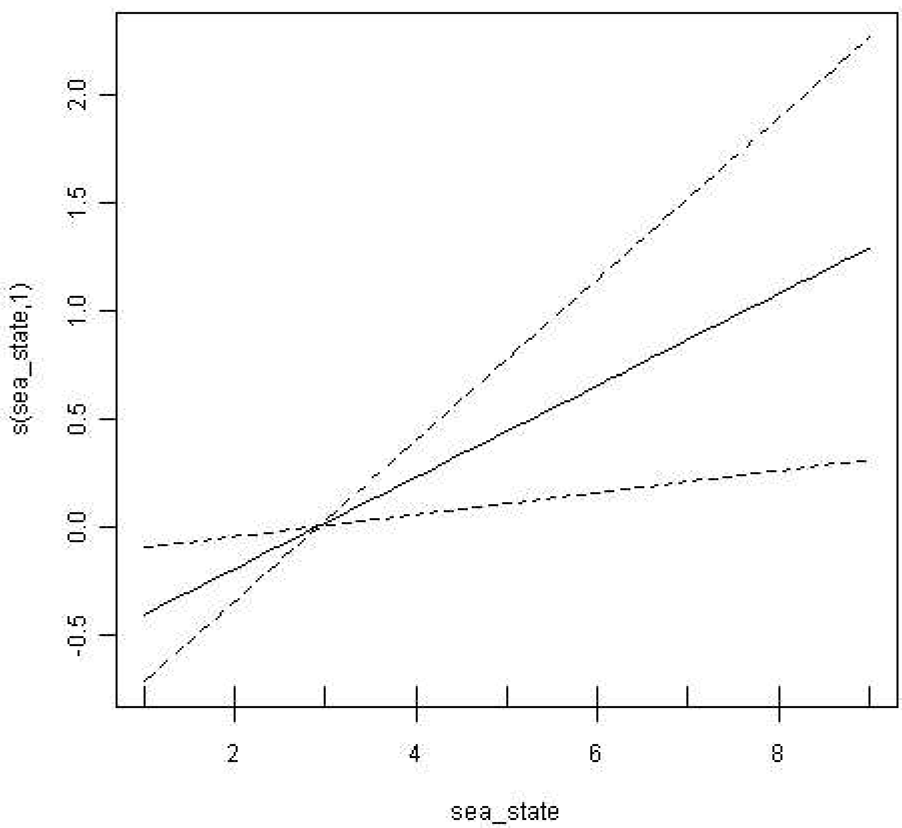
Umbrella (MBED) design & mechanism.
214x173mm (72 x 72 DPI)



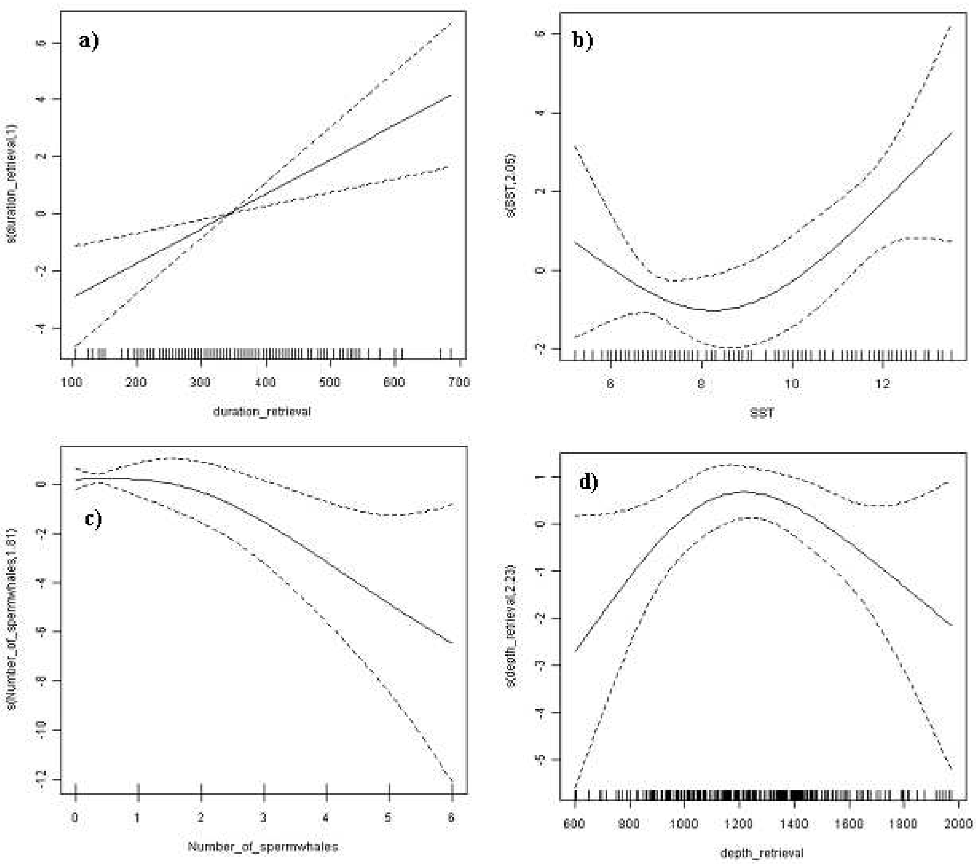
Evidence of sperm whale depredation on toothfish a) only head or b) lips left on the hook, c) fractured cranium, d) blunt tooth marks, e) missing body parts and crushed tissue, f) bent fishing hooks.
247x247mm (72 x 72 DPI)



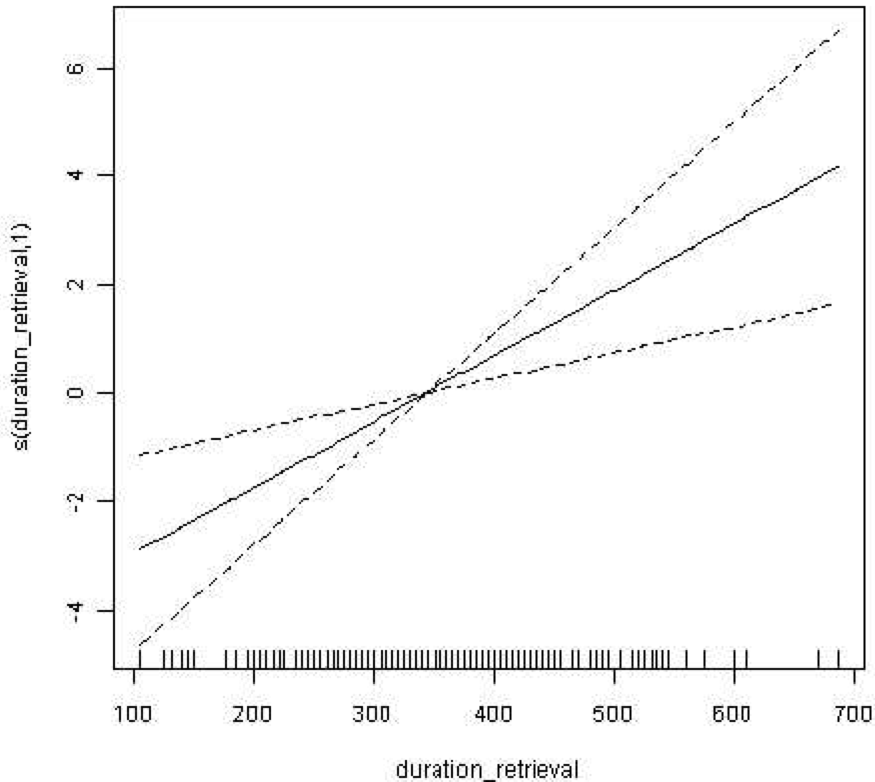
Proportion of hauls (n= 297) with sperm whale sightings (sight), evidence of depredation (deprd) and mean cpue of toothfish for different subareas.
188x113mm (72 x 72 DPI)



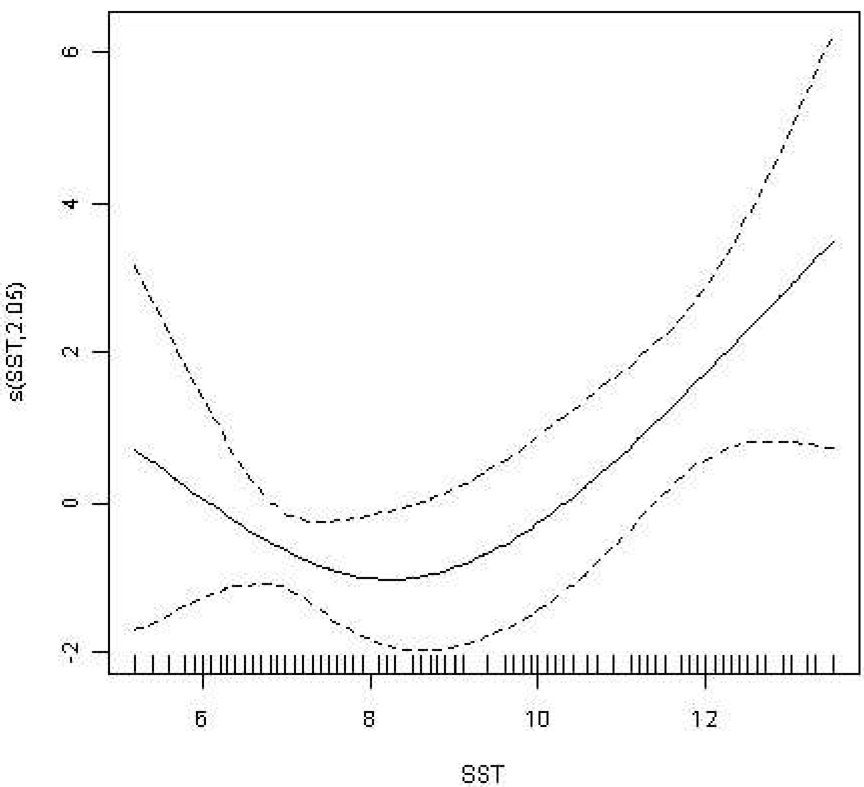
GAM results for sperm whale sightings: smoothing curve for partial effect of SST. Dotted lines indicate 95% confidence bands.
169x169mm (72 x 72 DPI)



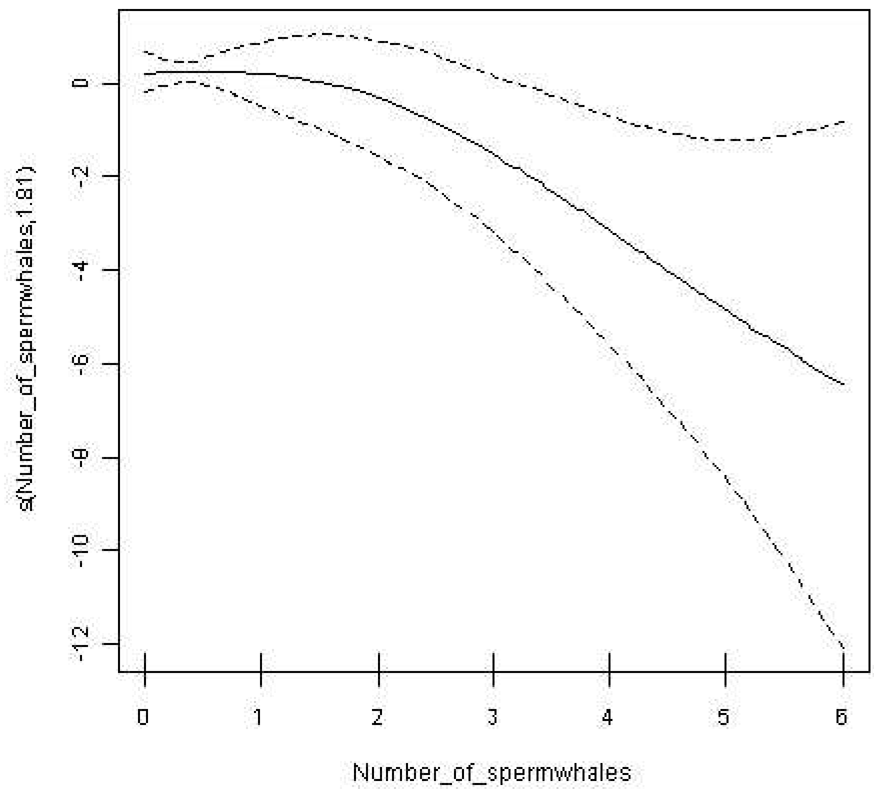
GAM results for cpue of toothfish: smoothing curve for partial effect of a) duration of gear retrieval, b) SST, c) Nº of sperm whales and d) depth of gear retrieval. Dotted lines indicate 95% confidence bands.
221x204mm (72 x 72 DPI)



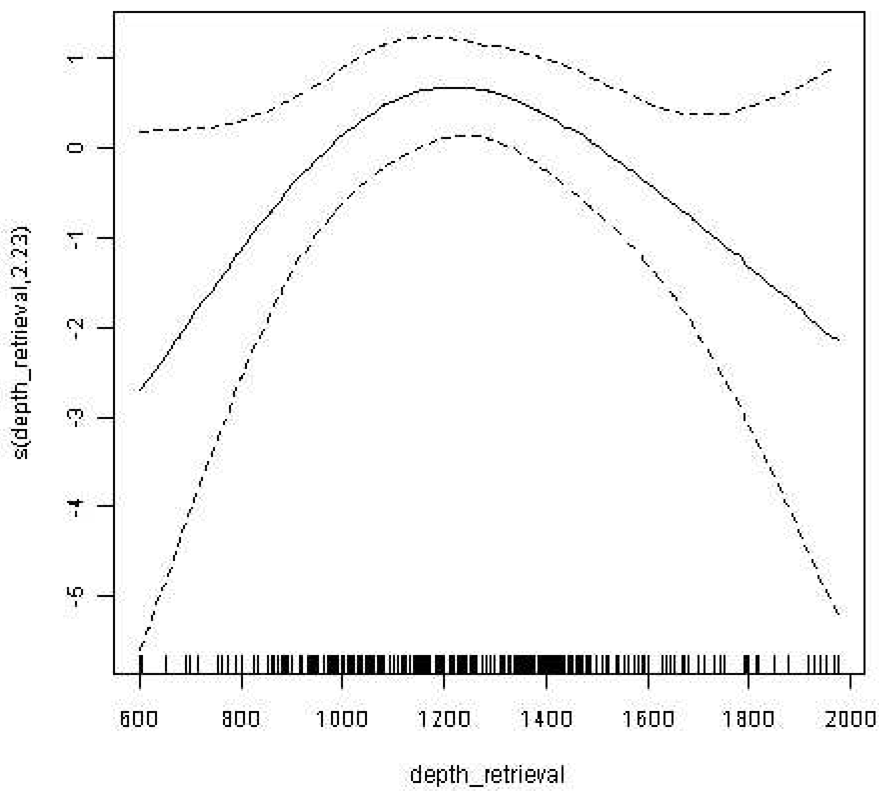
GAM results for cpue of toothfish: smoothing curve for partial effect of duration of gear retrieval. Dotted lines indicate 95% confidence bands.
162x161mm (72 x 72 DPI)



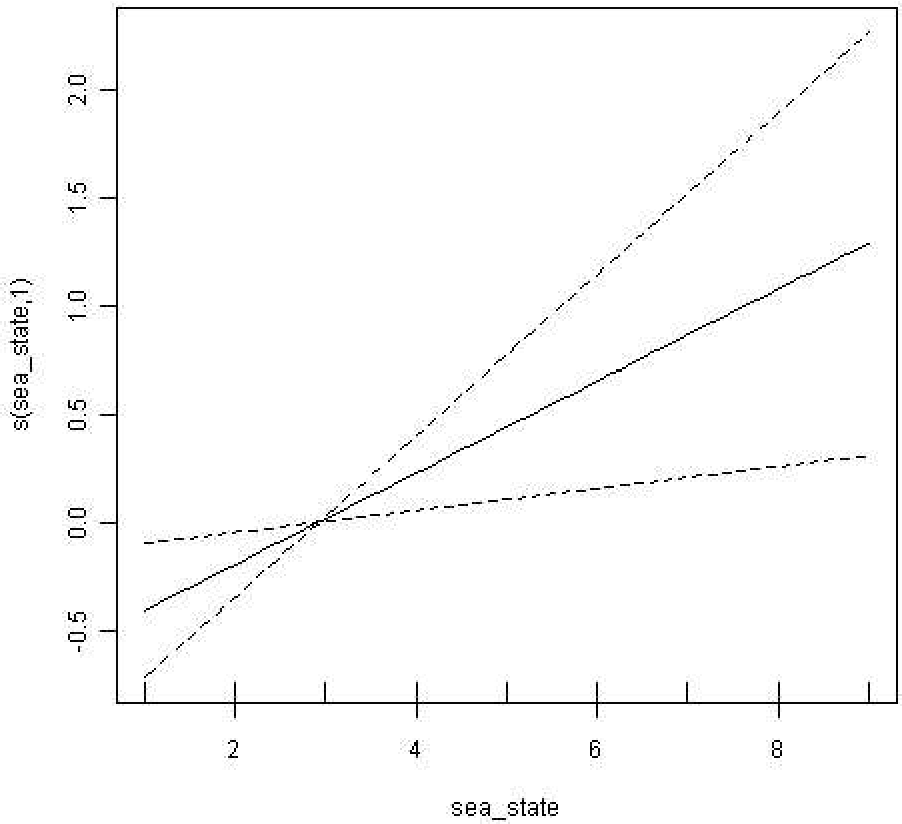
GAM results for cpue of toothfish: smoothing curve for partial effect of SST. Dotted lines indicate 95% confidence bands.
162x161mm (72 x 72 DPI)



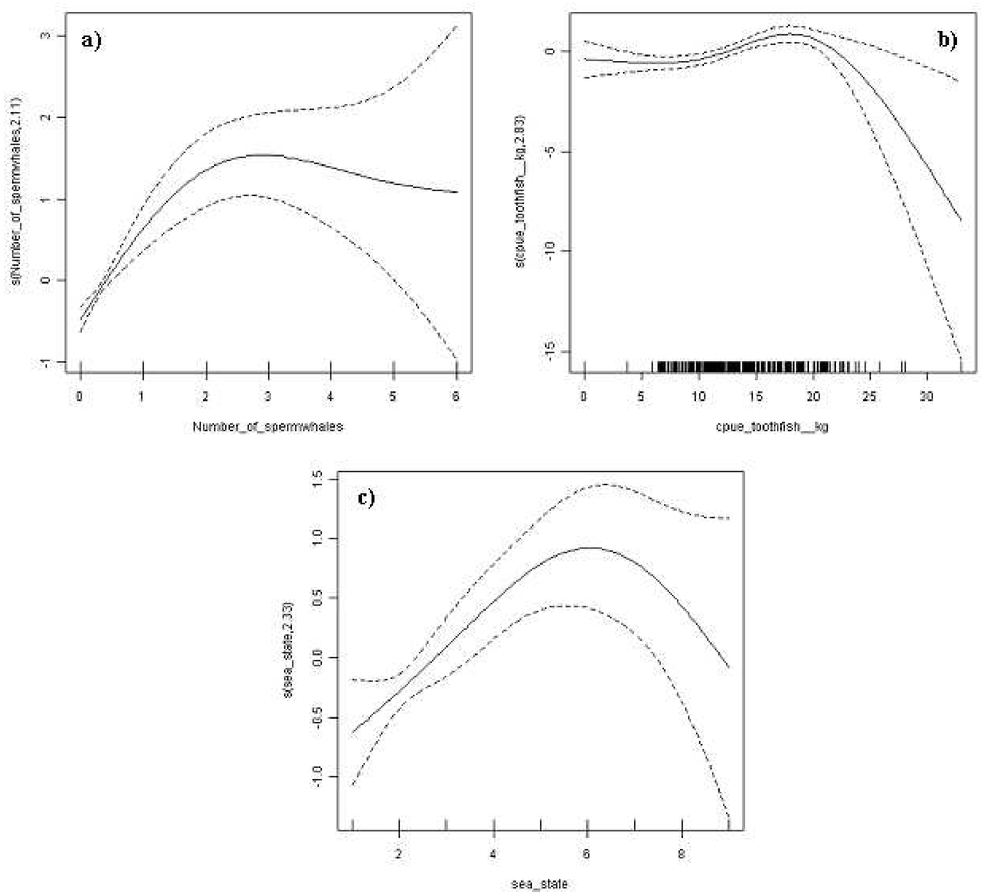
GAM results for cpue of toothfish: smoothing curve for partial effect of Nº of sperm whales. Dotted lines indicate 95% confidence bands.
162x161mm (72 x 72 DPI)



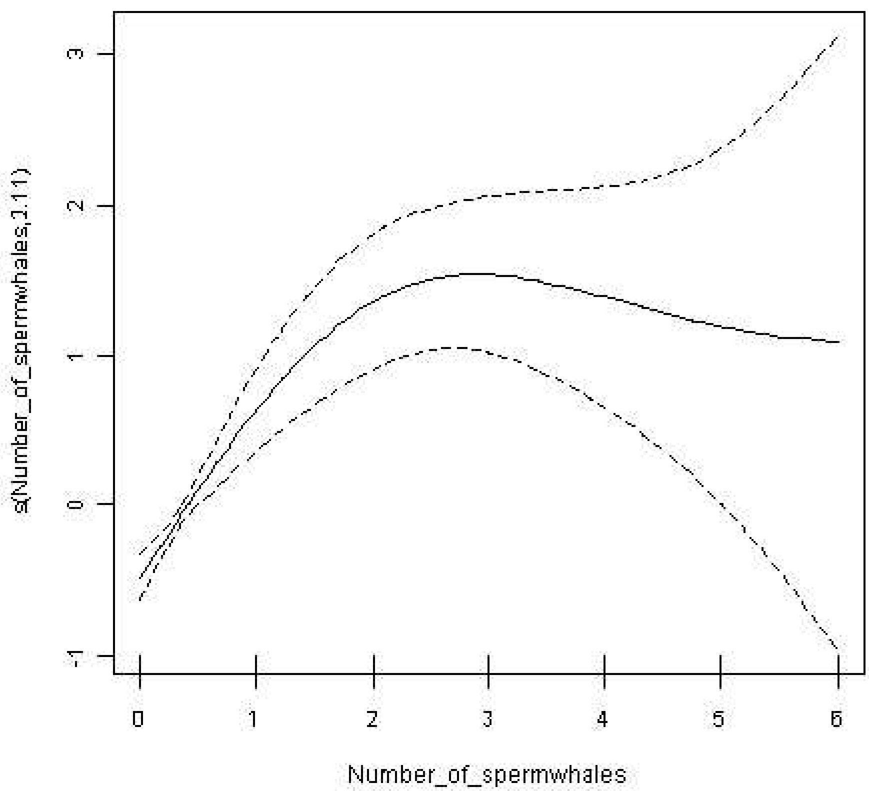
GAM results for cpue of toothfish: smoothing curve for partial effect of depth of gear retrieval.
Dotted lines indicate 95% confidence bands.
162x161mm (72 x 72 DPI)



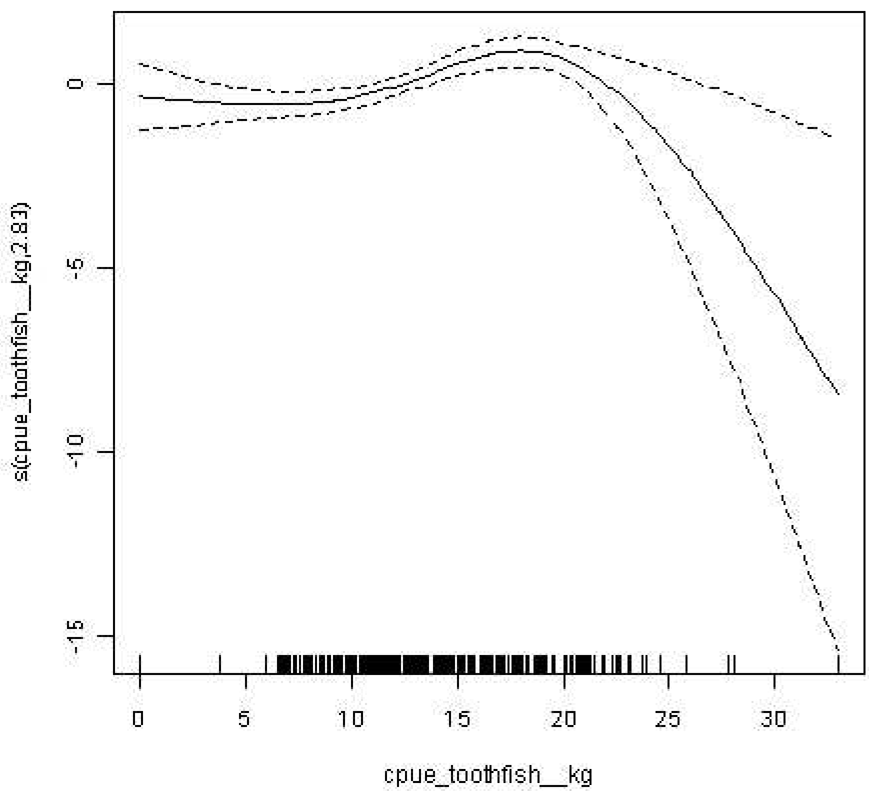
GAM results for occurrence of depredation: smoothing curve for partial effect of sea state. Dotted lines indicate 95% confidence bands.
169x169mm (72 x 72 DPI)



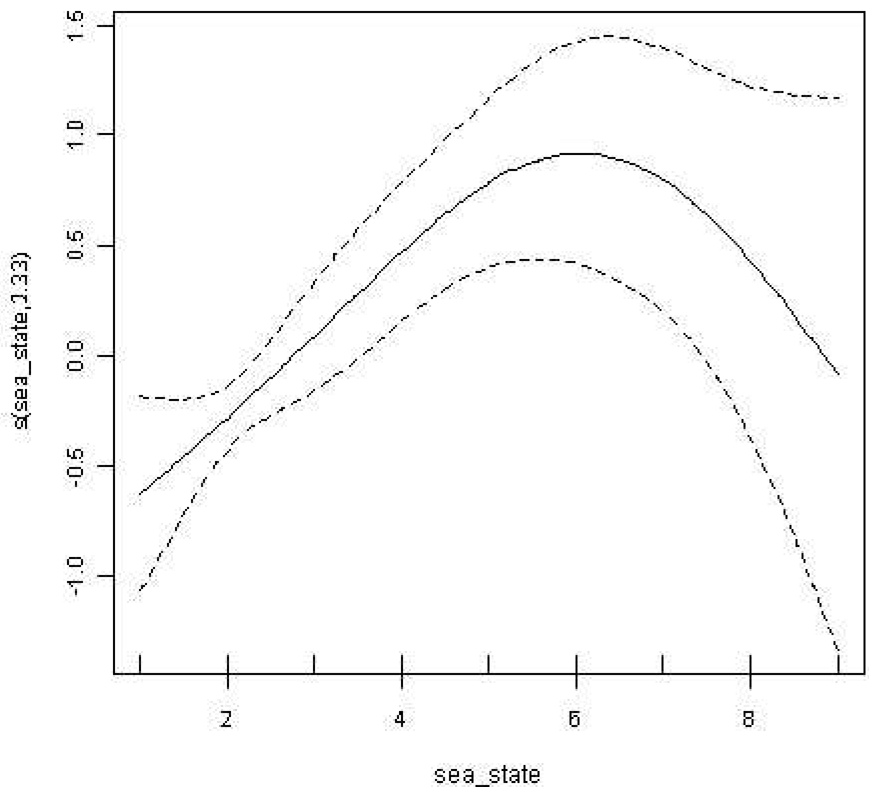
GAM results for Nº of toothfish damaged: smoothing curve for partial effect of a) Nº of sperm whales, b) cpue of toothfish and c) sea state. Dotted lines indicate 95% confidence bands.
221x211mm (72 x 72 DPI)



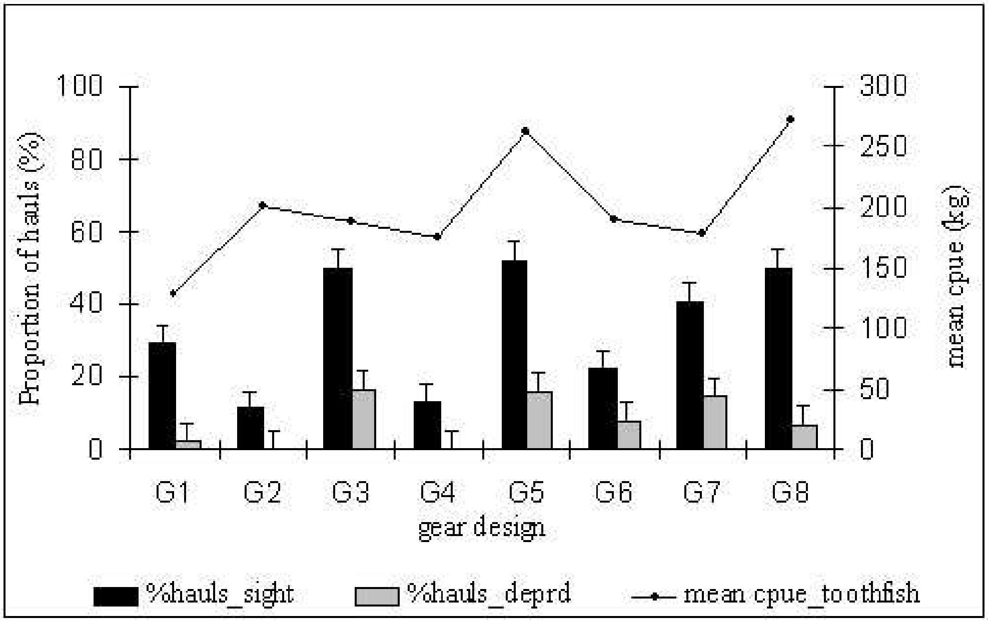
GAM results for Nº of toothfish damaged: smoothing curve for partial effect of Nº of sperm whales. Dotted lines indicate 95% confidence bands.
162x161mm (72 x 72 DPI)



GAM results for Nº of toothfish damaged: smoothing curve for partial effect of cpue of toothfish.
Dotted lines indicate 95% confidence bands.
162x161mm (72 x 72 DPI)



GAM results for Nº of toothfish damaged: smoothing curve for partial effect of sea state. Dotted lines indicate 95% confidence bands.
162x161mm (72 x 72 DPI)



Proportion of hauls (n=297) with sperm whale sightings (sight), evidence of depredation (deprd) and mean cpue of toothfish for different gear designs.
179x113mm (72 x 72 DPI)