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Experimental fishing with an "umbrella-and-stones" system to reduce interactions of sperm whales (*Physeter macrocephalus*) and seabirds with bottom-set longlines for Patagonian toothfish (*Dissostichus eleginoides*) in the Southwest Atlantic

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Depredation, i.e. the 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 the Southwest Atlantic. The fishery also suffers 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 the so-called "umbrella" system, coupled with attached stones for faster sinking, for minimizing both. Moreover, we investigated the relationships between sightings of sperm whales, depredation, catches, and environmental variables using generalized additive modelling. Data were collected during 297 hauls on a longliner in 2007/2008 in international waters of the Southwest Atlantic. Sperm whales were sighted during 35% of the hauls, always during gear retrieval, and their presence was positively related to fish damage. The overall depredation rate (0.44% of the total catch) was low, but is assumed to be underestimated because sperm whales were suspected of also taking fish without leaving visual evidence. The "umbrella-and-stones" system was highly effective in preventing bycatch and appeared to restrict depredation, but significantly reduced the catches. The results demonstrate that there is still some way to go to solve the problem of depredation.

Keywords: depredation, longline, Patagonian toothfish, sperm whale, umbrella system.

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 off Chile and in many northern hemisphere fisheries. In 1992, the total reported catch of the Patagonian toothfish reached 40 710 t worldwide (FAO, 2003), and the fishery developed into an important and highly valuable one, with reported annual catches (1995–2001) of between 28 035 and 44 047 t (FAO, 2003; Laptikhovsky and Brickle, 2005). In 2007/2008, the total landings of toothfish were 12 573 and 10 291 t within and outside the CCAMLR (Commission for the Conservation of Antarctic Marine Living Resources) Convention Area, respectively (STECF, 2009).

Two types of longline gear are used in the toothfish fishery around the Falkland Islands/Islas Malvinas: (i) the MUSTAD autoline system, which utilizes lines made up of 250-m sections, with snoods (short hook lines with baited hooks) connected with crimps and swivels at intervals of 1.2–1.4 m; and (ii) the "Spanish system", which utilizes two lines, a fishing line and a safety line, and two winches for hauling. The longline fishery takes place year-round at fishing depths of 650–2000 m.

The Patagonian toothfish is a long-lived, slow-growing notothenid endemic to Antarctic and Subantarctic waters (Agnew, 2004) and distributed from 36°39′ to 55°S in water temperatures of 2–12°C. Concentrations of the species are found south and northeast of the Falklands/Malvinas, over the shelf break of Buenos Aires Province and between Burdwood Bank and Staten Island. Toothfish vary in size by depth (depth range 80–2500 m), with adults (>80 cm) living below 900 m (Preński and Almeyda, 2000). The species is commercially very valuable, reaching market prices averaging US$14 kg^{-1} (J. A. Novo, captain FV "Arnela", pers. comm.). Damaged fish are usually discarded because only immaculate specimens can be sold. Cetacean depredation, i.e. the damage and the 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. Depredation has been widely reported for the fishery, primarily involving the sperm whale (*Physeter macrocephalus*; Ashford *et al.*, 1996; Kock, 2001; Hucke-Gaete *et al.*, 2004; Purves *et al.*, 2004; Kock *et al.*, 2006; Pin and Rojas, 2007; Moreno *et al.*, 2008).

Sperm whales are the largest toothed whales, with mature animals recorded up to 21 m long (Berzin, 1971). They have a complex social organization in which 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, migrating to higher latitudes in spring/summer and returning to lower latitudes in winter; females and calves remain in low latitudes year-round (Berzin, 1971).

Sperm whales are found in deep waters of all oceans, and results from many studies (originally based on the analysis of stomach contents of animals killed commercially and more recently on stranded specimens) indicate a diet based largely on deep-sea cephalopods of various size, followed by fish (see Kawakami, 1980; Rice, 1989; Santos *et al.*, 1999). Korabelnikov (1959), Clarke (1980), and Abe and Iwami (1989) reported the presence of Patagonian toothfish in the diet of sperm whales 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).

Sperm whales may occasionally become entangled in the longline and cause breakage of the line (Kock *et al.*, 2006), but they are rarely entrapped. Bycatch of seabirds, however, is a much bigger conservation issue in the fishery, mostly affecting albatrosses and petrels (Ashford *et al.*, 1995; Moreno *et al.*, 1996). When longlines are set, birds are frequently hooked or entangled while feeding on the bait, being dragged underwater and drowned as the gear sinks (Gilman *et al.*, 2005). The area in and around the Falklands/Malvinas supports seabird populations of international importance (Woods and Woods, 1997) and, according to Gales (1993), population declines of several albatross species have been linked to longline fisheries in the southern ocean. Consequently, many (in August 2010, the figure was 29 species; http://www.acap.aq/) species of albatross and petrel have been listed under the Agreement on the Conservation of Albatrosses and Petrels (ACAP), negotiated under the UN Convention on the Conservation of Migratory Species of Wild Animals (CMS) in 2004, to stop or reverse population declines by mitigating known threats to species.

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

In the fishery for Patagonian toothfish, there have been several attempts in recent years to reduce interactions by limiting the cetacean and seabird access to catch and bait. Pin and Rojas (2007) and Moreno *et al.* (2008) used mammal excluder devices (MEDs), also known as an "umbrella system" or "Chilean longline", which consist of cone-shaped umbrella-like net sleeves that protect the hooked fish from depredation during hauling. To deter seabirds, CCAMLR Conservation Measure 25-02 of 2005 requires vessels using the autoline or Spanish system to deploy weights on hook lines to allow for a faster sinking rate and, as a consequence, to minimize the bycatch of seabirds by reducing the time the bait remains at the surface.

The main goal of the present study was to assess the extent of depredation by sperm whales on catches and cetacean/seabird bycatch in a scientifically, largely unexplored fishing area, and to test the potential of different longline designs, including "umbrellas" and stone weights, to minimize depredation and the bycatch of seabirds. Moreover, we investigated how sightings of sperm whales, depredation, and catch rates are related to each other and to environmental and fishery-related variables.

Material and methods

Data were collected by an experienced fisheries observer (ML) on board the Spanish commercial longlining vessel "Arnela", which targeted mainly Patagonian toothfish between 23 November 2007 and 7 April 2008. Fishing took place in two areas: (i) area AI46 (extending east of the Argentine EEZ between 41° and 48°S and up to 56°W), and (ii) area AI54 (bordering Falklands/Malvinas waters to the west and extending between 53 and 55°S and to 50°W). To investigate spatial trends, the study area was divided into 25 subareas of 1 × 1°. The fishing effort for each subarea is shown in Figure 1.

Longline design and experimental setting

The experimental longline design tested in our study is similar to that used by Moreno *et al.* (2008). The method originated in the Chilean artisanal toothfish fishery (Moreno *et al.*, 2006), where it was used to minimize depredation, and was adopted with some modifications by the commercial longline fleet in Chile for the same reason. In each experimental longline, the single monofilament hook line was replaced by a polypropylene main line carrying several branch lines. 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 six snoods with baited hooks, a stone (~8 kg) to weigh down the branch line and increase sink speed, and an "umbrella". The bait used during the study was mostly sardine (*Sardina pilchardus*). Each umbrella was composed of an upper and a lower ring (Ø 10 and 80 cm, respectively) supporting a cone-shaped net sleeve of length 1.5–2 m (Figure 2a). The rings and the net were positively buoyant in water, allowing the umbrella to float over the baited hooks while the gear was soaking. When the mainline is hauled back during gear retrieval, the net sleeve slides down, covering the hooked toothfish (Figure 2b). As depredation is believed to take place primarily during gear retrieval, it was assumed that this mechanism could protect hooked fish from sperm whales and reduce damage to the catch.

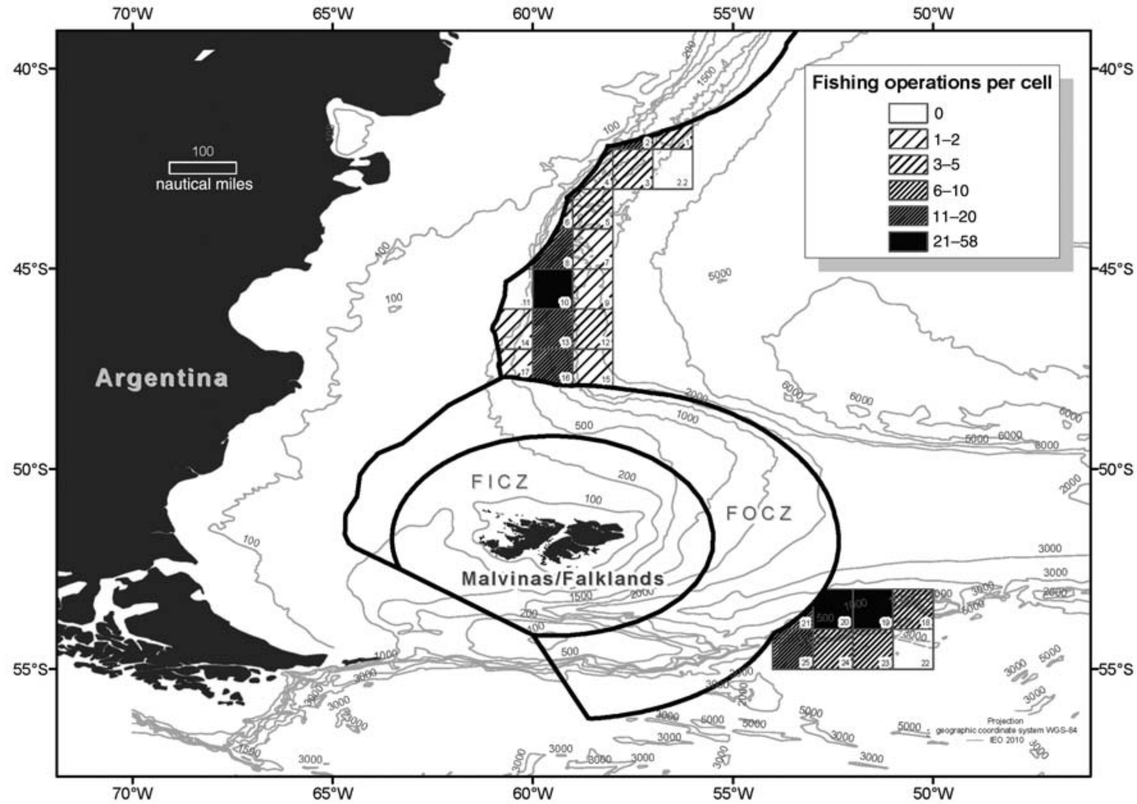

Figure 1. The study area and the fishing effort by subarea.

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

Data collection and analysis

During each set, the on-board observer recorded the start/end time of gear setting/retrieval, fishing location, number of branch lines, experimental longline setting used, amount (in kg and number of individuals) of each species caught, sea surface temperature (SST), sea state (Douglas scale), windspeed, moon phase, cloud cover, sightings of cetaceans (species and number observed) and seabirds (species only), depredation on catches (occurrence of depredation and number of fish damaged), and accidental bycatch of seabirds and cetaceans (Table 2). In addition, the vessel captain registered toothfish catches and sightings of sperm whales for each segment of the longline in a logbook. Each segment consisted of 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 3a–f). Photos were taken of damaged fish to facilitate identification of bite marks.

As sightings of sperm whales by both the observer and the captain were opportunistic, we combined both datasets for analysis. Catches of toothfish were transformed into cpue (catch per unit effort), expressed as kilogramme of fish per hook.

It is very likely that sperm whales remove an unknown number of fish entirely from the longline. Consequently, taking into account only the fish damaged may underestimate the real level of depredation. Therefore, we 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 smaller catches. To assess whether sperm whales really remove whole hooked fish directly from the line during retrieval, we analysed whether the presence of sperm whales close to the vessel had an immediate effect on catches. For this purpose, the sums of fish caught on the longline segments before and after a sperm whale sighting were compared applying the Mann–Whitney test. The five segments before and after the sperm whale sighting were coded as −5, −4, −3, −2, −1, 0, +1, +2, +3, +4, and +5, with 0 representing the segment when the sperm whale was first seen. The number of fish was then summed for the 5, 4, 3, 2, and 1 segments before/after the 0 segment, then compared pairwise.

To assess how the presence of sperm whales, depredation, catch rates, and environmental and fishery-related variables are related to each other, we used generalized additive models (GAMs; Hastie and Tibshirani, 1990; Zuur *et al.*, 2007). The response and explanatory variables are listed in Table 2. Before running the models, we explored the 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. To reduce the influence of small

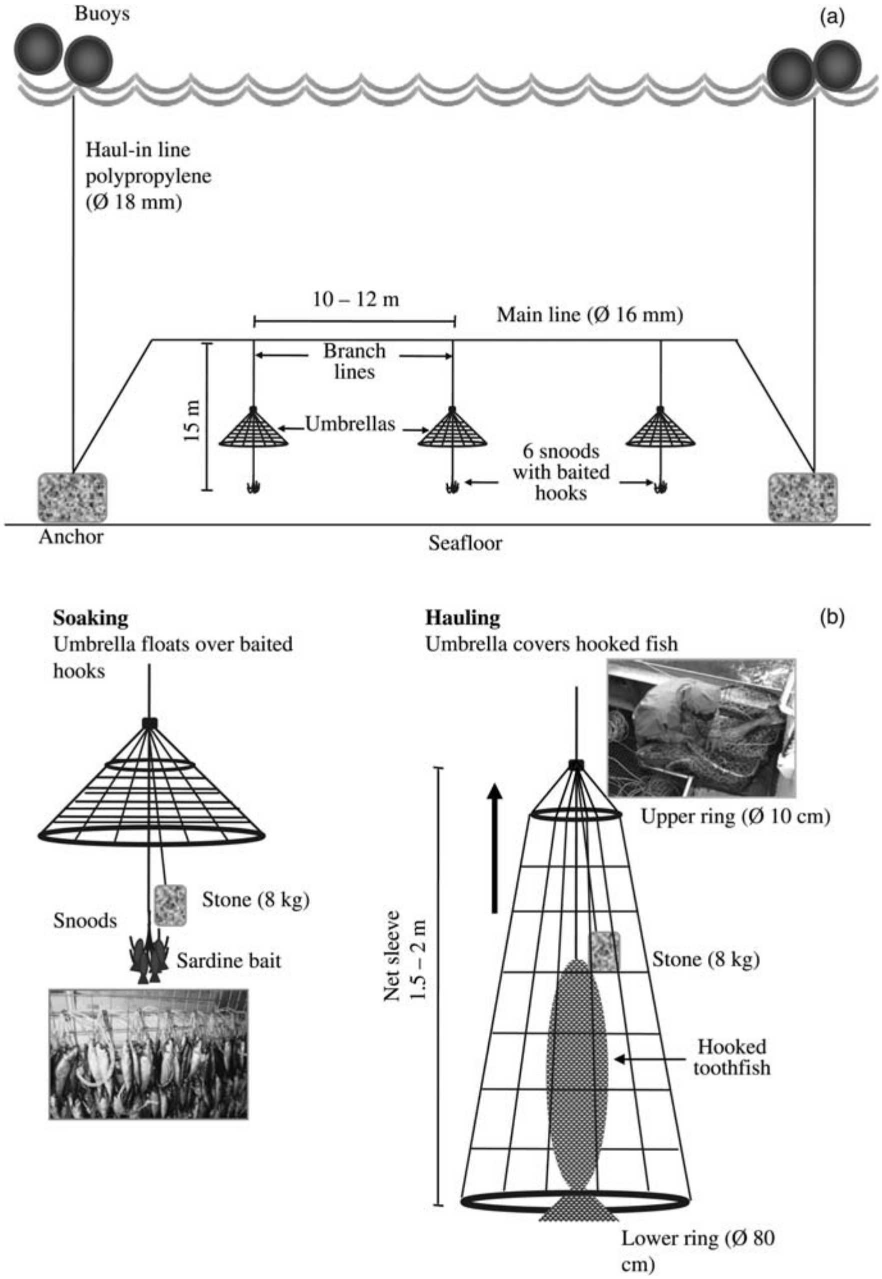

Figure 2. (a) Experimental longline setting and (b) the umbrella design and mechanism.

numbers of large values, the variables cpue of toothfish and soak time were square-root transformed. One sample was omitted from the analysis because of its extreme values for number of branch lines and duration of retrieval. The variables sea state and cloud cover were treated as continuous variables in the analysis, resulting in better models, i.e. a 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.

Response variables followed Gaussian (continuous data), Poisson (count data), or binomial (presence/absence data) distributions. Continuous explanatory variables were entered into the model as smoothers, and the maximum number of degrees of freedom (k) was restricted to 4 to avoid overfitting and selecting biologically unrealistic models. Models were fitted using backward selection, sequentially excluding individual variables to identify the model that would result in the lowest AIC (Akaike's 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 biggest catches. For this purpose, the number of fish caught per set with each umbrella type was standardized for a mean number of branch lines, then averaged.

All GAMs were run in Brodgar 2.6.5 (www.brodgar.com); the Mann–Whitney tests were performed using Minitab 15.

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: 1.5 m
2	Base ring: rope/net sleeve length: 1.5 m
3	Base ring: rope/net sleeve length: 1.7 m
4	Base ring: rope/net sleeve length: 2.0 m
Complete hook coverage	
G1: 1–2–1–2–1–2–1	All hooks covered
G2: 2–2–2–2–2–2–2	
G3: 4–4–4–4–4–4–4	
Partial hook coverage	
G4: 2–3–0–2–3–0–2	Two-thirds of hooks covered
G5: 2–0–2–0–2–0–2	Half of hooks covered
G6: 2–0–3–0–2–0–3	
G7: 2–0–4–0–2–0–4	
G8: 4–0–4–0–4–0–4	

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

Variables	Descriptor
Fishery data	
Toothfish catches	Cpue (kg fish hook^{-1})
	Number of fish
Number of branch lines/hooks	
Soak time	min
Duration of gear retrieval	min
Depth of gear retrieval	m
Gear design used	Four umbrella designs (1–4)
	Complete/partial hook coverage
	Eight experimental longline settings: G1–G8
Sightings	
Sightings of sperm whale	Presence/absence of sperm whales
	Number of sperm whales
Depredation	
Depredation on toothfish	Occurrence of depredation
	Number of fish damaged
Environmental/oceanographic data	
Sea state (S)	Douglas scale: 0–9
Cloud cover (C)	Scale: 0–8
Moon phase (M)	M1: new moon
	M2: waxing moon
	M3: full moon
	M4: waning moon
Sea surface temperature (SST)	°C
Time of day	Day/night

Results

In all, 297 hauls were carried out in water depths of 600–2200 m ($\bar{x} = 1264 \pm 283$). Each longline carried between 900 and 3000 hooks ($\bar{x} = 1794 \pm 480$) and was left to soak in the water for 3–67 h ($\bar{x} = 20.67 \pm 11.22$ h). Fishing effort in zones AI46 and AI54 were 336 414 (62.8%) and 199 500 (37.2%) hooks, respectively. In all, 61 t of toothfish were caught during the study, 65% in area AI54. The cpue varied for the different subareas, with values highest in areas 1, 2, 10, and 25. The highest cpue was obtained in depths of 1000–1600 m.

Cetacean and seabird sightings

Sperm whales were sighted during 104 of 297 longline sets (35%) and exclusively during gear retrieval. The proportion of hauls with sperm whales present was 37.4% for area AI46 and 32.9% for area AI54. The number of sperm whales sighted per haul ranged between 1 and 6, and they were usually swimming alone (72%), or in groups of two (16%) or three (10%).

Sightings of sperm whales were most numerous in subareas 2, 5, 8, 14, 19, and 25 and in depths of 1000–1400 m. 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*). The seabirds sighted consisted of several species of albatross, petrel, and shearwater (Table 3).

Depredation by sperm whales on the catches

Evidence of depredation on the catch was found in 24 longline sets (damage rate 8%). Usually just 1–2 fish were damaged, but depredation was occasionally as much as five fish per set. Most of the toothfish 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 fish were covered with umbrellas during hauling, observed evidence of depredation by sperm whales mainly consisted of missing body parts and crushed tissue with typical blunt tooth marks. Some fish hooks were observed bent, indicating that bait or hooked fish had been torn off by force (Figure 3a–f).

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

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

All pairwise comparisons of the numbers of fish 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 the two segments ($W = 5180.5$; $p < 0.001$) and three segments ($W = 3116$; $p < 0.001$) before and after the appearance of sperm whales were compared, suggesting that sperm whales take hooked fish entirely from the line and that the fish damage we recorded is an underestimate of total depredation. We found no significant difference in cpue when comparing sets with/without evidence of depredation ($W = 40\,414$; $p = 0.52$) and sets with/without presence of sperm whales ($W = 28\,344$; $p = 0.56$), suggesting no significant reduction in overall catch rates even if sperm whales remove fish entirely from the line.

Factors affecting sightings of sperm whales, catch rates, and depredation on catches

The GAM revealed that sperm whales were more frequently sighted close to the vessel by day than by night, and more often during a waxing moon than during other moon phases (Table 4). Another factor found to influence the frequency of sightings of sperm whales was SST, with the lowest frequency of

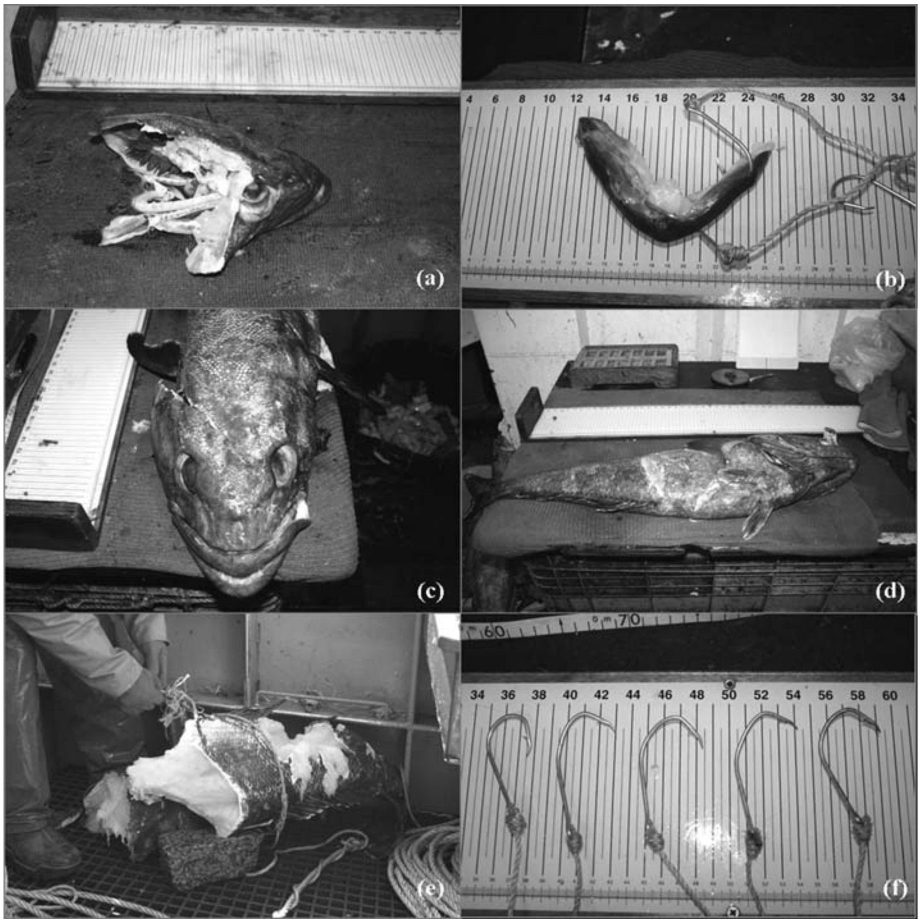

Figure 3. Evidence of sperm whale depredation on toothfish (a) only head or (b) lips left on the hook, (c) fractured cranium, (d) blunt tooth marks, (e) missing body parts and crushed tissue, and (f) bent fishing hooks.

sighting in water temperatures of ~8°C and the highest frequency at ~11°C (Table 4, Figure 4a).

The cpue of toothfish was related to the duration of gear retrieval, gear design, SST, the number of sperm whales sighted, and the depth of gear retrieval (Table 4). It increased linearly with longer retrieval times and was higher for partial coverage of hooks. Moreover, the cpue exhibited a minimum at SST of ~8–9°C, decreased with increasing numbers of sperm whales around the vessel, and increased with water depth out to 1200 m, after which it decreased (Figure 4b–d).

The GAM results showed that evidence of depredation on catches was highly positively related to the presence of sperm whales (Table 4). In addition, we detected a positive linear trend between the frequency of depredation and sea state (not shown). No relationships were found between depredation and the cpue or the duration of gear retrieval. The number of fish damaged showed a strong relationship with the number of sperm whales sighted around the vessel, first increasing with larger numbers of sperm whales, then remaining relatively stable if more than three sperm whales were in the vicinity (Table 4, Figure 4e). There were fewer damaged fish when cpue was high (>0.5 kg hook^{-1}; Table 4, Figure 4f). Moreover, the quantity of fish damaged increased with sea state until state 6, then dropped again in rough conditions (Table 4, Figure 4g).

The impact of "umbrella" design and experimental longline setting on catch and depredation rates

The Mann–Whitney test demonstrated that hooks with no coverage from umbrellas caught more fish than hooks that were covered. Comparing the different umbrella designs, designs 1, 2, and 4 yielded better catches than design 3, but there were no significant differences in catch rates between designs 1, 2, and 4 (Table 5).

When comparing the eight experimental longline settings, we found that settings with partial hook coverage had a higher cpue than settings with complete coverage (GAM: $t = -2.83$; $p = 0.0050$; %dev = 15.4; AIC = −354.53). Among the three settings with complete coverage (G1–G3), there were no significant differences in catch rates. Of the settings with partial coverage, G5 and G8 achieved significantly higher cpue than the other settings (G5 > G6: $t = 2.41$, $p = 0.0166$; G5 > G7: $t = 2.83$, $p = 0.0050$; G8 > G4: $t = 2.28$, $p = 0.0012$; G8 > G6: $t = 4.0$, $p < 0.0001$; G8 > G7: $t = 2.57$, $p = 0.0108$; %dev = 17; AIC = 359.19).

There were no significant differences in the records of depredation between the two levels of hook coverage or between the eight longline settings. Depredation was low for longline settings G1, G6, and G8, and there was no depredation registered for settings G2 and G4 (Figure 5).

Table 3. Sightings of cetaceans (sighting frequency, species, and number of individuals sighted) and seabirds (species sighted only).

Scientific name	Common name	Sighting frequency	Number of individuals
Cetaceans			
Physeteridae			
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 chrysostoma	Grey-headed albatross		
Thalassarche melanophrys	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 stormpetrel		
Fregetta tropica	Black-bellied stormpetrel		

Table 4. GAM results ($n = 296$ sets).

Response variable	Explanatory variable	Type	$z/F/\chi^2$	*p*-value	Sign	Edf	%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		2.89		
Toothfish cpue	Duration of gear retrieval	S	10.72	0.0012		1.00	15.4	−354.53
	Complete/partial hook coverage	N	−2.83	0.0050	−			
	SST	S	5.25	0.0054		2.05		
	Number of sperm whales	S	4.76	0.0116		1.81		
	Depth of gear retrieval	S	3.17	0.0376		2.23		
Occurrence of depredation	Presence/absence of sperm whales	N	4.79	<0.0001	+		10.3	155.46
	Sea state	S	6.91	0.0086		1.00		
Number of fish damaged	Number of sperm whales	S	39.60	<0.0001		2.11	22.4	233.28
	Toothfish cpue	S	17.59	0.0004		2.84		
	Sea state	S	17.21	0.0003		2.33		

The response variables presence/absence of sperm whales and the occurrence of depredation both followed a binomial distribution, whereas a Gaussian distribution was appropriate for the cpue of toothfish and a Poisson distribution for the number of fish damaged. The results displayed are: 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 the value of *p*), and the direction (sign) of the effect (+ or −). Edf is the estimated degree of freedom of the examined smoothers. Edf = 1 implies a linear effect, and values >1 indicate a progressively stronger non-linear effect. Also given are the overall percentage of deviance explained (%dev) and the AIC value for the model. For the explanatory variables used, see the list of variables (Table 2). For the variable gear design, only the descriptor of complete/partial coverage of hooks was considered in the model.

Bycatch of cetaceans and seabirds

There was no bycatch of seabirds and cetaceans during normal fishing operations over the whole study period. One seabird, a black-browed albatross (*Thalassarche melanophrys*), was caught accidentally on a longline when some of the stone weights were not attached correctly to the line and became detached and sank, leaving the baited hooks floating at the surface for a period.

Discussion

Sightings

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

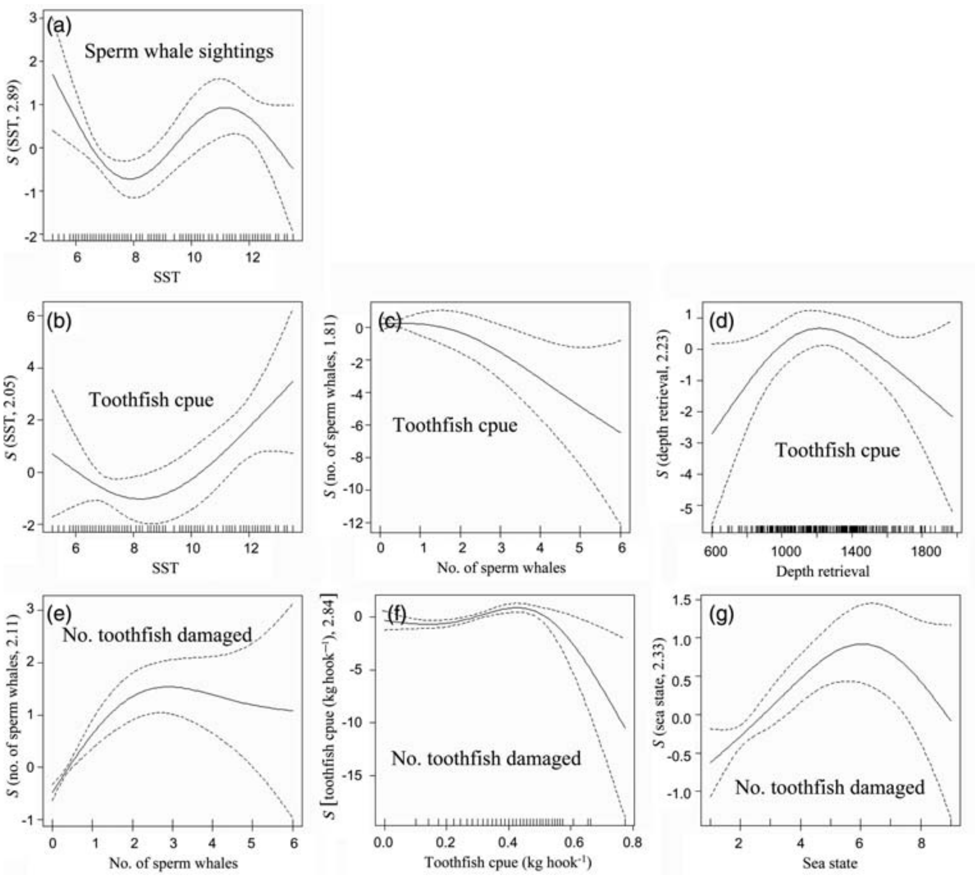

Figure 4. GAM results: smoothing curves for partial effect of (a) SST (°C) on sperm whale sightings, (b) SST (°C), (c) number of sperm whales, (d) depth of gear retrieval (m) on toothfish cpue, (e) number of sperm whales, (f) toothfish cpue, and (g) sea state on number of toothfish damaged. The *y*-axis indicates the partial additive effect that the explanatory variable on the *x*-axis has on the response variable. The numbers in parenthesis indicate the estimated degrees of freedom (also listed in Table 4). The influence of a variable increases as the values on the *y*-axis depart from zero. Dotted lines indicate 95% confidence bands.

Table 5. The Mann–Whitney test comparing catch rates (number of fish 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*-value
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

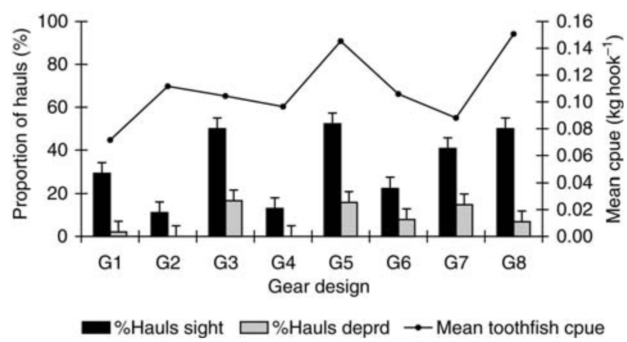

Figure 5. Proportion of hauls ($n = 297$) with sightings of sperm whales (sight), evidence of depredation (deprd), and mean toothfish cpue for different gear designs.

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 two or three were also observed. Similar group sizes were reported by Purves *et al.* (2004) and White *et al.* (2002) in Southwest Atlantic waters. The large-scale distribution of sperm whales depends primarily on that of their major prey, i.e. cephalopods, and suitable conditions for breeding. In the Southwest Atlantic, they are mainly found in the warm waters of the Brazil Current off Brazil and Uruguay, where cephalopods are abundant (Berzin, 1971). Nevertheless, sperm whales do follow their prey along warm, deep currents into higher latitudes, concentrating in areas where warm currents reach into areas of cooler water (Kirpichnikov, 1950). Our study area, particularly area AI46, directly borders the Brazil–Malvinas Confluence (BMC) zone. This region, recognized as one of the most high-energy zones in the world, is characterized by the confluence between the warm, saline Brazil Current that flows south, and the cold, fresh Falklands/Malvinas Current, which flows in the opposite direction (Olson *et al*., 1988). The area is a transition zone inhabited by a mixture of subtropical and Subantarctic organisms (Boltovskoy, 1986); it is rich in fish resources.

Sperm whales are thought to feed primarily on meso- and bathypelagic cephalopods, squid being of much greater importance than octopus (Akimushkin, 1955; Rice, 1989). Fish are an important component of the diet in some areas, e.g. off Iceland (Martin and Clarke, 1986), Gulf of Alaska, and East Bering Sea (Okutani and Nemoto, 1964). The most common fish recorded in the diet have been demersal species that, in some cases, could attain large size (1–3 m long; Berzin, 1971). Kawakami (1980) reported 68 species of fish belonging to 49 families in his review of the diet of sperm whales.

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

According to Hucke-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 sightings of sperm whales, but sightings and toothfish catches increased towards warmer water and were concentrated in areas with mean water depths of 1000–1600 m. This indicates that sperm whales are likely to be found in areas with high density of toothfish, though if the sperm whales preyed regularly and directly on toothfish close to the seafloor, they would have to exceed their common diving range considerably. Therefore, the distribution of sperm whales might be determined instead by the distribution of their principal prey, squid, or perhaps they may congregate in areas where toothfish are usually caught, i.e. feeding primarily on hooked fish during longline retrieval.

We also found that sightings of sperm whales were more common by day than by night, a finding also reported by Purves *et al.* (2004). This result may, however, be simply attributed to the fact that sighting probability is much less at night because of the lack of light; nocturnal sighting frequency may, therefore, be underestimated in our study.

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

Depredation on catches

As sperm whales were present in proximity to the vessel in almost three-quarters of the depredation events, they are assumed to be the main predators on hooked toothfish. They were sighted exclusively during longline hauling and, in addition, the number of fish caught on the longline was significantly less 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 seafloor. As longlines were usually set in depths of >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 h in our study, and significantly increased in duration (up to 12 h) when the cpue of toothfish was high. Consequently, sperm whales would have plenty of time to feed on the catch. The sound of the hydraulics might serve as a cue to the start of hauling, consistent with the observations of Ashford *et al.* (1996) and Purves *et al.* (2004), who suggested that sperm whales take fish off the line close to the surface. 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 significant positive relationship we found between the depredation and the presence of sperm whales around the vessel.

Damage and depredation rates in our study were low. The damage rate (the percentage of longline sets with evidence of depredation) was less than that reported by Pin and Rojas (2007) for longlines equipped with MEDs, i.e. 16% of sets with depredation. The overall depredation rate (the percentage of fish damaged during all longline sets) is similar to the rates found by Moreno *et al.* (2008) with MEDs (0.5%) and lower than the rate found by Hucke-Gaete *et al.* (2004) without MEDs (1.73%). Although we found no significant difference in the cpue from sets with/without visual evidence of depredation, we have to consider that cpue decreased when there were more sperm whales around the vessel. This suggests that the whales may actually have a negative impact on catch rates, particularly if they attack the longlines in large groups. If we consider that, on most 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 the depredation remains undetected. We also discovered that depredation and the number of fish damaged were positively related to sea state. As hauling usually takes longer in rough seas, sperm whales might have more time to prey on the hooked fish than when the weather is calm. Sea states 7–9 were only registered in 3% of all hauls, so there were insufficient observations to make a clear statement about depredation levels under very rough sea conditions.

Kock (2001), Purves *et al.* (2004), and Pin and Rojas (2007) mention that sperm whales occasionally take 80% and more of the catch in a single set. In our study, the maximum percentage of fish damaged per set was <20% (except the set where the whole catch was one fish), indicating that the umbrellas are most likely efficient in preventing sperm whales from taking a large part of the catch from the longline. However, damage and depredation rates in our study are most likely underestimated because only fish damaged were considered as lost.

The economic loss through interactions with sperm whales

Although the average loss attributable to damaged fish appears to be small, the financial loss to fishers may be significant because of the high market value of toothfish and the likelihood that some depredation goes unrecorded. Moreover, steaming to alternative fishing areas to "escape" from the sperm whales results in additional expense for fuel and loss of fishing time.

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

Hooks covered with umbrellas caught fewer fish than uncovered hooks, and cpue was higher for longline settings with partial hook coverage than settings with complete coverage. In a comparable study by Moreno *et al.* (2008), in contrast, the use of MEDs had no adverse effect on catch rates. In our experimental setting, the umbrellas were knotted to the branch lines, whereas 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 yielded better catches than design 3. Of the different longline settings with partial hook coverage, G5 and G8 delivered the highest cpue. Both settings included only one type of umbrella, in contrast to settings G4, G6, and G7 that combined different umbrella types, a fact that might increase the stability of the gear in the water and reduce entanglement of the net sleeves. There was no depredation for settings G2 (complete coverage) and G4 (two-thirds of hooks covered). However, small sample size is an issue in those cases, because the number of observations for those longline settings was very low compared with the other settings. Among the settings that reduced depredation most efficiently, G8 had the best catch rates and might, therefore, be the most appropriate of the settings tested.

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

Success of the umbrella-and-stones system

Clearly, the umbrella-and-stones system was effective in preventing the accidental bycatch of seabirds and marine mammals. The effectiveness of umbrellas in reducing sperm-whale depredation on catch, however, was not very evident in the study, although some results indicate that, given an appropriate umbrella design, they might be useful in preventing sperm whales from taking large quantities of catch from the longline. Nevertheless, they could not prevent depredation completely. Material costs for the umbrellas are relatively low, and if the fishers build them themselves, production costs can be reduced. Moreover, they can be used for a long time, and if umbrellas prove to reduce depredation on catches, they are a reasonable investment that could eventually pay off. However, we have to bear in mind that umbrellas reduced catches significantly in our study, so their negative effects might undermine their benefits.

Modifications to the umbrellas, such as allowing the net sleeve to move along the branch line (as in the study of Moreno *et al.*, 2008) or reducing the visibility of the umbrellas in the water, might help to improve the catch rates. Fishers and longline associations should be encouraged to become active participants in the improvement of existing longline designs and the development of new designs.

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