



Pelagic longline fishing trials to shape a mitigation device of the depredation by toothed whales

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ABSTRACT

Depredation is defined as the damage or removal of fish from fishing gear by predators, and is a crucial issue leading to negative impacts on both animals involved in depredation and fisheries. Depredation in longline pelagic fisheries targeting swordfish (*Xiphias gladius*) and tuna (*Thunnus* spp.) involves short-finned pilot whales (*Globicephala macrorhynchus*), false killer whales (*Pseudorca crassidens*) and some pelagic sharks. Since no long-term solution could be found to date, we investigated fishing gear improvement by deploying a technology designed to physically protect the hooked fish by hiding it to predators: the DMD (depredation mitigation device). Two types of DMDs were designed: “spiders” and “socks”. The efficiency of “spiders” was tested in November 2007 during a fishing trial of 26 longline fishing operations when 12,480 hooks and 1970 devices were set. The efficiency of “socks” was tested in October 2008 during a fishing trial of 32 longline fishing operations when 13,220 hooks and 339 devices were set. 117 and 24 fish were hooked on branchlines equipped with spiders and socks, respectively and among those devices, 87.3% versus 69.2% were correctly triggered and 80% versus 15% of the fish were correctly protected. A low entanglement rate of the spiders with the fishing gear was found (3.6%), but a higher one was associated to the socks (17.8%). Operational constraints to routinely deploy “spiders” were examined. The number of sets impacted by shark depredation was significantly greater than the number of sets involving toothed whale depredation. However, when depredation occurred, the proportion of fish damaged by toothed whales was significantly greater. While more trials should be carried out to deeply verify the efficiency of DMDs, we remain convinced that considerations of fishing gear technologies might be more actively investigated to propose innovative measures to mitigate toothed whale depredation in pelagic longlining. For this type of gear, innovative technology is an important issue of the ecosystem approach to fisheries (EAF) framework.

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1. Introduction

Negative interactions between marine mammals and fisheries are known to occur worldwide, affecting many species and many fisheries (Northridge, 1991). Depredation is part of those interactions and is defined as the removal or damage of fish from fishing gear by large marine predators, mostly toothed whales and sharks (Donoghue et al., 2002; Gilman et al., 2008). Over the past decades, the scale of interactions between toothed whales and pelagic longline fisheries in particular has expanded, altogether with an increase of the fishing effort. Depredation damage evolved in time from a few capture among the whole catch in the first years up to the entire catch of longliners currently (Nishida and Tanio, 2001). In pelagic longline fisheries targeting tuna (*Thunnus* spp.) and swordfish (*Xiphias gladius*), depredation on

catch involves false-killer whales (*Pseudorca crassidens*), short-finned pilot whales (*Globicephala macrorhynchus*), killer whales (*Orcinus orca*) and pelagic sharks (Dalla Rosa and Secchi, 2007; IOTC, 2007; Mandelman et al., 2008; Nishida and Tanio, 2001; Secchi and Vaske, 1998; Sivasubramanian, 1964).

The monitoring of the extent and magnitude of toothed whale depredation is of a great importance since it leads to many negative consequences affecting assessment, biological, ecological and commercial aspects (Gilman et al., 2006; Perrin, 1991). As an impact on assessment, fish loss due to depredation is not taken into account in stock assessment analysis (Donoghue et al., 2002). As an impact on biology and ecology, toothed whales hunting behaviour is changing as they will get used to search after boats to get easy-to-catch preys instead of hunting their common feeding preys (McPherson et al., 2003; Ramos-Cartelle and Mejuto, 2007; Secchi and Vaske, 1998). Moreover increased risks of injury or mortality of cetaceans occur, firstly in a deliberate way from fishermen (retaliation) and second in an accidental way due to negative interactions with the fishing gear (bycatch). For instance, previous photo-identification studies

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of false-killer whales evolving around Hawaii and short-finned pilot whales around Mayotte Island exhibited obvious signs of their interactions with longline fisheries (Baird and Gorgone, 2005; Kiszka et al., 2009). As an impact on commercial aspects, depredation represents an economic loss as fishermen spend extra money when fixing fishing gears damaged by predators, altogether with an increased fuel expenditure when they move away to avoid areas of high depredation rate (Secchi and Vaske, 1998). However the main loss of profits is related to fish damage.

In the Indian Ocean, toothed whale depredation on pelagic longliners is characterised by a data-limited situation. Few scientific papers or grey literature deal with this issue (Nishida and Shiba, 2007; Nishida and Tanio, 2001; Rabearisoa et al., 2007; Romanov et al., 2007; Sivasubramanian, 1964). In Seychelles, the toothed whale depredation rate for swordfish was estimated at 10.3% (Rabearisoa et al., 2007). Therefore, professional longliners are in an urgent need of mitigation devices which could help them to significantly reduce the financial impact of depredation. Moreover they might produce beneficial effects for the conservation of toothed whales and the management of pelagic target species.

In the US, first depredation mitigation measures consisted in the promulgation of permits by the NMFS (National Marine Fisheries Service) allowing fishermen to do whatever may be necessary to protect their gear and their catch from damage by toothed whales (including killing and harassing), which meant that a significant number of them may have been killed (Mate, 1980). Over the last decades, non-lethal control actions (conservation strategy) progressively replaced those lethal ones (eradication strategy) (Breitenmoser et al., 2005). Most research, less radical, are currently focusing on the use of active acoustic means to deter depredation from cetaceans. ADD (Acoustic Deterrent Device), or pingers, and AHD (Acoustic Harassment Device) acoustically bother toothed whales and aim at preventing them from approaching the fishing gear to steal the fish and/or the bait and from being incidentally captured (McPherson et al., 2008). If active acoustic can be efficient at short term it generates opposite effect at medium term as pingers end up at being used as an acoustic attractor by cetaceans (Brotons et al., 2008; Jefferson and Curry, 1995).

There is good evidence that cetaceans use their hearing to locate the gear and/or the boat (Thode et al., 2007). In response, some mitigation measures regarding noise reduction onboard fishing vessels were also proposed (Purves et al., 2004), but despite those advices, depredation still leads to important fish loss. Other depredation mitigation methods have been tested so far, such as using explosives, chemical deterrents, flare guns or predators sounds, but none of them were proved to be successful (Gilman et al., 2006; Jefferson and Curry, 1995; Werner et al., 2006). This lack of success may be due to the behavioural adaptability of toothed whales to new stimuli, and this adaptability is the main difficulty met by researchers dealing with depredation mitigation (Nitta and Henderson, 1993). Changing fishing strategies, such as setting shorter lines or travelling long distances to avoid predators, was somewhat efficient in reducing depredation by killer whales (*O. orca*) (Tixier et al., 2010).

As depredation deterrence by using acoustic devices or other preventive methods did not prove to be efficient so far, we suggest acting on the end of the depredation process, i.e. once toothed whales have located the fishing gear, get close to it and prepare for attacking the captured fish. Therefore, we propose to develop devices shaped to produce a physical protection of capture to mitigate depredation events and to test them on field. It must be noted that fishing trials to assess the impact of a device developed to mitigate the depredation in pelagic longlining were very rare so far. For the first time, our study presents results dedicated to the physical protection of capture to deter predators in pelagic longlining. This depredation mitigation principle is also currently in the development phase in both Tropical South Pacific and Indian oceans, but has not been already trialled (Hamer et al., 2012).

In this context, a first trip was conducted off the Seychelles archipelago onboard a commercial longliner in November 2006. It allowed us to study the fishing operations in order to design appropriate depredation mitigation devices (DMD) to be deployed on the fishing gear. Two types of DMD, named “spider” and “sock”, were designed and tested at sea during commercial fishing operations respectively in November 2007 and November 2008. Both surveys aimed at checking the efficiency of each DMD regarding toothed whale depredation and assessing whether they fit the fishing gear and fishing technique parameters and constraints.

2. Materials and methods

2.1. The “spider”

The first depredation mitigation device (DMD) was named “spider” after its eight strands (Fig 1). We opted for a dissuasive device made up of a 100 mm diameter plastic disc with sixteen holes in its outer range and a 37 mm diameter central hole. Four polyester strands were inserted in those outer holes, forming eight 1200 mm long hanging legs. Theoretically, the whole system can only be triggered by a biting fish. The triggering system was made up of a beta pin and an elastic ring. The branchline was inserted in the pin, and this latter was tightened by the ring. The device was designed so that the hooked

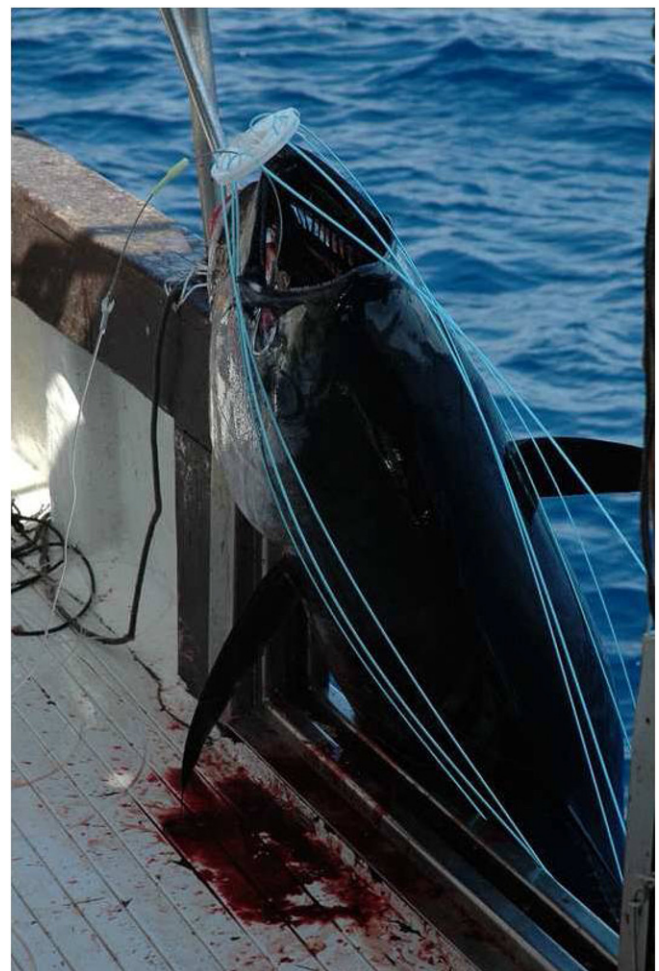


Fig. 1. A baited tuna covered by spider. The spider is a device made up of eight polyester legs. The legs are maintained by using a 100 mm diameter plastic disc, with 16 holes in its outer range and a 37 mm diameter central hole through which the hooked branchline is inserted. The triggering system consists of a beta pin through which the line was inserted and was tightened by an elastic ring. The whole system could only be released by a pulling of the hooked fish on the branchline.

fish was covered by the eight strands, with the disc placed at the level of its bill or its mouth.

2.2. The “sock”

The configuration of the second DMD named “sock” was based on results obtained during the previous trials. In comparison to the spider, the sock was designed to totally cover the fish and to better hide it from predators. We set up two kinds of devices: one conical net made up of fibreglass mosquito netting and a second one made up of propylene fibre net (Fig. 2). A metallic or plastic hoop was set at its base in order to keep it open. The hook was inserted through the upper opening of the device and the device was then fold-up by pulling on the branchline and inserting it in the beta pin. We added lead weights to increase the diving speed of the device. The same previous triggering system consisting in a beta pin and an elastic ring was used. As for the spider, the sock was fixed above the hook, and the triggering system was released when the fish pulled on the line when biting the bait. Then, the sock slid down, covered the captured fish and hid it from predators.

2.3. Experimental procedure and data collection

With regard to the first survey (November 2007), the experimental protocol initially consisted in setting up a device every two hooks. Unfortunately, as the deployment of spiders was a time consuming operation, only a feasible deployment frequency of one device every four hooks was tested on field.

As for the second survey (November 2008), given the low number of devices available onboard (50), the socks were concentrated in the middle of a single longline section, every two hooks, to increase opportunities of obtaining interactions between socks and predators on aggregated catches on the longline.

The DMDs were set up on the branchline during the line setting, simultaneously with hook baiting. An observer stood nearby the fishermen in charge of this activity and collected data about the speed and easiness of their task when setting the device up.

As the line was being hauled, detailed data related to both each individual caught (species, weight, depredation type if any) and the behaviour of each DMDs retrieved (release status with or without catch, entanglement, deployment quality on the fish caught) were collected.

Five indices were considered to quantify both the mitigation depredation efficiency of devices and the feasibility of the deployment and the retrieve of each DMD design:

- the trigger rate = number of correctly triggered DMDs/total number of DMDs associated with a capture (a DMD being correctly triggered if activated when a hooked fish pulled on the branchline),



Fig. 2. A baited tuna covered by a sock. The sock is a conical net made up of fibreglass mosquito netting or propylene fibre net. The hook was inserted through the upper opening of the device and the device was then fold-up by pulling on the line. The same triggering system was used: the beta pin and the elastic ring.

- the untimely triggered rate = number of DMDs triggered without capture/total number of triggered DMDs,
- the protection rate = number of DMDs correctly covering the catch/number of correctly triggered DMDs,
- the efficiency = proportion of undepredated fish protected by DMDs/proportion of undepredated fish unprotected by DMDs. This index was calculated only for sets affected by depredation, and the efficiency was considered as satisfying if the ratio was greater than 1.

It was assessed by considering fishing sets affected by shark and/or toothed whale depredation for which DMDs were deployed (all longline sections of the first survey and half part of longline sections for the second survey).

- the entanglement rate = proportion of entangled DMDs.

2.4. Fishing trials

First fishing trials carried out to test the “spider” device took place in the northeast of Mahe plateau for a 13 days-long trip (Fig. 3). Between 60 and 222 spiders were set up among 960 hooks each day, and 26 fishing sets (two longline sections per day) were set during the whole survey. The distance between the two sections was about 4 nautical miles (nm). A total number of 12,480 branchlines with hook were set and among them 1970 were equipped with the “spider” device (Table 1).

The second fishing survey to test the “sock” device was carried out on the same fishing ground (Fig. 3) and lasted 17 days. As they were hand-made, less than 50 socks were ready to be set up among the 850 branchlines deployed daily. A total of 13,220 hooks was deployed for 32 longline settings (two longline sections set per day), but devices were set during the first thirteen fishing days (Table 2). The distance between the two longline sections was about 4 nm. In total, 339

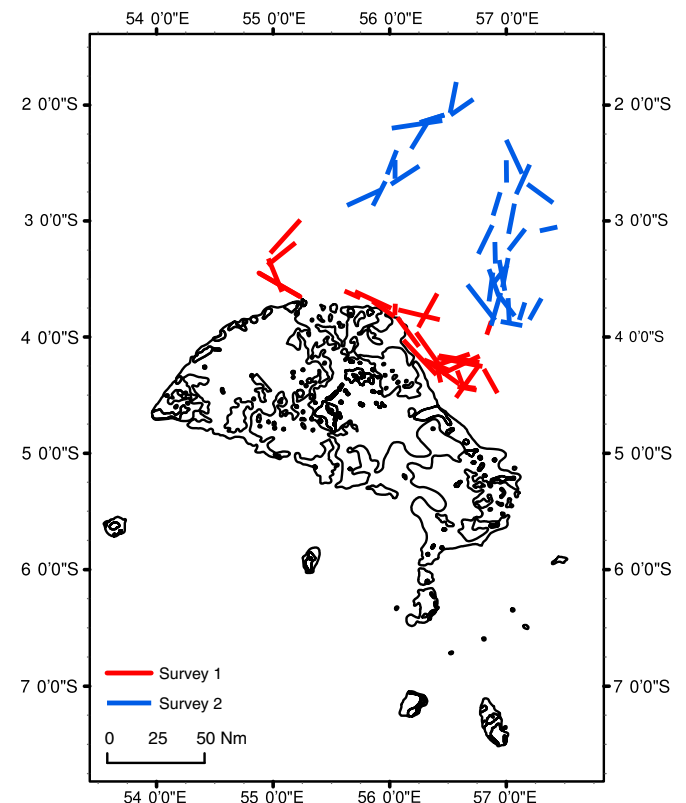


Fig. 3. Location of the fishing operations obtained with Arcview 9.3. In red, fishing sets deployed during the survey 1. In blue, fishing sets deployed during the survey 2.

Table 1
Summary of data of fishing operations, catch and technical results of the “spider” depredation mitigation device (DMD) collected during the first fishing survey. (Nb = Number, Dep = Depredated).

Fishing operations characteristics				Catch				Technical parameters of the DMDs					
Date of the fishing operation	Fishing set number	Nb hooks	Nb DMDs	Nb fish caught	Nb Dep toothed whales	Nb Dep sharks	Total depredation rate (%)	Nb entangled DMDs ⁽¹⁾	Nb untimely triggered DMDs ⁽²⁾	Nb fish with DMDs ⁽³⁾	Nb correctly triggered DMDs ⁽⁴⁾	Nb correctly covered fish ⁽⁵⁾	Nb covered and depredated fish ⁽⁶⁾
21/11/2007	1	480	110	20	0	2	10	51	9	8	6	3	0
21/11/2007	2	480	27	15	0	3	20	15	3	3	3	3	0
22/11/2007	3	480	30	5	5	0	100	11	10	0	0	0	0
22/11/2007	4	480	30	12	0	2	17	1	7	2	2	2	0
23/11/2007	5	480	75	1	1	0	100	1	19	1	1	1	0
23/11/2007	6	480	75	2	0	0	0	2	21	2	2	0	0
24/11/2007	7	480	89	19	5	0	26	6	7	9	8	8	0
24/11/2007	8	480	52	16	0	0	0	0	6	3	3	2	0
25/11/2007	9	480	90	30	0	2	7	2	5	5	5	3	0
25/11/2007	10	480	60	25	0	2	8	3	7	4	3	2	0
26/11/2007	11	480	97	29	0	0	0	5	4	9	5	5	0
26/11/2007	12	480	91	36	0	0	0	3	4	10	8	6	0
27/11/2007	13	480	107	13	0	1	8	3	12	3	3	2	0
27/11/2007	14	480	101	10	0	0	0	4	7	1	1	1	0
28/11/2007	15	480	104	12	0	0	0	4	2	4	3	3	0
28/11/2007	16	480	114	5	0	0	0	3	7	3	3	3	0
29/11/2007	17	480	100	26	0	3	12	1	2	17	13	11	0
29/11/2007	18	480	113	5	0	0	0	5	4	3	2	2	0
30/11/2007	19	480	95	11	4	0	36	2	9	2	2	2	2
30/11/2007	20	480	126	9	8	0	89	2	14	6	4	4	2
01/12/2007	21	480	62	20	0	1	5	5	2	8	6	6	0
01/12/2007	22	480	58	13	0	0	0	1	2	4	4	3	0
02/12/2007	23	480	50	20	0	6	30	4	2	5	3	3	0
02/12/2007	24	480	54	10	0	0	0	3	1	4	4	3	0
03/12/2007	25	480	30	8	0	0	0	1	1	0	0	0	0
03/12/2007	26	480	30	5	0	0	0	1	1	1	1	0	0

¹ Entangled devices with the fishing gear.
² Triggered devices in absence of catch.
³ Captured fish on a branchline equipped with a device.
⁴ Triggered devices in presence of catch.
⁵ Accurately covered capture by devices.
⁶ Totally covered capture but nevertheless depredated.

branchlines with hook were equipped with the “sock” during this second survey. For this second survey, the longline section without DMD will be considered as a check sample to compare depredation indices between longlines DMD-equipped and not equipped.

2.5. Predator identification

Distinction between toothed whale and shark depredations was done based on the damages left on the fish. Toothed whales' attacks lead to ragged wounds and torn flesh, leaving conical tooth marks on the fish. Only the head (or maxillary parts) generally remains on the hook. Toothed whale depredation can sometimes be directly observed from aboard the fishing boat, when it occurs during the setting or hauling operation. As for sharks, they leave several visible and clear bites on the fish body (Chapman et al., 2006; Dalla Rosa and Secchi, 2007).

Statistical analysis of data was performed with R 2.12.2.

3. Results

3.1. Catch and depredation events

Results related to catch and depredation events were summarised in Table 3. For both surveys, more fishing sets were affected by shark depredation but the average depredation rate was higher when toothed whale depredation occurred. A Kruskal–Wallis test showed that the presence of socks did not affect the catch per unit effort (CPUE) during the second survey ($H=1.87$, $p=0.17$). There was no significant difference between shark or toothed whale depredation rates observed for sets equipped or not with socks ($H=0.12$, $p=0.73$). In comparison with sets not affected by depredation, the

mean yield (i.e. the number of intact and marketable fish) was higher when shark depredation occurred, but it was lower when toothed whale depredation did. In other words, shark damage was common but affects fewer fish on the line whereas toothed whale depredation is sporadic but affects almost the whole catch.

3.2. Observations of toothed whale species involved in catch depredation

During the first survey, false-killer whales were seen twice as they were depredating the hauled line. They showed a hunting behaviour near the fishing gear, and some damaged fish were caught. Some pilot whales were also observed once while the vessel was moving towards a fishing area.

During the second survey, two unidentified cetaceans (presumably short-finned pilot whales or false-killer whales) were briefly seen once in front of the boat. They were possibly depredating since the whole catch was totally damaged on the longline (unequipped with DMDs).

3.3. Technical results (efficiency of the DMDs)

To assess the effectiveness of the DMDs, we calculated different indices. 117 and 24 fish were hooked on branchlines equipped with spiders and socks respectively and among those devices, the average trigger rate (number of correctly triggered DMDs/total number of DMDs associated with fish) reached 87.3% and 69.2% for spiders and socks, respectively. The average untimely triggered rate (number of DMDs triggered without capture/total number of DMDs deployed) reached 9.5% for spiders and 26.0% for socks. The protection rate, estimated for DMDs that were correctly deployed on the catches,

Table 2

Summary of data of fishing operations, catch and technical results of the “sock” depredation mitigation device (DMD) collected during the second fishing survey, (Nb = Number, Dep = Depredated).

Fishing operations characteristics				Catch				Technical parameters of the DMDs					
Date of the fishing operation	Fishing set number	Nb Hooks	Nb DMDs	Nb fish caught	Nb Dep toothed whales	Nb Dep sharks	Total depredation rate (%)	Nb entangled DMDs ^a	Nb untimely triggered DMDs ^b	Nb fish with DMD ^c	Nb correctly triggered DMDs ^d	Nb correctly covered fish ^e	Nb covered and depredated fish ^f
01/11/2008	1	425	12	10	0	0	0	9	0	3	2	0	0
01/11/2008	2	425	11	13	0	0	0	9	3	0	0	0	0
02/11/2008	3	425	15	18	0	0	0	10	1	3	1	1	0
02/11/2008	4	425	16	13	0	0	0	15	5	2	2	0	0
03/11/2008	5	425	12	9	0	0	0	15	5	1	0	0	0
03/11/2008	6	425	15	2	1	0	50	16	2	0	0	0	0
04/11/2008	7	425	12	19	0	3	16	13	0	0	0	0	0
04/11/2008	8	425	8	16	0	1	6	6	3	2	2	0	0
05/11/2008	9	425	11	2	2	0	100	11	8	0	0	0	0
05/11/2008	10	425	15	7	0	0	0	15	3	1	1	0	0
06/11/2008	11	425	0	9	0	0	0						
06/11/2008	12	425	30	10	0	2	20	29	17	1	1	0	0
07/11/2008	13	425	0	12	0	2	17						
07/11/2008	14	425	26	13	0	0	0	25	4	1	1	0	0
08/11/2008	15	425	26	6	0	0	0	20	1	2	1	0	0
08/11/2008	16	425	1	10	0	0	0	1	1	0	0	0	0
09/11/2008	17	425	26	9	0	0	0	24	2	2	2	0	0
09/11/2008	18	425	0	10	0	0	0						
10/11/2008	19	425	24	19	0	2	11	22	2	1	0	0	0
10/11/2008	20	425	0	11	0	0	0						
11/11/2008	21	425	24	14	0	1	7	23	6	3	3	2	0
11/11/2008	22	425	0	10	0	1	10						
12/11/2008	23	425	21	15	0	0	0	16	2	2	1	0	0
12/11/2008	24	425	0	12	0	1	8						
13/11/2008	25	425	22	10	0	0	0	22	4	0	0	0	0
13/11/2008	26	425	0	6	0	0	0						
14/11/2008	27	425	0	4	0	1	25						
14/11/2008	28	425	0	5	0	0	0						
15/11/2008	29	425	0	4	0	0	0						
15/11/2008	30	425	0	13	0	0	0						
16/11/2008	31	425	0	14	0	1	7						
16/11/2008	32	425	0	7	0	1	14						

^a Entangled devices with the fishing gear.

^b Triggered devices in absence of catch.

^c Captured fish on a branchline equipped with a device.

^d Triggered devices in presence of catch.

^e Accurately covered capture by devices.

^f Totally covered capture but nevertheless depredated.

reached 80% for spiders but only 15.5% for socks. For both devices, swordfish were generally less protected than tunas because of their bill, making the device stuck on the top of their head. Those devices, as they were designed, were not adapted for billfish.

The efficiency of DMDs represents the ratio between the proportion of undepredated fish while protected by DMDs and the proportion of undepredated and unprotected fish. Based on the two longline sets deployed a same day and affected by toothed whale depredation,

8 unprotected fish out of 15 and 4 spider-protected fish out of 6 were damaged (Fig. 4A), letting 2 protected fish out of 6 and 7 unprotected fish out of 15 undepredated. Those results represented a spider efficiency index of 0.72. However no differences can be found in the proportion of fish depredated between spider-protected hooks and unprotected ones, but sample size remains small. Socks' efficiency towards toothed whale depredation could not be tested as it occurred twice during the survey, on branchlines without device (Table 2). Finally, regarding the

Table 3

Summary of data of capture and depredation events during both surveys investigating depredation mitigation devices (DMDs) efficiency, (Nb = Number, Dep = Depredated).

	Survey 1			Survey 2					
				With DMDs			Without DMDs		
	No depredation	Shark depredation	Toothed whale depredation	No depredation	Shark depredation	Toothed whale depredation	No depredation	Shark depredation	Toothed whale depredation
Nb of sets	26*			19*			13*		
Nb of target fish caught	377*			215*			117*		
CPUE (number of fish captured per 100 hooks)	3.02*			2.66*			2.12*		
Nb of depredated sets	–	9	5	–	5	2	–	6	–
Depredation rate (%) (all sets)	–	4	14	–	3	8	–	6	–
Depredation rate (%) (depredated sets)	–	13	70	–	12	75	–	14	–
Mean yield (number of marketable fish per 100 hooks)	2.86	3.68	0.92	2.61	3.25	0.12	1.95	2.04	–

* Those numbers refer to the whole data set (fishing sets without depredation and impacted by shark or toothed whale depredation).

capture or not was about 3.6% for spiders (calculated from the fourth set, when we successfully found the optimal way to attach the device on the branchline, and then drastically reduced the number of entangled devices) and 17.8% for socks. Branchlines with socks not twisted were triggered in general. Finally, the storage of devices on board was not optimal because of the length of legs for the spider and the volume of socks.

To sum-up those results, we determined the satisfaction level regarding various factors related to the behaviour of both devices during both setting and hauling operations (Table 4).

4. Discussion

Acoustic device (ADD = Acoustic Deterrent Device named also pingers and AHD = Acoustic Harassment Device) is the mostly used measure to mitigate toothed whale depredation occurring in various fisheries, from longlines to gillnets (Bordino et al., 2002; Buscaino et al., 2009; López and Mariño, 2011; Mooney et al., 2009; Reeves et al., 1996). Longlines due to their length are almost impossible to protect efficiently with AHD. Furthermore the long-term effect and cetacean habituation to such acoustic device remain poorly investigated. Our study aims to test the efficiency of an innovative approach: the physical protection of a capture on a pelagic longline. Our hypothesis was based on the fact that toothed whales use their sight to locate and attack the fish, and that setting a barrier between them and their target could be efficient. This principle was inspired by observations that a captured tuna entangled with fishing gear was less likely to be depredated (McPherson et al., 2003; Nishida and Tanio, 2001). Moreover, the physical protection of fish caught is currently used on demersal longliners targeting Patagonian toothfish (*Dissostichus eleginoides*) also affected by the depredation by both sperm whales (*Physeter macrocephalus*) and killer whales (*O. orca*) (Purves et al., 2004; Sigler et al., 2008; Straley et al., 2002; Visser, 2000; Yano and Dahlheim, 1995). The use of net sleeves as a DMD in this fishery was based on previous experiments carried out in 2005 in Chile and aiming at testing a knotted line hiding the hooks and the captured fish. However, the current strength and the movements of the vessel made this device flap and did not hide the fish correctly (Moreno et al., 2008). Net sleeves protecting toothfish catches were therefore designed in Chile (Moreno et al., 2007, 2008), in Ukraine (Pshenichnov and Zaitsev, 2007), and in the South-western Atlantic (Goetz et al., 2011; Pin and Rojas, 2007). Those devices were triggered by the friction with the water while the line was being hauled, and covered the clusters of hooked fish. It has been proved that the physical protection of catches with these sleeves significantly reduced depredation by sperm whales at a short-term. However, recent observations highlighted this system's limits in terms of catch injuries (Mitchell et al., 2008). As depredation on demersal longline fishery mainly occurs during the hauling period (Gilman et al., 2006), fish caught were correctly protected. This differs from pelagic longline fishery by the fact that the line is exposed to depredation during all the fishing time (Moreno et al., 2008) and why in ideal conditions the deployment of the DMD occurs when the fish is biting the baited hook. As far as we know our fishing trials were the first carried out in 2007 and in 2008 to test DMD on field for pelagic longline fisheries, while some are currently ongoing (Hamer et al., 2012). Obviously our results show that socks and spiders are not yet ready to be deployed during commercial longline operations to mitigate toothed whale depredation. However, even if our devices clearly need many improvements regarding their design, our results gave us valuable insights on the operational aspects to go further. Primary results obtained during the first survey with spiders permitted to underline the weakness of the design regarding its ability to mitigate the depredation when the capture was well covered. Socks were designed based on the results obtained with spiders and were inspired from devices successfully deployed in demersal fisheries (Moreno et al., 2007, 2008). Unfortunately, better results were obtained with the spider, particularly with regard to

technical results and the easiness of their deployment. More socks were untimely triggered in absence of catch, and less were triggered when a fish was caught. However, without devices on branchlines allowing to quantify hooking contacts, such as hook timers (Somerton et al., 1988), the estimation of this parameter may be biased. Moreover, the entanglement problem could not be solved during the second trial. The entanglement rate was even higher for socks than for spiders and this issue dramatically increased the time for hauling. But even if their efficiency regarding toothed whale depredation could not be assessed and still needs to be proved, those trials (surveys 1 and 2) allowed us to check whether the devices fitted both the fishing gear and its manipulation. Both socks and spiders were still too bulky, and their triggering systems required a strong manual tension from the fishermen while setting. Furthermore, the level of the entanglement rate slowed down fishing operations. Smaller and easier to handle devices are required if we want to keep in mind our idea of physical protection of the catch and if we want to set them up on all hooks in the line.

The weak number of devices deployed during each trial did not allow us to obtain accurate results on DMDs efficiency. Indeed, whereas from 800 to 950 hooks were set each day, only 327 spiders and less than 50 socks were tested daily. Therefore, even if some catches were depredated despite their net protection, no definitive conclusions can be made. Moreover, the insignificant result obtained when comparing the depredation rate on sets equipped or not with socks by using a Kruskal–Wallis test implies that our DMDs did not significantly reduce depredation. Situations with a higher encounter rate between toothed whales and the fishing gear must be experimented. However, the fact that depredation both by cetaceans and sharks occurred while the fish was either covered by a spider (cetaceans) or a sock (sharks) suggests that this system is unlikely to be sufficient to fully protect the fish on line, and depredation rate is likely to raise again once the cetaceans have habituated to this new system.

In Florida, physical protection of fish has also been investigated in the frame of troll fisheries targeting Florida king mackerel (*Scomberomorus cavalla*), which are affected by depredation by bottlenose dolphins (*Tursiops truncatus*). A mechanical depredation mitigation device consisting in a metal wire was trialled. The pressure applied by the fish while it was fighting against the hook triggered the outrigger clip releasing a metal wire around the fish. Its principle was based on the assumption that dolphins would avoid physical injury or any risk of entanglement. This device successfully discouraged dolphins and no depredation events on catch were observed (Zollett and Read, 2006). Metal wire deployed in the frame of troll fisheries is related to depredation deterrence by using both passive acoustic and mechanical methods. Passive acoustic systems do not generate sounds by themselves and depend on the noise produced by an echolocation click of a toothed whale. They enable to change the backscattered echolocation clicks and return a modified target image. Mechanical depredation mitigation devices are made up of entangling streamers posing no danger to fishing crews, toothed whales and fish quality (McPherson et al., 2008). Nevertheless, this study was a short-term one and to date, no further research was done about its possible long-term efficiency.

Toothed whales use both their visual and echolocation abilities to detect their prey and discriminate its size, thickness and material composition (Au, 1993). Since depredation can occur either at day or at night, when visibility is low (McPherson et al., 2008; Read, 2007; Romanov et al., 2007), this suggests that echolocation is a main part of the depredation process. McPherson et al. (2004) confirmed this hypothesis by recording a broad range of echolocation clicks generated by toothed whales around longline gear. Longliner captains suggested adapting mechanical depredation mitigation devices by dropping a metal wire alongside the bait that would wrap around the catch as it spins on the line (TEC Inc., 2009). Metal is known as highly acoustically reflective and interferes with the backscatter reflection to an echolocating whale, confusing the acoustic picture of its target (McPherson et al., 2008). Some trials of a

mitigation device undertaken by a firm in San Diego have proved that fish entangled in fishing gear containing metal (such as iron) may not suffer depredation, whereas fish entangled in nylon alone may (Nishida, 2007; Nishida and Tanio, 2001), but no T-POD or C-POD hydrophones were deployed to confirm if the deterrent effect of the metal was due to acoustic properties of the material.

Depredation and bycatch (accidental capture) are both negative interactions between fisheries and toothed whales, and can occur simultaneously, bycatch sometimes coinciding with fish damage (Hernandez-Milian et al., 2008). Similar measures are therefore used to mitigate both of them, and most research are currently focusing on the use of active acoustic deterrents (McPherson and Nishida, 2010; McPherson et al., 2007, 2008).

The depredation occurrence during both fishing trials was not representative of the usual depredation. Previous studies evaluated the swordfish global depredation rate by sharks and toothed whales in Seychelles at 21% of the number of fish caught (Rabearisoa et al., 2007), whereas lower average depredation rates were observed during surveys 1 and 2 (18% and 9%, respectively). However the depredation pattern observed is consistent with the previous one usually described: toothed whale depredation is rare but leads to high catch damage, whereas shark depredation is more frequent but leads to sporadic damage on the fishing set (Rabearisoa et al., 2007; Secchi and Vaske, 1998). Toothed whale depredation is consequently the biggest issue faced by fishermen.

Few preconditions must be considered when designing depredation mitigation devices (Rowe, 2007). The first point is that the CPUE of target species must be maintained at its current level when DMDs are deployed. In other words, DMDs must not prevent target species from approaching the gear. The comparison of CPUE on sets equipped or not with socks during the second survey showed that our DMDs meet this first precondition ($H = 1.87$, $p = 0.17$). Second, the investment to deploy DMDs at a commercial operational level should neither increase operating costs and their price should not exceed the financial loss induced by depredation. Moreover, the reusable property of DMDs is a way to reduce the economic investment of their deployment from small to large scales. Third, fishermen should not risk being hurt when setting them on the longline, so the safer they are, the better they will be. Fourth, the DMD needs to be simple to deploy and to retrieve and must require minimum time consumption during both setting and hauling operations. Fifth, DMDs must be easily kept on board, requiring minimum storage space. Indeed, on fishing vessels such as longliners, the available volume on board is limited and the storage of devices such as DMDs involved to reduce negative impacts with the fishing activity is an important issue to consider. Sixth, in the frame of the ecosystem approach to fisheries, an environmental issue was also raised during both trials due to the loss of several devices at sea. Then, in addition to the adjustment of a prototype taking into account technical specifications aforementioned, the next prototype should be designed with a large amount of biodegradable materials to reduce its environmental impact. Seventh and finally, the DMD must not degrade the fish quality for marketable issues and the welfare of toothed whales for conservation purposes.

While limited in terms of data collected to estimate the efficiency of the physical protection of capture to mitigate the depredation in pelagic longlining, these first fishing trials carried out in the open ocean for this fishery gave us valuable insights to go further for the development of a new prototype. The negative consequences of interactions between toothed whales and pelagic longlines in terms of economy, stock assessment, ecology and conservation of marine mammals are worth thinking on long term solutions to mitigate them. However, we are facing a multidisciplinary question that must gather competences in fishery economy, fishery management, fishing gear technology, material engineering and marine mammal ecology. Jennings and Revill (2007) highlighted the major role of

gear technologists in supporting a sustainable approach to environmentally responsible fishing, by developing win-win solutions, where fishermen profits meet conservation concerns. The continuation of our work is then fully consistent with this ecosystem approach to fisheries, given the negative consequences aforementioned.

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