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Hooks equipped with magnets can increase catches of blue shark (*Prionace glauca*) by longline fishery

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ABSTRACT

Blue shark (*Prionace glauca*) populations are decreasing worldwide and the species is currently classified as near threatened. However, it is the main species caught by the Spanish and Portuguese longline fisheries; and blue shark is specifically targeted by a part of these fleets in the northeastern Atlantic Ocean. Sharks are well known to be able to detect electric fields in the microvolt range and this sense has been proposed to provide a mechanism to detect the earth's magnetic field. As a result, the use of magnets has been proposed as a method to reduce shark interactions with fishing gear. We therefore tested two models of high field strength neodymium magnets to effect shark catch rates during commercial longline fishing operations. Our results show that magnets do not reduce blue shark catch rates and can even have an attractive effect. This effect was significantly higher for the larger magnet model tested (26 mm × 11 mm × 12 mm, 0.885 T) compared to the smaller one (20 mm × 13 mm × 15 mm, 0.464 T). We also noted that hooks remain magnetized after removal of the magnets and are even slightly magnetized without any previous contact with a magnet.

1. Introduction

The blue shark *Prionace glauca* (Linnaeus, 1758) is a species with worldwide distribution (Moreno, 2004). Like most pelagic shark species, the blue shark presents a low fecundity rate, a slow growth rate (Ferretti et al., 2008) and is therefore particularly vulnerable to fishery exploitation. In the northeastern Atlantic Ocean, near the Azores Archipelago and between the Azores Archipelago and the Iberian Peninsula, one part of the Spanish and Portuguese longline fleet targets swordfish *Xiphias gladius* Linnaeus, 1758, tuna (teleosts of the group Thunini) and shortfin mako *Isurus oxyrinchus* Rafinesque, 1810 (Buencuerpo et al., 1998; Stevens et al., 2000; Baum and Myers, 2004). However, blue sharks represent about 60% of their catch (Xunta de Galica. i.e. regional government, pers. comm.). The second part of the longline fleet concerned by this study targets only blue shark (*P. glauca*) near the Iberian Peninsula. Overall, over 200 t of blue shark were landed each month in 2013 at Vigo (Xunta da Galicia, pers. comm.). In both cases, Spanish and Portuguese longline fishermen might be interested in a shark repellent system in order to increase their ratio of commercially valuable species such as swordfish and tuna and to increase their profit. Moreover most pelagic sharks are at the top of the food web and play an important role in marine ecosystems as they contribute to the management of healthy ocean ecosystems (Ferretti et al., 2010).

Permanent magnets have been shown (Stoner and Kaimmer, 2008; Tallack and Mandelman, 2009; O'Connell et al., 2011a, 2012; Hutchinson et al., 2012) to have a repellent effect on sharks by creating an abnormally strong electrical stimulus overwhelming the elasmobranch's acute electrosensory system, a cornerstone of two key processes: displacement and predation. Concerning predation, while at long range, chemoreception is most likely the dominant detection system, at close range however, elasmobranchs use their electrosensory system, via the ampullae of Lorenzini (Kalmijn, 1971), in order to detect the prey's movements. This was demonstrated for *P. glauca* by Hueter et al. (2004). The author showed that *P. glauca* was attracted to an area by odours, but, once in the vicinity of the prey, attacked an active dipole simulated the prey's

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bioelectric field rather than the odour source. Magnets constitute therefore a possible mean to reduce the by-catch.

Many studies, based on a wide range of magnets and different experimental conditions (in the field or in the lab), have attempted to test the deterrent electromagnetic effect on sharks (Appendix A). Overall, all the tests with an electromagnetic system obtained highly contrasted results between laboratory and field experiments, between species and according to the electromagnetic system used. Indeed, both laboratory experiments and field studies have found the magnets to act as a repellent (i.e. Brill et al., 2009; Rigg et al., 2009; O'Connell et al., 2010, 2011a,b, 2014a–d, 2015; Jordan et al., 2011; Smith and O'Connell, 2014; Rice, 2008; Wang et al., 2008) or an attractor or to be neutral (Stoner and Kaimmer, 2008; Rigg et al., 2009; Jordan et al., 2011; McCutcheon and Kajiura, 2013; Robbins et al., 2011; Tallack and Mandelman, 2009; O'Connell et al., 2011a,d; Hutchinson et al., 2012; Godin Cosandey et al., 2013; Smith, 2013). The same contrast results have been found for different species (both pelagic and benthic). For example, individual smooth dogfish *Mustelus canis* (Mitchill, 1815) are not repelled by neodymium (Nd) metal but individual in groups are (Jordan et al., 2011). *Carcharhinus plumbeus* (Nordo, 1827) is repelled by magnets in the laboratory (Brill et al., 2009) but not in the field (O'Connell et al., 2011a).

Even though EPMs have been proposed as a way to limit the intensive fishing activities of blue shark (*P. glauca*), previous experiments carried out in field and under real fishing conditions were inconclusive (Hutchinson et al., 2012; Godin Cosandey et al., 2013). The aim of the present paper is to test the effects of neodymium magnets on blue shark catches aboard a fishing vessel targeting pelagic species in the eastern Atlantic Ocean. For the first time, the physical properties of the magnets and their effect on the hooks are measured and taken into account.

2. Methods

2.1. Physical properties of the two magnet models

The magnet is mainly composed of neodymium, a magnetic element with high resistance in time and magnetic power. The magnets were of the N35-Ni and N35-NdFeB types. The higher the grade (the number following the 'N'), the stronger the magnet is. Ni indicates the presence of traces of nickel. NdFeB indicates that the magnet is composed of neodymium, iron and boron. Neodymium is a rare-earth magnet element with degradation trends in seawater. During the 3 days experiment, there was no degradation of the magnets. We did not measure the level of dissolution in the laboratory because as the lanthanides dissolve, the voltage (mV) remains unchanged despite the decreasing mass (McCutcheon and Kajiura, 2013).

The dimensions of the two cylindrical magnet models with a central hole, tested were 26 mm × 11 mm × 12 mm (model 1, 0.885 T—from Ingeniera Magnética Aplicada, Barcelona, Spain) and 20 mm × 13 mm × 15 mm (model 2, 0.464 T—from Firstmagnetic, Roncq, France). The magnetic fields produced by the two types of magnets mounted on the hooks were measured at several distances (between 7 and 70 cm). We also measured the magnetic fields of two hooks after contact with the two types of magnets and the magnetic fields of a hook that was never in contact with magnets.

As three magnets were always used for each model in the experiments, we report here the measurements for sets of three magnets. When magnets are concatenated, the magnetic field produced is not exactly equal to three times the field produced by one magnet since they are not physically at the same point (the magnet further away from the measurement point has a lower influence). But further away from the magnet, the field can be considered as approximately three times the field of each.

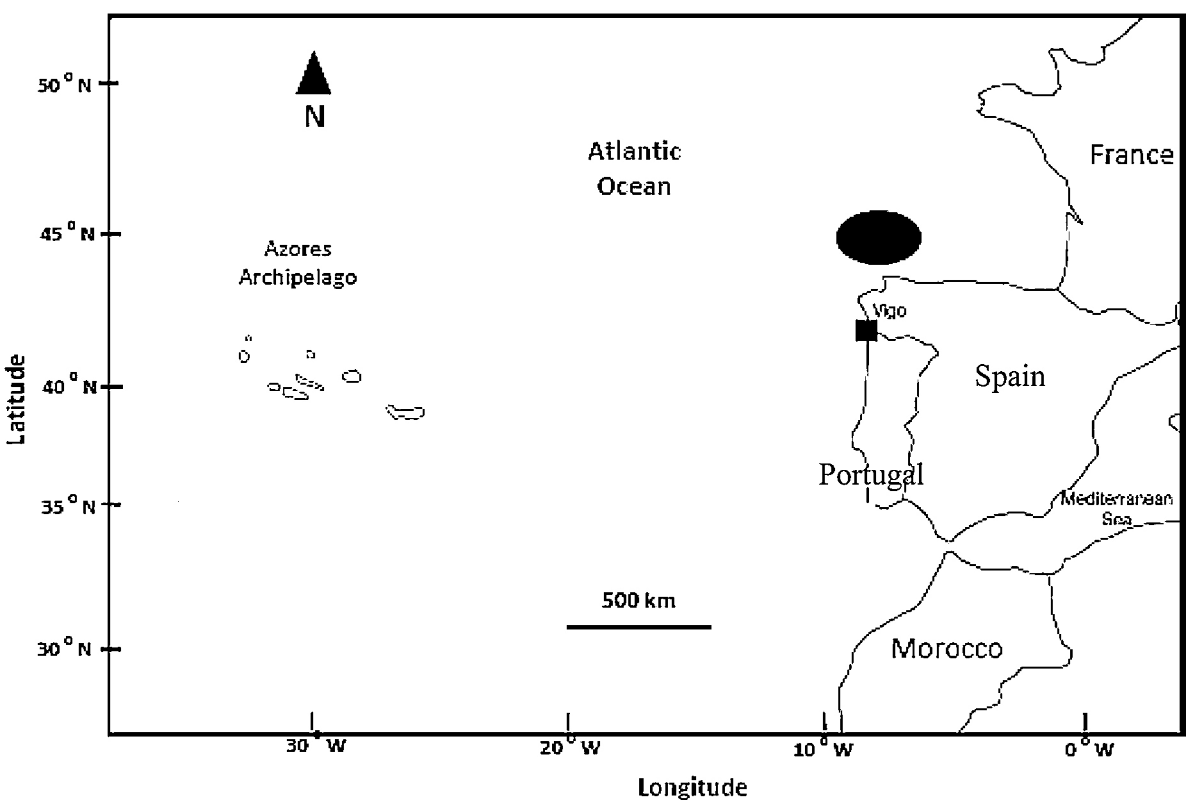

Fig. 1. Map of the marine area (northeastern Atlantic) and location of the fishing zone (black oval) where magnet experiments were conducted.

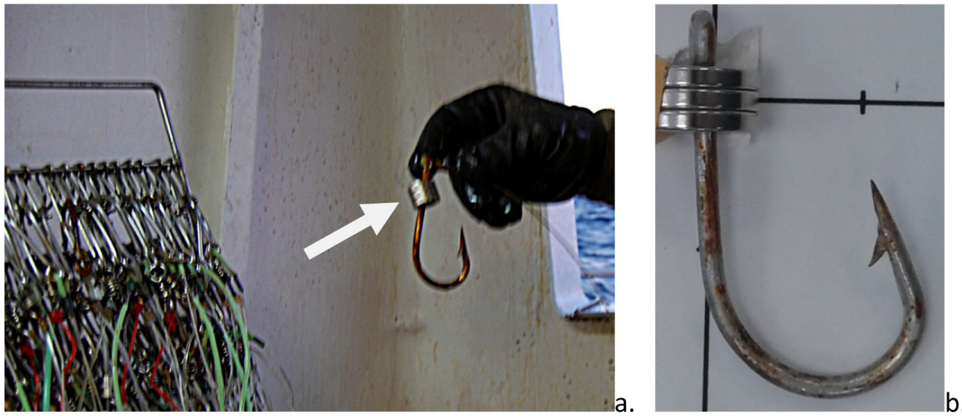

Fig. 2. (a) Position of the model 2 magnet with a hook under real fishing conditions. Photo: Sebastián Biton Porsmoguer. (b) Position of model 2 magnet on a hook measured for magnetic field in laboratory. Photo: Christophe Almarcha.

The hooks used in the experiments are made of steel, a ferromagnetic material. In consequence, a hook concentrates the magnetic lines and changes the map of the magnetic field. Moreover, the size of the hook is much greater than the size of the magnets so that very close to the hook, if the magnets are on the opposite side of the hook, the magnetic field can be greater than what it would be with the magnets alone. To measure precisely the field produced, we used a Gauss/Teslamètre Sypris 7030 F.W.Bell and recorded the variation in the magnetic field in tesla units along the distance X in centimetres for a hook fitted with, respectively, a large magnet (big circle), a small magnet (small circle), and control hook. The measurements were made from the position of the centre of the magnet on the hook (approximate position when the magnet was absent).

2.2. Experiments under real fishing conditions

The experiments were carried out in the northeastern Atlantic (Fig. 1) aboard a longline fishing vessel, the *Pescalema* based in Muxia, a small port in Galicia (Spain) during 3 days in October 2013. The experiments concerned 1076 shark individuals. We determined their sex and approximate size. They belonged to the following size classes (cm): [90–100), [100–110), [110–120), [120–130), [130–140), [140–150), [150–200), [>200).

The longline measured about 50 km with 1300 hooks about 40 m apart and immersed at 20 m. The ring-shaped hooks measured 8 cm in height and 2 cm in width. The shape and size of the magnets were chosen to fit the size of the hook (Fig. 2). The polarization of the magnets is orientated so that the magnetic field N or S corresponded to the hook axis. Fishermen had no difficulty to attach the magnets and to remove them from the hook. The bait, longfin inshore squid (*Doryteuthis pealeii*) was located close to the magnet so that sharks would feel intense magnetic field when trying to feed. The longline carried the same number of hooks during the three days of the experiment. The longline was divided into 3 test zones with the same number of hooks separated by a buffer zone 4 (Table 1; Fig. 3): zone 1 at the beginning of the longline, zone 2 in the middle of the line and zone 3 at the end. The reason for this partitioning is to minimize biases introduced by differences in the immersion time between zone 1 and zone 3 (approximately 7 h). Within each test zone, 5 hooks with model 1 magnet, 11 hooks with model 2 magnet and 16 control hooks without magnet were used (Fig. 3). The aim of this strategy was to observe whether there was any significant difference in the catch rate between test hooks and control hooks and between the two types of magnet within test zones.

The rate of catch per unit of effort (CPUE) represents the relation between the number of caught individuals and the number of hooks. The three days were considered as replicates. We compared catch values for the 144 hooks with magnets from test zones 1 to 3 with 144 control hooks under normal fishing conditions (i.e. without magnets) (Table 1). Inside the test zones, we analyzed the influence of different factors (size, sex, presence or absence of magnets and the models of magnet) on the CPUE values.

2.3. Data treatment

Data were analyzed with Statistica 9.1. Normality and homogeneity of variance were previously tested using Shapiro and Levene tests. One-way ANOVA was used in each zone individually and in combination to test the differences in CPUE values between hooks with magnets and control hooks as well as between the two models of magnet.

3. Results and discussion

3.1. Physical tests

Fig. 4 shows the intensity of the magnetic field in tesla (T) along the distance X in cm from a hook carrying, respectively, large magnets (large black circles) and small magnets (small grey circles) in a log–log scale. The thick black line corresponds to the dipole theoretical variation of the magnetic field as X^{-3}. We note that despite the presence of the hook, for a distance greater than 10 cm, the magnetic field intensity varies like that of a dipole. At these distances,

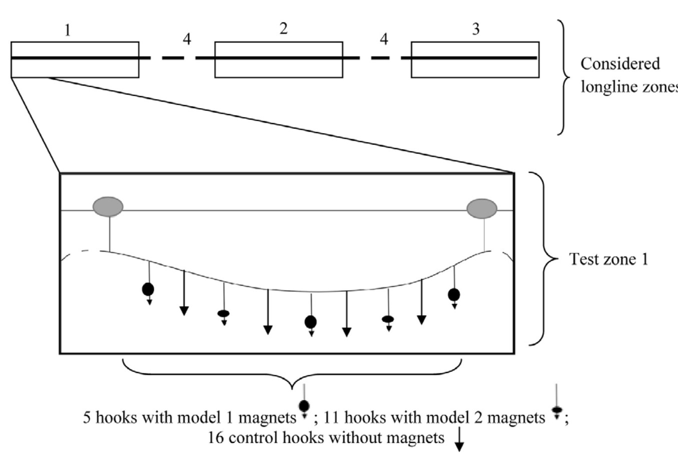

Fig. 3. Position of hooks with models 1, 2 magnet and control hooks in the tested zones 1, 2 and 3. The rest of the longline was zone 4.

Table 1
Comparison of mean values of CPUE (catch per unit of effort, where the unit of effort was the number of hooks) for blue shark (*Prionace glauca*) between longline zones during the test period (3 days). No = number. SD = standard deviation.

Blue shark catch tests	Zone 1			Zone 2			Zone 3		
	No of hooks	CPUE	SD	No of hooks	CPUE	SD	No of hooks	CPUE	SD
Magnet model no. 1	3 × 5	0.87	0.35	3 × 5	0.80	0.45	3 × 5	0.80	0.41
Magnet model no. 2	3 × 11	0.64	0.49	3 × 11	0.70	0.47	3 × 11	0.70	0.47
Hooks without magnets	3 × 16	0.52	0.51	3 × 16	0.52	0.50	3 × 16	0.38	0.49

the intensity of the large magnets was twice as high as that of the smaller magnets.

The intensity of the magnetic field produced by the magnets has been compared with the intensity of the magnetic field of the Earth (between 2.10^{-5} T and 7.10^{-5} T, depending on the position on the Earth). From Fig. 4, we note that, at a distance of 25 to 35 cm for small magnets, and 30 to 45 cm for large magnets, the intensity of the magnetic field from the magnets is of the same order than the Earth's magnetic field.

An important aspect to be considered is that hooks equipped with magnets remain magnetized when the magnets are removed (Fig. 4). This phenomenon is permanent (Almarcha, pers. comm.). For example, a hook magnetized after contact with a large magnet induced the same magnetic field at 10 cm as a hook with a large magnet at 20 cm distance. Moreover, a hook alone which was not in contact with a magnet also shows a small but measurable magnetic field. For example, the hook that was never in contact with any magnet produced a magnetic field equivalent to half of that of a hook which was previously in contact with a large model 1 magnet.

3.2. *Experiments under real fishing conditions*

During the fishing campaign, 1 076 blue shark *P. glauca* were caught by the longline vessel (Table 2). The total length of the captured blue sharks ranged from 70 to 240 cm, corresponding mainly to juvenile individuals (Table 2). For the blue shark, sexual maturity is reached at 180 cm for males and 200 cm for females (Moreno, 2004).

The sex ratio (% of males) was 0.52–0.55 in the tested zones 1 to 3 and 0.77 in the zone 4. The total size and sex of the caught individuals did not differ significantly according to whether they were caught with hooks equipped with magnets or not ($F = 1.65$; $p = 0.143$ for length, $F = 0.22$; $p = 0.638$ for sex).

The impact of magnets on the catch rate per unit of effort (CPUE) is highly variable.

Overall, for the 3 tested zones considered together, the catch rate per unit of effort (CPUE) values were higher for hooks with magnets than for hooks without magnets (mean 0.74, SD 0.15 and mean 0.47, SD 0.17, respectively) ($F = 18.29$, $p < 0.001$). These values were also higher than those in zone 4 (mean 0.25, SD 0.43) possibly suggesting that magnets act as an attractor rather than a repellent.

Looking at the spatial distribution of CPUEs, the presence of magnets (models 1 and 2) had a significant effect only in zones 2 and 3, where higher CPUE values for magnetized hooks (compared to control hooks) were observed ($F = 10.48$; $p = 0.014$ and $F = 7.99$; $p = 0.026$, respectively) (Table 1; Fig. 5). However, we note that CPUE values were only significantly higher for the hooks equipped with the model 1 magnet (0.80) than for the control hooks in the zone 2 (0.52) ($F = 5.25$; $p = 0.048$).

It remains unclear whether it is the absolute strength of the magnetic field in the water, which at some level induces the reaction behaviour of blue sharks, or whether it is the magnitude of the change in magnetism with distance that elicits this response. Experiments made under real fishing conditions may have been biased because of the contact between the hooks used with a magnet and the control hooks stored in the same box at the end of each fishing day. As magnets seem to have an attractive effect and increase shark catch, we compared catches between the three days expecting to have an increase in catch after each day. We noticed an increase in catches only in zone 1 and not in zones 2 and 3 and

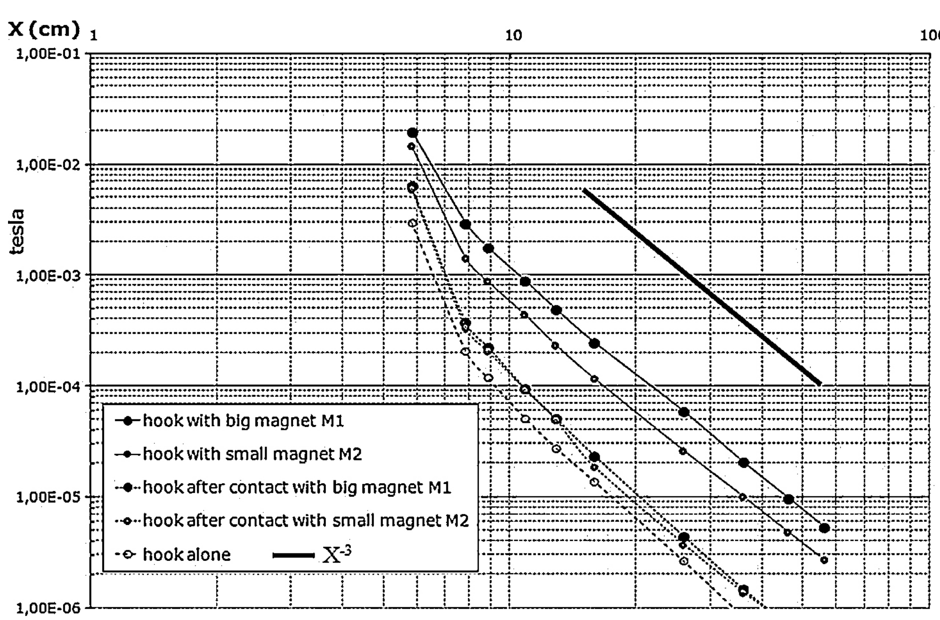

Fig. 4. Measurement of the maximum magnetic field B in tesla (T) along the distance *X* in cm for a hook filled with, respectively, large magnet for model 1 (large black circles), small magnet for model 2 (small grey circles), a hook alone after contact with large magnet model 1, a hook alone after contact with small magnet model 2 and a hook alone which was never in contact with a magnets (white circles), in a log–log scale.

Table 2
Total length (TL) of caught blue sharks. – = missing data, Min = minimum, Max = maximum, SD = standard deviation.

Blue sharks catch	*n*	Min. and max. TL (cm)	Mean length (SD) (cm)	Sex ratio (% of males)
Total caught individuals	1076	70 to 240	–	–
Individual caught by hooks equipped with magnets inside the zones 1, 2 and 3	94	100 to 200	109 (18)	52
Individual caught by control hooks inside the zones 1, 2 and 3	75	100 to 200	112 (15)	55
Individual caught by hooks without magnets in the zone 4	907	100 to 200	–	77

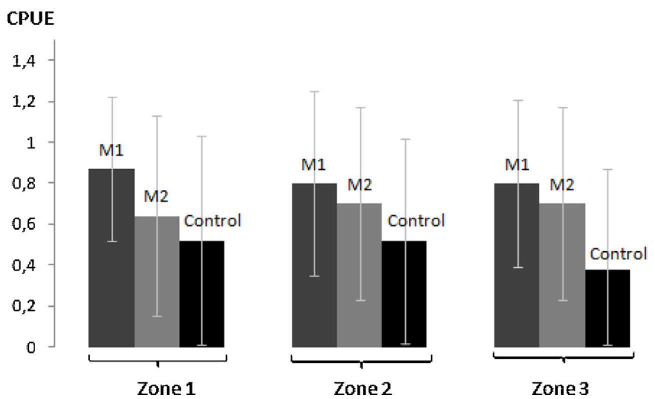

Fig. 5. Comparison of the CPUE (catch per unit of effort) with mean values and standard deviation for blue shark (*Prionace glauca*) between the two model of magnets (M1 = model 1, M2 = model 2) and the control hooks within the tested zones. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

concluded that this bias may not be significant. In addition, as CPUE were highly variable from one day to another, the increase of the catches in zone 1 might result from this variability alone.

The presence of magnets on the hook did not provide the expected repellent effect, Magnet 1 even increasing the catch rate. Magnets would therefore not appear to constitute an effective device to avoid by-catch for this species under real fishing conditions. Our results would appear to contradict some promising previous experimental results reported in the literature. Nevertheless, several factors are to be considered. (i) Results from the literature are mainly based upon laboratory experiments, and/or *in situ* experiments more or less remote from the real conditions of a professional fishing fleet (Stoner and Kaimmer, 2008; Tallack and Mandelman, 2009; O'Connell et al., 2011a, 2014a–d; Robbins et al., 2011). (ii) Clearly, the non-congruence of deterrent effects noted by previous authors is species-dependent (Hutchinson et al., 2012); for example, some authors showed that while EPM are ineffective with blue shark and shortfin mako, they can be effective for other species (Appendix A). (iii) Our results, together with similar results from the literature (e.g. Hutchinson et al., 2012), concern juveniles. It is known that the electrosensory sensitivity, in many elasmobranchs, increases with growth (e.g. Fishelson and Baranes, 1999; Tricas and Sisneros, 2004). (iv) The repellent devices used in the literature are rather disparate and their characteristics and strength are often poorly described. In addition, the effectiveness of the magnet could be influenced by the parallelism, or non-parallelism, of the axis of polarization with the axis of the hook (O'Connell et al., 2011a).

This is the first paper describing the magnetic effect on blue shark catches in real fishing conditions. Previous papers concerning the blue shark analyzed only the electropositive effects (Godin Cosandey et al., 2013; O'Connell et al., 2014d) (Appendix A). In our case, the blue shark probably detects the presence of bait on the longlines at long distance. However, at a short distance when swimming towards the bait, it should feel the electrical field induced by both the magnet and the electropositive metal. There is probably a cumulated effect between the electrical field induced by the shark movement in the magnetic field and the electrical field generated by the electropositive metal in contact with seawater, but these cannot be dissociated under field conditions.

Our results, as well as other experiments under real fishing conditions (Godin Cosandey et al., 2013), did not reduce the by-catch of sharks Permanent magnets or electropositive metal is not yet proved to be effective as a solution to limit by-catch of blue sharks. As magnets seem to even have an attraction effect, and as suggested by Jordan et al. (2013), new approaches will need to be explored in order to reduce by-catches of sharks.

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Appendix A. References concerning tests of electropositive and magnetic effects on elasmobranchs in laboratory (Lab) and in the field. B: Benthic; P: Pelagic; BP: Bentho-pelagic. Grey: Blue shark data.

Species	B/P	Electromagnetic dispositive	Study	Detterent effect	References
Amblyraja radiata	B	Electropositive metal	Field	No	O'Connell et al. (2014d)
Dasyatis americana	B	BaFe12O19	Field	Yes	O'Connell et al. (2011a)
Dasyatis americana	B	Nd2Fe14B	Field	No	O'Connell et al. (2011a)
Dasyatis americana	B	BaFe12O19	Lab	Yes	O'Connell et al. (2010)
Dipturus laevis	B	Electropositive metal	Field	No	O'Connell et al. (2014d)
Ginglymostoma cirratum	B	BaFe12O19	Lab	Yes	O'Connell et al. (2010)
Raja clavata	B	Nd2Fe14B	Lab	Yes	Smith and O'Connell (2014)
Raja eglanteria	B	Nd2Fe14B	Field	No	O'Connell et al. (2011a)
Scyliorhinus canicula	B	Nd2Fe14B	Lab	Yes	Smith and O'Connell (2014)
Squalus acanthias	BP	Electropositive metal	Field	Yes	O'Connell et al. (2014d)
Squalus acanthias	BP	Nd2Fe14B	Field	No	O'Connell et al. (2011a)
Squalus acanthias	BP	Electropositive metal	Lab	Partial	Tallack and Mandelman, 2009
Squalus acanthias	BP	Electropositive metal	Field	Partial	Tallack and Mandelman, 2009
Squalus acanthias	BP	Neodymium (Nd) metal	Lab	Yes	Jordan et al. (2011)

Species	B/P	Electromagnetic dispositive	Study	Detterent effect	References
Squalus acanthias	BP	Electropositive metal	Lab	No	Stoner and Kaimmer (2008)
Squalus acanthias	BP	Nd2Fe14B	Lab	No	Stoner and Kaimmer (2008)
Carcharhinus acronotus	P	BaFe12O19	Field	No	O'Connell et al. (2011a)
Carcharhinus amblyrhynchos	P	Ferrite magnet	Lab	Yes	Rigg et al. (2009)
Carcharodon carcharias	P	BaFe12O19	Field	Yes	O'Connell et al. (2014b)
Carcharhinus galapagensis	P	Neodymium (Nd) metal	Field	No	Robbins et al. (2011)
Carcharhinus galapagensis	P	PrNdA	Field	No	Robbins et al. (2011)
Carcharhinus galapagensis	P	Electropositive metal	Field	Yes	Wang et al. (2008)
Carcharhinus leucas	P	BaFe12O19	Lab	Yes	O'Connell et al. (2014a)
Carcharhinus limbatus	P	Neodymium (Nd) metal	Field	No	Smith (2013)
Carcharhinus limbatus	P	Nd2Fe14B	Field	No	O'Connell et al. (2011a)
Carcharhinus limbatus	P	BaFe12O19	Field	Yes	O'Connell et al. (2011a)
Carcharhinus limbatus	P	Nd2Fe14B	Field	Yes	O'Connell et al. (2011a)
Carcharhinus plumbeus	P	PrNdA	Field	No	Hutchinson et al. (2012)
Carcharhinus plumbeus	P	BaFe12O19	Field	No	O'Connell et al. (2011a)
Carcharhinus plumbeus	P	Nd2Fe14B	Field	No	O'Connell et al. (2011a)
Carcharhinus plumbeus	P	Electropositive metal	Lab	Yes	Brill et al. (2009)
Carcharhinus plumbeus	P	Electropositive metal	Field	Yes	Wang et al. (2008)
Carcharhinus tilstoni	P	Ferrite magnet	Lab	Yes	Rigg et al. (2009)
Glyphis glyphis	P	Ferrite magnet	Lab	No	Rigg et al. (2009)
Isurus oxyrinchus	P	Electropositive metal	Field	No	Godin Cosandey et al. (2013)
Isurus oxyrinchus	P	PrNdA	Field	No	Hutchinson et al. (2012)
Lamna nasus	P	Electropositive metal	Field	No	Godin Cosandey et al. (2013)
Mustelus canis—group	P	Neodymium (Nd) metal	Lab	No	Jordan et al. (2011)
Mustelus canis—individual	P	Neodymium (Nd) metal	Lab	Yes	Jordan et al. (2011)
Mustelus canis	P	Nd2Fe14B	Field	Yes	O'Connell et al. (2011a)
Mustelus canis	P	Neodymium (Nd) metal	Lab	Yes	Jordan et al. (2011)
Negaprion brevirostris	P	BaFe12O19	Lab	Yes	O'Connell et al. (2014c)
Negaprion brevirostris	P	Neodymium (Nd) metal	Lab	No	McCutcheon and Kajiura (2013)
Negaprion brevirostris	P	BaFe12O19	Field	Yes	O'Connell et al. (2011a)
Negaprion brevirostris	P	BaFe12O19	Lab	Yes	O'Connell et al. (2011b)
Negaprion brevirostris	P	Electropositive metal	Field	Yes	Rice, 2008
Prionace glauca	P	NdFeB N35—NdNi N35	Field	No	This study
Prionace glauca	P	Electropositive metal	Field	No	O'Connell et al. (2014d)
Prionace glauca	P	Electropositive metal	Field	No	Godin Cosandey et al. (2013)
Prionace glauca	P	PrNdA	Field	No	Hutchinson et al. (2012)
Rhizoprionodon acutus	P	Ferrite magnet	Lab	Yes	Rigg et al. (2009)
Rhizoprionodon terraenovae	P	Neodymium (Nd) metal	Field	Partial	Smith (2013)
Rhizoprionodon terraenovae	P	Nd2Fe14B	Field	Yes	O'Connell et al. (2011a)
Rhizoprionodon terraenovae	P	Nd2Fe14B	Field	Yes	O'Connell et al. (2011a)
Sphyrna lewini	P	PrNdA	Field	Yes	Hutchinson et al. (2012)
Sphyrna lewini	P	Ferrite magnet	Lab	Yes	Rigg et al. (2009)
Sphyrna mokarran	P	BaFe12O19	Field	Yes	O'Connell et al. (2015)
Sphyrna tiburo—group	P	Neodymium (Nd) metal	Lab	No	McCutcheon and Kajiura (2013)
Sphyrna tiburo—individual	P	Neodymium (Nd) metal	Lab	No	McCutcheon and Kajiura (2013)

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