

Errata

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Analysis of permanent magnets as elasmobranch by-catch reduction devices in hook-and-line and longline trials

Corrections

Page 397. Last paragraph of left column

Please note that the original article included typographical errors in the catch statistics between the control and procedural control (i.e., sham magnet) treatments for 4 species of elasmobranch (i.e., *S. acanthias*, *M. canis*, *R. eglanteria*, and *C. limbatus*). These values are corrected here; however, these errors did not influence the associated conclusions made in this article. The paragraph that begins at the bottom of the left column should read as follows:

For all species combined, no statistical significance in capture was found between control and procedural control hooks: *R. terraenovae* ($\chi^2=0.419$, $P=0.518$); *S. acanthias* ($\chi^2=0.000$, $P=1.000$); *M. canis* ($\chi^2=0.000$, $P=1.000$); *R. eglanteria* ($\chi^2=0.077$, $P=0.719$); *C. limbatus* ($\chi^2=0.143$, $P=0.706$); and *S. lewini* ($\chi^2=0.000$, $P=1.000$). Therefore, direct comparison between combined control and magnetic treatments was statistically warranted.

Page 397. Table 2 caption

Please note that the original caption for this table contained an error in the accepted P -value that denotes significance (i.e., $P<0.005$). This value was a typographical error for $P<0.05$. All text in this manuscript was prepared originally with a P -value of $P<0.05$; therefore, this typographical error had no effect on the text of this article. The caption for Table 2 should read:

Table 2. Elasmobranch catch composition from longline gear with barium-ferrite magnets in 54 sets. Asterisks indicate significant ($P<0.05$) differences between control and magnetic treatments in chi-square analyses.

Page 397, Table 3

Please note that this table contained 2 errors. The first error was the accepted P -value that was used to denote significance (i.e., $P<0.005$). This was a typographical error for $P<0.05$; however, the manuscript was prepared originally with a P -value of $P<0.05$, and, therefore, this typographical error had no effect on the text of this article. The second error pertained to the number of "Total elasmobranchs" captured. The value entered, "147," was a typographical error and should have been "300." The corrected Table 3 is presented below:

Table 3. Elasmobranch catch composition from hook-and-line gear with neodymium-iron-boron magnets in 660 trials. Procedural control data were not included because no significant difference in catch for control and procedural control was observed. Asterisks indicate significant ($P<0.05$) differences between control and magnetic treatments in chi-square analyses.

| Species | <i>n</i> | Control | Magnets |
|-------------------------------------|----------|---------|---------|
| <i>Rhizoprionodon terraenovae</i> * | 169 | 67 | 30 |
| <i>Mustelus canis</i> * | 21 | 10 | 1 |
| <i>Squalus acanthias</i> | 85 | 31 | 23 |
| <i>Raja eglanteria</i> | 16 | 6 | 3 |
| <i>Carcharhinus limbatus</i> | 7 | 4 | 0 |
| <i>Sphyrna lewini</i> | 2 | 1 | 0 |
| Total elasmobranchs* | 300 | 119 | 57 |
| Total teleosts | 16 | 6 | 5 |

Abstract—Previous studies indicate that elasmobranch fishes (sharks, skates and rays) detect the Earth's geomagnetic field by indirect magnetoreception through electromagnetic induction, using their ampullae of Lorenzini. Applying this concept, we evaluated the capture of elasmobranchs in the presence of permanent magnets in hook-and-line and inshore longline fishing experiments. Hooks with neodymium-iron-boron magnets significantly reduced the capture of elasmobranchs overall in comparison with control and procedural control hooks in the hook-and-line experiment. Catches of Atlantic sharpnose shark (*Rhizoprionodon terraenovae*) and smooth dogfish (*Mustelus canis*) were significantly reduced with magnetic hook-and-line treatments, whereas catches of spiny dogfish (*Squalus acanthias*) and clearnose skate (*Raja eglanteria*) were not. Longline hooks with barium-ferrite magnets significantly reduced total elasmobranch capture when compared with control hooks. In the longline study, capture of blacktip sharks (*Carcharhinus limbatus*) and southern stingrays (*Dasyatis americana*) was reduced on magnetic hooks, whereas capture of sandbar shark (*Carcharhinus plumbeus*) was not affected. Teleosts, such as red drum (*Sciaenops ocellatus*), Atlantic croaker (*Micropogonias undulatus*), oyster toadfish (*Opsanus tau*), black sea bass (*Centropristis striata*), and the bluefish (*Pomatomus saltatrix*), showed no hook preference in either hook-and-line or longline studies. These results indicate that permanent magnets, although eliciting species-specific capture trends, warrant further investigation in commercial longline and recreational fisheries, where bycatch mortality is a leading contributor to declines in elasmobranch populations.

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Analysis of permanent magnets as elasmobranch bycatch reduction devices in hook-and-line and longline trials

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Elasmobranch (sharks, skates, and rays) populations are being subjected to large-scale anthropogenic mortality, resulting in significant population declines of numerous species (Musick et al., 1993; Stevens et al., 2000; Baum and Myers, 2004). Directed commercial fisheries for shark meat and fins, combined with substantial bycatch, are thought to be the main cause of elasmobranch mortality (Bonfil, 1994; McKinnell and Seki, 1998; Megalofonou et al., 2005; Poisson, 2011). Furthermore, recreational impact is increasing as charter boats have redirected their efforts to shark fishing to compensate for the lack of teleost targets such as tuna, marlin, and snapper (Anderson, 1990; Musick et al., 1993; NMFS¹). The decline of several elasmobranch populations is particularly significant because these animals are K-selected species, and therefore populations do not rebound

quickly with changes in management practices (Smith et al., 1998).

One strategy for managing shark fisheries and reducing bycatch is to employ repellents that selectively repel elasmobranchs but do not repel target species. A promising line of research involves the use of permanent magnets to create an abnormally strong electrical stimulus to overwhelm the acute electrosensory system of elasmobranchs and thus repel them (Rigg et al., 2009; O'Connell et al., 2010, 2011). This electrosensory system, comprising many individual ampullae of Lorenzini, is used to detect minute electrical impulses for detection of prey and may also provide geolocation information (Murray, 1962; Kalmijn, 1982; Klimley, 2002).

In laboratory trials, Rigg et al. (2009) evaluated the effects of permanent magnets on five elasmobranch bycatch species: scalloped hammerhead (*Sphyrna lewini*); Australian blacktip shark (*Carcharhinus tilstoni*); gray reef shark (*C. amblyrhynchos*); milk shark (*Rhizoprionodon acutus*); and the speartooth shark (*Glyphis glyphis*); as well as the baramundi (*Lates calcarifer*), a teleost.

¹ NMFS (National Marine Fisheries Service). 1991. Draft Secretarial shark fishery management plan for the Atlantic Ocean (19 April 1991), 127 p. U.S. Dep. Commer. NOAA, NMFS, Southeast Regional Center, St. Petersburg, FL.

This study showed that ferrite magnets induced behavioral responses in all the tested elasmobranchs and that permanent magnets may be able to reduce elasmobranch bycatch. Similarly, O'Connell et al. (2010, 2011) showed that permanent magnets are effective elasmobranch-selective repellents in field and controlled laboratory experiments involving tests with magnets and procedural controls on baited apparatuses. Robbins et al. (2011) concluded that magnetic deterrents in the form of rare-earth magnetic discs have high potential for reducing the bycatch of shark species that occur in low densities, but their use in repelling shark species that occur in high densities, such as the Galapagos shark (*Carcharhinus galapagensis*), was concluded to be minimal.

In addition to magnetic repellents, electropositive metal (EPM) repellents have also been explored for their ability to overstimulate the electrosensory system of an approaching shark (Rice, 2008; Stoner and Kaimmer, 2008). In both laboratory and field studies, EPMS were shown to repel juvenile sandbar sharks (*Carcharhinus plumbeus*; Brill et al., 2009). In laboratory studies, the duration of the EPM repellency was short lived (~three minutes), a phenomenon attributed to competitive interactions among the sharks. In field trials, there was a 62% decrease in the capture of *C. plumbeus* with EPM hook treatments. Additionally, electropositive metals have been shown to deter spiny dogfish sharks (*Squalus acanthias*) from baits in both laboratory (Stoner and Kaimmer, 2008) and field experiments (Kaimmer and Stoner, 2008). Although Kaimmer and Stoner (2008) showed that the capture of *S. acanthias* was reduced by 19% on hooks containing EPMS in the Pacific halibut (*Hippoglossus stenolepis*) commercial fishery, Tallack and Mandelman (2009) conducted both laboratory and field experiments in the Northwest Atlantic, producing contradictory results. The reasoning for the contrasting findings is unclear.

In the present study, we explore the effectiveness of two different permanent magnets on hooks as elasmobranch repellents. We hypothesize that the capture of elasmobranchs would be reduced with hooks containing magnets in comparison with control hooks in hook-and-line and longline studies. Additionally, we further hypothesize that the presence of permanent magnets on hooks would not alter teleost capture because teleosts lack the ampullary organ.

Methods

Longline study

For the present study we employed grade N52 neodymium-iron-boron cylinder magnets on 30 longline sets and grade C8 barium-ferrite permanent cylinder magnets on 54 sets in North Inlet and Winyah Bay, Georgetown County, South Carolina, between April and September 2008. North Inlet (33°19'N, 79°10'W) is a tidally dominated, well-mixed estuary comprising 32 km² of

mudflats, oyster reefs, tidal creeks, and salt marshes dominated by *Spartina alterniflora* (Dame et al., 1986). It has a mean tidal depth of 2.5 m. Winyah Bay (33°12'N, 79°11'W) is a partially mixed estuary during periods of low to moderate river discharges, and a salt wedge estuary during higher flows. Winyah Bay averages about four meters in depth and has various substrate types: mud, sand, silt, and clay (Patchineelam et al., 1999).

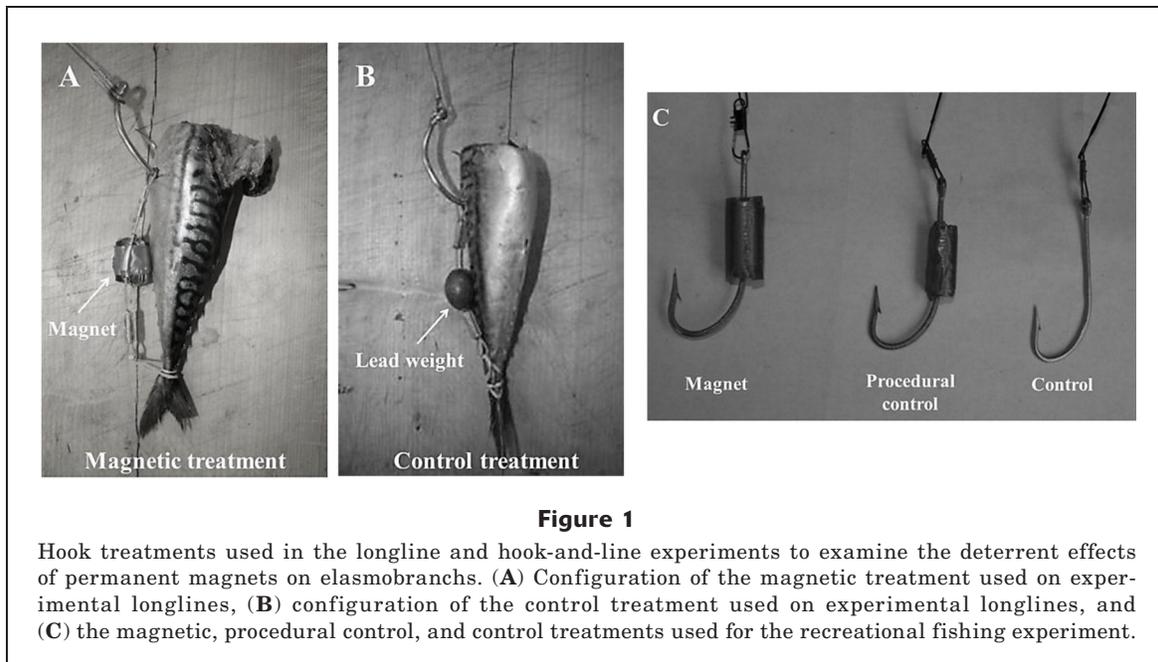
Longlines consisted of a 150-m tar-coated nylon mainline with 24 evenly spaced gangions (branches), each with a single hook. Gangions consisted of 0.75 meters of 317.5-kg 49-strand stainless cable and 0.75 meters of 226.8-kg monofilament line and were attached to the mainline with tuna clips. The hooks were 16/0 Mustad® 3996 open-eye circle hooks and were baited with Atlantic mackerel (*Scomber scombrus*).

The magnetic flux of the longline treatments, with 2.5-cm diameter, 85-g neodymium-iron-boron (Nd₂Fe₁₄B) and a 2.5-cm diameter, 85-g grade C8 barium-ferrite (BaFe₁₂O₁₉) permanent magnets, was measured with a model 4048 teslameter and a transverse probe, model T-4048-001 (F. W. Bell, Milwaukie, Oregon). The former produced a maximum flux of approximately 14,800 gauss at the surface and were polarized through the diameter. The latter were similar in shape to the neodymium-iron-boron cylinder magnets but were polarized through the height and produced a maximum flux of approximately 3850 gauss at their surface. Before experimentation, the axis of polarization was not assumed to be a contributing factor to repellent effectiveness, which is why the axes differed between magnets.

An alternating experimental design consisted of magnetic gangions (treatment) and control (sham-magnet) gangions that were characterized by having an 85-g lead weight similar in appearance to the magnet (Fig. 1, A and B). Magnet-type (i.e., neodymium-iron-boron or barium-ferrite) was consistent for each longline set. Of critical importance was that treatment and control gangions remained separated throughout the study to prevent the magnetization of the control gangions. Magnets were attached to hooks during deployment and removed during retrieval. Also, to prevent the magnetization of control gangions for subsequent trials, the tuna clips on the magnetic treatment gangions were marked, allowing us to properly separate the control and magnetic treatment gangions when not in use.

Longlines were deployed several times each week during slack tides (for safety and to avoid gear tangling) in daylight (between 0800–1700 h) for one hour. Each longline was set in a double-drape configuration with the use of a polyform buoy attached midway on the mainline. With this configuration, approximately 50% of the hooks (i.e., 12 hooks) rested on the substrate, while the remaining hooks were suspended in the water column.

During longline retrieval, teleost and elasmobranch fishes were identified to species, counted, measured (precaudal length [PCL], fork length [FL], total length [TL], stretch total length [STL]), elasmobranch sex was determined, and treatment type noted.



Hook-and-line study

The hook-and-line fishing experiment was conducted off Springmaid Pier (33°39'N, 78°54'W) in Myrtle Beach, South Carolina, between January 2008 and April 2009. Three medium-action rods and reel combinations were used in each trial. Rods were equipped with Penn Captiva CLL4000 reels with 9.07-kg-test monofilament line, 0.30-m steel leader, and egg-shaped sinkers weighing between 85 and 142 g.

Because elasmobranch fauna varied with water temperature, 6/0 hooks baited with pink shrimp (*Penaeus* spp.), squid (*Loligo* spp.), or freshly caught pinfish (*Lagodon rhomboides*) were used during warmer months (April–October; mean sea surface temperature 24°C), and 2/0 hooks baited with 50 g pieces of Atlantic menhaden (*Brevoortia tyrannus*) were used in colder months (December–March; mean sea surface temperature 11°C).

At equally spaced locations along the pier, the rods were randomly arranged. Lines were cast, fished for fifteen minutes, and then retrieved. Each trial consisted of three hook treatments: 1) control, 2) procedural control (sham magnet), and 3) magnetic treatment (Fig. 1C). The control consisted of an untreated hook (i.e., no addition to the shank). The procedural control contained a lead weight of similar dimensions to those in the magnetic treatment and was attached to the hook shank with duct tape. The magnetic treatment contained a neodymium-iron-boron tube magnet (12-mm outer diameter, 5.5-mm inner diameter, and 25-mm height), magnetized through the height, and attached with duct tape to the shank of a hook. If any bait was removed or tampered with, all three treatments were rebaited with fresh bait of identical species. If a fish was found on any of the three lines, the remaining two

lines were retrieved so that all three lines were in the water for the same duration. When a fish was caught, it was identified, measured (PCL, FL, TL, STL), the sex of elasmobranchs was determined, and treatment type was noted. Once the fish was de-hooked, all three lines were redeployed for the remaining minutes of the trial. Fishing occurred irrespective of tides and day or night.

Statistical analysis

For both the hook-and-line and longline experiments, total elasmobranch and teleost catches were analyzed separately. For the longline study, an individual chi-square analysis was used to compare the effectiveness of magnet type compared to the control. Also, a chi-square analysis was conducted on individual species if more than five individuals were caught during one treatment.

For the hook-and-line study, a chi-square analysis was conducted to compare control and procedural control hook data in order to determine whether the presence of an object (sham-magnet) on a hook altered fish capture. If no statistical difference was observed, further analysis was conducted on catches of control versus magnetic treatments. As with longline analyses, if more than five individuals from one species were captured during one treatment, a chi-square analysis was conducted for that species to determine species-specific trends.

Results

Longline: neodymium-iron-boron magnets

Five species of elasmobranchs were captured on longlines during the neodymium-iron-boron magnetic trials

Table 1

Elasmobranch catch composition from longline gear with neodymium-iron-boron magnets in 30 sets. No significant differences were found between control and magnetic treatments for any of the species or all species combined.

| Species | <i>n</i> | No. of control treatments | No. of magnet treatments |
|-----------------------------------|----------|---------------------------|--------------------------|
| <i>Rhizoprionodon terraenovae</i> | 15 | 7 | 8 |
| <i>Carcharhinus limbatus</i> | 6 | 3 | 3 |
| <i>Carcharhinus plumbeus</i> | 4 | 2 | 2 |
| <i>Dasyatis americana</i> | 4 | 1 | 3 |
| <i>Negaprion brevirostris</i> | 1 | 0 | 1 |
| Total elasmobranchs | 30 | 13 | 17 |

(*n*=30 sets): Atlantic sharpnose shark (*Rhizoprionodon terraenovae*), blacktip shark (*Carcharhinus limbatus*), sandbar shark (*Carcharhinus plumbeus*), southern stingray (*Dasyatis americana*), and lemon shark (*Negaprion brevirostris*). Total capture between magnetic and control treatments was not significant ($\chi^2=0.533$, $P=0.4652$), nor was there a significant difference in catch for *R. terraenovae* ($\chi^2=0.067$, $P=0.7963$), the only species for which sufficient catch allowed analysis by species (Table 1). No teleosts were caught on any hooks.

Longline: barium-ferrite permanent magnets

Seven different species were captured during the barium-ferrite permanent magnetic trials (*n*=54 sets): *C. limbatus*, *D. americana*, *C. plumbeus*, *N. brevirostris*, bonnethead shark (*Sphyrna tiburo*), blacknose shark (*Carcharhinus acronotus*), and one teleost—red drum (*Sciaenops ocellatus*). Elasmobranch catch with the use of barium-ferrite permanent magnets was significantly lower than the catch with controls ($\chi^2=4.235$, $P=0.0396$). Among individual species with sufficient numbers to analyze, catches of *D. americana* and *C. limbatus* were significantly greater on control hooks than on magnetic treatment hooks ($\chi^2=4.455$, $P=0.0348$). There was no difference in the catch of *C. plumbeus* ($\chi^2=1.286$, $P=0.257$; Table 2).

Hook-and-line

Six elasmobranch species were captured by hook-and-line: *R. terraenovae*, spiny dogfish (*Squalus acanthias*), smooth dogfish (*Mustelus canis*), clearnose skate (*R. eglanteria*), *C. limbatus*, and scalloped hammerhead (*Sphyrna lewini*).

For all species combined, there was no statistical significance in capture found between control and procedural control hooks: *R. terraenovae* ($\chi^2=0.419$, $P=0.5175$); *S. acanthias* ($\chi^2=0.019$, $P=0.8907$); *M. ca-*

Table 2

Elasmobranch catch composition from longline gear with barium-ferrite magnets in 54 sets. Asterisks indicate significant ($P<0.005$) differences between control and magnetic treatments in chi-square analyses.

| Species | <i>n</i> | Control | Magnets |
|--------------------------------|----------|---------|---------|
| <i>Dasyatis americana</i> * | 11 | 9 | 2 |
| <i>Carcharhinus limbatus</i> * | 11 | 9 | 2 |
| <i>Carcharhinus plumbeus</i> | 7 | 2 | 5 |
| <i>Negaprion brevirostris</i> | 2 | 2 | 0 |
| <i>Carcharhinus acronotus</i> | 2 | 0 | 2 |
| <i>Sphyrna tiburo</i> | 1 | 1 | 0 |
| Total elasmobranchs* | 34 | 23 | 11 |
| Total teleosts | 4 | 2 | 2 |

Table 3

Elasmobranch catch composition from hook-and-line gear with neodymium-iron-boron magnets in 660 trials. Procedural control data were not included because no significant difference in catch for control and procedural control treatments was observed. Asterisks indicate significant ($P<0.005$) differences between control and magnetic treatments in chi-square analysis.

| Species | <i>n</i> | Control | Magnets |
|-------------------------------------|----------|---------|---------|
| <i>Rhizoprionodon terraenovae</i> * | 169 | 67 | 30 |
| <i>Mustelus canis</i> * | 21 | 10 | 1 |
| <i>Squalus acanthias</i> | 85 | 31 | 23 |
| <i>Raja eglanteria</i> | 16 | 6 | 3 |
| <i>Carcharhinus limbatus</i> | 7 | 4 | 0 |
| <i>Sphyrna lewini</i> | 2 | 1 | 0 |
| Total elasmobranchs* | 147 | 119 | 57 |
| Total teleosts | 16 | 6 | 5 |

nis ($\chi^2=0.222$, $P=0.6374$); *R. eglanteria* ($\chi^2=0.2860$, $P=0.5930$); *C. limbatus* ($\chi^2=1.000$, $P=0.3173$); and *S. lewini* ($\chi^2=0.000$, $P=1.000$). Therefore, direct comparison between combined control and magnetic treatments was statistically warranted.

Compared with control hooks, neodymium-iron-boron magnets significantly reduced elasmobranch capture ($\chi^2=21.841$, $P=0.0001$; Table 3). The capture of both *R. terraenovae* and *M. canis* was significantly reduced by magnets (*M. canis*: $\chi^2=7.364$, $P=0.0067$; *R. terraenovae*: $\chi^2=14.113$, $P=0.0002$). *Squalus acanthias* and *R. eglanteria* catch was not significantly different between control and magnet treatments (*S. acanthias*: $\chi^2=1.185$, $P=0.2763$; *R. eglanteria*: $\chi^2=1.000$, $P=0.3173$). Low *C. limbatus* and *S. lewini* catch did not allow experimental

analysis. Four species of teleost fishes were captured: Atlantic croaker (*Micropogonias undulatus*: control (C)=3, procedural control (PC)=2, magnet (M)=1), oyster toadfish (*Opsanus tau*: C=1, PC=2, M=2), black sea bass (*Centropristis striata*: C=0, PC=0, M=1), and the bluefish (*Pomatomus saltatrix*: C=2, PC=1, M=1). There was no significant difference in the total number of teleost fish captured between control and procedural control treatments ($\chi^2=0.077$, $P=0.7815$) nor between control and magnetic treatments ($\chi^2=0.077$, $P=0.7815$; Table 3).

Discussion

Magnets were associated with a species-specific catch in elasmobranchs in both longline and hook-and-line studies. Longline hooks treated with neodymium-iron-boron magnets had no effect on any captured elasmobranchs (Table 1). Longline hooks with barium-ferrite permanent magnets produced a reduction in capture of *C. limbatus* and *D. americana*, whereas all other species were either not affected or were data-deficient (Table 2). In the hook-and-line study, neodymium-iron-boron magnets reduced the capture of two species, *R. terraenovae* and *M. canis*, compared with controls and procedural controls (Table 3). Teleost species were captured in both experiments and capture rate did not vary with treatment type.

Longline study

Barium-ferrite magnets repelled elasmobranchs, whereas neodymium-iron-boron magnets did not. Neodymium-iron-boron magnets ($\text{Nd}_2\text{Fe}_{14}\text{B}$) contain neodymium from the lanthanide group of elements, as well as iron (a ferromagnet) and boron. The neodymium-iron-boron magnets (grade N52) used in our study produced a maximum flux of 14,800 gauss at their surface. Barium-ferrite permanent magnets ($\text{BaFe}_{12}\text{O}_{19}$: grade C8) are also alloys with a solidified structure and produce a maximum flux of 3850 gauss at their surface.

A species-specific difference in catch was observed when using barium-ferrite magnets. Capture of *C. limbatus* and *D. americana* was significantly associated with control hooks; however, capture of *C. plumbeus* was not affected. Species-specific differences may be due to morphological (i.e., ampullary pore density or canal depth) or behavior (i.e., foraging strategy) (see additional discussion below). Because *D. americana* is a benthic elasmobranch whose vision is not the primary sense in locating buried prey (Raschi, 1986; Jordan, 2008; Jordan et al., 2009), especially in the turbid waters of our study sites, we hypothesize that *D. americana* may rely more heavily on electroreception, and therefore the strong induced current produced by the barium-ferrite magnets elicited a repellent response. O'Connell et al. (2010) conducted a study which examined the effects of grade C8 barium-ferrite permanent magnets, identical to the magnets used in the present longline study, on *D. americana* and found that the feeding response

of this species was highly correlated with procedural control and control regions, and there were significantly greater quantities of avoidance behaviors toward the magnetic regions. Similarly, Rigg et al. (2009) showed that ferrite magnets induce repellent responses in five elasmobranch species, *S. lewini*, *C. tilstoni*, *C. amblyrhynchos*, *R. acutus*, and *G. glyphis*. These findings support the results obtained from field trials in the present study.

In addition to these results, it is unclear why *C. limbatus* catch was significantly associated with control hooks and *C. plumbeus* catch was not. One possible explanation for this result may be animal size and maturity. The size of the animal is directly correlated to ampullary canal length, resulting in differing electroreception capabilities (Sisneros et al., 1998; Sisneros and Tricas, 2002). Studies show that as the Atlantic stingray (*Dasyatis sabina*) and clearnose skate (*Raja eglanteria*) mature there is a gain of electrosensory primary afferents and, presumably, neural sensitivity (Sisneros et al., 1998; Sisneros and Tricas, 2002). More specifically, the neural sensitivity of *R. eglanteria* was five times greater in juveniles and eight times greater in adults than in embryos, (Sisneros et al., 1998). Similarly, in *D. sabina*, the neural sensitivity is three times greater in juveniles and four times greater in adults than in embryos (Sisneros and Tricas, 2002). All *C. plumbeus* captured in this experiment were juveniles (Sminkey and Musick, 1995), whereas all *C. limbatus* were adults (Killam and Parsons, 1989). It is possible that in the case of these two species, maturity was an important characteristic in determining the success of magnetic repellents and therefore could also explain why magnets successfully repelled *D. americana*, which were all adults. Intraspecific comparisons between animal maturity and repellent success could not be made because only one size class per species being was present in the catch; therefore we could not accurately conclude whether or not animal maturity reflects the effectiveness of the magnets as repellents.

Supporting our *C. plumbeus* findings, Brill et al. (2009) found that juvenile *C. plumbeus* catch was significantly reduced with the use of electropositive metals on longline hooks; however, preliminary laboratory investigations have demonstrated that juvenile *C. plumbeus* quickly habituate to magnetic stimulation (R. Brill, personal commun.²)—a finding that serves as a possible explanation for the observed *C. plumbeus* results in our study. Lastly, differences in *C. plumbeus* and *C. limbatus* results may be an artifact of small sample size.

Hook-and-line study

Neodymium-iron-boron magnets polarized through the longitudinal axis repelled *M. canis* and *R. terraenovae*

² Brill, Richard. 2009. Virginia Institute of Marine Science, PO Box 1346, Gloucester Point, Virginia, 23062.

during the hook-and-line experiment. Other species of elasmobranchs did not show any significant responses to the magnetic treatment hook (*S. acanthias* and *R. eglanteria*) or were data deficient (*C. limbatus* and *S. lewini*).

The ineffectiveness of electrosensory stimuli on *S. acanthias* is supported by the results of Tallack and Mandelman (2009), who reported that the effectiveness of electrosensory stimuli was reduced owing to a high level of food deprivation (four days) for captive *S. acanthias*. Moreover, electrosensory stimuli had no affect in field studies involving this species. Because *S. acanthias* is found in dense schools, it is possible that the ineffectiveness of the magnetic stimuli in our experiment was due to factors such as social-facilitation (Guttridge et al., 2009). In teleosts fishes, social facilitation due to increasing group size increased intraspecific feeding activity (Major, 1978; Ryer and Olla, 1991); therefore these findings may correlate with our results for *S. acanthias* and indicate that high shark densities may influence conspecific feeding activity. Additionally, because *S. acanthias* may be found in dense schools, it is possible that the ineffectiveness of the electrosensory stimuli was due to the abundance of conspecific behavior and competition which simply overrode the electrosensory stimulation induced by the magnets. High densities of elasmobranchs have been previously postulated as a potential explanation for repellent ineffectiveness (Kaimmer and Stoner, 2008; Robbins et al., 2011) and therefore may explain our *S. acanthias* results.

Contrasting with *S. acanthias*, *M. canis* responded very differently to the treatment hooks and catch was significantly associated with control hooks. Kalmijn (1982) showed that *M. canis* was highly electroreceptive and oriented itself toward or bit electrodes, which mimicked the bioelectric fields produced by prey. An explanation for our findings may be that a stronger, induced voltage produced by an electrosensory stimulus, such as a barium-ferrite magnet, may repel *M. canis*.

Unlike our hypothesis above for *C. plumbeus* catch on longlines, the relationship between catch and animal size or ampullary canal length is weak and therefore cannot be used to explain catch in the hook-and-line study. For *M. canis*, ampullary canal length as a result of stage of maturity may explain the hook-and-line results because catch was significantly higher in controls and all animals were adults (Conrath et al., 2002); however, other examples of catch trends between an animal's maturity and magnetic effectiveness do not exist. For example, all *S. acanthias* were mature adults (Hammock et al., 1985), yet no significant trends in catch existed. Also, although catch of *R. terraenovae* was significantly higher for control hooks, catch was mixed between juvenile and adults (Parsons, 1985) and no distinct catch relationship was observed between control and treatment hooks, therefore minimizing the potential of animal maturity as a pertinent indicator of the effectiveness of the repellents.

Longline vs. hook-and line

Differences in catch rates for longlines and hooks-and-lines may be due to species-specific responses, as we discuss above. Additionally differences in magnetic characteristics, namely the axis of polarization, may have led to significant catch trends. Neodymium-iron-boron magnets used on longlines were polarized through the diameter, whereas barium-ferrite magnets and the hook-and-line neodymium-iron-boron magnets were polarized through a longitudinal axis (height)—a part of the experimental design that we initially overlooked. Because the longline neodymium-iron-boron magnets were placed approximately six centimeters away from the hook, the measurable magnetic field did not fully protect the bait, (peaks in magnetic flux occurred side to side instead of surface-to-substrate), whereas in the barium-ferrite magnets and hook-and-line neodymium-iron-boron magnets, the magnetic field covered the entire bait and hook, which may have been sufficient to deter elasmobranchs from feeding on the baited hooks.

Deployment methods may also be a possible explanation for these experimental differences. Because longlines are immersed (i.e., soaked) for longer time intervals, it is possible that elasmobranchs attracted by the bait were initially repelled but lingered owing to the continuous scent emanating from the bait. In this situation it is possible that sensory habituation to the magnetic field may have occurred, rendering the magnets less effective. Numerous studies have demonstrated that habituation is a common phenomenon in organisms subjected to repeated sensory stimulation (Myrberg et al., 1969; Myrberg et al., 1978; Givois and Pollack, 2000). Moreover, in a previous study, lemon sharks (*Negaprion brevirostris*) repeatedly exposed to a magnetic stimulus reacted at first but became unresponsive after several exposures (O'Connell et al., 2011). However, if repeated exposure to magnets during longline experiments resulted in sensory habituation with the use of neodymium-iron-boron magnets, this explanation is not supported by results with the use of barium-ferrite magnets, where there was significantly less elasmobranch catch on magnetic treatment hooks during the longline experiments.

Conclusion

In conclusion, magnets used as elasmobranch-selective repellents during both the longlining and hook-and-line fishing experiments produced positive result. Although the effectiveness of magnets may be influenced by animal density (Kaimmer and Stoner, 2008; Robbins et al., 2011) and by the level of satiation (Tallack and Mandelman, 2009), we found that magnetic polarization may effectively "protect" fish hooks and reduce unwanted elasmobranch capture in commercial and recreational fishing. Although promising, these results warrant further investigation before recommendations can be made to fishery managers and policy makers.

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