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Do rare-earth metals deter spiny dogfish? A feasibility study on the use of electropositive “mischmetal” to reduce the bycatch of *Squalus acanthias* by hook gear in the Gulf of Maine

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Catches of spiny dogfish (*Squalus acanthias*) are considered by commercial and recreational fishers to be unacceptably high during summer and autumn in the Gulf of Maine off the northeast coast of the USA. Consequently, there is interest in finding a dogfish deterrent for application in various fishing gears. Field studies tested triangular slices of the rare-earth metal cerium/lanthanide alloy (“mischmetal”) incorporated into longlines and rod-and-reel gear to assess its effectiveness in reducing dogfish catches. Treatment catches (mischmetal present) were compared with control (no mischmetal) catches. Laboratory studies provided video-taped, behavioural observations on the effects of alloys under variable levels of food deprivation and dogfish density. No significant reductions in dogfish catch were recorded for either rod and reel or longline, and *in situ* video footage verified persistent dogfish feeding behaviour, regardless of mischmetal presence. The laboratory trials found some evidence of avoidance behaviour in dogfish approaching treatment baits, but only with dogfish fed to satiation; no aversion to the material was observed after 2 and 4 d of food deprivation. Dogfish density had no effect on feeding behaviour in the laboratory. Overall, there is little evidence to suggest that mischmetal can significantly reduce catches of dogfish in hook gears in the Gulf of Maine.

Keywords: aversion, bycatch reduction, electropositive alloy, hook gear, mischmetal, spiny dogfish, *Squalus acanthias*.

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Introduction

The spiny dogfish (*Squalus acanthias*) is a small coastal squaloid shark with circumboreal distribution. In the temperate waters of the Northwest (NW) Atlantic, it is densely distributed inshore from summer through autumn (NEFSC, 2003), and incidental and unwanted catches of dogfish are high across all fishing gear types (trawl, gillnet, hook, and lobster pot) and most fisheries (multispecies groundfish, lobster, herring, and tuna) operating in depths of ~20–200 m. Despite its perceived ubiquity, the dogfish is a *K*-selected species with slow growth, late maturation, low fecundity, long gestation, and high maximum age (Sosebee, 2000) and, as such, is considered vulnerable to overfishing throughout its distribution globally (Fordham *et al.*, 2006). In fact, dogfish in the NW Atlantic have been documented as overfished as recently as 2003, with a 75% decrease in spawning-stock biomass since its US fishery began in 1988 (NEFSC, 2003). Despite recent population increases, the stock has not yet rebuilt to its target spawning biomass, and with a decade-long lull in recruitment, population declines are projected for 2010 (NEFMC, 2007). Although dogfish are no longer overfished or subject to overfishing (NEFSC, 2006), discard rates (9267–12 330 t from 2003 to 2005) remain high.

Both commercial and recreational fishers in the US Gulf of Maine and southern New England waters consider dogfish, long referred to as “sea wolves” (Hess, 1963), a nuisance species. The grounds for this reputation include: (i) seasonal dominance in the catch as a discard species; (ii) damage caused to gear and the need for careful handling because of the dogfish’s rough integument, dorsal spines, and sharp teeth; (iii) low trip limits introduced for stock rebuilding mean that there is little possibility for a directed fishery, and a concomitant decline in dogfish market opportunities on the east coast of the US; and (iv) concerns that the dogfish is “a voracious killer of valuable commercial species” (Hess, 1963) and hence surmised as partly responsible for the poor recovery of valuable groundfish stocks in the Gulf of Maine (Link *et al.*, 2002). A management objective to decrease the incidental catch of the species would serve the best interests of both dogfish stock stability and the recreational and commercial fishing industries. This would not only reduce each fishery’s impacts on the dogfish population, but would also improve each fishery’s efficiency by minimizing dogfish handling time, depredation on bait, and enforced gear maintenance. However, very few strategies to meet this goal have been explored.

It has long been known that elasmobranchs respond to electrical fields using the ampullae of Lorenzini located on their rostrum (Murray, 1960; Kalmijn, 1971) and that they utilize electroreception for navigation and prey location (Heuter *et al.*, 2004). Recently, researchers have taken advantage of this highly sensitive sensory system to develop deterrents. Rare-earth magnets have recently been highlighted as a novel and effective approach to reduce the bycatch of shark species from longline and recreational hook gears in the Gulf of Maine (WWF, 2006). However, initial laboratory studies on the Pacific coast of the US (Stoner and Kaimmer, 2008) found that, while dogfish "flinch" at rare-earth magnets (NdFeB), they show much stronger aversion (characterized by a sudden change in swimming direction away from the stimulus) to "mischmetal" (lanthanide/cerium alloy), a non-magnetic rare-earth metal. The electropositive mischmetal reacts in salt water, releasing electrons that, when drawn by the electronegative skin of a shark, induce an electrical field thought to deter the animal (Stoner and Kaimmer, 2008). Moreover, the use of non-magnetic electropositive metals (which do not cause magnetized clusters of hooks) would be far less cumbersome and hazardous to fishers. Stoner and Kaimmer (2008) observed significant repelling effects of mischmetal on dogfish in the laboratory. More recently, they have also reported a significant reduction in the catch of dogfish in subsequent field trials (Kaimmer and Stoner, 2008), although the result was reportedly less dramatic than anticipated from the laboratory findings. As discrepancies in certain dogfish life-history characteristics have recently been shown to exist between the Pacific and Atlantic populations (Campana *et al*., 2006), it was considered possible that the foraging and sensory modalities of the two stocks might vary too. Hence, with the goal of reducing dogfish catches in commercial and recreational hook gear fishing operations, we assessed the repelling effects of mischmetal on NW Atlantic dogfish through complementary field and laboratory investigations.

Our study consisted of two parallel components. In collaboration with commercial fishers, the field component tested the feasibility and effectiveness of applying mischmetal to commercial and recreational hook and lobster gear. Under more-controlled conditions, the laboratory study evaluated the behavioural responses of dogfish to mischmetal during feeding events.

Methods

Field assessments

Fishing experiments took place in August/September 2007 during a total of 6 vessel days over a period of 10 d. The commercial lobster vessel, FV "Survivor" (13 m), was utilized as the research platform, affording extensive deck space and winch gear for efficient operation of the longline and jig gear. The study location was in inshore waters of the State of Maine (~43°33′N 70°15′E).

To prepare for deployment on fishing gear, industry standard trapezoidal mischmetal ingots (HEFA Rare Earth Canada Ltd, Richmond, BC, Canada) measuring ~45 × 45 × 45 × 130 mm were sliced into pieces measuring ~45 mm on each side and ~5 mm thick. For attachment to fishing gear, holes of ~2-mm diameter were drilled ~5 mm above the bottom edge and ~5 mm below the top corner of each mischmetal slice; the slices were then attached to jigging gear using 2-mm cable-ties and to the longline gear by threading the twine leaders through the drilled holes. On both jigging and longline gears, the mischmetal was secured ~10 cm above the hook and bait. Budget limitations meant that mischmetal was purchased and cut into sufficient quantities to equip all longline gear once, with ~30 extra slices for use in jig gear, so once attached, each mischmetal slice was used for the duration of the field study.

In all, four (100-hook) longlines were constructed, each consisting of 50 control hooks (hook and bait) and 50 treatment hooks (hook, bait, and mischmetal). The hooks were arranged along the longline in alternating groups of 10 (i.e. ten control, ten treatment, etc.) as a means of efficiently verifying that equal numbers of treatment and control hooks were attached to each longline. This approach also allowed effective gear maintenance in the field aboard the vessel where deck space was limited. Four longlines each with 100 hooks were set on trips 1–3; one longline was lost overboard at that time. On trips 4–6, three longlines were set, two with 100 hooks each and one with 140 hooks. The additional hooks were added to compensate for the lost longline, but mischmetal availability limited this increase to 40 hooks. In total, 21 longlines were set across 6 sampling days, totalling 2080 hooks (50% control and 50% treatment). All longlines were set at similar depth each day (~60–100 m) in proximity to each other, to ensure similar fishing conditions between each set. Soak times ranged from 1 to 2 h.

Jigging using rod and reel took place on each of the 6 vessel days to test the effectiveness of mischmetal at deterring dogfish from recreational hook gear. Jigging was undertaken during the soak time for each longline. Each rod and reel ($n = 3$) was configured with two hooks (2–4 hooks is typical while fishing for groundfish), with one treatment and one control hook; 73 jig lines were set, a total of 146 baited hooks (50% control, C, and 50% treatment, T).

All animals caught by both jig and longline gears were noted for hook type (i.e. treatment or control), bait presence, species, size (total length, TL), and sex where possible, then released.

In situ video footage was obtained through collaboration with the University of New Hampshire's Atlantic Marine Aquaculture Center (Durham, NH, USA). A PVC camera frame was deployed to ~20 m, with control and treatment baits (hookless). The camera had a live feed umbilical cord allowing bait monitoring and camera panning to capture observations of dogfish approaching and removing the bait. The footage was reviewed to supplement field and laboratory trials to generate better understanding of how dogfish react to mischmetal baits (vs. control baits), so assisting in the interpretation of dogfish catch rates in the longline and jig data.

To assess the rate of dissolution of a typical slice of mischmetal used during both field and laboratory experiments, we used time-lapse photography. One slice of mischmetal was suspended by nylon in seawater [collected at ambient temperature of ~10°C, but which gradually warmed to room temperature (~18°C) during the course of the experiment], and a Nikon D40x 10.1 megapixel camera was mounted on a tripod and programmed to take one frame every 15 min for a total of 48 h. A subsample of these images (frames at 60-min intervals until the mischmetal dissolved off the nylon) was analysed in MATLAB. A tailor-made program was written to calculate the two-dimensional area (mm^2) of mischmetal remaining in each hourly interval image; from these data, an approximate dissolution rate (%) was estimated.

Laboratory assessments

As a complement to the field component, we assessed the responses of dogfish ($n = 77$ collectively for the study) to mischmetal in a contained laboratory environment at the Marine Biological Laboratory (Woods Hole, MA, USA). Feral dogfish were captured by otter trawl in Vineyard Sound south of Cape Cod, MA, USA, and were held in deck tanks containing ambient (~12–15°C) surface seawater. Following boat transport to the captive facility, animals underwent 7 d of acclimation before the experiments. Experimental tanks measured 3.4 m in diameter and, to approximate presumed field conditions, contained treated seawater chilled to 15°C. Dogfish were exchanged from the experimental tanks weekly to reduce the effects of learned behaviours and to inflate the sample of individual dogfish subjected to trials. The effect of animal tank density (low $n = 3$ vs. high $n = 15$ dogfish) on feeding behaviour during exposure to the deterrent was evaluated in separate trials. In addition, the extent of food deprivation [1 h (0 d), 2 d, and 4 d before a trial] was examined for influences on bait selectivity in trials according to protocols from Stoner and Kaimmer (2008). Allotments of dogfish in our study, whether low or high density, were subjected to trials at all three hunger stages before exchange for new animals. Rations for between-trial *ad libitum* feeding ranged from 2 to 8 kg (longfin inshore squid, *Loligo pealeii*) and were administered until animals no longer took food, at which point satiation was assumed. Ontogeny (dogfish TL ranged from 66 to 88 cm in the laboratory component) and sex were not factors considered in the laboratory analysis.

In all, 24 videotaped laboratory trials were conducted, eight for each of the three food deprivation stages described. During trials, dogfish were simultaneously exposed to two squid-baited (mock) hook configurations separated along the bottom inside wall by 1.2 m, one "protected" by the experimental alloy (mischmetal) and the other by a corresponding grade 316 passive stainless steel decoy (control) of equal size and shape. Similar to Stoner and Kaimmer (2008), who utilized decoys made of aluminium, we assumed the stainless steel decoys to be minimally reactive in seawater compared with the mischmetal, and subsequent investigation has confirmed that only a negligible field is produced (S. Kajiura, unpublished data). Aside from the hooks being replaced by plastic wire-ties, the precise configurations of baited lines mirrored those used in the field component. Trials began with the simultaneous introduction of both "protected" baits and continued until either both baits were consumed or 20 min had elapsed. Each trial was timed and coded both in real time with annotation and, for reliability, by subsequent video analysis. To enhance objectivity, the number of individuals coding these trials was kept to a minimum; a standard protocol was used, and the array of possible behaviours categorized by conservatively broad definitions. An approach was defined as any movement by an animal demonstrating discernible intent (e.g. on a direct track to and on the same plain as the bait) to within 60 cm of either a mischmetal- or decoy-protected bait. At this juncture, an animal could either avoid or attack (bite) the bait. Again to enhance objectivity, an averted approach was characterized as avoidance regardless of whether a rapid 180° flinch or merely a general change in direction bending away from the bait was observed.

Within a given trial, the numbers of respective dogfish approaches and bites on the mischmetal and the control were recorded separately. The number of approaches varied across trials, so percentages of overall approaches were calculated when analysing aversion behaviour (as a function of bite rate) within specific trials (number of overall bites/number overall approaches) for the mischmetal and control individually. Correspondingly, the time delay (s) between the initial approach and the first bite made on respective baits (time to first bite − time to first approach) was calculated as a function of overall avoidance behaviour in relation to the mischmetal and control. If the first approach coincided with the first bite, it was scored as a 1 (as opposed to a 0) for ease of analysis. For each dependent variable assessed, a ratio (mean mischmetal response / mean control response) was derived. Consequently, bite-rate ratios were viewed as inversely related to the aversion to baits protected by mischmetals, whereas the time-delay ratio would positively vary with aversion to mischmetal protected baits. Finally, the bait first bitten was recorded for each trial.

During high-density trials, it was not possible to monitor the feeding behaviour of individual dogfish accurately. To offset this and the vagaries of individual behaviour within trials, the trials themselves were treated as conditional replicates for the different phases of the laboratory component. Data were analysed using one-way repeated measure ANOVAs, with the lone factor being density (high vs. low), and response variables were analysed between trials and within trials across time (food deprivation of 0, 2, and 4 d). Depending on whether significant effects and/or interactions existed, selected pairwise comparisons were achieved using paired samples *t*-tests. For cases of heteroscedastic variances, Welch ANOVA tests were employed. In addition, a Bonferroni correction was conducted to account for the three feeding stages, with data considered significant according to a more conservative $\alpha = 0.017$. Unless noted otherwise, data are presented as means ± s.e. The categorical frequency data recorded for dogfish caught by control vs. mischmetal hooks was analysed using a standard Chi-squared analysis, according to $\alpha = 0.05$. Analyses were performed using a combination of SPSS 15.0 software (SPSS, Inc., Chicago, IL, USA), MATLAB (The MathWorks, Inc., Natick, MA, USA), JMP 4.04 Software (SAS Institute, Cary, NC, USA), and Grapher 6 (Golden Software, Inc., Golden, CO, USA).

Results

Jig gear

As jigging was frequently interrupted by the need to set or haul longlines, the total catch from jig gear amounted to just 32 animals. The jig catch was dominated by dogfish (93.8%, $n = 30$), with redfish (*Sebastes fasciatus*; 3.1%, $n = 1$) and sea raven (*Hemitripterus americanus*; 3.1%, $n = 1$) the only other species caught. With so few animals caught by jig gear collectively, the analysis by trip for jig data could not be conducted statistically, so is not presented. However, of the pooled dogfish caught by jig, most were females (65%) of 73–94 cm TL, with males ranging from 69 to 81 cm. The total number of dogfish caught with mischmetal present ($n = 14$) and absent ($n = 16$) was virtually identical.

Longline

As stated above, the control and mischmetal hooks were attached to the longlines in groups of 10. Catch data pooled across trips gave some indication that hooks closest to each end of the line may catch fewer dogfish than hooks in the middle section (Figure 1). However, this did not likely bias the results, because experimental (mischmetal) and control hooks were evenly distributed at either terminus of each longline, so both treatments had an equal probability of catching dogfish.

Dogfish catch rates and sample sizes varied between trips (Table 1); sample sizes were low during the first two trips, but subsequent trips, aside from trip 4, yielded a substantial increase. The total catch amounted to 472 animals, largely dominated by dogfish (98.5%, $n = 465$), with haddock (*Melanogrammus aeglefinus*; 0.8%, $n = 4$) and sea raven (0.6%, $n = 3$) being the only other

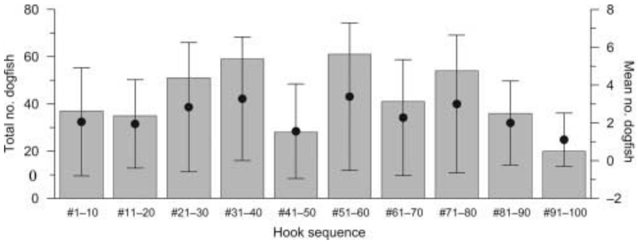

Figure 1. The relative performance of each sequential set of ten hooks pooled across six trips and expressed as the total number of dogfish caught (solid bars) and the mean number of dogfish caught (dots); error bars indicate the s.d. around the mean.

species caught (Table 1). The longline dogfish catch was predominantly males (75%) of 65–87 cm TL, with females ranging from 68 to 97 cm. The dogfish catch per unit effort (cpue, standardized to 100 hooks) ranged from 0.3 to 57.0 across all trips, with an average of 22.4 dogfish per 100 hooks for the whole study (Table 1).

The relative effectiveness of mischmetal on each longline set varied considerably in the early trips when sample sizes were low (Figure 2). Consequently, initial statistical analysis on differences in dogfish catch rates between control and mischmetal hooks considered only longline data where the catch was >40 dogfish. No significant reduction in dogfish catch was observed ($\chi^2 = 1.510$, d.f. $= 7$, $p = 0.982$), despite recording 5–10% fewer dogfish on mischmetal hooks than on control hooks for five out of eight longlines. Similarly, when looking at the effectiveness of mischmetal across all longline hauls, Chi-squared analysis (data pooled for ten longlines with <5 observations per treatment) again confirmed no significant difference between control and mischmetal hooks ($\chi^2 = 4.60$, d.f. $= 10$, $p = 0.917$), despite recording 4.95% fewer dogfish on treatment hooks.

Our study faced one major practical challenge: mischmetal dissolution. Over the course of the field experiment (6 vessel days across a 10-d window), the deterioration of the mischmetal slices was considerable (Figure 3); some slices were barely present by the end, and others had dissolved completely. Dogfish catch rates by hook treatment were plotted for each set ($n = 20$) against time (study day), to investigate whether the relative catch by treatment was influenced by deteriorating mischmetal slices (Figure 4). The large variation in catch rates between study days was again evident, but catch rates were consistent between treatment and control hooks on each trip, regardless of time into the study.

In situ video

An opportunistic day of video shooting yielded a total of ∼2 h of *in situ* video footage. The live feed and panning capacity of the video camera ensured that multiple interactions of dogfish feeding off both control and treatment baits were captured. A qualitative assessment showed that responses of dogfish towards the bait with mischmetal (new slices of mischmetal were used) were essentially no different from those towards bait without mischmetal. One instance of right-angled change in direction on approach to the mischmetal was observed, and this was recorded as aversive behaviour. However, all baits with mischmetal attached were consumed. Moreover, the activity of one dogfish feeding on the bait (both control and treatment) often attracted many other dogfish (up to ∼10), and bouts of more aggressive feeding would ensue.

Dissolution

Laboratory-based dissolution studies confirmed that the cerium/lanthanide mischmetal dissolves fast when submerged in salt water of ∼10–18°C. Estimates of the dissolution rate (%) were derived from image analysis on time-lapse photography of a newly submerged piece of mischmetal (Figure 3). In all, 26 h were captured before the mischmetal dissolved off the nylon; as the mischmetal became hidden in the precipitate at this point, additional image analysis was not possible, so our data are limited to 26 h of submersion. At 26 h, the two-dimensional surface area of mischmetal had decreased by ∼40%. The estimates of percentage dissolved during the first 26 h indicate that the rate of dissolution speeds up as the slice gets smaller and thinner, although the increase in dissolution could also have been influenced by the seawater gradually warming to room temperature. Therefore, by applying polynomial regression analysis to these data to project dissolution beyond 26 h, it was estimated that a typical slice of mischmetal will be 50% dissolved at ∼30 h and 100% dissolved at ∼40 h (Figure 5) under the condition of continuous contact with salt water.

Laboratory findings

In general, feeding behaviour in satiated dogfish (0 d no food) was far more passive than in dogfish deprived of food for 2- and 4-d periods (Table 2). Therefore, the extent of food deprivation had a significant effect on the trial duration within groups of dogfish (one-way repeated measures ANOVA, $F = 845.997$, d.f. $= 2, 5$, $p < 0.0001$; Table 2). Specifically, the duration of trials just after dogfish had been fed (0 d no food) was significantly longer than those following 2 and 4 d of food deprivation (Table 2). In trials

Table 1. Catch composition from longline gear categorized by species and experimental condition, i.e. absence (C, control) or presence of mischmetal (T, treatment).

	Haddock		Sea raven		Dogfish			
Trip	**C**	**T**	**C**	**T**	**C**	**T**	**Total**	**Total cpue (per 100 hooks)**
1	–	–	1	–	19	17	36	9.0
2	1	–	–	1	6	2	8	2.0
3	1	–	–	–	59	59	118	39.3
4	–	–	–	–	1	0	1	0.3
5	2	–	–	–	69	62	131	38.5
6	–	–	1	–	90	81	171	57.0
Total	4	0	2	1	244	221	465	22.4

The cpue (for dogfish only) is standardized to lines of 100 hooks.

where both mischmetal and decoy protected baits were bitten, the vast majority saw the decoy protected baits attacked first (7/8 at 2 d no food; 6/7 at 4 d no food; Table 2). However, the time-delay ratio from first approach to eventual bite, and hence the relative aversion to mischmetal, did not differ as a function of the extent of food deprivation (one-way repeated measures ANOVA, $F = 0.605$, d.f. = 2, 5, $p = 0.307$) within groups or dogfish density (one-way repeated measures ANOVA, $F = 0.009$, d.f. = 1, 6, $p = 0.822$) between groups of dogfish.

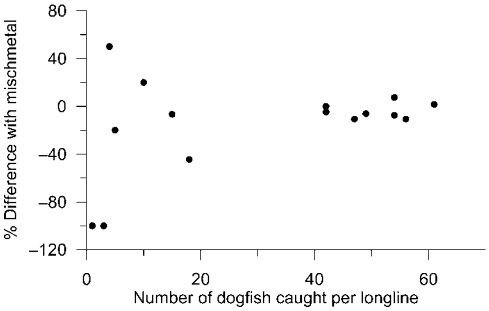

Figure 2. The relative consistency in the relationship between sample size per longline and the difference (%) in the number of dogfish caught by control hooks vs. mischmetal hooks. Dogfish catches >40 yielded a mean reduction of 3.8% in catch (s.d. = 6.36), whereas dogfish catches <40 showed a mean reduction of 18.9% (but s.d. = 59.7).

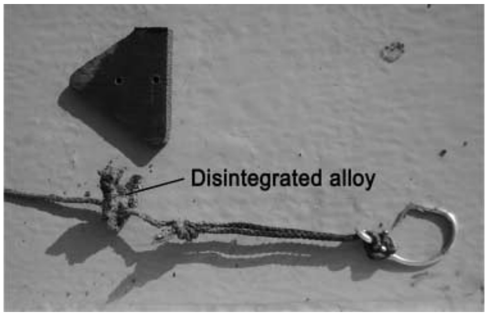

Figure 3. A new, unused slice of mischmetal (top), compared with the dissolved remainder recorded on trip 3, i.e. after just three longline usages (bottom).

Dogfish density in trials failed to influence the bite rates on mischmetal protected baits significantly (one-way repeated measures ANOVA, $F = 0.434$, d.f. = 1, 6, $p = 0.157$). The extent of food deprivation, however, significantly influenced the bite rates relative to mischmetal- and decoy-protected baits within groups of dogfish (one-way repeated measures ANOVA, $F = 8.867$, d.f. = 2, 5, $p = 0.003$). Specifically, the bite-rate ratio, and hence the propensity to bite the mischmetal protected baits, was significantly less in trials 1 h after feeding than in those after both 2 and 4 d without food (Figure 6). Aversion to mischmetal, therefore, diminished once dogfish eclipsed a certain hunger level.

Discussion

The bycatch of elasmobranchs is an issue of global concern, particularly in high seas pelagic longline fisheries where ~25% of the catch is non-target sharks and rays (Mandelman *et al.*, 2008). Within the Gulf of Maine, the elasmobranch most frequently caught as incidental catch by all gear types is the spiny dogfish. Although some fishery stakeholders are concerned about the resilience of dogfish against such indirect and possibly underreported exploitation levels, other stakeholder groups are exasperated by the current increased dogfish abundance (Plante, 2008), and dominance in the catch at certain times of the year. Regardless of personal perspective, the desire to improve gear selectivity and reduce dogfish catch when targeting other species is universal.

Investigations into potential shark repellents have been extensive, particularly in relation to the use of chemicals and surfactants (Sisneros and Nelson, 2001), rare-earth magnets (WWF, 2006; Stoner and Kaimmer, 2008), and most recently, electropositive non-magnetic rare-earth alloys (Stroud, 2005; Brill, 2008; Kaimmer and Stoner, 2008; Stoner and Kaimmer, 2008; Wang *et al.*, 2008). The work described here has included parallel field and laboratory experiments which assessed the responses of dogfish to a rare-earth metal alloy (lanthanide/cerium) in the

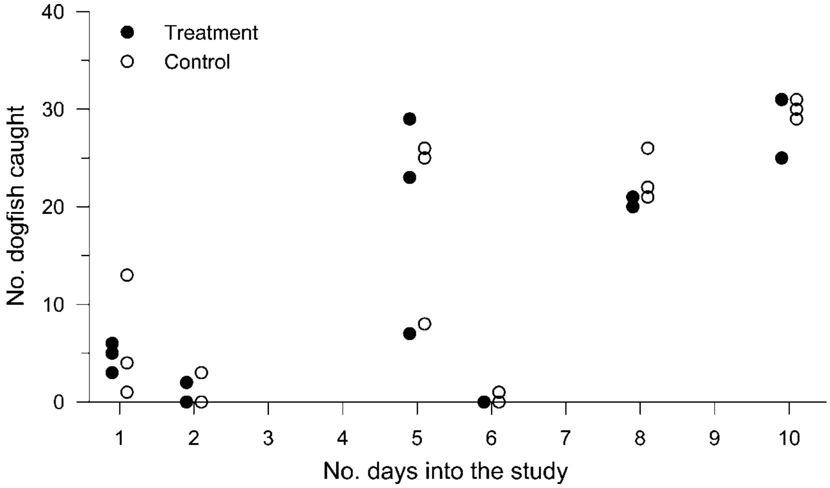

Figure 4. Dogfish catch frequency by hook treatment (treatment/control) for each longline set ($n = 20$) relative to time (number of study days), with deterioration of mischmetal slices over time.

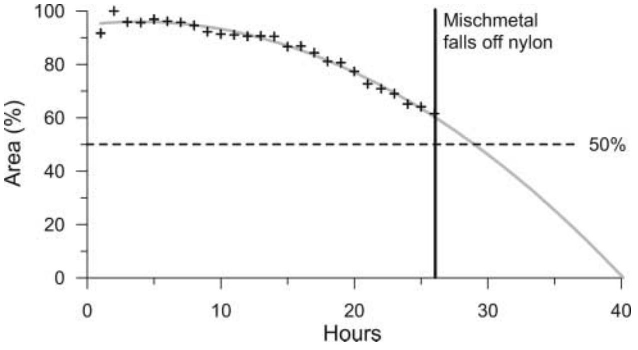

Figure 5. Image analysis on hourly time-lapse images shows a fast decrease in the two-dimensional area (%) of a slice of mischmetal submerged in salt water.

NW Atlantic through laboratory observations and deployment on fishing gear in the field.

Laboratory studies revealed that, when deprived of food for 2- or 4-d increments, dogfish selectivity and hence aversion to mischmetal-protected baits was absent. Animals were only significantly averse to baits protected by mischmetal when fed to apparent satiation and less apt to forage in the face of an impediment; this is not likely a condition that will occur with any regularity in their natal environment. In addition, although decoy-protected baits in our study were usually the first attacked, often they were the first bait approached, which fails to inform whether dogfish were more or less averse to the decoy. The lag until mischmetal-protected baits were then also consumed was minimal; the extent of food deprivation, rather than mischmetal or decoy stimulus, appeared to mediate feeding behaviour. These results differ somewhat from those of Stoner and Kaimmer (2008), from whom we adopted several aspects of our study design. Although akin to our study where the repelling effect of the mischmetal deterrent relative to a decoy declined with increased food deprivation, the repelling effect remained significant in their study. Moreover, although dogfish in their study exhibited a clear change in behaviour when in proximity to the mischmetal, such behaviour was only rarely recorded in our study. These differences between studies are intriguing. A possible explanation is that differences in tank seawater temperature, ~9.8°C in Stoner and Kaimmer (2008) and ~15°C in our study, influenced feeding selectivity by dogfish when encountering mischmetal-protected baits. Future studies seeking to compare Pacific and Atlantic dogfish behavioural responses to mischmetal would need to standardize factors such as tank seawater temperature, salinity, and pH before concluding basic differences between the two stocks.

Through social facilitation, increasing shoal size has been shown repeatedly to enhance intraspecific feeding activity in teleost fish (e.g. Major, 1978; Morgan, 1988; Ryer and Olla, 1991, and see review by Stoner, 2004). Surprisingly, there is little in the primary literature documenting how group size and perceived intra- and interspecific competition mediate elasmobranch foraging behaviour, despite the ubiquitous association of the term "feeding frenzy" with this group by the popular media. Stoner and Kaimmer (2008) hypothesized that shoaling behaviour in dogfish might lessen the effectiveness of mischmetal as a deterrent under natal conditions. In our study, however, a fivefold increase in dogfish group size influenced neither the vigour nor the selectivity of the conspecifics during foraging. Again, the extent of food deprivation was the governing influence on feeding behaviour where, for example, a group of three dogfish fed just as aggressively and with the same seeming ignorance of the deterrent as a group of 15 dogfish after days without food. Although perhaps the magnitude of difference in the two group sizes may not have been enough to elicit an experimental effect on feeding, the fact that even a small cluster of three dogfish ignored a deterrent when deprived of food is a telling indication that mischmetal will likely not sufficiently repel the species under field conditions.

In the field, two gear types were tested: jig and longline. Results from both gear types indicated a slight reduction in the catch rate of dogfish by hooks with mischmetal present vs. those without. However, the reduction was very small (up to 10%), and in neither gear was the result significant, unlike the 19% reduction reported by Kaimmer and Stoner (2008). Although the fast dissolution (Stoner and Kaimmer, 2008) of this alloy may have reduced its effectiveness as a deterrent, there is no evidence to suggest that earlier trips (when mischmetal was more intact) deterred dogfish better than later trips (when mischmetal slices were greatly disintegrated), because catch rates were consistent between treatments on each day of the study (Figure 4). Furthermore, *in situ* video footage supported these data, with dogfish showing considerable determination to take the bait presented whether or not guarded by mischmetal. Therefore, from the perspective of field studies and actual dogfish catch rates, mischmetal does not appear to show promise for reducing the unwanted catch of dogfish.

If dogfish had been significantly repelled by the mischmetal, the fishery would have been faced with additional practical and logistic hurdles with regard to this rare-earth metal alloy, the most pronounced being dissolution. The hydrolysis resulting from the cerium/lanthanide alloy in salt water caused rapid dissolution (Stoner and Kaimmer, 2008), as evidenced in the current study during both the temporal analysis of submerged mischmetal images and on longline gear (submerged, then stored attached to the longline in damp conditions at unstable temperatures). Over

Table 2. Trial conditions according to food deprivation, with number of baits bitten, first bait bitten, and trial duration.

Days without food	Number of trials	Treatment	Number of trials with baits bitten	First bait bitten	Least-squares mean trial duration (min) (±s.e.)
0 (1 h)	8	M	0	–	20 (0)*
		D	2	2	
2	8	M	8	1	6.67 (2.5)
		D	8	7	
4	8	M	7	1	1.54 (0.25)
		D	7	6	

M, mischmetal alloy; D, control (decoy).

*Paired *t*-tests showed significant ($p < 0.017$) pairwise differences with other treatments (2 and 4 d without food).

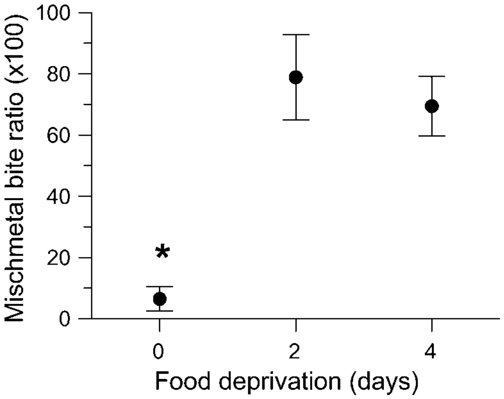

Figure 6. Bite-rate ratio [(number of mischmetal bites/number of mischmetal approaches)/(number of decoy bites/number of decoy approaches)] of dogfish across three periods of food deprivation. The asterisk represents significant (paired *t*-test, $p < 0.017$) pairwise differences between periods of food deprivation (0, and 2 and 4 d).

the course of the experiment (6 d of vessel time within a 10-d window), the deterioration of the mischmetal slices was considerable; some were barely present after experimentation, others had dissolved completely. Consequently, the relative effectiveness of a deteriorated piece of mischmetal over a new piece was questioned. To minimize dissolution, the alloy would need to be stored dry between usages. However, drying and aridly storing individual pieces of mischmetal between sets would be both cumbersome and impractical and, therefore, not likely to be accepted by industry as good use of time, particularly without overwhelming evidence that mischmetal would really deter dogfish. Finally, were mischmetal to be used on a large scale by industry, additional questions would likely arise regarding the potential environmental impact of the insoluble hydroxide precipitate resulting from dissolution. Indeed, the safety of those working with this material (which produces highly flammable filings during the cutting process) would also be a logistic hurdle to overcome (Stoner and Kaimmer, 2008).

Overall, the different components in our study arrive at the collective conclusion that lanthanide/cerium mischmetal is not a solution to reducing the bycatch of dogfish from hook gears in, and likely outside of, the Gulf of Maine. Although some evidence of aversive behaviour was observed in both laboratory settings and on the underwater *in situ* footage, the behaviour did not significantly alter the feeding selectivity in laboratory dogfish, nor did it drastically reduce the catch of dogfish in the field assessments. Social facilitation was not evidenced in the laboratory studies, but perhaps schooling behaviour played a role in the field study. As dogfish often occupied sequential hooks on the longline, it may be that, if any aversion to the mischmetal existed, dogfish, independent of hunger levels, were possibly socially facilitating more aggressive and selective feeding by conspecifics. Certainly the *in situ* video footage demonstrated that when one dogfish pursued the bait, the situation quickly escalated to the stereotypical frenzied and competitive attempts to feed by multiple dogfish, with or without mischmetal present.

Ongoing unpublished research on other shark species has shown that rare-earth metal alloys effectively repel juvenile sandbar sharks (*Carcharhinus plumbeus*; Brill, 2008) and Galapagos sharks (*Carcharhinus galapagensis*; Wang *et al.*, 2008); the lack of a strong effect in dogfish is, therefore, intriguing. However, as the dogfish family (Squalidae) is systematically distinct from the Carcharhinidae, perhaps their functional morphologies and sensory physiologies are quite different; electroreception in dogfish may play a comparatively minor role in sensory functioning and/or have a different threshold from electrical stimuli. The difference observed between taxa justifies the need to study and compare the aversion of individual species/groups to these alloys.

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