ELECTROGENIC METALS FOR ELASMOBRANCH BYCATCH MITIGATION

by

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ABSTRACT

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Commercial longline fishing results in large amounts of incidental bycatch of elasmobranch fishes (sharks, skates, and rays). Teleost species lack electrosensory systems and development of technologies which target the ampullary organs of sharks provides an avenue to selectively deter elasmobranchs without affecting the catch rate of target teleosts. Electric field measurements and a controlled scientific longline study were conducted testing whether the lanthanide metal neodymium or zinc/graphite might reduce elasmobranch catch per unit effort (CPUE). Baited longline hooks were treated with neodymium and zinc/graphite and catch rates were compared to that of controls. Shark CPUE decreased by 60% on neodymium treated hooks and 80% on zinc/graphite treated hooks. The effectiveness of both treatments varied among species with significant reductions shown for Atlantic sharpnose sharks (*Rhizoprionodon terranovae*) but less dramatic differences for others. Zinc/graphite is potentially a viable tool for reduction of shark bycatch in a commercial longline fishery.

ELECTROGENIC METALS FOR ELASMOBRANCH BYCATCH MITIGATION

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I. INTRODUCTION

As the human population continues to grow, rising demand for fish protein has fueled dramatic increases in commercial and artisanal fishing worldwide (FAO, 2010). Technological advances in commercial fishing gear have allowed international fleets to substantially increase both their range and harvest (Kennelly and Broadhurst, 2002). However, increased catch results in a concomitant increase in unwanted, non-target species, or bycatch. The US National Oceanic and Atmospheric Administration (NOAA), National Marine Fisheries Service, defines bycatch as "discarded catch of any living marine resource plus retained incidental catch and unobserved mortality due to a direct encounter with fishing gear". In pelagic longline fisheries, bycatch animals include sea birds, sea turtles, marine mammals, non-targeted teleost fishes and elasmobranchs (Lewison *et al*., 2004).

The elasmobranch fishes (sharks, skates and rays) constitute a large percentage of bycatch throughout much of the world's pelagic longline fisheries and accounted for approximately 25% of the total catch on US longline vessels between 1992-2003 (Abercrombie *et al*., 2005). Total worldwide catch of elasmobranchs was estimated at 750 000 tonnes for 2009 (FAO, 2012) and this level of harvest has contributed to large population declines for certain shark species (Baum and Blanchard, 2010; Clarke *et al*., 2012; Cortes *et al*., 2007). The K-selected life history characteristics of most elasmobranch fishes (slow growth, late maturation, long gestation, and low fecundity) make them extremely vulnerable to overfishing and often result in harvests which exceed maximum sustainable yield (MSY) (Barker and Schluessel, 2005). Removal of top level predators can have long term effects upon marine fish communities (Hoenig and Gruber, 1990). Therefore, to conserve shark populations it is essential to mitigate bycatch of elasmobranchs without affecting catch rates of target species.

Although the target species and elasmobranch bycatch are trophically similar, only the elasmobranchs possess an electrosensory system. Elasmobranchs use their highly developed electrosensory system to aid in prey capture, predator detection, and possibly for use in navigation (Kalmijn, 1982; Tricas and Sisneros, 2004; Tricas *et al*., 1995; Coombs *et al*., 2002). Because teleost species targeted by commercial longline fishing lack electrosensory systems, recent work has investigated whether electric stimuli can be employed to deter sharks from biting baited hooks (Kaimmer and Stoner, 2008; Stoner and Kaimmer, 2008; Wang *et al*., 2008; Brill *et al*., 2009; Tallack and Mandelman, 2009; Robbins *et al*., 2011; Jordan *et al*., 2011; Hutchinson *et al.*, 2012; McCutcheon, 2012). These studies have focused on the naturally electrogenic lanthanide elements as potential shark deterrents.

Lanthanide metals undergo hydrolysis when immersed in seawater and produce an electric field within the range of detection by the shark's electrosensory system. In some studies this electric field has successfully deterred sharks from biting baited hooks

(Stoner and Kaimmer, 2008; Wang *et al*., 2008; Brill *et al*., 2009; Hutchinson *et al*., 2012) whereas other studies report no significant deterrent effect of lanthanide metals (Tallack and Mandelman, 2009; Robbins *et al*., 2011; Jordan *et al*., 2011; Hutchinson *et al*., 2012; McCutcheon, 2012). Further investigation is needed to explain these conflicting results. High cost, rapid dissolution, and the flammable nature of lanthanide metals limit their utility for commercial applications, making the development of less hazardous, cheaper alternatives desirable.

Initial fishing trials using the lanthanide metal neodymium (Nd) and a lead (Pb) procedural control spawned the development of a less expensive electrogenic alternative to lanthanide metals. If proven effective, this alternative zinc and graphite (Zn/Gr) deterrent might be economically feasible for use by commercial fishers. Therefore, the goals of this study were 1) to measure the electric field generated by the lanthanide metal Nd and an economical alternative Zn/Gr, and 2) to conduct a controlled scientific longline survey to determine whether Nd and Zn/Gr reduce shark catch.

II. METHODS

Electric field measurements

To determine the electric stimulus presented to the sharks, the voltage produced by the Nd and Zn/Gr treatments and Pb control metals was measured in seawater. Treatments consisted of Nd (99.5%, CSTRAM Advanced Materials Co. Shanghai, China), zinc (99.7%, McMaster Carr. Santa Fe Springs, CA USA), and GM-10 isomolded graphite (Graphtek LLC, Buffalo Grove, IL USA) each cut into bricks measuring 5.08 x 5.08 x 0.635 cm. Voltage was measured from two Nd bricks with their faces juxtaposed, and for Zn and Gr bricks with their faces juxtaposed. Controls consisted of Pb, and Pb encased within clear epoxy resin to shield the metal from contact with seawater. Pb controls were cut into "L" shaped samples (Figure 1) designed to attach easily to the hook and leader used in the scientific longline portion of this study. Prior to voltage measurement, Pb controls were attached to 14/0 and 16/0 Mustad circle hooks and stainless steel leader, just as they would be deployed in the field.

To measure voltage, a sample was affixed to an acrylic arm on a vertical linear actuator which was mounted to a horizontal 300mm eTrack linear translation stage (Newmark Systems Incorporated, Rancho Santa Margarita, California) adjacent to an acrylic experimental tank (89 x 43 x 21cm) equipped with flow-through seawater (Figure 2). This enabled precise placement of samples in the seawater at desired distances from a recording electrode mounted in the center of the tank. This electrode was a non-polarizable Ag-AgCl pellet electrode (E45P-M15NH, Warner Instruments, Hamden, CT, USA) in 3.0 M KCl and fitted with a seawater/agar-filled glass capillary tube that terminated in a 100µm diameter tip at mid-depth in the tank. A reference electrode was positioned in the far corner of the experimental tank. The output from the two electrodes was differentially amplified (DP-304, Warner Instruments, Hamden, Connecticut) at 1000-10,000x, filtered (0.1 Hz – 0.1 kHz, 60 Hz notch; DP-304, Warner Instruments & Hum Bug, Quest Scientific, North Vancouver, British Columbia), digitized at 1 kHz using a Power Lab® 16/30 model ML 880 (AD Instruments, Colorado Springs, CO, USA) and recorded using Chart™ Software (v.5, AD Instruments).

To measure the voltage, a sample (Pb-hook-leader; epoxy encased Pb-hook-leader (E.E.L); Nd; Zn/Gr) was zip tied to the non-conductive acrylic arm of the linear actuator. The sample was translated to a position 1, 2, 3, 4, 5, 10, 15, 20, 25, or 30 cm from the recording electrode. The actuator then dipped the sample into the water and a voltage measurement was obtained. The actuator removed the sample from the water, the sample was translated to one of the other randomly chosen distances, dipped again, and the process repeated until measurements were obtained at all distances from the recording electrode. Each sample was replaced after every cycle of measurements and 6 replicates were conducted for each sample type.

The replicate measurements were averaged and plotted against distance to determine the rate of voltage decay. The data from the uncoated Pb and epoxy encased Pb samples were log transformed and compared to each other with an ANOVA (SAS 9.3). The data from the Nd and Zn/Gr samples were also log transformed and compared to each other using ANOVA (SAS 9.3).

Longline Fishing

Scientific longline fishing was conducted in Apalachee Bay in collaboration with the Florida State University Coastal Marine Lab located in St. Theresa, FL. This area was chosen based on its historically high shark catch rate. Fishing was conducted during daylight hours between May 21 2012 and June 13 2012 using 4.0 mm monofilament mainline deployed from the RV/ Calcutta (FSU Coastal Marine Lab). Each 60 hook set used modified demersal longline gangions which consisted of a tuna clip attached to a 2m length of 1.80 mm monofilament line that terminated in a 1m length of 1.80 mm stainless steel leader which reduced “bite offs”. To the stainless steel leader was attached either a 14/0 or 16/0 Mustad model 9960D circle hook. A float was fastened via zip tie on each gangion where the monofilament attached to the stainless steel leader. The float maintained the hook within the water column allowing the bait to remain off the substrate to reduce bait loss from scavenging (Figure 3).

A total of 34 longline sets were conducted with 17 sets using Nd treatments and 17 sets using Zn/Gr (Figure 4). A systematic block design was implemented in both Nd treatment and Zn/Gr treatment longline sets. The Nd (treatment), epoxy encased Pb (procedural control), and untreated hook (control) were alternated among 16/0 and 14/0 hooks. Zn/Gr treatment sets utilized the same systematic block design alternating Zn/Gr (treatment), grey/black acrylic (procedural control), and untreated hook (control) among 16/0 and 14/0 hooks. Treatments and controls were affixed with zip ties to the stainless steel leader directly above the hook (Figure 5). The hooks were baited with cut Spanish mackerel (*Scomberomorus maculatus*) or Atlantic bonita (*Euthynuus alleteratus*). Within a single set the same bait type was used on all hooks to eliminate any bait preference biases. Each gangion was attached to the mainline via the longline snap at approximately 10 m intervals. A lead sash weight was clipped to the mainline after every 8 gangions to keep the mainline along the substrate and distribute the hooks evenly within the water column (Figure 3). Procedures for the Zn/Gr treatment sets were identical to Nd sets with two exceptions; in place of Nd, the treatment consisted of Zn and Gr bricks (6.4 x 1.3 x 0.635 cm) with their faces juxtaposed and held in place with a zip tie, and in place of the epoxy encased Pb, the procedural control consisted of gray/black acrylic bricks equal in size to the Zn/Gr. The target soak time for each set was 1 - 1.5 hours. After every three sets, neodymium treatments were replaced with new samples due to rapid dissolution. Also, the zinc was separated from the graphite and sanded using an angle grinder to remove oxidation then juxtaposed with the graphite again for use the following day.

As the sets were retrieved, the species, size, and hook treatment were recorded for all specimens. Data were converted to catch per unit effort CPUE (# sharks / hook hour). Shark catch was analyzed by means of Chi Square tests with the significance level set at

$p < 0.05$ to test the null hypothesis that shark catch rates were similar between treatments and controls.

III. RESULTS

Electric field measurements

A measurable voltage could be obtained from all of the metal samples in seawater. Galvanic interaction between the stainless steel leader and untreated lead control metals produced an average voltage of ~50μV at 1 cm from the source. When the Pb control was encased in epoxy resin the average voltage 1 cm from the source was ~1.50 μV as the electric field was effectively negated (Figure 6). The epoxy-encased Pb/hook/leader (E.E.L) produced a significantly smaller voltage than the untreated-Pb/hook/leader (ANOVA, F = 7.01, $p = 0.0163$), and was used as a non-electrogenic procedural control in neodymium treatment longline fishing sets.

The voltage produced by Nd samples in seawater at 1cm from the source averaged ~12.1mV and decayed with distance as a power function ($y = 23.792x^{-1.953}$). Similarly, the voltage produced by Zn/Gr in seawater at 1cm from the source averaged ~19.5mV and also decayed as a power function with distance ($y = 35.477x^{-1.437}$). The voltage produced by the Nd and Zn/Gr did not differ significantly (ANOVA, F = 2.39, $p = 0.1397$) (Figure 7). However, the voltage produced by Zn/Gr and Nd samples was approximately 1000x greater than that produced by the epoxy encased Pb procedural control.

Longline Fishing

A total of 34 demersal longlines were set in Apalachee Bay, FL (average depth = 3.95m) resulting in 326 sharks caught. Of this catch, 74.8% were Atlantic sharpnose sharks (*Rhizoprionodon terranovae*), 21.2% were blacktip sharks (*Carcharhinus limbatus*) and the remaining 4% were various other species (Table 1). In total, 49.4% were caught on untreated hooks, 38.8% were caught on procedural controls and 11.8% were caught on an electrogenic treatment, either Nd or Zn/Gr.

On Nd treatment sets 170 sharks were caught with 76 (45.7%) on untreated hooks, 67 (38.7%) on epoxy encased Pb controls, and 27 (15.6%) on Nd treated hooks (Figure 8). Catch on untreated hooks and procedural controls did not differ significantly ($\chi^2 = 0.97$, $p = 0.321$, $N = 143$) but both yielded significantly greater catch rates than the Nd treated hooks. There was a 65% reduction in sharks caught on Nd treated hooks compared to untreated hooks ($\chi^2 = 25.51$, $p < 0.001$, $N = 103$) and a 60% reduction in sharks caught on neodymium treated hooks compared to epoxy encased lead procedural controls ($\chi^2 = 17.02$, $p < 0.001$, $N = 94$).

On Zn/Gr treatment sets 156 sharks were caught with 83 (53.5%) on untreated hooks, 61 (38.9%) on acrylic controls, and 12 (7.6%) on Zn/Gr treated hooks (Figure 8).

Catch on untreated hooks and acrylic controls did not differ significantly ($\chi^2 = 3.65$, $p = 0.056$, $N = 144$) but both yielded significantly greater catch rates than the Zn/Gr treated hooks. There was an 85% reduction in shark catch rates on Zn/Gr treated hooks compared to untreated hooks ($\chi^2 = 54.00$, $p < 0.001$, $N = 94$) and an 80% reduction on Zn/Gr treated hooks compared to acrylic procedural controls ($\chi^2 = 32.89$, $p < 0.001$, $N = 73$).

The efficacy of neodymium varied among species (Figure 9). In total, 126 Atlantic sharpnose sharks were caught on Nd longline sets (mean FL 67cm, range 25-85 cm FL); 57 (40.5%) on untreated hooks, 51 (45.2%) on epoxy encased Pb controls, and 18 (14.3%) on Nd treatments. Significantly fewer Atlantic sharpnose sharks were caught on Nd treatments compared to both procedural controls ($\chi^2 = 15.78$, $p < 0.001$, $N = 69$) and untreated hooks ($\chi^2 = 20.28$, $p < 0.001$, $N = 75$). In contrast, no significant difference in catch was found among treatments and controls for blacktip sharks ($\chi^2 = 1.087$, $p = 0.2971$, $N = 23$). In total, 40 blacktip sharks were caught (mean FL 88 cm, range 63-136 cm FL); 17 on untreated hooks, 14 on epoxy encased lead controls, and 9 on neodymium treatments. Catch for other shark species and teleost species were too low for statistical tests (Table 1).

The efficacy of Zn/Gr also varied among species (Figure 9). In total, 118 Atlantic sharpnose sharks were caught on Zn/Gr longline sets (mean FL 68 cm, range 24 - 88 cm FL); 59 (50.0%) on untreated hooks, 51 (43.2%) on acrylic controls, and 8 (6.8%) on Zn/Gr treatments. Catch on Zn/Gr treated hooks was significantly lower than both acrylic controls ($\chi^2 = 31.34$, $p < 0.001$, $N = 59$) and untreated hooks ($\chi^2 = 38.82$, $p < 0.001$, $N = 67$). Of the total 29 blacktip sharks caught (mean FL 90 cm, range 64-131 cm FL), 18 were on untreated hooks, 8 on acrylic controls, and 3 on Zn/Gr treated hooks. Significantly fewer blacktip sharks were caught on Zn/Gr treated hooks compared to untreated hooks ($\chi^2 = 10.71$, $p = 0.001$, $N = 21$). No significant difference was found between catch on acrylic controls and zinc/graphite treated hooks ($\chi^2 = 2.27$, p = 0.132, $N = 11$). Catch between untreated and acrylic control hooks were marginally insignificant ($\chi^2 = 3.85$, $p = 0.05$ ($N = 26$). Catch rates for other shark species and teleost species were too low for statistical tests (Table 1).

IV. DISCUSSION

Due to the highly indiscriminate nature of some commercial fishing practices, developing tools to mitigate substantial landings of non-target species or bycatch is paramount for fisheries conservation (Werner *et al*., 2006). Analysis by Dulvy *et al*. (2008) suggests an elevated extinction risk for three quarters of all oceanic pelagic sharks and rays due to overfishing and removal of these apex predators can lead to cascading deleterious ecological effects (Stevens *et al*., 2000; Myers *et al*., 2007; Heithaus *et al*., 2008). Therefore, the need to reduce capture of non-target shark species in commercial longline fishing without affecting catch rates of target species is essential (Mandelman *et al*., 2008; Gilman, 2011). To determine if electrogenic stimuli are a viable option for commercial deployment, it is first necessary to understand their electrochemical properties and test their efficacy in controlled scientific fishing.

Electrogenic Metals

In recent years lanthanide elements or "electropositive metals" have received attention as potential elasmobranch-specific repellents (Kaimmer and Stoner, 2008; Stoner and Kaimmer, 2008; Wang *et al*., 2008; Brill *et al*., 2009; Tallack and Mandelman, 2009;

Robbins *et al*., 2011; Jordan *et al*., 2011; McCutcheon, 2012; Hutchinson *et al*., 2012; O'Connell *et al*., 2012). The dissolution of lanthanide metals in salt water creates a voltage gradient that exceeds anything naturally encountered and is believed to overwhelm the elasmobranch electrosensory system which results in a startle response (Kaimmer and Stoner, 2008; Brill *et al*., 2009; Tallack and Mandelman, 2009; Hutchinson *et al*., 2012; O'Connell *et al*., 2012). However, their efficacy at repelling sharks has met with varying success in both laboratory and field trials, thus warranting further investigation. Requisite to addressing their efficacy is an understanding of their electrochemical properties.

The galvanic interaction between metals commonly used in fishing (lead weights, stainless steel leader, and steel hook) can produce a measurable voltage close to the source. Given a median electrosensory sensitivity of 25-48 nV cm^{-1}(Kajiura, 2003; Kajiura & Holland, 2002), a shark would be able to detect this voltage from between 20-26 cm away. This electric field provides an additional sensory stimulus that may elicit a bite or flee reaction from a shark when it is very close to the hook. By encapsulating the lead in a non-conductive epoxy, the galvanic electric field was effectively negated thus eliminating any electrical stimulus at the hook.

The electric field produced by the galvanic interaction of standard fishing gear is small in comparison to the field produced by the electrogenic lanthanide metal Nd. At 1cm from the source, the Nd electric field is 1000x greater than the field produced by an untreated Pb/leader/hook assembly. The electric field of Nd decreases as a power function with distance and recent work has investigated its electrochemical properties in seawater (McCutcheon 2012). The electric field is generated by the electrochemical interaction with seawater in which the metal is hydrolyzed to produce hydrogen gas and a metallic precipitate. Consequently an electrical charge distribution develops around the metal. Because of the nature of the hydrolytic reaction, the Nd dissolves in seawater at a rate of approximately -0.68 to -0.91 g/h (McCutcheon, 2012). This rapid dissolution presents one of the limitations of applying lanthanide metals to large scale commercial fisheries. Other factors impacting the widespread adoption of Nd include its price and machinability.

During the course of this study Nd ranged in price from US $145 to $445 kg^{-1} (HEFA Rare Earth Canada Ltd, Richmond, BC, Canada) In addition, lanthanide metals are difficult to refine and produce highly flammable dust and metal filings during machining that pose a fire hazard (Hutchinson *et al*., 2012). The material safety data sheet (MSDS) for Nd (ESPI Metals, 2006) lists it as not only highly flammable but also moderately to highly toxic thus introducing an additional health concern. These factors highlight the limitations of neodymium and illustrate that electrogenic metals chosen for shark bycatch mitigation should be selected based on cost, safety, and practicality.

The Zn/Gr alternative relies upon a galvanic reaction rather than a hydrolytic reaction to produce its electric field. The magnitude and decay rate of the electric field produced by Zn/Gr bricks did not differ significantly from those produced by Nd bricks of the same size. However, because the reaction was galvanic rather than hydrolytic, neither the zinc nor the graphite was consumed in the process, unlike the neodymium. In order for galvanic interaction to occur, several conditions must be met: 1) the metals must have different galvanic potentials, 2) the metals must be in electrical contact with one another, and 3) the metal junction must be bridged by an electrolyte (Atlas, 2010). The combination of zinc and graphite was chosen based on their widely disparate galvanic potentials. The reaction that occurs between Zn/Gr in saltwater oxidizes the zinc anode and renders the graphite cathode nearly unchanged. The oxidation layer that accumulates on the zinc limits reaction rate and likely diminishes the voltage produced. Fortunately, this oxidation is easily removed to expose bare metal, making the zinc reusable.

In addition, both zinc and graphite are easy to refine, not highly flammable, and non-toxic. Zinc and graphite are also relatively economical with zinc at ~ US \$2.00 kg^{-1} (Quindao Jiya Cable Co., Ltd, Shandong, China) and isomolded graphite at ~ US \$6.00 kg^{-1} (Royal Elite New Energy Science & Technology Co., Ltd, Shanghai, China). Therefore, because the Zn/Gr combination possesses these positive attributes and still produces the same voltage magnitude and decay as the Nd, it provides a promising alternative to lanthanide elements. Regardless of which deterrent is used, Nd or Zn/Gr, the rapid voltage decay with distance necessitates that the deterrent be placed close to the baited hook to provide maximum repellency.

Longline Fishing

During the course of longline fishing trials approximately 3-4 times more sharks were caught on the control treatments than on the electrogenic treatments. This suggests that the electrogenic treatments did have a deterrent effect on the sharks, a trend which holds when examining each of the electrogenic stimuli separately. These reductions are significant and illustrate that both neodymium and zinc/graphite can successfully reduce catch rate of coastal sharks. The reductions achieved in this study are similar to or greater than those obtained in previous studies using lanthanide metals. Kaimmer and Stoner (2008) found a significant reduction in spiny dogfish (*Squalus acanthias*) caught on cerium alloy treated hooks compared to controls. Results from Tallack and Mandelman (2009) show a 10% decrease in catch of spiny dogfish, however these findings were not statistically significant. Brill *et al*. (2009) found a 62% reduction in catch of sandbar sharks (*Carcharhinus plumbeus*) on hooks treated with lanthanide metals when compared to plastic controls. Finally, Hutchinson *et al*. (2012) found a significant reduction in catch of juvenile scalloped hammerhead sharks (*Sphyrna lewini*) on lanthanide treated hooks but little difference for other shark species.

Although the overall catch rate was significantly reduced on the electrogenic treatments, for certain shark species statistical power was low due to limited catch. The numbers of Atlantic sharpnose and blacktip sharks were sufficiently large to permit testing for interspecies differences in efficacy. The Atlantic sharpnose shark is a small coastal species that feeds primarily upon clupeid and sciaenid fishes (Bethea *et al*., 2004; Bethea *et al*., 2006). They are known to recruit to the coastal waters of the northern Gulf of Mexico in early spring, remain throughout summer, and travel offshore in the fall (Carlson and Brusher, 1999; Bethea *et al*., 2006). Fishing was conducted during months of high recruitment which ensured a wide range of life stages in our catch and a large enough sample size for statistical analysis. The other shark species for which catch could be tested statistically was the blacktip shark. Unlike with the Atlantic sharpnose shark, the catch rate of blacktip sharks on neodymium treated hooks was not significantly different from the catch rate on untreated hooks and procedural controls. However, the catch rate of blacktip sharks was significantly lower for the zinc graphite treated hooks, than the untreated hooks. These results mirror those found for the Atlantic sharpnose sharks on the zinc/graphite treated hooks.

Although the catch rate was not significantly reduced for blacktip sharks on neodymium treated hooks, only 40 blacktip sharks were caught during neodymium treatment longline sets compared to 126 Atlantic sharpnose sharks caught. A larger sample size of blacktip sharks may help to discern whether a significant reduction can be obtained. All fishing was conducted during daylight, however Driggers *et al.* (2012) suggests increased feeding activity for blacktip sharks during nocturnal hours so future sets to increase sample size may serve best if conducted at night.

Blacktip sharks grow to a much larger total length than Atlantic sharpnose sharks but both averaged less than 1m TL in this study. Both species overlap in habitat for at least part of their life (Bethea *et al*., 2004), however we found mainly immature blacktip sharks and mature Atlantic sharpnose sharks. Interestingly, the Atlantic sharpnose possesses nearly 25% more electrosensory pores than the blacktip (Kajiura *et al*., 2010), but it remains to be determined whether pore number affects susceptibility to these repulsive electric fields.

Very few individuals of the remaining shark species were caught and the numbers were too low to conduct statistical analyses. However, it is noteworthy that of the 13 other sharks caught, only a single nurse shark (*Ginglymostoma cirratum*) was caught on an electrogenic treatment (zinc/graphite). Similarly, very few teleost fishes were caught in this study, primarily because the gear was designed to preferentially catch larger fishes like sharks. Although the sample sizes were again too small for statistical tests, there was a nearly even distribution of fishes caught among the untreated hooks (8), procedural controls (4), and electrogenic treatments (6). This might suggest that catch rates of teleosts were unaffected by the presence of the electrogenic treatments. Similar results were reported by Kaimmer and Stoner (2008) who found no significant difference in halibut CPUE between lanthanide treated hooks and controls. Additionally, Stoner and Kaimmer (2008) conducted lab testing on the Pacific halibut (*Hippoglossus stenolepis*) and found no significant behavioral response to lanthanide treatments.

All of the fishing in this study was conducted in Apalachee Bay, FL which is characterized by sea grass beds, muddy or sandy seafloor, and turbid water. The water clarity for all fishing sets averaged just 260cm. Environmental conditions have the potential to impact the efficacy of electrogenic metals. Fishing conducted in the turbid waters of a tidal lagoon in coastal Virginia yielded a 62% reduction in catch rate of sandbar sharks (*Carcharhinus plumbeus*) (Brill *et al*., 2009). Similarly, a 57% reduction in catch rate of juvenile scalloped hammerhead sharks was achieved in the turbid waters of Kaneohe Bay, Hawaii (Hutchinson *et al.*, 2012). In contrast, no significant reduction in catch rate was seen when fishing for sandbar sharks in the clear, deeper water off the reef outside Kaneohe Bay and when fishing for pelagic species in off-shore cruises (Hutchinson *et al.*, 2012). These results suggest that elasmobranchs which inhabit a turbid coastal environment may rely more heavily on electroreception than vision for prey capture when compared to sharks that inhabit open ocean systems dominated by clear blue water. This is supported by brain morphology and electrosensory-pore count data that correlate structure and function of elasmobranch sensory systems with their environment (Kajiura *et al.*, 2010; Yopak, 2012). Thus, the efficacy of electrogenic metals might prove most useful in turbid coastal fisheries and less effective in a clear pelagic setting.

Intraspecific competition has been demonstrated to increase feeding motivation and thus potentially decrease the efficacy of the lanthanide deterrents (Parrish, 1993; Stoner & Ottmar, 2004). Jordan *et al.* (2011) found decreased deterrent effects from lanthanide metals on groups of smooth dogfish (*Mustelus canis*) compared to individuals. Similar results were found by Robbins *et al*. (2011) for the Galapagos shark (*Carcharhinus galapagensis*) which suggests that sharks found in high conspecific densities may be deterred less effectively than more solitary species. Hence, schooling species such as spiny dogfish (*Squalus acanthias*) could be less deterred by electrogenic metals than more solitary species such as blue sharks (*Prionace glauca*), potentially limiting their effectiveness as a universal shark bycatch mitigation technique.

Fisheries Implications

All elasmobranchs exhibit a K-selected life history, but some species are more vulnerable to over exploitation than others. For instance, the most commonly captured species in pelagic longline fishing is the blue shark (*Prionace glauca*) (Hoey and Moore, 1999; Stevens *et al*., 2000; Cortéz *et al*., 2007; Mandelman *et al*., 2008) The blue shark reaches sexual maturity between 4-7 years of age, reproduces every 1-2 years, and has an average litter size of 37 pups (Stevens, 1975; Pratt, 1979; Skomal, 1990; Castro and Mejuto, 1995; Skomal and Natanson, 2003; Dulvy *et al*., 2008). These factors render blue sharks relatively resilient to overfishing. This contrasts with the second most commonly encountered species, the silky shark (*Carcharhinus falciformis*) (Hoey and Moore, 1999; Mandelman *et al.*, 2008).

The silky shark reaches sexual maturity between 6-12 years of age, reproduces every 2 years, and has an average litter size of 11 pups (Branstetter, 1987; Bonfil, 1990; Bonfil *et al*., 1993; Dulvy *et al*., 2008). In addition to differences in life history between the two species, the silky shark has a much higher at vessel mortality (66.3%) compared to the blue shark (12.2%) (Beerkircher *et al*., 2002). The greater fecundity of blue sharks relative to silky sharks, coupled with their lower at vessel mortality illustrates that some shark species are more susceptible to fishery induced population declines than others.

If electrogenic metals are demonstrated to be effective on species most susceptible to population decline, implementation as a bycatch mitigation tool might be warranted. However, even if proper conservation efforts are implemented, the limited rebound potential of most shark species has led researchers to conclude that recovery times for depleted populations could take decades or centuries (Simpfendorfer, 2000; Ward-Paige *et al*., 2012). This further emphasizes the importance of developing tools and regulations which can be implemented as soon as possible to conserve and protect existing shark populations.

A variety of criteria must be considered during the development and implementation of novel fishing technologies. Effective bycatch mitigation tools must aim to avoid interactions, minimize catch, and reduce injury and mortality of non-target species (Gilman, 2011; Gilman *et al*., 2012). One example is the shift from J-style hooks to circle hooks. This simple gear modification eased the impact of longline fishing by reducing bycatch of sea turtles (Watson *et al*., 2005), minimizing internal injury from gut hooking, and increasing post release survival of non-target species (Epperly *et al*., 2012; Graves *et* al., 2012) without negatively affecting catch rates of target species (Kerstetter & Graves, 2006; Gilman *et al*., 2007). Gear modifications must also be safe, practical, and implemented in ways that provide operational and economic benefits to the crew (Gilman *et al*., 2012). Gilman *et al*. (2008) states that five major economic and practical concerns arise from shark interactions in pelagic longline fisheries: 1) depredation of target catch, 2) damage and loss of gear, 3) reduced catch of marketable species, 4) risk of injury to crew, and 5) expenditure of time removing sharks from gear. Electrogenic metals will likely do little to reduce depredation of hooked target catch due to their limited voltage propagation, however they might be a useful tool to mitigate the four remaining economic and practical concerns.

It is possible that a visual or mechanical deterrent effect could occur by attaching an electrogenic metal above the hook. However, adding lead swivels or weights to the terminal end of branch lines or directly above longline hooks has been employed to reduce seabird, sea turtle, shark, and billfish bycatch with minimal impact on target catch rates (Brothers *et al*., 1999; Beverly & Robinson, 2004; Gilman, 2008; Gilman *et al*., 2005, 2006, 2008; Robertson *et al*., 2006; FAO, 2008). The construction of swivels, weights, or even hooks comprised of electrogenic materials such as zinc and graphite may effectively decrease bycatch across multiple taxa. When coupled with other mitigation strategies listed by Gilman (2011), fisheries managers might have the necessary tools to effectively reduce the impact of longline fishing on shark populations worldwide.

V. CONCLUSION

The reduction of bycatch in commercial fishing is of primary concern for management of our marine ecosystem. The use of lanthanide metals as a shark bycatch mitigation technique has shown some promise for reducing shark catch rates. However, high cost and rapid dissolution warrant the development of more cost effective alternatives. The Zn/Gr deterrent tested in this study reduced shark catch rates by 80%. However, further testing in a commercial longline setting is needed in order to determine its efficacy on shark species most impacted by fishing. If proven to effectively reduce elasmobranch catch in a commercial setting, the development of products which emphasize user-friendliness and reusability will be vital to facilitate the adoption of this technology by fishers. The use of electrogenic metals does not suppose the elimination of shark bycatch, however when coupled with other mitigation techniques, it could be an effective conservation tool for use by commercial and recreational fishers.

Table 1: Total catch rates for all elasmobranch and teleost species captured on neodymium treatment and zinc/graphite treatment sets.

		Neodymium Sets			Zinc/Graphite Sets		
Elasmobranch Species	**Mean FL (cm)**	**Untreated**	**EEL**	**Nd**	**Untreated**	**Acrylic**	**Zn/Gr**
Rhizoprionodon terraenovae	67.7	57	51	18	59	51	8
Carcharhinus limbatus	89.4	17	14	9	18	8	3
Carcharhinus acronotus	86.2	Ø	1	Ø	3	2	Ø
Galeocerdo cuvier	196.5	2	Ø	Ø	1	Ø	Ø
Carcharhinus leucas	158.0	Ø	1	Ø	Ø	Ø	Ø
Carcharhinus brevipinna	176.0	Ø	Ø	Ø	1	Ø	Ø
Ginglymostoma cirratum	160.0	Ø	Ø	Ø	Ø	Ø	1
Sphyrna mokarran	165.0	Ø	Ø	Ø	1	Ø	Ø
Teleost Species	**Mean FL (cm)**	**Untreated**	**EEL**	**Nd**	**Untreated**	**Acrylic**	**Zn/Gr**
Bagre marinus	42.5	1	1	2	6	2	Ø
Echeneis naucrates	42.7	Ø	Ø	1	1	Ø	1
Ariopsis felis	34.0	Ø	1	Ø	Ø	Ø	1
Rachycentron canadum	50.0	Ø	Ø	1	Ø	Ø	Ø

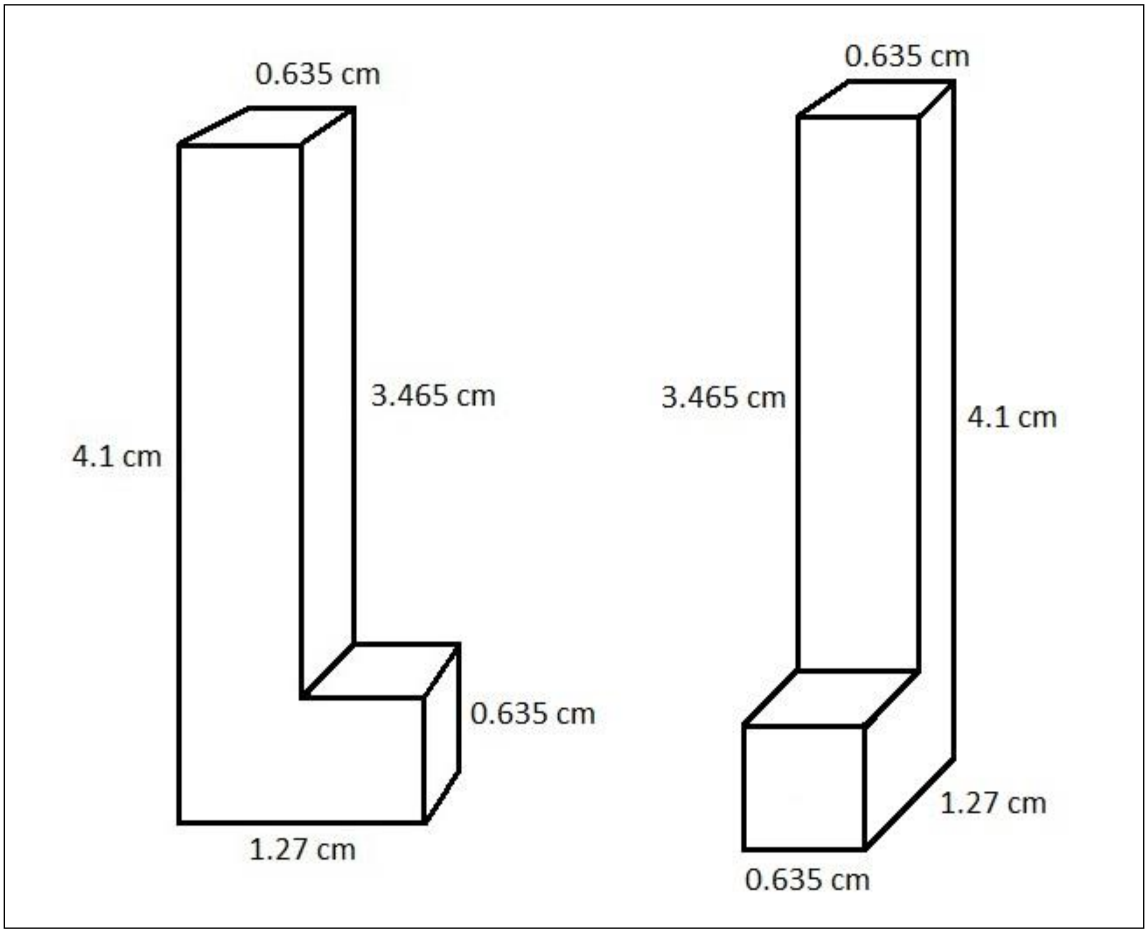

Figure 1 Measurements of the "L" shaped neodymium treatments and lead controls used in controlled scientific longline fishing. The lead was encased in a two part epoxy resin to shield the metal from the saltwater to inhibit galvanic interactions between the stainless steel leader and the procedural control which marginally increased the size.

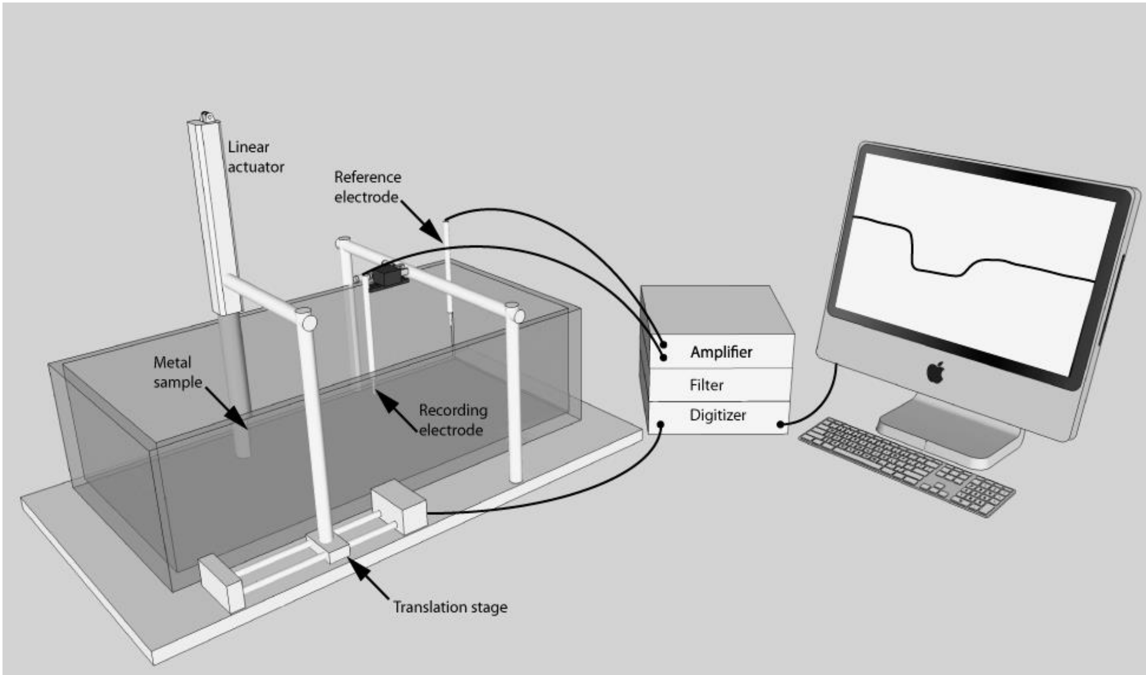

Figure 2: The apparatus used to measure voltage production. Each sample was zip tied to the linear actuator. The sample was then translated to a random position from the recording electrode. The actuator then dipped the sample into the water and a voltage measurement was obtained.

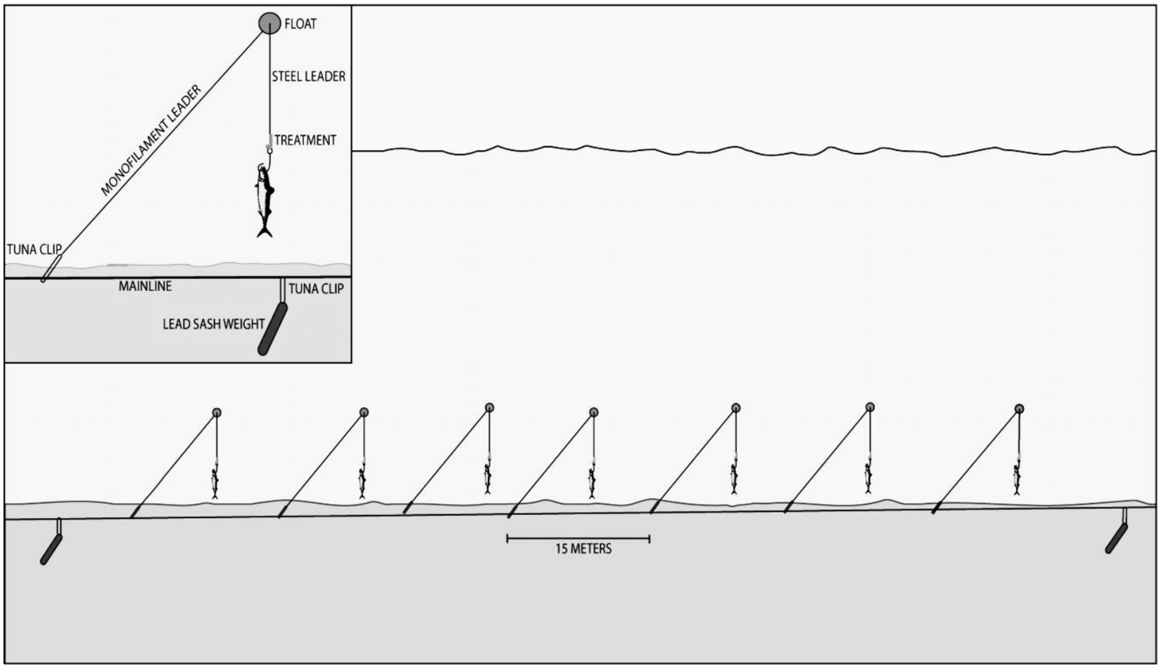

Figure 3: Scientific longline gear configuration.

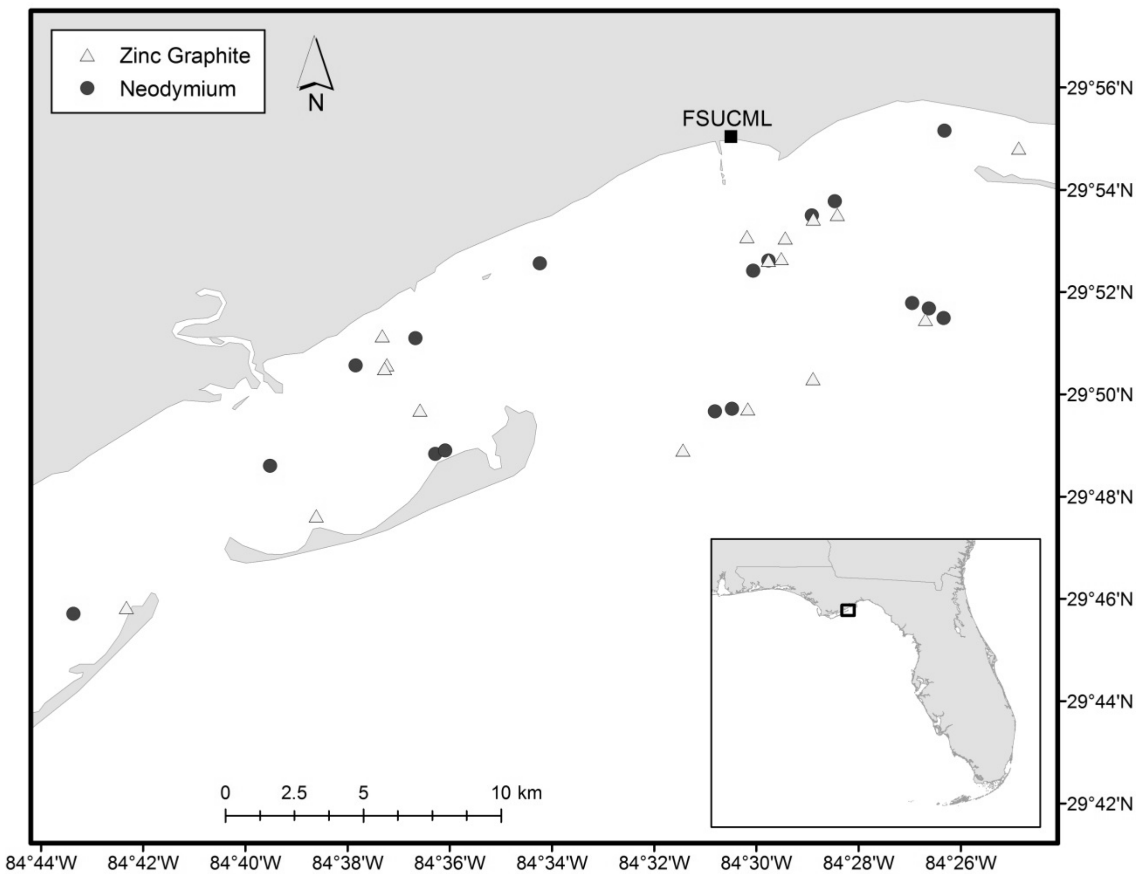

Figure 4: Map of Apalachee Bay, FL where 34 controlled scientific longline sets were conducted. Zinc/graphite treatment sets (N = 17) are indicated by triangles and neodymium treatment sets (N = 17) are indicated by circles (inset shows location of study on west coast of Florida).

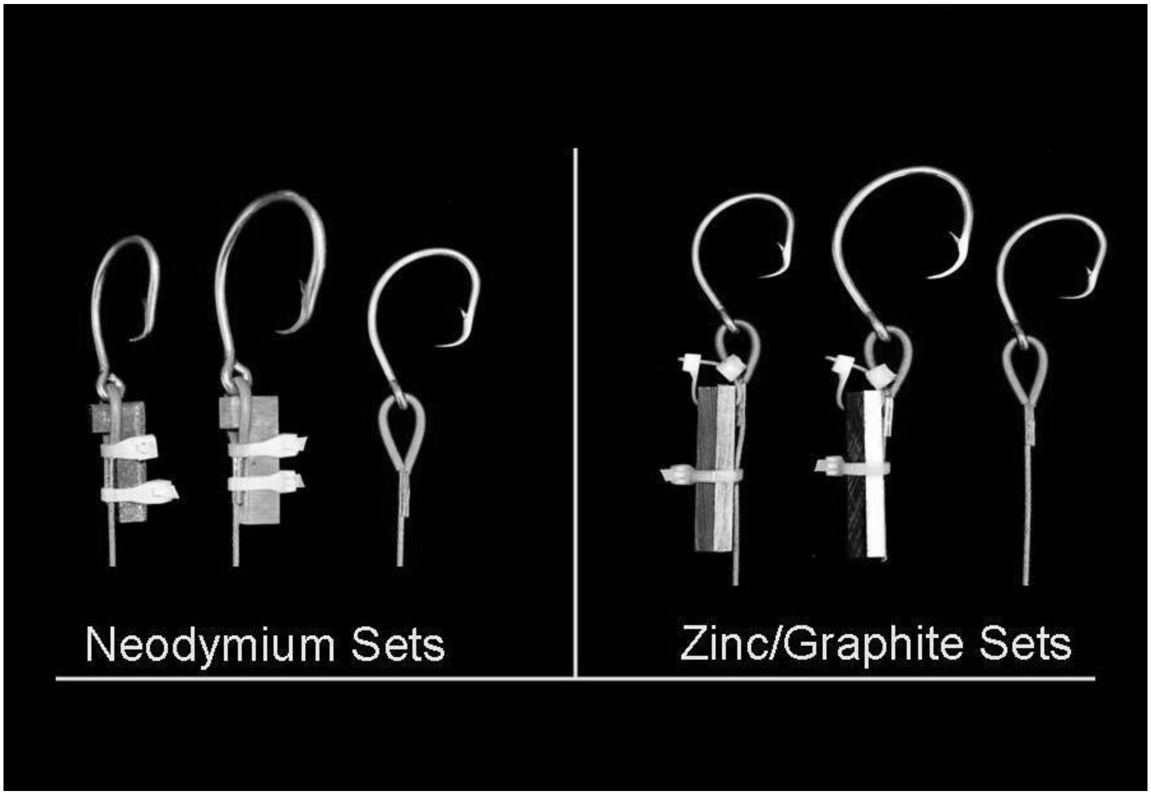

Figure 5: The systematic block design used in 60 hook sets which alternated hook sizes and treatments for both neodymium treatment sets and zinc/graphite treatment sets. All treatments and controls were attached directly above the hook using zip ties. Neodymium treatment sets alternated 14/0 and 16/0 circle hooks and alternated neodymium (treatment), epoxy encased lead (procedural control), and untreated hooks (control). Zinc/graphite treatment sets alternated 14/0 and 16/0 circle hooks and alternated zinc/graphite (treatment), acrylic (procedural control), and untreated hooks (control).

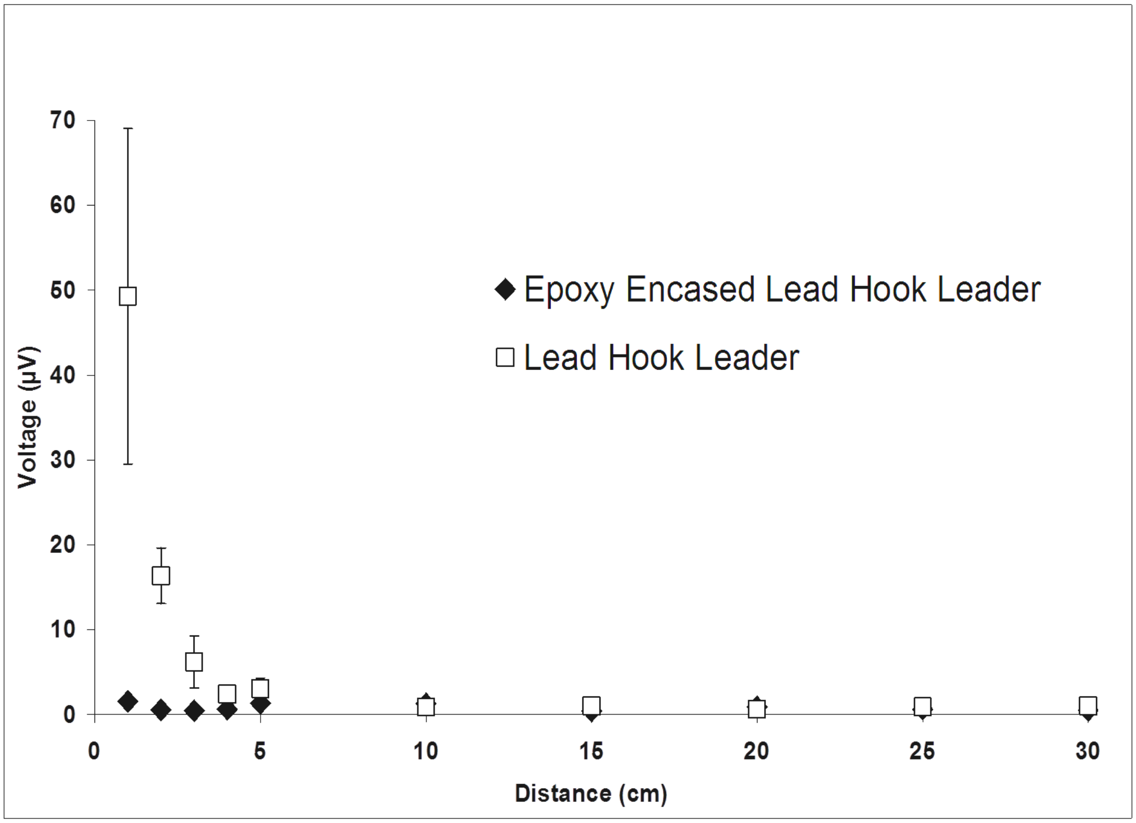

Figure 6: Voltage produced by epoxy encased lead and hook with stainless steel leader compared to unadulterated lead and hook with stainless steel leader in seawater at various distances from a recording electrode. The magnitude of the voltage and the slope of the decay with distance are statistically different for the two procedural controls.

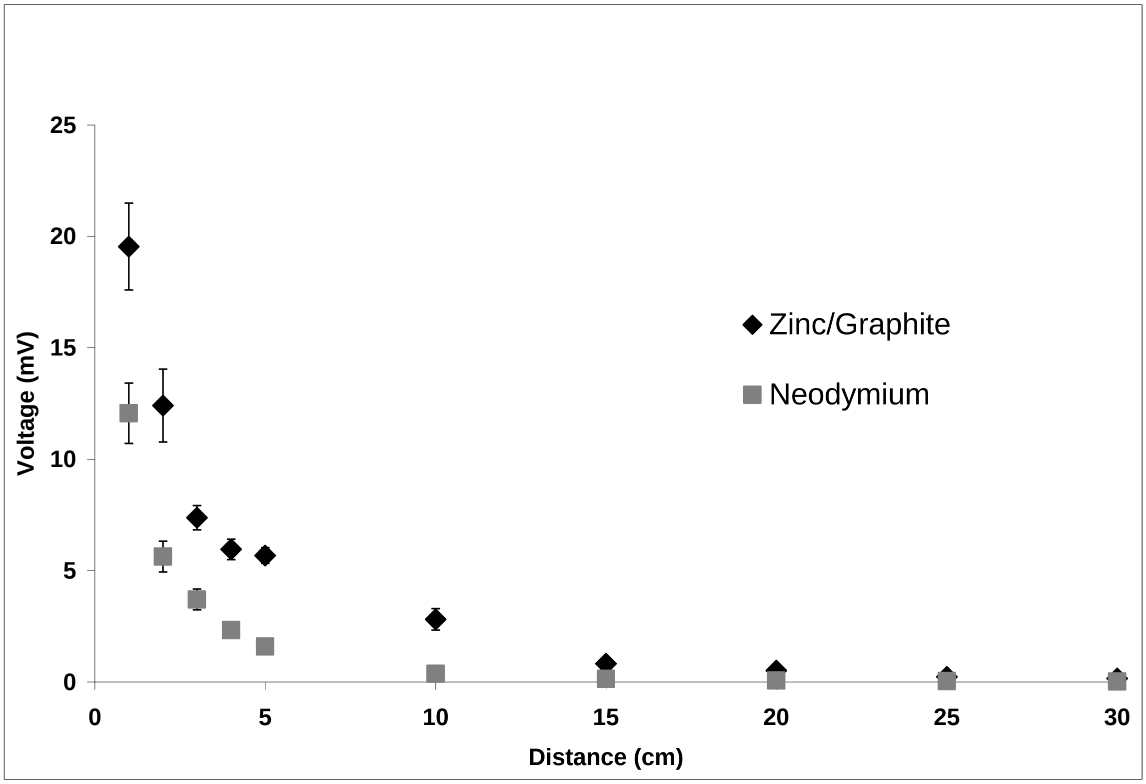

Figure 7: Voltage produced by equal size Zinc/Graphite and Neodymium samples in seawater at various distances from a recording electrode. Both the magnitude of the voltage and the slope of decay with distance are not significantly different for the two treatments.

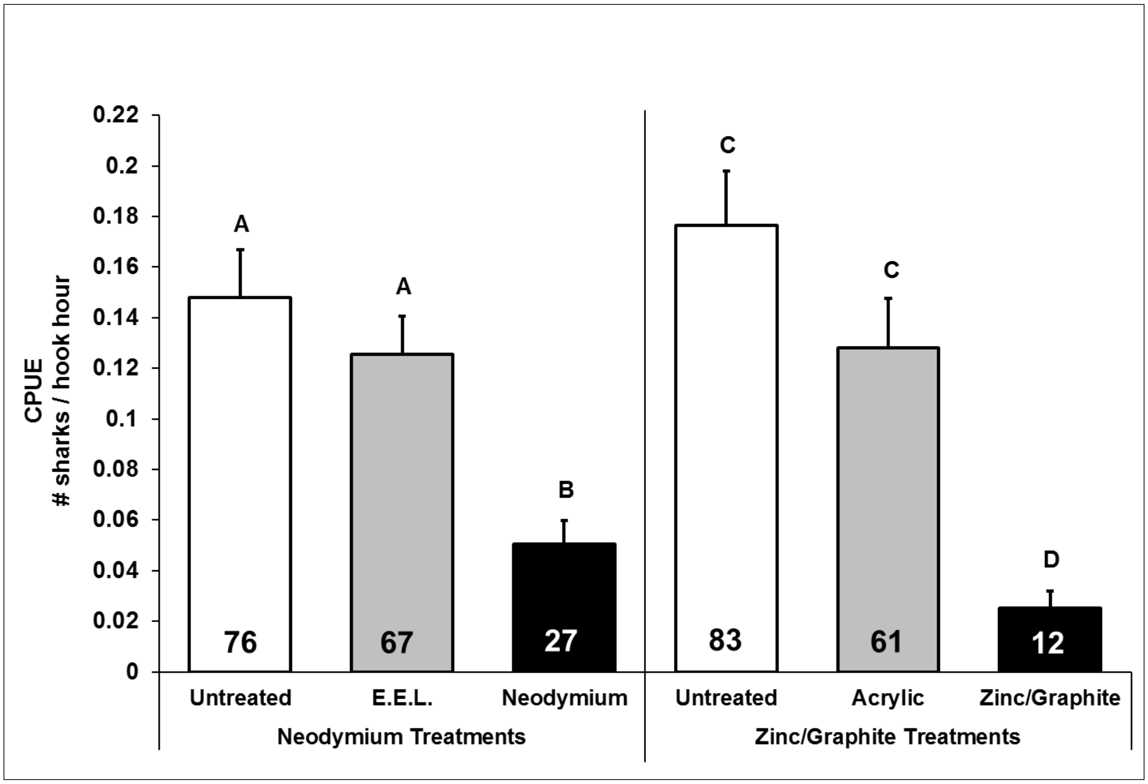

Figure 8: CPUE and total number of elasmobranch catch on 17 neodymium treatment sets and 17 zinc/graphite treatment sets. Neodymium treatment sets show no significant difference when comparing untreated hooks and epoxy encased lead (E.E.L.) procedural controls. A significant 60% reduction was found when comparing shark catch rates on neodymium treated hooks to E.E.L. procedural controls. Zinc/graphite treatment sets show no significant difference when comparing untreated hooks and acrylic procedural controls. A significant 80% reduction in shark CPUE was found when comparing catch on zinc/graphite treated hooks and acrylic procedural controls.

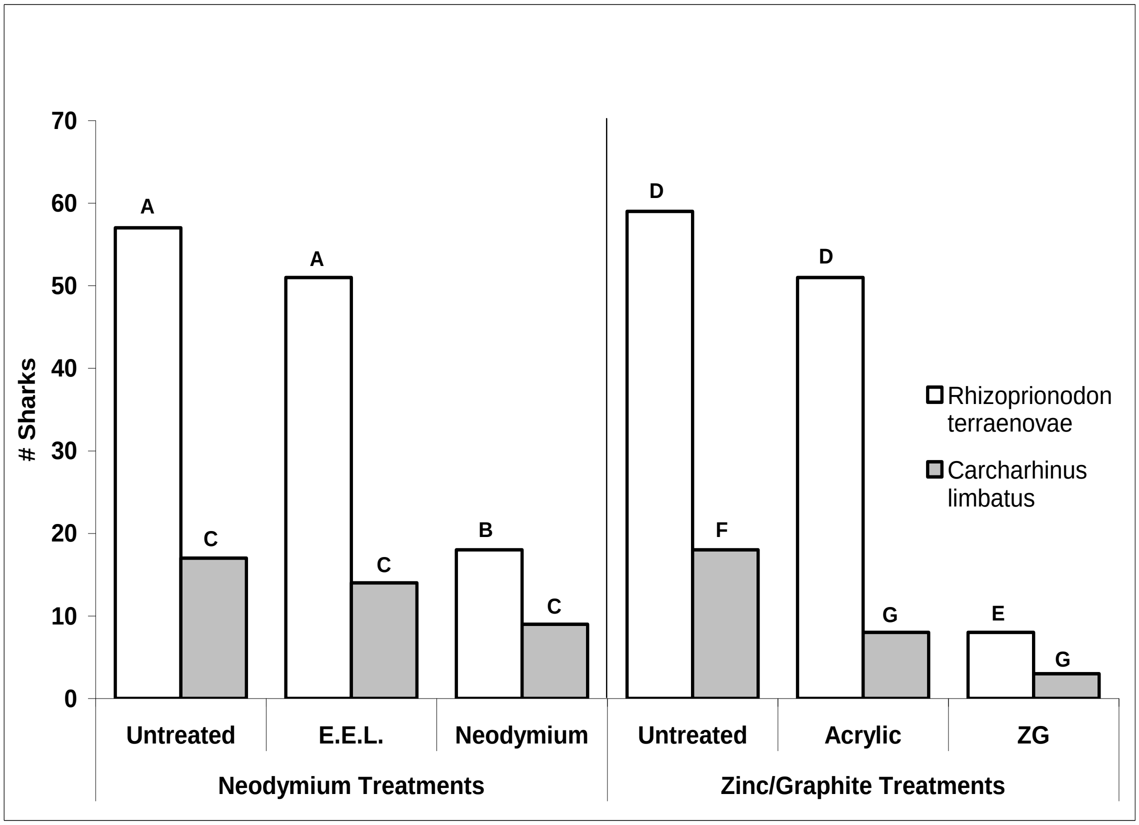

Figure 9: Total elasmobranch catch by treatment set and species. On neodymium treatment sets Atlantic sharpnose (*Rhizoprionodon terraenovae*) sharks show no significant difference between untreated hooks and epoxy encased lead (E.E.L.) procedural controls. Catch rates on neodymium treatments and E.E.L. procedural controls were significant showing a 65% reduction. Blacktip (*Carcharhinus limbatus*) sharks showed no significant difference between treatments. On zinc/graphite treatment sets Atlantic sharpnose (*Rhizoprionodon terraenovae*) sharks show no significant difference between catch on untreated hooks and acrylic procedural controls. Catch rates on zinc/graphite treatments and acrylic procedural controls were significant showing an 80% reduction on zinc/graphite treated hooks. Blacktip (*Carcharhinus limbatus*) sharks showed a significant difference between untreated hooks and zinc/graphite treated hooks. Catch rates for other species were too low for analysis.

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