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Deterrent Effects of the Select Magnetic and Repellent Treated (SMARTTM) Hooks and the Recently Developed "SMARTER" Hooks on Sharks in Recreational Hook-and-Line and Longline Trials

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Deterrent Effects of the Select Magnetic and Repellent Treated (SMART^{TM}) Hooks and the Recently Developed "SMARTER" Hooks on Sharks in Recreational Hook-and-Line and Longline Trials

By

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Abstract

As bycatch continues to impact global shark populations, there is a continuing need for effective bycatch reduction devices. Prior research has shown promise in exploiting sharks' electrosensory ability to this end. We tested the deterrent efficacy of the Select Magnetic and Repellant Treated (SMART^{TM}) and the newly developed "SMARTER" hooks in experimental longline and hook-and-line trials. Both are magnetized and contain an electropositive metal component made of magnesium (SMART) and a magnesium alloy designed to extend longevity (SMARTER). We deployed 127 longlines with SMART hooks, SMARTER hooks, controls, and procedural controls from 2021-2022 in Winyah Bay, South Carolina, and caught 134 sharks composed of 7 species (*Carcharhinus isodon, Carcharhinus leucas, Carcharhinus limbatus, Carcharhinus plumbeus, Negaprion brevirostris, Rhizoprionodon terraenovae, Sphyrna tiburo*). Additionally, hook-and-line trials testing the SMART hook alongside controls were conducted over 73 days from 2021-2022 at Myrtle Beach (South Carolina) State Park and caught 117 sharks composed of 5 species (*Carcharhinus acronotus, C. plumbeus, Mustelus canis, R. terraenovae, Sphyrna lewini*). Catch-per-unit-effort did not significantly differ among SMART, SMARTER, and control hooks in longline or hook-and-line trials. Further testing of SMART and SMARTER hooks with other species and increased strength of the hooks' electromagnetic fields is needed to determine if electropositive hooks are a viable option for reducing shark bycatch.

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INTRODUCTION

Declines in many shark populations have been observed globally over the past several decades (Camhi *et al*., 2009; Dulvy *et al*., 2008; Dulvy *et al*., 2014; Pacoureau *et al.*, 2021; Roff *et al*., 2018), mainly due to targeted overfishing (Abel & Grubbs, 2020; Camhi *et al*., 2007; Dulvy *et al*., 2008) and unintentional capture (bycatch; Abel & Grubbs, 2020; Dulvy *et al*., 2008; Favaro & Côté, 2013; Gilman *et al*., 2008; Molina & Cooke, 2012). Bycatch is considered one of the greatest threats to sharks worldwide (Oliver *et al*., 2015; Dulvy *et al*., 2014) and occurs in both commercial and recreational fisheries. The International Union for Conservation of Nature (IUCN) currently lists 218 species of shark as “Near Threatened” or worse, with 95% chiefly in danger of “unintended effects of fishing and harvesting aquatic resources” (IUCN, 2022). Population recovery can be challenging for many of these species, as most exhibit k-selected life history characteristics such as slow growth rates, low fecundity, and late age of maturity (Abel & Grubbs, 2020; Klimley, 2013; Morgan & Burgess, 2007; Gilman *et al*., 2007; Dulvy *et al*., 2008; Hart & Collin, 2015). Though recent international efforts have been made to afford much-needed protections to sharks, such as the addition of all carcharhinids to the Convention on International Trade in Endangered Species (CITES) Appendix II (Shark Research Institute, 2022), and an agreement on establishing catch limits of South Atlantic Shortfin Mako (*Isurus oxyrinchus*) by the International Commission for the Conservation of Atlantic Tuna (ICCAT) (Ziegler, 2022), bycatch will likely continue because sharks that cannot be legally targeted or retained can still be caught unintentionally.

Pelagic longlines set in commercial fisheries are known to have the highest overall shark bycatch, which is estimated to total over 10,000 tons annually in some fisheries (Oliver *et al*., 2015). Longlines can reach one hundred kilometers in length, with hundreds to thousands of smaller lines bearing baited hooks branching off from the mainline. Longlines can be deployed in several fashions that vary by fishery but are typically set to drift over open water or are anchored to the bottom (Abel & Grubbs, 2020). Pelagic longlines often target valuable bony fishes such as tuna and swordfish but will incidentally catch a substantial number of unintended species, the majority of which are sharks (Beerkircher *et al*., 2002; Francis *et al*., 2001; Oliver *et al*., 2015; Abel & Grubbs, 2020). The most frequently caught sharks include Blue Sharks (*Prionace glauca*), Shortfin Makos (*Isurus oxyrinchus*), and Oceanic Whitetip Sharks (*Carcharhinus longimanus*), though some fisheries see higher occurrences of other species (Francis *et al*., 2001; Beerkircher *et al*., 2002; Cortés *et al*., 2009; Francis *et al*., 2001; Gallagher *et al*., 2014; Oliver *et al*., 2015; Abel & Grubbs, 2020).

Blue Sharks are the most frequently captured species in pelagic longline fisheries worldwide, ranging from 50 to 90% of total shark bycatch (Oliver *et al*., 2015; Campana *et al*., 2009). Campana *et al*. (2009) observed that 98 Blue Sharks were caught on average per longline in a Canadian fishery, but in some instances exceeded 400 individuals on a single line. A study that quantified ten years of bycatch data in a New Zealand tuna longline fishery found that nearly half of the total reported catch was composed of nontargeted elasmobranchs, notably the Blue Shark, Porbeagle (*Lamna nasus*), and Shortfin Mako (Francis *et al*., 2001). Sharks also dominated the bycatch numbers in the U.S. swordfish and tuna longline fishery in the South Atlantic Bight from 1992-2000, though the most abundant species observed in that time, the Silky Shark (*Carcharhinus falciformis*), made up almost a third of the 4,612 sharks recorded (Beerkircher *et al*., 2002). These findings were based on National Marine Fisheries Service (NMFS) observer data that covered only 3% of total fishing effort, indicating total shark bycatch across the fishery was likely much higher (Beerkircher *et al*., 2002). Another study that drew data from the NMFS observer program found that nearly 18,000 Blue Sharks and just over 2,100 Shortfin Makos were caught on roughly 5,000 U.S. tuna and swordfish longlines set in the Atlantic from 1995 to 2012 (Gallagher *et al*., 2014). The fate of the sharks caught as bycatch varies by fishery as many marketable species (e.g., Shortfin Mako) are retained with their meat or fins sold to offset the loss of bait and targeted catch (Oliver *et al*., 2015; Beerkircher *et al*., 2002; Abel & Grubbs, 2020; Francis *et al*., 2001). Sharks that are not kept may still suffer a myriad of injuries and other stressors that can lead to death.

Many sharks arrive dead upon longline retrieval (hereafter referred to as "at-vessel mortality"), and many do not survive post-release (e.g., Whitney *et al*., 2021). Becoming hooked can be highly stressful for many species, as most sharks are obligate ram ventilators that need swimming space to pass adequate water over their gills and space for swimming becomes restricted when caught on a longline (Mandelman & Skomal, 2008). In addition to the sharks' efforts to escape, this restriction of movement results in both a buildup of lactic acid and carbon dioxide that may lead to death due to slower muscle contractions and significant loss of oxygen in the blood (Klimley, 2013; Mandelman & Skomal, 2008). Injury from the hook itself, whether swallowed or foulhooked in sensitive areas like the gills or stomach, will often be fatal to the shark as well (Campana *et al*., 2009).

Though many sharks die before they reach the boat, those released alive still face several challenges. The first comes immediately upon unhooking, as sharks may be injured by machinery (Abel & Grubbs, 2020) or gaffed and handled roughly by fishers as gear is retrieved. In some cases, the sharks' jaws are broken as hooks are jerked from their mouths (Campana *et al*., 2009), and some fishers are reported to kill sharks to prevent future inconveniences (Gilman *et al*., 2007). Even with successful release without visible harm, many sharks do not recover from the stress of the event and suffer post-release mortality (Campana *et al*., 2009; Whitney *et al*., 2021; Skomal, 2007). Whitney *et al*. (2021) found low blood pH due to extensive struggle to be the most effective predictor of post-release mortality compared to multiple other factors. There is also an inherent risk of injury to live sharks while handling them when they struggle and are tangled in gear, and thus sharks may die during or prior to handling by fishers (Gilman *et al*., 2007).

In addition to the detrimental effects on sharks, bycatch causes numerous problems for the commercial longline fishers. Sharks may damage or destroy expensive equipment not designed for catching them and depredate targeted catches from the lines (Gilman *et al*., 2007). Hooked fishes present an easy prey opportunity that requires less energy to capture than free-swimming individuals, likely increasing the number of sharks that become hooked (Mitchell *et al*., 2018). The global economic cost of shark longline depredation is unknown, but some instances can be substantial, with upwards of several thousand dollars lost in intended catch on a single line (Gilman *et al*., 2007).

Though the negative effects of bycatch in commercial fishing have been assessed numerous times around the world, the potential influence of recreational fishing on the environment, targeted species populations, and bycatch have been relatively neglected (Coleman *et al*., 2004; McPhee *et al*., 2002; Cooke & Cowx, 2004). This disparity is due in part to the difficulty of obtaining reliable data because of poor or inconsistent reporting that is mainly reliant on surveys (Arlinghaus & Cooke, 2009), and insufficient monitoring (Cooke & Cowx, 2004). Despite these impediments, reported data and surveys indicate that recreational fishing participation is on the rise around the world (Arlinghaus & Cooke, 2009; Cooke & Schramm, 2007; McClellan Press *et al*., 2015; McPhee *et al*., 2002) and that recreational hook-and-line fishermen catch sharks both intentionally (Danylchuk *et al*., 2014; Heberer *et al*., 2010; McClellan Press *et al*., 2015; Sepulveda *et al*., 2015; Shiffman *et al*., 2017), and as bycatch (McClellan Press *et al*., 2015; Dicken *et al*., 2006). Kilfoil *et al*. (2017) reported that over 66 million sharks were caught via recreational fishing from 2005-2015 on the Atlantic coast of the United States alone.

Though catch-and-release recreational fishing is gaining popularity in the United States (Bartholomew & Bohnsack, 2005) and many other countries (Cooke & Schramm, 2007), it is conducted under the often-incorrect assumption that the released fish is in good health (Kilfoil *et al*., 2017). As in commercial fishing, several studies have found that sharks caught via hook-and-line fishing may die after release. Danylchuk *et al*. (2014) observed that all juvenile Lemon Sharks (*Negaprion brevirostris*) that died after release in hook-and-line trials had been hooked in the basihyal cartilage, and indicators of elevated stress (e.g., lactate levels) were strongly associated with longer time on the line. Kneebone *et al*. (2013) also observed similar blood disturbances in juvenile Sand Tiger Sharks (*Carcharias taurus*) shortly after being hooked, in addition to higher post-release mortality rates in gut-hooked sharks. Common Thresher Sharks (*Alopias vulpinus*) have exhibited significantly higher post-release mortality because of both time on the line (Heberer *et al*., 2010) and foul-hooking in the tail (Sepulveda *et al*., 2015). These observations are consistent with longline studies that found elevated lactate levels (Frick *et al*., 2010; Mandelman & Skomal, 2008; Weber *et al*., 2020; Whitney *et al*., 2021) and gut-hooking (Campana *et al*., 2009) were significantly correlated with post-release mortality in several other species of sharks. Although the practice of catch-and-release fishing is on the rise (Bartholomew & Bonsack, 2005; Cooke & Schramm, 2007), it does not guarantee post-release survival.

Individuals that do not die from heightened stress or injury may experience behavioral changes due to being caught, as observed by Knotek *et al.* (2022), where Blacknose Sharks (*Carcharhinus acronotus*) caught by rod-and-reel exhibited a reduction in swimming ability with increases in handling time, leading to post-release predation. Sand Tigers were observed to rest on the bottom of an experimental tank in recovery for up to 2 hours following captive hook-and-line experiments (Kneebone *et al*., 2013). Additionally, young-of-the-year Atlantic Sharpnose Sharks and Scalloped Hammerheads (*Sphyrna lewini*) have exhibited sluggish or absent swimming motion when returned to the water due to exhaustion or rough handling, often resulting in quick predation by opportunistic, larger sharks (Pers. obs.). Additionally, shark bycatch holds the same risks to recreational fishers as it does to those from the commercial sector. Fishers who target valued teleost species (e.g., King Mackerel, *Scomberomorus cavalla*) chance personal injury when incidentally catching a shark and may lose a significant amount of bait, gear, targeted catch, and by extension, time and money due to shark depredation.

The combination of conservation and economic factors observed in both commercial and recreational fisheries provides sufficient incentive for the development of a bycatch reduction device (BRD) or method that repels sharks without affecting catch rates of targeted fishes (O'Connell *et al*., 2014d). There has been substantial effort in exploring potential solutions to shark bycatch in commercial longline fisheries, and some recreational ones as well. Attempts at reducing shark bycatch in commercial longlines have included but not been limited to: changing gear, altering set depths, reducing soak time of lines, and attaching magnets and electropositive metals (Favaro & Côté, 2015). Afonso *et al*. (2011a) evaluated nylon leaders against steel and circle hooks against J-hooks, finding that 97% of bite-offs occurred on nylon leaders and that J-hooks were bitten off more often than circle hooks. Overall, the use of nylon leaders seems a poor choice, as prior work has found swallowed hooks to cause post-release mortality (see Campana *et al*., 2009; Kneebone *et al*., 2013). Moreover, from the fisherman's point of view, nylon leaders promise a higher chance of lost gear or catch in the event of a shark interaction (Afonso *et al*., 2011a).

Circle hooks significantly increase chances of jaw-hooking and thus lower chances of internal injury (Carruthers *et al*., 2009; Afonso *et al*., 2011a), but they do not eliminate the sometimes-fatal stress and exhaustion that sharks may experience when struggling on the line (Frick *et al*., 2010), nor do they discourage depredation of targeted species, and they may increase shark catch rates in some cases (Afonso *et al*., 2011a). Changes in set depth of longlines have reduced catch rates of some species (i.e., setting at mid-depth reduces catches of sharks that typically associate with the bottom) yet increased catch rates of others (Afonso *et al*., 2011). A proposed remedy for at-vessel mortality is a shorter soak time of fishing gear, but studies have found varying correlations between mortality and soak time on a species-by-species basis (see Morgan & Carlson, 2010; Morgan & Burgess, 2007). While this may improve at-vessel survivability in some species, it will not necessarily prevent them from becoming hooked in the first place or from suffering post-release mortality.

Electromagnetic deterrents are thought to act on the specialized organs all elasmobranchs possess, the ampullae of Lorenzini. The ampullae are primarily located anteriorly on a shark's body, are clustered around the rostrum and mouth, and are individually composed of an exposed surface pore heading a sub-dermal jelly-filled tube, which in turn connects to a cluster of sacs lined with specialized cells capable of detecting electrical gradients in the nearby environment (Josberger *et al*., 2016). Kajiura and Fitzgerald (2009) found that juvenile Scalloped Hammerheads could detect voltage gradients as small as 1 $nV \cdot cm^{-1}$, indicating an extreme sensitivity to minute electrical fields. The AoL are used in locating prey, as Kalmijn (1971) confirmed when Small-Spotted Catsharks (*Scyliorhinus canicula*) and Thornback Rays (*Raja clavata*) were able to detect the presence of a European Plaice (*Pleuronectes platessa*) in tank-bound experiments even when the Plaice was hidden in a sealed container beneath sand with all visual and olfactory stimuli removed.

All living animals generate minuscule electrical fields with every muscle contraction, even a heartbeat (O'Connell *et al*., 2014d), which a shark can detect at distances less than half a meter and even while prey are buried in sediment (Kalmijn, 1971; Abel & Grubbs, 2020; Kajiura & Fitzgerald, 2009). In addition to prey detection, the AoL may also be utilized in navigation, as electrical fields are created when sharks move through the earth’s magnetic fields (Kalmijn, 1978). These electrical fields will vary in strength based on direction of swimming and location on the earth, giving sharks a sense of orientation as they travel (Kalmijn, 1978; Keller *et al.*, 2021).

Electromagnetic deterrents seek to take advantage of the sensitivity in the ampullae of Lorenzini by presenting electrical or magnetic stimuli many magnitudes greater in strength (i.e., supranormal) than what the shark would come across naturally, with the assumption that it will be overwhelming and irritating (O’Connell *et al*., 2011). An electrical charge is generated when a shark swims through the magnetic field (O’Connell *et al*., 2014d), while electro positive metals undergo hydrolysis in seawater, producing positively charged cations (O’Connell *et al*., 2014d). Though differently sourced, both charges will create an electrical gradient when in contact with the AoL (Robbins *et al*., 2011; McCutcheon & Kajiura, 2013; O’Connell *et al*., 2014d). With very few exceptions such as paddlefish and sturgeon (Bouyoucos *et al*., 2013), teleosts do not possess AoL; however, some can detect magnetic fields via magnetite crystals present in their skull (Walker, 1984). Despite this, many studies that have tested electromagnetic deterrents on elasmobranchs found that these deterrents did not visibly affect teleosts (O’Connell & He, 2014; See Stoner & Kaimmer, 2008; Richards *et al*., 2018), thus making magnets and electropositive metals appealing as potential solutions to shark bycatch.

Experimental results have varied with powerful magnets and electropositive metals; there is evidence of a deterrence effect in some species, whereas in others, none was observed. For example, Spiny Dogfish have been observed avoiding feeding near electropositive metals (Stoner & Kaimmer, 2008; Jordan *et al*., 2011), but are undeterred by rare earth magnets in multiple other cases (O'Connell *et al*., 2011; Stoner & Kaimmer, 2008). Sandbar Sharks (*Carcharhinus plumbeus*) have also avoided electropositive metals in both captive settings and on experimental longlines (Brill *et al*., 2009) but were not deterred by barium-ferrite magnets (O'Connell *et al.,* 2011). Caribbean Reef Sharks (*Carcharhinus perezi*) and Nurse Sharks (*Ginglymostoma cirratum*) have been observed avoiding a hanging wall of permanent magnets even with a chum slick spread on the opposite side of the magnets from the sharks. In contrast, Blacknose Sharks were undeterred (O'Connell & He, 2014). Varying effectiveness of magnets and electropositive metals on multiple species led to the development of the Select Magnetic and Repellant Treated (SMART^{TM}) hook that combines both magnetic and electropositive metal elements to maximize deterrence effects (O'Connell *et al*., 2014b).

The SMART hook is magnetized and incorporates an electropositive metal as a strip of magnesium wrapped tightly around the shank. Presently, only two published studies have evaluated the efficacy of SMART hooks in reducing elasmobranch bycatch, one conducted in the Gulf of Maine (O'Connell *et al*., 2014b), the other in Cumberland Sound, Canada (Grant *et al*., 2018). O'Connell *et al*. (2014b) reported a 28.2% reduction in Spiny Dogfish bycatch on commercial longlines compared to controls, though catch rates of other elasmobranchs (i.e., skates) were unaffected. Grant *et al*. (2018) tested the SMART hook to reduce Greenland Shark (*Somniosus microcephalus*) bycatch in a demersal halibut longline fishery but found that every shark caught had at least one SMART hook in their jaw. Given the wide range of observed responses to magnets and electropositive metals, the SMART hook warrants further exploration of its potential deterrence effects on other shark species. Additionally, no studies to date have examined the efficacy of the SMART hook in a recreational fishing capacity, which also warrants testing. Additionally, O'Connell *et al.* (2014b) concluded that the relatively short lifespan of the magnesium strip in the SMART hook before complete dissolution (~120 hours) likely made it impractical for commercial use as it would require replacement every 4-5 days. Though this conclusion may be accurate concerning commercial fishing application, the SMART hook may be viable in recreational fisheries. The "SMARTER" hook was conceived to address this concern by using a magnesium alloy as the electropositive metal component with the goal of extending its lifespan in seawater before necessary replacement, though it has not yet been tested in any capacity.

This project sought to assess the shark deterrent efficacy of SMART and SMARTER hooks using both longline and hook-and-line methods with the following goals: (1) to test the efficacy of the SMARTER hook in deterring sharks when compared to the SMART hook and controls in longline trials, (2) to test the SMART hook's efficacy in deterring sharks in recreational hook and line trials compared to controls, and (3) to test the longevity of the new electropositive metal component in the SMARTER hook.

METHODS

Hook Treatments

The magnetic field of a SMART hook (See Figure 1) was created by repeatedly rubbing a permanent neodymium magnet unidirectionally down the hook's length from the eye to the tip approximately 10 times (pers. comm., C. O'Connell, 4/19/2021). The strength of the magnetic field was recorded at the eye, bend, and the tip of the hook using a Td8620 model gaussmeter with a transverse probe (Top-Tool/Amazon, Seattle, Washington) and averaged to determine the magnetic field strength of every hook. Once the hooks were magnetized, a thin strip of magnesium was wrapped tightly around the hook's shank from under the eye to the bend so as not to interfere with the hook's barb in any way per O'Connell *et al*., 2014b. SMART procedural control hooks with a thin strip of duct tape wrapped around the shank were made to account for any influence hook appearance might have on catch rates. The SMART procedural controls contained no magnetic or electropositive metal elements.

The magnetic field of the SMARTER hook (See Figure 1) was created using the same method as the SMART hook. The magnesium-alloy component of the SMARTER hook was in the form of a large barrel swivel and attached with black zip ties at the eye and shaft of the hook to keep its position consistent. Procedural control hooks were also made for the SMARTER hooks, consisting of a barrel swivel of similar size and shape to the electropositive metal component attached to the eye and shank of the hook with zip ties. The SMARTER procedural control hooks contained no magnetic or electropositive metal components. All hooks utilized in the longline trials were size 16/0 circle hooks, and all hooks utilized in the hook-and-line trials were size 2/0 circle hooks.

Recreational Hook-and-Line Trials

Sampling occurred from June 2021 - August 2022 at the pier in Myrtle Beach State Park (MBSP), a popular recreational fishing spot year-round. The pier faces the open ocean and is surrounded by public beach space. Depth at the end of the pier is about 6 meters at high tide, with a 2–3-meter difference between high and low tide Three identical rod-and-reel setups were used, consisting of 7’ medium-heavy action spinning rods with 30 lb-test braided line, each ending with 18” one-arm wire trace rigs made of 90-lb test steel leaders. The 3-way rigs were attached to the line at the top barrel swivel with the hook on the rig arm and a 4 oz. pyramid sinker at the bottom of the rig. This orientation suspended bait just off the bottom, and the small 2/0 hooks disproportionately targeted the numerous age-0 Atlantic Sharpnose Sharks in the area during the warmer months of May through September. Each rod-and-reel setup received a different treatment: control (regular hook), procedural control (hook wrapped with silver duct tape to mimic Mg^{2+} ribbon), and experimental (magnetized hook wrapped with Mg^{2+} ribbon). Prior to baiting, the voltage of the SMART hook was measured with a VPro 850L model voltmeter (WeePro/Amazon, Seattle, Washington) by submerging the hook in seawater with a positive anode attached along with a fin clip of an Atlantic Sharpnose Shark with a negative anode attached. This was made possible by the flow of positively charged ions from the magnesium strip of the SMART hook creating a measurable electrical potential with the negatively charged flesh of the Sharpnose fin clip. Control hooks were tested periodically with the gaussmeter to ensure no unintentional magnetization occurred. All hooks received identical bait in both size and species (i.e., all shrimp, all squid, all mullet, etc.) for each set to eliminate any feeding bias in sharks or teleosts. All three treatments were deployed from the pier at the same distance, with roughly 3 m between the lines. The 3-m gap between treatments was chosen to keep environmental conditions as consistent as possible (e.g., depth) without treatments interacting with each other and to prevent crossover and entanglement with other fishermen's lines as the pier often became crowded. Hooks were deployed for 15-minute intervals, following the protocol of O'Connell *et al*. (2011). A line that caught an animal was rebaited and redeployed for any time remaining in the 15-minute set along with the other two lines to maintain consistency in bait freshness. If there were no discernable bites on any line, all were retrieved, rebaited, and redeployed to begin a new 15-minute set. Caught animals were identified to species, measured at pre-caudal length (PCL), fork length (FL), and stretch total length (TL), sexed (only in the case of elasmobranchs because the sex of angled teleosts could not be visually determined), and immediately released. Disk width (DW) and inter-spiracle width (IW) were measured for angled batoids. Time of first set in and last set out, tide, moon phase, air and water temperature, air pressure, wind speed and direction, salinity, dissolved oxygen, and water clarity were recorded each sampling day.

At the end of each sampling day, the voltage of the SMART hook was measured again to note changes (if any) in voltage during the sampling day. SMART hooks were examined after each sampling day to note any deterioration of the magnesium strip that necessitated replacement, then dipped repeatedly in fresh water, followed by deionized water, then dried to remove excess salt and reduce corrosion rates. When not in use, the

SMART hook was kept in a clearly marked container far apart from the control hooks to avoid unintended magnetizing.

Experimental Longline Trials

Sampling took place in the lower-middle portion of Winyah Bay, South Carolina from June 2021 - August 2022. Winyah Bay is a 65 km^2, tidally dominated, partially mixed estuary fed by four major rivers: the Waccamaw, Sampit, Black, and Pee Dee. The average depth is about 4 m, with a bottom composition varying between sand, mud, clay, and silt (Abel *et al*., 2007). Sampling began about 1 h before peak high tide as prior studies have confirmed significantly greater shark catch rates during that period (Collatos *et al*., 2020). 150-m bottom-set longlines were deployed from the Coastal Carolina R/V *Coastal Research* and contained 25 hooks per set. Each hook was attached to a longline via a tuna clip at the end of a meter-long gangion composed of 200 lb. monofilament and a 400 lb. steel leader joined by rolling swivels. Gangions were attached to each longline at 4-m increments. Size 16/0 offset circle hooks were used across all five treatments: control (regular hook), SMART procedural control (Hook wrapped with silver electrical tape to mimic Mg^{2+} ribbon), SMARTER procedural control (Hook with a steel barrel swivel attached via zip tie), SMART experimental, and SMARTER experimental. Every hook was baited with equally sized pieces of Boston Mackerel (*Scomber scombrus*). Each longline contained five hooks from each treatment for 25 hooks total. The order of treatment placement on the lines was randomized each sampling day with a number randomizer app and applied to all lines deployed during that day. The hook order repeated after every 5 hooks, ensuring that all treatments were theoretically presented to a shark simultaneously while remaining far enough apart to avoid interactive effects. Five longlines were deployed each sampling day in a staggered pattern and parallel with current flow for a total of 125 hooks in the water, and soak time for all lines was 45-50 minutes to maximize catch and minimize time spent on the line for any caught animals. At the end of each sampling day, all SMART and SMARTER hooks were dipped in freshwater, followed by deionized water to reduce corrosion rates of the magnesium components. All magnesium ribbons on SMART hooks were replaced if any individual ribbon was in poor condition. All control hooks were randomly tested with the gaussmeter periodically to ensure no unintended magnetization occurred.

Due to the difficulty in procuring the magnesium-alloy material for SMARTER hooks, this treatment had all electropositive metal components replaced only if five or more required it. All caught animals were identified to species, sexed (again, only for elasmobranchs), measured (PCL, FL, and TL), and released. Tide, moon phase, air temperature, air pressure, wind speed and direction, and treatment order. GPS coordinates, time of first hook in, last hook in, first hook retrieved, last hook retrieved, depth, surface water temperature, surface salinity, surface dissolved oxygen, bottom water temperature, bottom salinity, and bottom dissolved oxygen were recorded each sampling day. When not in use, SMART and SMARTER hooks were kept in respective containers separate from all other hooks to prevent unintentional magnetization of controls.

SMARTER Hook Longevity

The lifespan of the SMARTER hooks' magnesium alloy component was tested in-lab by soaking a completed SMARTER hook in a 1-Liter container of seawater (salinity of 34 ppt) collected from the MBSP pier. Ideally, the hook would have been suspended in seawater at a pier and tested repeatedly per O'Connell *et al*. (2014b). However, there was no suitable location to conduct the study this way where it would be free from public interference. The seawater in the container was refreshed every 12 hours, at which time both the magnetic field strength and conductivity of the SMARTER hook were recorded using the gaussmeter and voltmeter, respectively. Simultaneously, a SMART hook received the same treatment in a separate container to compare the lifespans of the magnesium components in both treatments.

Analysis – Longline Trials

Data were analyzed using R software within Rstudio, version 2022.07.01. Because sampling effort varied slightly between treatments due to occasional missing hooks on longlines, shark catch per unit effort (CPUE) was used for comparison of treatments rather than total sharks caught. Catch per unit effort was determined by dividing the number of sharks caught each day by the number of hooks deployed for each treatment. Teleost CPUE was calculated in the same manner. Due to non-normal distribution of CPUE and unequal variance between treatments in addition to many zero values, a zero-inflated Kruskal-Wallis test from the "ZIR" package (Wang *et al.*, 2022) was used to compare median CPUE for both sharks and teleosts. A separate analysis was conducted on the median Sandbar Shark CPUE since it was the most-often caught species using the zero-inflated Kruskal Wallis Test (Wang *et al.*, 2022). Additionally, correlations between shark and teleost CPUE and all recorded abiotic factors were examined via Spearman Rank correlations to assess the degree of relatedness between them. Batoid catch between treatments was not assessed because total sample size was too small for meaningful analysis.

Analysis – Hook and Line Trials

Because sampling effort was equal across all treatments on each sampling day, total shark and teleost catch per sampling day were analyzed respectively for each treatment. As with the longline data, both shark and teleost catch were not normally distributed with many zero values and unequal variance, so a zero-inflated Kruskal-Wallis Test (Wang *et al.*, 2022) was used to compare median catch between treatments. A separate analysis was also conducted on Atlantic Sharpnose Shark catch because it was the most often caught species, using the zero-inflated Kruskal Wallis test (Wang *et al.*, 2022). Spearman Rank correlations were again used to compare recorded abiotic factors with shark and teleost catch. Batoid catch was again not assessed due to a small sample size.

RESULTS

Experimental Longlines

One hundred and twenty-seven longlines were deployed in Winyah Bay over 27 sampling days from July 2021 - July 2022, totaling 2,996 hooks. One hundred and thirty-four sharks representing seven species were caught: Sandbar (*n* = 112), Atlantic Sharpnose (*Rhizoprionodon terraenovae*; *n* = 9), Blacktip (*Carcharhinus limbatus*; *n* = 7), Finetooth (*Carcharhinus isodon*; *n* = 2), Lemon (*n* = 2), Bonnethead (*Sphyrna tiburo*; *n* = 1), and Bull (*Carcharhinus leucas*; *n* = 1) (Table 1). Twenty-six Red Drum (*Sciaenops ocellatus*) and four Southern Stingrays (*Hypanus americanus*) were also caught over this period (Table 1). Catch per unit effort did not differ between hook treatments (zero-inflated Kruskal-Wallis test; $H = 2.7367$, $df = 4$, $p = 0.5689$). Additionally, no significant difference was found in Red Drum CPUE between treatments (zero-inflated Kruskal-Wallis Test; $H = 3.2397$, $df = 4$, $p = 0.3956$). Because Sandbar Sharks made up over 80% of the shark catch and were the only shark species for which more than 10 individuals were caught, a separate analysis was conducted to compare median Sandbar CPUE between treatments, and no significant difference was detected (zero-inflated Kruskal-Wallis test; $H = 0.7238$, $df = 4$, $p = 0.9303$). Abiotic factors were also assessed against overall shark CPUE (Table 2) and Sandbar shark CPUE (Table 3) via Spearman Rank correlation. No factor exhibited a correlation value (rs) greater than +/- 0.27. The correlation between abiotic factors and Red Drum CPUE was not assessed due to low catch total (*n* = 26).

Hook and Line Sampling

Angling was conducted over 73 days for a combined 290.75 sampling hours from June 2021 to August 2022. One hundred and seventeen sharks were caught comprising five species: Atlantic Sharpnose (n = 107), Dusky Smooth-Hound (n = 5), Blacknose (n = 2), Scalloped Hammerhead (n = 2), and Sandbar (n = 1). Three hundred and fifty-six teleosts of 11 species, 13 Rajiformes from 3 species, and 22 invertebrates were also caught (Table 4). No significant difference in median shark catch was found between treatments (zero-inflated Kruskal-Wallis test; H = 3.64, df = 2, p = 0.15). There was also no significant difference in median teleost catch between treatments. (zero-inflated Kruskal-Wallis test; H = 0.29, df = 2, p = 0.86). Because Atlantic Sharpnose Sharks comprised over 90% of total shark catch, a separate analysis was conducted, finding no significant difference in median catch between treatments (zero-inflated Kruskal-Wallis test; H = 2.9527, df = 2, p = 0.2106). Environmental factors were not found to be strongly correlated with overall shark catch (Table 5) or shark catch by treatment (Table 6). No environmental factors were correlated with overall teleost catch (Table 7) or teleost catch by treatment (Table 8).

SMARTER Hook Longevity

A SMART Hook and SMARTER hook were submerged in separate 1-Liter containers of collected seawater over several days. Time and inability to collect sufficient seawater for repeated refilling of the containers restricted the sample size significantly. Each hook's voltage and magnetic field were recorded every 12 hours after refreshing the seawater in the containers (Figure 2). The magnetic field of both hooks remained near constant throughout testing; the SMART hook averaged 146.0 +/- 0.65 Gs, and the

SMARTER hook averaged 160.7 +/- 1.22 Gs. The voltage for the SMART hook remained relatively steady until hour 180, at which point the magnesium strip began deteriorating and began to break apart at hour 228, at which point measurements stopped. The magnesium alloy component of the SMARTER hook dissolved much faster than the SMART hook's magnesium strip and was completely gone after hour 96, after which measurements stopped.

DISCUSSION

A significant difference in shark CPUE was not found between treatments in either the hook-and-line ($N = 117$, $H = 2.7367$, $df = 4$, $p = 0.5689$) or longline ($N = 134$, $H = 3.64$, $df = 2$, $p = 0.15$) trials, but many promising aspects of these experiments warrant consideration.

Longline Trials

Shark CPUE did not significantly differ between the five treatments deployed in the longline trials, and there are many factors to consider as to why. The first is potential for simply too small a sample size; 134 sharks across 5 treatments may not be representative enough to observe accurate results. This is especially important when considering SMARTER hooks caught the fewest sharks: 46% less than controls for all shark species and 33% less than controls for Sandbar Sharks. Though ultimately these observations were not found to be statistically significant, they are promising. A larger sample size could have revealed a statistically significant reduction in shark catch and should be sought in future testing of the SMARTER hook. After sample size, environmental variables were assessed but were not found to be significantly associated with CPUE of any treatment (Table 3) and so were not considered explanatory factors. Caught species may have influenced results; catch was dominated by juvenile Sandbar Sharks (<135 cm PCL; see Collatos et al., 2020), comprising 65.2% and 83.5% of total species and sharks, respectively. This result is not surprising as Winyah Bay is a confirmed secondary nursery for juvenile and subadult Sandbar Sharks with recurring seasonal residency (Collatos *et al.*, 2020). However, Sandbar Sharks may be less responsive to the SMART and SMARTER hooks than other species. O'Connell *et al.* (2011) found that Sandbar Sharks were not deterred by powerful neodymium-iron-boron or barium-ferrite magnets on experimental longlines in the same location as this study. Conversely, Brill *et al.* (2009) observed Sandbar Sharks avoiding experimental electropositive metal treatments in captive studies and field tests utilizing longlines. The electropositive metals used in the Brill *et al.* (2009) study were composed of neodymium, praseodymium, and other trace lanthanide metals. Although Brill *et al.* (2009) did not report voltage, the resulting voltage gradient produced by the dissolution of these materials in salt water may be greater than that of the magnesium and magnesium alloy materials used with the SMART and SMARTER hooks. These observations may indicate that in the case of Sandbar Sharks, an electropositive metal that generates a powerful electrical gradient may be more effective than a strong magnetic field in deterring sharks. It is also possible that the electrical potential generated by the hydrolysis of the electropositive metal components in this study was reduced due to lower salinity. The average bottom salinity observed during longline trials was 25.34 ppt, and conductivity may be lower as a result, potentially resulting in lower detectability by elasmobranchs (Harris *et al*., 2015). Future research should confirm the voltage output of the electropositive metal components on SMART and SMARTER hooks in a range of salinities to determine whether there is an observable correlation. The possibility of reduced detectability could also result from the sharks' size. Kajiura (2001) examined the ampullae of Lorenzini pore densities and counts between Sandbar Sharks and two species of hammerhead and found that pore counts do not increase with size; instead, the density of the pores decreases. With this decrease in ampullae of Lorenzini density coinciding with a lengthening of the highly conductive jelly-filled canal in each pore, the sensitivity to electrical fields within each pore will potentially increase (Kajiura, 2001). Thus, juvenile Sandbar Sharks may be less sensitive to electrical currents than adults, which combined with the lower salinity of Winyah Bay may have reduced the effectiveness of the experimental hooks. Unfortunately, an insufficient quantity of adult Sandbar Sharks (>135 cm PCL; *n* = 3) were captured during this study to perform a meaningful analysis based on maturity. Future research exploring the relationship between size and electrical sensitivity may provide needed insight.

While juvenile Sandbar Sharks dominated catch, other species were underrepresented by comparison. No other species of shark had a sample size greater than nine individuals, with only *C. limbatus* and *R. terraenovae* represented by more than 5 (*n* = 7 and *n* = 9, respectively) animals. Blacktip, Bull, and Lemon Sharks have all been observed avoiding electromagnetic fields in other studies (see O'Connell & He, 2014; O'Connell *et al*., 2014a; O'Connell *et al*., 2014e; O'Connell *et al*., 2011a), but small sample sizes for these species prohibited statistical analysis. It should be noted that the permanent magnets used by O'Connell *et al*. (2011a; 2014a; 2014c) generated fields more powerful than those of the SMART and SMARTER hooks used in this study, so we must also consider that the magnetized hooks may simply be emitting fields that are too small (i.e., does not fully encompass the bait) or too weak to be perceived as a deterrent. The former notion is likely a significant factor, as the gaussmeter did not detect the magnetic field of the experimental hooks until the probe was within roughly 8 cm of the hooks themselves. Even if the field was of sufficient strength, it is possible that sharks did not detect it until they were already taking the bait. At this point, the olfactory and gustatory cues of the Boston Mackerel bait may have overridden any perceived irritation from an electromagnetic field. Future consideration should be given to expanding and strengthening the experimental hooks' electromagnetic field to account for this possibility.

It is encouraging to find that Red Drum catch was not significantly affected by any treatment, as this observation coincides with prior studies that have found no observable effects of electromagnetic deterrents on teleosts (O'Connell *et al*., 2014c; Stoner & Kaimmer, 2008; O'Connell & He, 2014), and a deterrent effect on this popular sportfish would render the experimental hooks useless for their intended purpose. A larger sample size of not only Red Drum but additional species would be beneficial in future work to support this finding.

Hook-and-Line Trials

Neither shark nor teleost CPUE was significantly influenced by any treatment in the hook-and-line trials, and no abiotic factor was found to significantly influence the catch rate of any treatment (see Table 6). The species that dominated shark catch from the pier was young-of-the-year (YOY) Atlantic Sharpnose (n = 107), and all but two individuals measured less than 40 centimeters PCL. It is possible that like *C. plumbeus* (see Kajiura, 2001), *R. terraenovae* begins life with more densely packed ampullary pores that eventually spread out and theoretically become more sensitive to electrical stimuli with age, though no studies presently exist that confirm this. If true, YOY Atlantic Sharpnose could be less sensitive to the electromagnetic field of the SMART hook than larger individuals. As with the longline study, the possibility also exists that the electromagnetic field generated by the SMART hook was not large or powerful enough to elicit a negative response. O’Connell *et al*. (2011) observed a significant reduction in Atlantic Sharpnose Shark catch in hook-and-line trials with hooks attached to neodymium-iron-boron magnets compared to controls. The magnets were reported to emit a magnetic field as strong as 14,800 Gs, far more powerful than the magnetic field produced by the SMART hooks used in this study. Future work should determine the threshold of electromagnetic field strength at which Atlantic Sharpnose Sharks are deterred from feeding and if that threshold changes with the size of the sharks. In addition to this potential deterrence threshold, the number of conspecifics present may influence reactions to electromagnetic fields.

Atlantic Sharpnose Sharks are common along the east coast of the United States, with both pupping and mating seasons occurring May through July in nearshore waters (NOAA, 2023; Loefer & Sedberry, 2003). The YOY pups are encountered frequently by recreational fishermen at the sampling site during this time, and multiple pups were sometimes caught simultaneously on two or all three treatments, indicating a high density of young Atlantic Sharpnose Sharks. Conspecific density was observed to reduce the deterrent efficacy of lanthanide electropositive metals on Sandbar Sharks (Brill *et al*., 2009) and Dusky Smooth-hound Sharks (*Mustelus canis*) (Jordan *et al*., 2011) in lab trials. Jordan *et al*. (2011) also observed that Spiny Dogfish (*Squalus acanthias*) did not feed without conspecifics present. Both studies contended that an increase in the number of conspecifics would correlate with an increase in feeding competition and potentially reduce the efficacy of electropositive metal deterrents. However, it is important to note that Jordan *et al.* (2011) asserted that the minimum group size needed to elicit competitive feeding could vary by species. It is unknown if Atlantic Sharpnose Sharks also engage in density-dependent competitive feeding, and if so, what that threshold conspecific number would be; however, the density of the YOY Atlantic Sharpnose in the sampling area could have significantly influenced (i.e., reduced) the effectiveness of the SMART hook in this study. Testing whether density-dependent competitive feeding (and any subsequent reduction in electromagnetic deterrent efficacy) occurs with Atlantic Sharpnose would be prudent going forward, as it remains one of the most encountered shark species by commercial and recreational fishermen on the east coast of the United States (Loefer & Sedberry, 2003) and is often perceived as a nuisance by the latter (pers. obs.).

Similar to the longline observations, teleost catch was not significantly associated with any treatment, though a notable limiting factor is that 87% of the teleosts were represented by Atlantic Croaker (*Micropogonias undulatus*) and the Southern Kingfish (*Menticirrhus americanus*). The former species is occasionally kept for consumption by anglers, and the latter is a popular eating fish for many (pers. obs.). Therefore, additional trials should be run on other species of fishes that are popular with recreational anglers to confirm that the SMART hook is a practical tool for other fisheries or areas.

SMARTER Hook Longevity

It is not clear why the magnesium alloy electropositive metal component of the SMARTER hook had a far shorter lifespan than the magnesium ribbon of the SMART hook. One major limitation of this study was that only one representative from each type was tested. Unfortunately, time and resources limited the number of hooks that could be assessed for this portion of the study. Therefore, more SMARTER hooks should be tested again to determine if dissolution times are consistent with those observed here. It is also important to consider that though abiotic conditions were kept consistent and equal between the two hooks, they were not exposed to wave action, currents, or temperature shifts. These environmental factors could potentially hasten the dissolution process of electropositive metals and may also explain why the longevity of the SMART hook's magnesium ribbon was roughly twice that reported by O'Connell *et al*. (2014b), who suspended SMART hooks in seawater from a harbor pier to examine dissolution rates. If changes in temperature, salinity, suspended solids, and movement do heavily influence dissolution rates, then the electropositive metal component of the SMARTER hook would need to be reassessed, as it would likely have an even shorter lifespan under more volatile conditions.

CONCLUSION

Innovation and testing of shark bycatch reduction devices are critical needs in the effort to protect threatened species and populations (Favaro & Côté, 2013). This study carried out novel experiments in testing SMART hooks in recreational fishing and the SMARTER hook with its modified magnesium alloy electropositive metal for the first time. Though neither the SMART nor SMARTER hooks were observed to significantly reduce shark catch in longline or hook-and-line trials, this study provided insights into future avenues of research that could greatly benefit efforts to develop a practical electromagnetic bycatch reduction devices. Future efforts should be made to increase magnetic field size and strength, confirm the voltage strength of the hooks' electropositive metals in varying salinities, and confirm the deterrence threshold of various species as it relates to individual size and the number of conspecifics present.

TABLES

Table 1

Summary of catches by treatment from 127 longlines. Three *C. plumbeus* and one *S. ocellatus* were not included in these counts due to foul-hooking or no treatment recorded.

Species	Control	SMART PC	SMARTER PC	SMART	SMARTER	*n*
Carcharhinus plumbeus	27	21	22	24	18	112
Rhizoprionodon terraenovae	3	2	2	1	1	9
Carcharhinus limbatus	4	1	0	2	0	7
Carcharhinus isodon	1	1	0	0	0	2
Negaprion brevirostris	0	1	0	0	1	2
Carcharhinus leucas	1	0	0	0	0	1
Sphyrna tiburo	1	0	0	0	0	1
Total Sharks	37	26	24	27	20	134
Hypanus americanus	0	2	1	0	1	4
Total Elasmobranchs	37	28	25	27	21	138
Sciaenops ocellatus	5	6	9	4	2	26

Table 2

Abiotic factors and their respective Spearman Rank Correlation (r_s) values associated with shark CPUE across 127 longlines.

Abiotic Factor	(r_s)
Moon Phase	0.1986
Depth of Line	-0.1958
Secchi Depth	-0.1050
Air Pressure	-0.2446
Air Temperature	0.2250
Wind Speed	0.1059
Surface Water Temperature	0.2710
Surface Salinity	-0.0774
Surface Dissolved Oxygen	-0.1218
Bottom Water Temperature	0.2628
Bottom Salinity	-0.1243
Bottom Dissolved Oxygen	-0.1614
Line Soak Time	0.1882

Table 3

Abiotic factors and their respective Spearman Rank Correlation (r_s) values associated with shark CPUE by treatment across 127 longlines.

	Hook Treatments and r_s Values				
Abiotic Factor	Control	SMART PC	SMARTER PC	SMART	SMARTER
Moon Phase	0.0010	0.0228	0.2188	0.1457	0.0496
Depth of Line	-0.1214	-0.1411	-0.0308	-0.1681	0.0816
Secchi Depth	0.0542	0.0152	-0.1175	-0.0336	-0.1249
Air Pressure	-0.1010	-0.1796	-0.0614	-0.0939	-0.1556
Air Temperature	0.1962	0.1512	-0.0047	0.1434	-0.0421
Wind Speed	0.0476	0.0576	-0.0010	-0.0856	0.1143
Surface Water Temperature	0.2529	0.1240	0.1581	0.0981	-0.0731
Surface Salinity	-0.0904	-0.0831	0.0577	-0.0327	0.0109
Surface Dissolved Oxygen	-0.1467	-0.1125	-0.0373	0.0388	-0.0206
Bottom Temperature	0.2281	0.1290	0.1027	0.1375	-0.0819
Bottom Salinity	-0.1533	-0.1231	0.0792	-0.0552	-0.0082
Bottom Dissolved Oxygen	-0.1322	-0.0922	-0.1563	0.0034	0.0007
Line Soak Time	0.0799	0.1029	0.1836	0.0824	0.0590

Table 4

Summary of catch by treatment from 290.75 sampling hours of hook-and-line sampling.

Species	Control	SMART PC	SMART	*n*
Rhizoprionodon terraenovae	47	24	36	107
Mustelus canis	1	1	3	5
Carcharhinus acronotus	1	0	1	2
Sphyrna lewini	1	0	1	2
Carcharhinus plumbeus	0	1	0	1
Total Sharks	50	26	41	117
Dasyatis sabina	5	1	3	9
Hypanus americanus	0	1	2	3
Gymnura micrura	0	0	1	1
Total Elasmobranchs	55	28	47	130
Micropogonias undulatus	78	73	60	211
Menticirrhus americanus	35	26	38	99
Prionotus carolinus	5	11	3	19
Cynoscion regalis	4	2	4	10
Cynoscion nebulosus	3	1	4	8
Pomatomus saltatrix	0	3	1	4
Leiostomus xanthurus	0	1	0	1
Rachycentron canadum	0	1	0	1
Sciaenops ocellatus	1	0	0	1
Trachinotus carolinus	0	0	1	1
Urophycis regia	0	0	1	1
Total Teleosts	126	118	112	356
Sea Star (Sp. Unknown)	5	5	1	11
Whelk (Sp. Unknown)	3	3	0	6
Hermit Crab (Sp. Unknown)	0	2	0	2
Spider Crab (Sp. Unknown)	0	1	0	1
Callinectes sapidus	1	0	0	1
Limulus polyphemus	0	0	1	1
Total Invertebrates	9	11	2	22

Table 5

Abiotic factors and their respective Spearman Rank correlation (r_s) values associated with total shark catch from 290.75 hours of hook-and-line sampling.

Abiotic Factor	(r_s)
Moon Phase	-0.0732
Secchi Depth	-0.0353
Air Pressure	-0.1783
Air Temperature	0.3858
Wind Speed	0.0741
Water Temperature	0.2469
Salinity	-0.0935
Dissolved Oxygen	-0.1046
Fishing Time	0.3736

Table 6

Abiotic factors and their respective Spearman Rank correlation (r_s) values associated with shark catch by treatment across 290.75 hours of hook-and-line sampling.

	Hook Treatments and r_s Values		
Abiotic Factor	Control	SMART PC	SMART
Moon Phase	-0.0672	-0.1973	0.0008
Secchi Depth	-0.0754	0.1263	-0.1389
Air Pressure	-0.2211	-0.1415	-0.2117
Air Temperature	0.4341	0.3047	0.4396
Wind Speed	0.0667	0.1342	0.0258
Water Temperature	0.2635	0.1623	0.3368
Salinity	-0.1523	-0.0537	-0.0559
Dissolved Oxygen	-0.0670	-0.0262	-0.2287
Fishing Time	0.3809	0.2748	0.4310

Table 7
Abiotic factors and their respective Spearman Rank Correlation (r_s) values associated with total teleost catch from 290.75 hours of sampling.

Abiotic Factor	(r_s)
Moon Phase	0.0614
Secchi Depth	-0.0244
Air Pressure	-0.1419
Air Temperature	0.0249
Wind Speed	0.1197
Water Temperature	0.0353
Salinity	-0.2006
Dissolved Oxygen	-0.1188
Fishing Time	0.2313

Table 8
Abiotic factors and their respective Spearman Rank Correlation (r_s) values associated with teleost catch by treatment across 290.75 hours.

	Hook Treatments and r_s Values		
Abiotic Factor	Control	SMART PC	SMART
Moon Phase	0.0539	-0.0281	0.1135
Secchi Depth	-0.1370	0.0921	-0.0786
Air Pressure	-0.1948	-0.1739	-0.1118
Air Temperature	-0.0713	0.1160	0.1052
Wind Speed	0.2624	0.0532	0.1104
Water Temperature	-0.0259	0.1121	0.0585
Salinity	-0.2745	-0.1128	-0.3067
Dissolved Oxygen	-0.1136	-0.2136	-0.0344
Fishing Time	0.3668	0.3266	0.3311

FIGURES

Figure 1

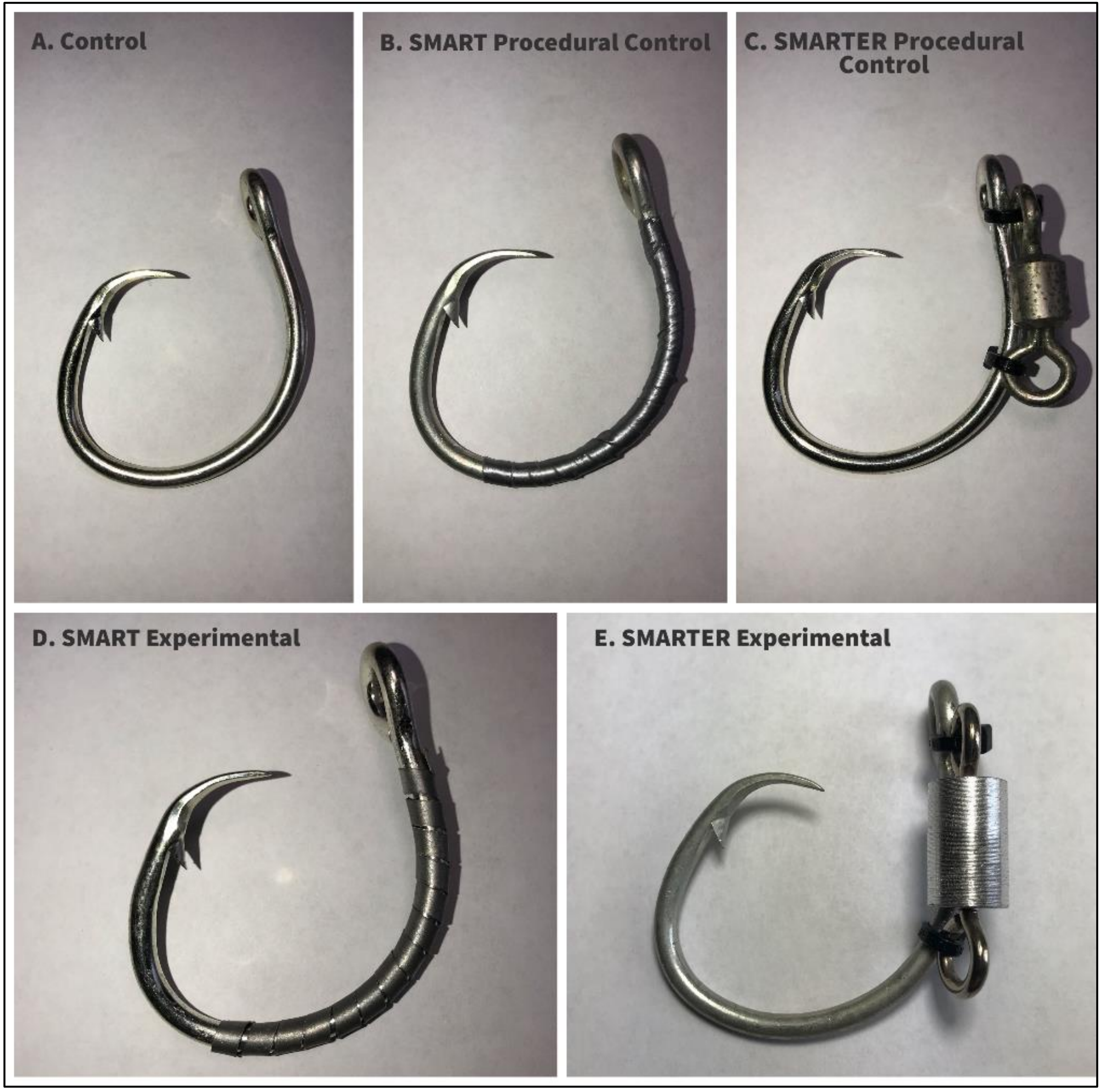

Figure 1
The hooks used during longline trials. (A) Control, unmagnetized, with no attachments, (B) SMART Procedural Control, unmagnetized, wrapped with a thin strip of duct tape to mimic the magnesium strip on SMART Experimental, (C) SMARTER Procedural Control, unmagnetized, with a large barrel swivel attached via zip ties to mimic magnesium alloy component on SMARTER Experimental, (D) SMART Experimental, magnetized and wrapped with a thin strip of magnesium ribbon, and (E) SMARTER Experimental, magnetized with a magnesium alloy attached via zip ties. Note that all hooks are size 16/0.

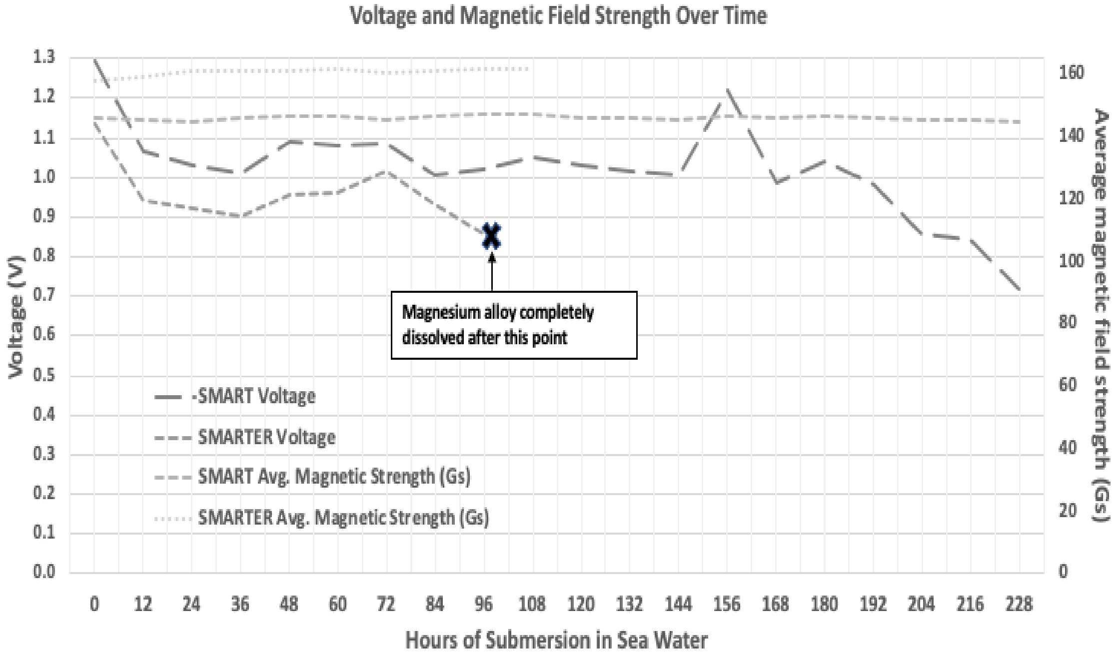

Figure 2
Line graph of the SMART and SMARTER hooks' recorded voltage and average magnetic fields over submersion time.

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