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Non-lethal efforts to deter shark predation of Hawaiian monk seal pups

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ABSTRACT

1. More than a decade of shark predation on nursing and newly weaned pups of the endangered Hawaiian monk seal (*Monachus schauinslandi*) has significantly contributed to a steep decline of the French Frigate Shoals (FFS) subpopulation.
2. In an effort to develop non-lethal methods of mitigating predation, the feasibility of deploying potential shark deterrents at FFS was examined, and then tests were done to see if any of the successfully deployed devices or a continuous human presence deters shark predation of monk seal pups.
3. During the feasibility trial, an underwater acoustic playback and a moored boat performed without issue. A float array proved hazardous to non-target wildlife and electronic diver devices functioned poorly; both were omitted from further experimentation.
4. The number of shark sightings and predation incidents at two pupping islets was compared across two experimental treatments: (1) acoustic playback and a moored boat, and (2) continuous human presence, versus a control. Sharks were sighted with a remote camera system; predation incidents were evident from bite wounds or the disappearance of pups.
5. Observed shark activity was rare (12 sightings on video and six predation incidents) but similar to recent years. The number of shark sightings and predation incidents did not differ significantly between the two treatments and the control.
6. The relative scarcity of shark activity in the shallows around the pupping islets made detecting a treatment effect challenging. Sharks' wariness to humans is probably variable, unpredictable, possibly individualistic and unreliable at FFS. The acoustic playback as a deterrent could benefit from further testing and development. Other non-lethal or lethal approaches for mitigating predation should be investigated to protect monk seal pups at FFS.

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KEY WORDS: Hawaiian monk seal; *Monachus schauinslandi*; Galapagos shark; French Frigate Shoals; predation deterrence

INTRODUCTION

Shark predation on Hawaiian monk seal pups (*Monachus schauinslandi*) is unusually common at one breeding site in the north-western Hawaiian Islands (NWHI). Since 1997, shark predation on pups at French Frigate Shoals (FFS) has resulted in an increase of pup mortality compared with previous years at this site, and compared with historical and current trends at all other monk seal breeding sites. In years when survival is poor, mortality of juvenile seals is size-dependent across the monk seal

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subpopulations in the NWHI, except at FFS where the pattern of juvenile mortality is consistent with size-independent predation (Baker, 2008). Typically monk seal survival during the approximately 6-week-long nursing period is greater than 90% because of maternal protection and provisioning, and the existence of few threats at this stage of life (Johanos *et al*., 1994). However, pup survival at FFS during the nursing period has been below 75% in some years as a result of shark predation (Gobush, 2010). Between 1997 and 2010, the number of shark incidents (bite wounds, disappearances categorized as shark-related and confirmed shark kills) on pups (pre-weaned and newly weaned) was 207 of 854 (24.2%) born at FFS (Gobush, 2010). In contrast, wounds and disappearances attributable to sharks at other breeding sites such as Laysan Island and Lisianski Island were 10 of 520 pups (1.9%) and 13 of 334 pups (3.9%), respectively (Gobush, 2010).

In 1999, shark attacks on monk seal pups at FFS peaked with the death of 22 pups (24% of the annual cohort). Thereafter, pup losses declined to 5 to 11 pups a year. However, the percentage of pups lost to predation (12–28% annually) remains high as pup production has fallen for other reasons at this site. The causes of the spike in predation, as well as the subsequent decrease are unknown. The disappearance of Whaleskate islet, partially in 1997 and completely by 1998, and an increased incidence of adult male seal aggression towards pups at Trig islet (Figure 1) may have contributed to the peak in predation because both events may have interfered with maternal protection of pups (Craig *et al*., 1999; Harting, 2010). In addition, the carcasses of the pups that were killed by adult male seals may have attracted sharks to the nearshore areas of Trig (Craig *et al*., 1999; Harting, 2010). A constellation of factors that occurred in 2000 may have contributed to the subsequent decrease, including limited shark culling and commercial fishing, lowered incidence of adult male seal aggression towards pups and increased human presence related to intensive monitoring (NMFS unpublished, Gobush, 2010; Harting, 2010). However, the impact of predation on the subpopulation's recovery remains considerable.

Since 1997, we have frequently observed Galapagos sharks (*Carcharhinus galapagensis*) patrolling and attacking pups during their nursing period or within days of weaning. Tiger sharks (*Galeorcerdo cuvier*) also prey on monk seals and are abundant at FFS (DeCrosta, 1984); however, this species has not been observed to attack pups of this age class during daytime monitoring (approximately 0600 to 2000 h) spanning the last 15 years. For these reasons, monitoring and mitigation at FFS has historically focused on Galapagos sharks, however, the ideal mitigation measure would be effective against any large shark.

Galapagos sharks can be found across the globe, most commonly associated with oceanic islands (Wetherbee *et al*., 1996). Depth of capture for Galapagos sharks across the Hawaiian Archipelago ranges from 1 to 286 m; adult females average the

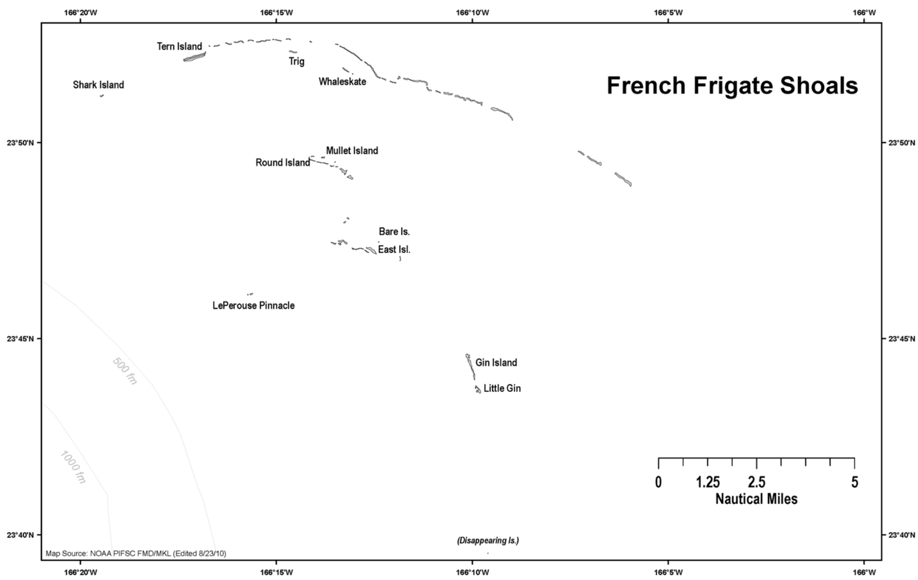

Figure 1. Map of French Frigate Shoals with islets within the atoll indicated.

shallowest depth of 34.2 m versus adult males at 60.2 m (Papastamatiou *et al.*, 2006). The primary prey in 96 Galapagos shark stomachs examined consisted of teleosts and molluscs. Mammalian prey was rare (2.1% occurrence) (Papastamatiou *et al.*, 2006), and dietary diversity increased with individual size of the shark (Wetherbee *et al.*, 1996). Together, these findings suggest preying on pinnipeds at extremely shallow depths is not common for Galapagos sharks but is within the foraging repertoire of large individuals of the species.

Reducing shark predation on pups at FFS is one of several key activities identified in the Hawaiian monk seal recovery plan (NMFS, 2007). FFS has experienced the most precipitous decline among the NWHI breeding sites based on beach counts of seals and number of pups born since the 1980s (Carretta *et al.*, 2009). Predation mitigation attempts have included harassment and culling of sharks, and translocation of weaned pups to islets in the atoll with low incidence of shark attacks (Baker *et al.*, 2011). In total 13 Galapagos sharks were captured by daytime fishing with handlines or harpoons from shore or small boat and lethally removed between 2000 and 2005 and in 2011; an additional Galapagos shark was caught with a 5-hook bottom-set longline and lethally removed in 2010 (NMFS unpublished; Gobush, 2010). Deterring sharks from nearshore areas of islets with pups may be a practicable alternative to lethal removals.

Anti-shark measures tested for protecting humans have included acoustic playbacks (Myrberg *et al.*, 1978), visual devices (Doak, 1974), chemical repellents (Gruber and Zlotkin, 1982) and electrical repellents (Marcotte and Lowe, 2008; Stoner and Kaimmer, 2008), although these have had limited success (Sisneros and Nelson, 2001). At FFS, we identified two categories of possible deterrents that could be readily tested and not likely to affect the behaviour of non-target wildlife: devices that emit electric fields and devices that mimic the sights and sounds of human activity. Elasmobranchs sense electric fields with their ampullae of Lorenzini (gel-filled pores homogeneously distributed around the nose and mouth), and some species avoid taking bait in the presence of electric fields (Marcotte and Lowe, 2008; Stoner and Kaimmer, 2008). Thus, placement of commercially available electronic diver devices that emit a pulsed, direct current electric field in the nearshore area around pupping islets have the potential to repel sharks.

An increased human presence associated with intensive monitoring at Trig may have functioned as a shark deterrent there in the past. Nearly all sightings of patrolling and attacking Galapagos sharks, as well as injured and killed pups that occurred at FFS between 1997 and 2001 occurred at Trig (Gobush, 2010; Harting, 2010). Observations of shark activity significantly decreased in successive seasons from 2001 to 2003 during intensive and systematic daytime monitoring from a 12-foot observation tower (totalling 2638 h) (NMFS unpublished; NMFS, 2004). Galapagos sharks appeared to be temporarily displaced when hazed by thrown coral rubble and by small boat ingress and egress from Trig during this same period (NMFS unpublished). However, mortality of monk seal pups remained essentially unchanged in these years, suggesting that sharks preying on monk seal pups at FFS grew wary of daytime human activity in the area, shifting their behaviour to hunt when humans were absent. Incidentally, pup predation was initially localized at Trig and then expanded to include other islets in the atoll starting in 2002 this expansion may have been a reaction to the increased human presence at Trig as well (Gobush, 2010; Harting, 2010).

The effect of increased human presence on shark activity has not been tested in isolation (i.e. without other mitigation measures) at FFS to date. In most years, a programme to cull a small number of Galapagos sharks occurred alongside an increased human presence associated with intensive monitoring. The number of days with fishing gear in the water was relatively few during this period; however, a pairing of an occasional cull with increased human presence may have been an effective combination for deterring daytime shark activity in the nearshore areas of Trig.

For this study, it was concluded that testable, nonlethal options for repelling sharks from areas near pupping islets included continuous human presence on the islets and the application of devices that either mimic human activity, otherwise function as a negative stimulus, or both. For example, acoustic playbacks that replicate the sounds of boats and also have other acoustic properties that sharks react negatively to might be an effective deterrent. Field and laboratory experiments demonstrate that numerous species of sharks can hear sounds with frequencies ranging from 10 Hz to 1500 Hz, with heightened response below 400 Hz and attraction below 200 Hz (Myrberg, 2001). Withdrawal was elicited in lemon sharks (*Negaprion brevirostris*) and silky sharks (*Carcharhinus falciformis*) by projecting broadband underwater sounds that suddenly increased in sound level or changed from an attractive sound to that of another sound when the subject was within 10 m of the source (Myrberg *et al.*, 1978; Klimley and Myrberg, 1979; Myrberg, 2001).

Here, the feasibility is examined of deploying (1) devices that emit an electric field; and (2) visual implements and acoustic playbacks that mimic human activity, in the nearshore around pupping islets. The hypothesis that these devices, or a continuous human presence, can deter shark predation on Hawaiian monk seal pups is then tested. Also described is a novel method for shark detection using an all-weather remote camera system. The methodology described demonstrates the application of predation mitigation measures in a situation where it is paramount that the prey, an endangered species, is not disturbed or put at risk by human activities.

METHODS

Study area

FFS (N23° 45′ W166° 10′) is part of the Papahānaumokuākea Marine National Monument (PMNM) and consists of a 34-km-long oval area bounded on the east side by a 50km long crescent-shaped barrier reef, and nine sandy islets with a total land area of 0.25 km^2 (Figure 1) (Dale *et al.*, 2011). Water depths ranged from <1 to 10 m in the eastern lagoon and 20 to 100 m in the western half of the atoll. The base station was at Tern Island. Neighbouring islets include Trig (0.79 ha at mean low water (MLW)), 3 km east of Tern and Gin (1.38 ha at MLW) and Little Gin (1.78 ha at MLW), 12 km south-east of Tern. All islets were a maximum of 2.4 m above sea level (Baker *et al.*, 2006)

The research was focused at Trig and the Gins. Since 1998, the majority of pup births and subsequent deaths by sharks occurred at Trig. A fewer number of pups have been born at the Gin islets (Gin and Little Gin) but a high percentage of these have also succumbed to shark predation in recent years (Gobush, 2010).

Device feasibility trial

Between May and July 2008, a feasibility trial was conducted of electronic, visual, and acoustic devices in a shallow sand flat (1 to 3 m depth) on the north side of Trig. The majority of the mother–pup seal pairs nursed at the beach adjacent to this deployment area. The devices were deployed simultaneously because of the short duration of the field season. If a device remained functional for the duration of the trial and did not disturb wildlife other than sharks, it was considered feasible for further testing. In 2009, a controlled study was conducted of the devices demonstrated to be the most feasible in 2008.

Up to three electronic diver devices were applied at a time (model Freedom 7 ™, manufacturer Shark Shield) in the same nearshore area of Trig (Figure 2 (a)). Each device consisted of a 2.2 m flexible whip antenna, a compact electronic device with two external charging electrodes, encased in plastic housing within a neoprene pouch, powered by a rechargeable lithium battery. Each device was suspended in the water column by attaching it to an anchored polypropylene line and a surface float. Based on the manufacturer's specifications, the devices emit a pulsed, direct current electrical field with an 80 V charge up to 5 m radius. The device operation was limited to a 7 h battery life; recharging was only possible once every 24 h as a result of logistical constraints of the remote setting. The units were operated daily from approximately 1630 to 2330 h because it was considered that sharks in the area might be more active during nocturnal periods. The devices were arranged perpendicular to the shore and spaced 10m apart. The linear arrangement maximized the likelihood of a shark encountering the electric field emitted when engaged in typical shoreline patrolling behaviour.

Separately, the impact zones of the diver devices were tested on four free-ranging Galapagos sharks at two locations 3 miles offshore of Hale'iwa, O'ahu, Hawaii (approximately 550 miles from FFS). Caged shark diving tours occur offshore of Hale'iwa and large sharks frequently approach boats (Meyer *et al.*, 2009). The aim was not to replicate the conditions of FFS in this test, rather the purpose was to determine a minimum distance a free-ranging Galapagos shark that was stimulated by food might approach the operating diver device. The sharks were baited with squid from the side of a 17 ft boat. After observing sharks feed for 5 min, a device was deployed boatside as bait was repeatedly dropped in the water and the nearest distance from the device

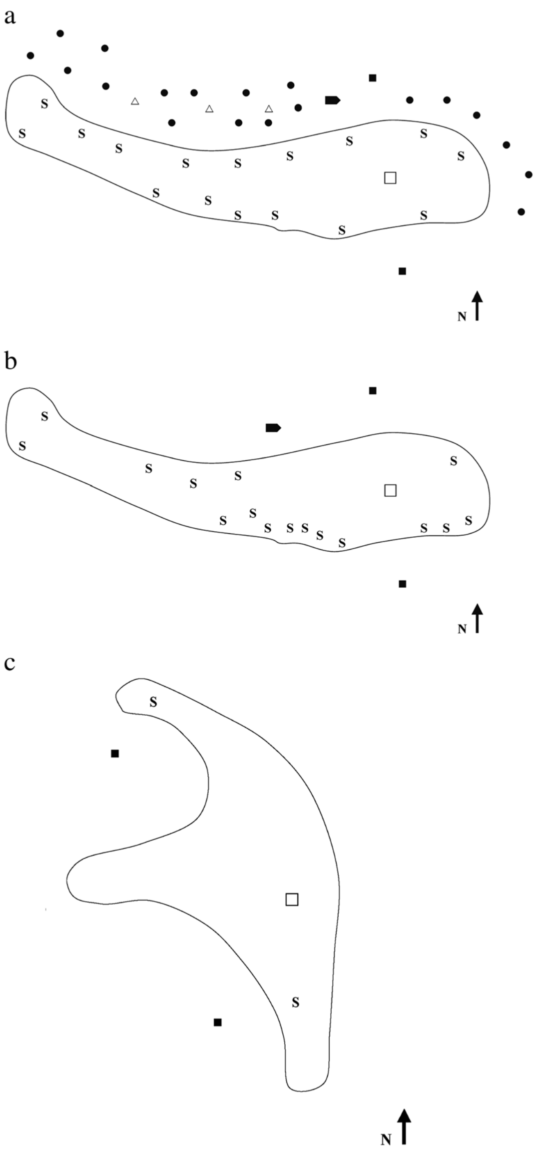

Figure 2. Placement of camp and devices aimed to deter shark predation at (a) Trig islet, French Frigate Shoals in 2008, and (b) 2009, and (c) Gin islet, French Frigate Shoals in 2009: closed square, underwater speakers; closed circle, floats; closed pentagon, moored boat; open triangle, electronic diver devices; open square, personnel camp. The approximate locations of nursing monk seal mother–pup pairs are demarcated with an 'S'; figures are not drawn to scale.

that each shark continued to pursue the bait over a 15 min time period was recorded. This procedure was carried out once at each location. A similar test was not feasible in FFS because food reinforcement of sharks in this manner was prohibited there.

Visual implements included an anchored boat and a float array. A 15 ft twin hull boat (Livingston) was moored off the north-east side of Trig 15 m offshore; the bow was secured to a concrete mooring anchor placed on a sandy substrate (Figure 2(a)). The float array consisted of foam fishing floats of various sizes and closed-cell foam floats, each anchored with polypropylene line and weights.

An acoustic playback system included amplified man-made noise transmitted from 1 to 2 speakers placed off the north-east and south-east ends of Trig (Figure 2(a)). Cage-mounted underwater speakers (Lubell Labs Inc. LL916c; frequency response 200 Hz–20 kHz) were suspended in 2 to 3 m of water within 10 to 20 m of the shoreline, secured with a surface float anchored on sandy substrate. Shielded cable connected the speakers to an onshore transformer box (Lubell Labs Inc. AC205C) and a 60 W public address amplifier (InterM A-60), powered by a solar panel and DC batteries. The acoustic source level of sound transmissions ranged from 80 to 180 dB re 1 μPa at 1 kHz; the upper limit was based on constraints from marine mammal protection regulations in order to prevent a permanent threshold shift in pinnipeds (Marine Mammal Protection Act (MMPA) 1972). Four sound recordings were played on a rotating basis for approximately 15 to 20 min each hour for 24 h per day. A programmable timer (Intermatic, HB77R) controlled the operation. Sounds included three different outboard motors (28, 29, and 41 s long) and a jetski (49 s long), each with a frequency between 200 and 800. The acoustic source level of sound transmissions ranged from 80 to 180 dB re 1 mPa at 1 kHz; the upper limit was based on constraints from marine mammal protection regulations in order to prevent a permanent threshold shift in pinnipeds (Marine Mammal Protection Act (MMPA) 1972).Sounds permitted were limited to those that were similar to sounds typically generated during routine monk seal monitoring via small boats at FFS. Overall, the sound transmissions were chosen because they were expected to be audible above ambient noise levels, had acoustic properties that might induce a behavioural change in sharks, and were not likely to disturb monk seals.

Experiment to deter shark predation

Only the devices that remained functional for the duration of the feasibility trial and did not disturb wildlife other than sharks were retained for further systematic testing. In May to August 2009, shark activity (described below) was compared across the following three experimental treatments at two pupping islets: (1) continuous human presence; (2) visual implements and acoustic playbacks mimicking human activity; and (3) a control. Constant human presence (treatment 1) involved one to two people on the islet for at least 23 h a day, stationed in a small tented camp that was centrally located to monitor seals and sharks (Figure 2(b) and (c)). The activities of personnel were generally limited because it was paramount that mother seals and nursing pups not be disturbed, flushed into the water, or otherwise put at further risk of predation. Personnel conducted general camp activities, and periodic ground and boat patrols. If a large shark was sighted within approximately 15 m from shore, personnel hazed it by throwing large coral rubble.

The device treatment (treatment 2) included the deployment of the moored boat on the north-east side of Trig (the boat was not moored at the Gins because of logistical constraints and rough ocean conditions) and broadcasting the acoustic playbacks from two speakers either at the north-east and south-east ends of Trig or the north-west side and south-west side of Gin (Figure 2(b) and (c)). During the control treatment, no devices were deployed and human visitation was limited to 30 min per day.

Treatments were rotated among islets (Trig and the Gins) weekly as long as pups were present. Treatments typically ended at midday on the seventh day of application, whereupon the next treatment in the schedule was immediately initiated.

Monitoring shark activity

Shark presence in nearshore areas was determined by viewing video recorded during daytime hours with an all-weather remote camera system, installed at Trig but not at the Gins because of their greater distance to the receiving station at Tern. Thus, shark presence and predation incidents could be accounted for at Trig, but only predation incidents at the Gins. Direct observations of sharks by personnel were not included because an obvious sightings bias occurred during the 'human presence' treatment.

The camera system, custom-built by Sun Surveillance Systems, relayed programmable video via microwave signal between Trig and Tern. On Trig, the system components included a 3 m $\times$ 11 cm diameter aluminum bracketed pole with a power supply (three DC batteries housed in an aluminium box and one solar panel) connected to a compact transmission device. An antenna panel (Powerstation 5-22V, Ubiquiti Networks) and two cameras, a Mobotix (model M12), and a Sony (model RZ25N), were mounted on the pole. The Sony camera was encased in a spherically shaped, weather-proof housing. Brackets and a weighted base allowed the structure to stand erect in heavy winds. On Tern, system components included a 16-channel digital video recorder with 6 Tb of storage (DS NVR purpose-built Network solution) and a 21 inch monitor housed indoors, and a second antenna panel installed on a roof. The cameras were directed toward the area where the greatest number of pups was typically nursing. The estimated visual range of the cameras was approximately 120 m to the south and east in optimal light conditions (sand berms blocked views to the west).

A large shark was recorded as present if either a characteristic dorsal fin profile on the water's surface, an elongated dark shape swimming underwater or a break in the water's surface indicative of a fast-moving, large-bodied animal that could not be identified as a seal, turtle or ray was observed. The wounding of a pup or a shark-inferred disappearance observed during monk seal population assessment surveys were considered as evidence of a shark predation incident. Wounds were designated as shark-inflicted if the tooth marks, bite radius or severity of the wound was consistent with a shark attack. Disappearances were attributed to shark attack if (1) a nursing pup aged 7 days or greater was absent and the mother present, (2) there were no extreme high tides, and no inclement weather within a day of the incident, and (3) no adult male seal aggression occurred within a week of the incident. Male seal aggression has been rare at FFS in recent years and no known adult male injuries to pups were documented during the study.

Seal surveys were conducted near daily at Trig, thus incidents were recorded as occurring on the date they were first observed. Surveys occurred every 2 to 3 days at the Gins because of their remoteness, thus we recorded incidents as occurring on the date midway between the date that an incident was realized and the prior survey date.

Video recording and viewing

The camera system operated in the daytime (approximately 0530 to 2000) for 73 days between 26 May and 13 August 2009. Temporary camera malfunction meant that some days in early June were excluded. Video recordings were viewed for a total of 826.5 h across 57 days evenly distributed across the three treatments. Each video was categorized by the treatment applied on that date. The device treatment (treatment 2) had the least number of days (19) of video recorded as a result of camera malfunction. An equal number of video days were randomly selected for the remaining treatment and the control to maintain a consistent number of video days per treatment in the analysis.

Analysis

To determine whether frequency of shark presence on Trig and predation incidents on Trig and Gin combined differed by treatment likelihood ratio tests were conducted with SAS version 9.2 (Cary, North Carolina). An exact multinomial test (100 000 Monte Carlo simulations) was conducted because shark activity was expected to be rare (i.e. some expected values might be less than 5 in the contingency analysis) (Sokal and Rohlf, 1981). The null expectation was that the proportion of sightings and incidents across the treatments and the control was the same. Shark sightings were assumed to be independent on a daily basis per islet because neither multiple incidents per islet nor simultaneous incidents across islets have occurred within a 24 h period over the last 5 years; this pattern of predation may be partly driven by a somewhat staggered pattern of seal births at FFS. It was assumed that there were no lag effects of treatment. Although wind speed, water clarity, cloud cover and glare may have influenced the ability to view a shark in the video frame, these variables were not included in the analysis because it was concluded that these factors differed randomly across the video days. Statistical power analysis using effect sizes of 0.3 and 0.5 (Cohen, 1988) indicated that a total sample size of 39 to 108 observation days should result in >80% probability of correctly detecting medium to large deviations between what was observed and the null expectation. Detecting a smaller deviation (e.g. effect size 0.1) would require a sample size of 964 observation days, which was not feasible given that the monk seal pupping season spans approximately 130 days each year.

RESULTS

DEVICE FEASIBILITY TRIAL (YEAR 1)

Acoustic playbacks and the moored boat were successfully deployed in 2008. The float array was removed because a green sea turtle became entangled (the turtle was safely freed with assistance). The electronic diver devices failed to function after 3 weeks of continuous nightly use. During impact zone tests, four Galapagos sharks either avoided (quick turn away) or did not approach the bait in an approximate 1 m zone around the diver device, despite the expected 5 m range based on the manufacturer's specifications. Based on these results, the diver devices were omitted in the device treatment in 2009 and only the acoustic playbacks and the moored boat were included.

Experiment to deter shark predation (Year 2)

Fourteen pups were born at Trig and two at the Gins between 18 May and 19 August 2009, representing 52% of the monk seal births at FFS for the year. Pups were present on Trig for a total of 94 days, ranging from 1 to 10 pups at a time, and the Gins for 50 days, ranging from 1 to 2 pups at a time. Pups that survived to weaning each nursed for approximately 35 days; once weaned, pups were translocated to Tern Island.

Three treatments were applied for 144 days (Table 1); poor weather conditions prevented planned treatments on some days, and such days became controls by default. The mean number of pups on Trig on a daily basis varied significantly between treatment types (all days: ANOVA, R^2 =0.08, $F_{2, 91}=4.1$, $P=0.02$; video days: ANOVA, R^2 =0.11, $F_{2, 54}$ =3.38, $P=0.04$) (Table 1). The probability of a shark incident occurring was not related to the number of pups on Trig (logistic

Table 1. Treatment application per islet at French Frigate Shoals, May to August 2009

Islet	Treatment	Days applied	Mean pups per day (SE)	Days of video viewed	Mean pups per day during video (SE)
Trig	Human presence	27	5.0 (0.4)	19	4.6 (0.5)
	Device	29	5.5 (0.5)	19	4.4 (0.5)
	Control	38	4.1 (0.3)	19	3.2 (0.2)
Gins	Human presence	7	1.6 (0.2)	Not applicable	
	Device	18	1.4 (0.1)		
	Control	25	1.4 (0.1)		

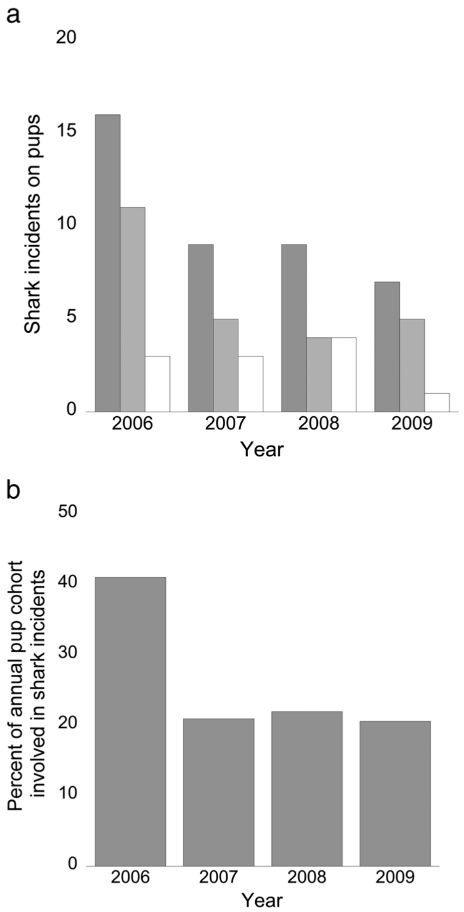

Figure 3. (a) The number of shark predation incidents on nursing and newly weaned Hawaiian monk seal pups by location (grey: atoll-wide, hashed: Trig, white: the Gins) and year at French Frigate Shoals, 2006 to 2009. (b) The percentage of monk seal pups wounded, killed or disappeared as a result of shark predation at French Frigate Shoals, 2006 to 2009.

regression R^2=0.01, $\chi^2_{1,94} = 0.001$, $P = 0.97$). These relationships were not examined for the Gins because only two pup births and one shark incident occurred there.

Six shark incidents occurred in 2009, affecting 19.1% of the FFS cohort and was comparable to recent years (Figure 3(a) and (b)). These incidents consisted of one minor and three fatal woundings and two shark-inferred disappearances (all but one at Trig). Sharks were present during 12 of 57 days of video examined, spread across all treatments. Shark presence at Trig did not differ significantly between the treatments and the control (R^2 =0.05, $n = 57$, Likelihood ratio test $\chi^2_2 = 2.6$, $P = 0.27$, exact multinomial test $P > 0.05$) (Figure 4(a)). Although no predation incidents occurred during the device treatment, the frequency of shark incidents did not significantly differ between the treatments and the control at Trig and the Gins combined (R^2 =0.10, $n = 144$, Likelihood ratio test $\chi^2_2 = 4.88$, $P = 0.08$) nor when stratified by islet (Cochran–Mantel–Haenszel test $\chi^2_1 = 1.64$, $P = 0.20$) (Figure 4(b)).

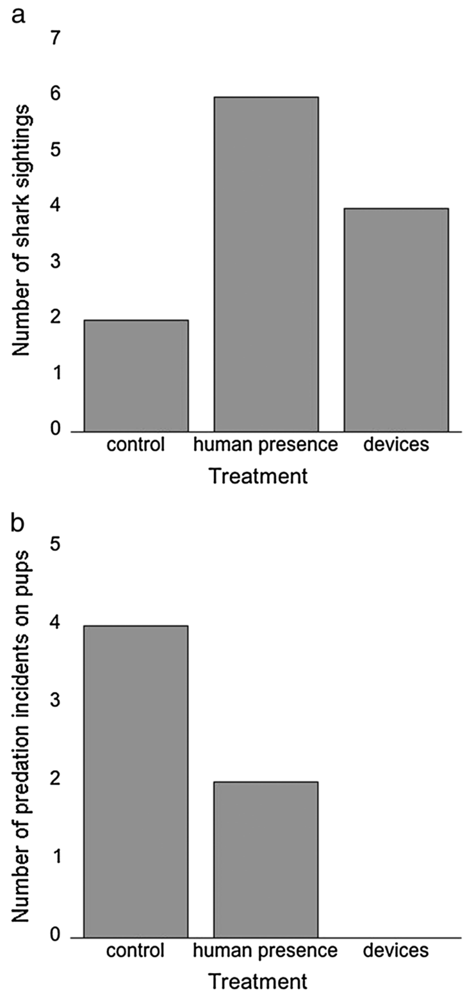

Figure 4. (a) The number of large shark sightings per treatment as recorded on video across 19 days (14.5 h of video per day) per treatment at Trig, French Frigate Shoals (2009). Differences between treatments were not significant. (b) The number of shark predation incidents on Hawaiian monk seal pups per treatment at Trig and the Gins (combined), French Frigate Shoals (2009). Differences between treatments were not significant.

DISCUSSION

Deterring sharks from nearshore areas in a reliable, repeatable, humane manner is an appealing concept, especially if it eliminates the need for a controversial culling scheme and enables sustainable coexistence of predator and endangered prey. However, designing, installing and testing devices, especially electronic ones, presents unique logistical challenges in remote settings where factors such as poor access or inclement conditions interfere with device deployment, maintenance, and repair.

Motivating sharks to flee an area through a human presence on the beach, an admittedly simple notion, is supported by direct sighting rates in previous studies at FFS (NMFS unpublished; NMFS, 2004; Gobush, 2010). However, results here suggest that shark predation of Hawaiian monk seal pups was not mitigated by either the systematic application of feasible, reliable devices or a continuous human presence.

Effectiveness of shark detection by remote cameras

A remote camera system was useful for detecting shark presence at Trig, in part because of its proximity to a base station for video relay. A similar line-of-sight camera system was not possible at the more distant Gins. At Trig, however, Galapagos sharks were observed directly three additional times during the human presence treatment that were not captured on camera. Two incidents of shark predation occurred at night when the camera system was not operational as evidenced by newly wounded animals discovered at daybreak. However, when the number of shark sightings was considered rather than the number of shark predation incidents alone, camera detection of shark activity doubled. Additional testing and development of this camera system to overcome the limitations would be beneficial.

Effectiveness of shark deterrence

The requirement for reliable and continuous operation in the nearshore areas eliminated all deterrent options except acoustic playbacks, a moored boat, and human presence. Field tests of the diver devices with sharks indicated at most a 1 m effective range, suggesting that although the units might function acceptably well as a point deterrent they were unlikely to be effective across large areas unless strategically arranged at a high density. Devices powered via DC solar batteries (i.e. the acoustic playback system) proved to operate more reliably on a continuous basis than those with more involved charging schemes (lithium-battery-operated diver devices). Visual implements require lines, floats and anchors to stay in place and can be difficult to maintain and hazardous to marine wildlife, as demonstrated by the green sea turtle that became entangled in the float array. Although not tested here, physical barriers, such as netting, may carry similar hazards (Harting, 2010). Chemical repellents may be valuable to explore (Harting, 2010); investigating the response of Galapagos sharks to such compounds, the dissipation rate in the nearshore, and the impact on other coastal wildlife would be required.

A signifcant decrease in the number of shark sightings or predation incidents on pups was not detected with either the application of devices used to deter predation or a continuous human presence in this study. This finding is inconsistent with previous research that supported the conclusion that actual or mimicked human presence on land or nearshore might deter Galapagos sharks from the area. For example, Galapagos shark numbers at isolated reefs were 60–85% greater than those around similar islands that are near human-populated areas in the main Hawaiian Islands (NMFS, 2009). During an intensive monitoring period (2001 to 2003) at Trig (FFS), the sighting rate of Galapagos sharks declined over time, but shark predation on pups did not, suggesting a decrease in day predation when humans were present and an increase in predation when they were absent (NMFS unpublished; NMFS, 2004; Gobush, 2010). In contrast, the frequency of daytime shark sightings, as captured on video, was not statistically different when humans were present or absent on pupping islets in this study. Together, these findings suggest that sharks' wariness to humans is variable, unpredictable, possibly individualistic, and unreliable at these locations.

Between 2001 and 2003, when daytime shark sightings decreased with increased daytime monitoring, hazing and fishing also occasionally occurred, most often in direct response to a sighting of a patrolling shark. Determining which human activity, if any, may have deterred sharks in the past is therefore complex. The sounds of motorized watercraft associated with the increased human activity may have only displaced sharks when paired with the strong negative stimulus of the occasional culling success that occurred during that period. In the absence of a strong negative stimulus, habituation of individual sharks to only mildly noxious deterrents could become an issue.

Although no detectable response to acoustic playback was found, use of this deterrent method could conceivably benefit from additional testing to better identify the most appropriate negative stimulus. For example, the playbacks did not include sudden increases in source level by 20 dB that were demonstrated to deter sharks in other studies (Myrberg *et al.*, 1978; Klimley and Myrberg, 1979) because sound transmissions here were limited to those known not to disturb monk seals. Also, the nearest distance that sharks approached the sound source and the sound levels they might have received were not measured. Going forward, the response of captive Galapagos sharks and monk seals to such changes in sound magnitude could be tested. For example, a controlled exposure experiment could be designed for a captive setting in which the pattern of sounds, their frequency and magnitude were engineered to specifically impact Galapagos sharks but not monk seals, while lessening the chance of shark habituation. If a video–acoustic installation was included, then the approach and withdrawal of individuals to the sound source could be documented and received sound levels measured. Ultimately playbacks would need to comply with MMPA regulations if they are to be applied near wild monk seals or other marine mammals.

Although shark predation on monk seal pups continues to be a significant factor in the decline of the FFS population, the low observability of shark activity in the shallows around the pupping sites made detecting a treatment effect in this study challenging. Shark tagging studies at FFS indicate that although Galapagos sharks are the most abudant shark species in the atoll, they generally prefer deeper water and only a small fraction of the population, equating to a few tens of individuals, frequents the shallow areas around pupping sites (Dale *et al.*, 2011). Therefore, effective predation mitigation measures may only need to impact a small number of sharks; but evaluating the effectiveness of such measures becomes difficult because the sample size of sightings and total number of attacks on pups is also expected to be small. By examining the number of shark sightings recorded on video, nearly twice as much shark activity was detected during the pupping season than indicated based on predation incidents alone. Still, the sample size was only sufficient to test large deviations between observed and expected number of sightings per treatment (12 sightings across 57 video days yielded an effect size of 0.42). More days of video and fewer treatments could improve precision to a limited extent (e.g. camera systems at two islets operating from the time the first pup is born until the the last pup weans and viewing a larger area).

Management implications

Despite the limitations of the research approaches investigated here, mitigation of shark predation of pups is a requirement for recovery of the Hawaiian monk seal at FFS. Until further development and testing of the devices described occurs, other methods of predation mitigation, such as erecting barriers or culling sharks, may provide more benefit to improving the situation for monk seals at FFS.

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