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Site fidelity and movements of sharks associated with ocean-farming cages in Hawaii

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Abstract. Sharks are found in association with main Hawaiian Island ocean fish farms more frequently and at higher densities than is typical for coastal Hawaiian waters. Sharks attracted to fish farms could potentially threaten human water users, interact negatively with other fisheries, and seasonal migrations could be disrupted if individuals become entrained around farms throughout the year. We hypothesised that smaller coastal species would reside near farms, whereas more wide-ranging species would associate with farms only for short periods. We utilised passive acoustic telemetry to monitor the movements and behaviour of sandbar (*Carcharhinus plumbeus*) and tiger (*Galeocerdo cuvier*) sharks adjacent to two open ocean fish farms in Hawaii. Approximately half the tagged sandbar sharks showed site fidelity to the farms, with some individuals being detected repeatedly for 2.5 years. Sandbar sharks moved seasonally to the west coast of Oahu, suggesting that fish farms are not disrupting natural seasonal cycles in this species. Tiger sharks tagged near the cages were more transient, and showed much shorter residence times although some individuals returned sporadically to the cages over the 3-year period. Ocean fish cages appear to aggregate sandbar sharks, but are only 'visited' by tiger sharks. Although threats to public safety are probably minimal, the ecological effects of aggregating top-predators are still unknown.

Additional keywords: acoustic telemetry, fish cages, sandbar sharks, seasonal migrations, sexual segregation, tiger sharks.

Introduction

Ocean fish-farming operations are increasing in popularity because of their profitability and potential as an alternative to wild-capture fisheries. These farms grow fish in open-ocean cages where they are artificially fed. Ocean fish farms tend to aggregate wild fishes, and telemetry studies have shown that often these wild fish individuals display strong site fidelity to farms, but also move more widely (e.g. Uglem *et al.* 2009). Despite the large numbers of fish aggregating to fish farms, top-level predators such as sharks are rarely seen around cages (e.g. Boyra *et al.* 2004; Sanchez-Jerez *et al.* 2008). However, there are occasional reports of large, potentially dangerous species of shark being attracted to fish farms, raising concerns about possible threats to public safety (e.g. Galaz and De Maddalena 2004). Furthermore, many shark species undertake seasonal migrations which may be disrupted if sharks become entrained year round at ocean-farming sites (e.g. Wetherbee *et al.* 1994; Meyer *et al.* 2009*a*).

There are currently two open ocean fish-farming operations in the Hawaiian Islands. Of the southern shore of Oahu, there is a series of anchored, mid-water fish cages housing Pacific threadfin (*Polydactylus sexfilis*, Hawaiian name 'moi'; Chambers *et al.* 2001), whereas off the Kona coast (leeward Hawaii Island) are cages producing the Almaco amberjack (*Seriola rivoliana*; Engelhaupt 2007). Divers have reported seeing large numbers of sharks underneath the moi cages, whereas sharks are rarely seen during dive surveys around Oahu in similar habitats (e.g. Friedlander and DeMartini 2002). These aggregations suggest that the cages are attracting potentially dangerous species, which could then pose a threat to recreational water users or negatively interact with adjacent fisheries. Divers have also frequently sighted tiger sharks (*Galeocerdo cuvier*), considered a potentially dangerous species, around the Kona fish cages. There are currently no empirical data available to evaluate the impact of either of these operations on public safety or on the natural ecology of sharks.

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We conducted a 3-year telemetry study to quantify shark site fidelity to the fish-cage sites, and to identify other areas visited by sharks captured at these sites. Fishing surveys have shown that the most abundant shark species in the main Hawaiian Islands are sandbar (*Carcharhinus plumbeus*), Galapagos (*C. galapagensis*) and tiger (*Galeocerdo cuvier*) sharks (Wetherbee *et al.* 1994; Papastamatiou *et al.* 2006). On the basis of what is known about the movements of these species, we hypothesised that coastal sharks (sandbar or Galapagos) would show fidelity to the cages, whereas the wider-ranging tiger sharks would spend short periods of time associated with the cages (e.g. Holland *et al.* 2001; Lowe *et al.* 2006; Meyer *et al.* 2009*a*, 2009*b*, 2010; Papastamatiou *et al.* 2009). Our objectives were to (1) quantify species-specific site fidelity to ocean fish cages, (2) determine whether fish cages are disrupting natural seasonal migrations of sharks, and (3) determine whether sharks are frequently moving from the fish cages to beaches and fishing areas popular with human water users.

Materials and methods

Study site and shark capture and tagging

The moi ocean-farming operation (21.28°N, 158.04°W) consists of three fully submerged fish cages (25 m in diameter) less than 1 km from the south-western shore of the island of Oahu, in water 30–50 m deep (Fig. 1). The cages are stocked year round and captive moi individuals are fed automatically. A full description of the cages can be found in Chambers *et al.* (2001), and Lee *et al.* (2006). The Kona Blue Water Fish Farms (19.74°N, 156.06°W) consist of cages within 1 km from shore off the western coast of Hawaii Island, anchored in ~60 m of water (Fig. 1). These cages are raised daily so that only half the cage is submerged at night (Engelhaupt 2007).

Sharks were captured at both sites with 10-hook demersal long-line gear, baited with tuna pieces, and set within 1 km of the cages in depths of 50–100 m. Gear was set in the morning and allowed to soak for 2–3 h before being hauled. Captured sharks were tail-roped and restrained along the side of the boat where they were inverted and placed into tonic immobility (see Holland *et al.* 2001; Meyer *et al.* 2009*b*). Sharks were measured and sexed, a small incision was made in the abdomen and a coded acoustic transmitter (Vemco Ltd., Nova Scotia, V16-2 L-R04K, 16 mm × 20 mm, 150–165 dB) was inserted into the body cavity of each animal. These transmitters periodically emit a 'pulse train' of closely spaced 69-kHz 'pings', which uniquely identifies each shark. These pulse trains are a few seconds in length, and the transmitters remain silent for a randomised period of 150–300 s between each pulse train to reduce the likelihood of acoustic collisions. Each successfully decoded pulse train is recorded as a single detection by an omnidirectional underwater receiver (Vemco VR2), and is stored in the receiver memory as the unique transmitter number, with date and time of detection (detection radius ranged from 500 to 800 m). We also tagged three sandbar sharks with V16P pressure transmitters, which telemeter swimming-depth data to the VR2 receivers. Following transmitter insertion, the incision was closed with a single suture, an external Hallprint dart tag was applied at the base of the dorsal fin, and the animal was released. As part of a separate study (C. Meyer, unpubl. data), 10 male

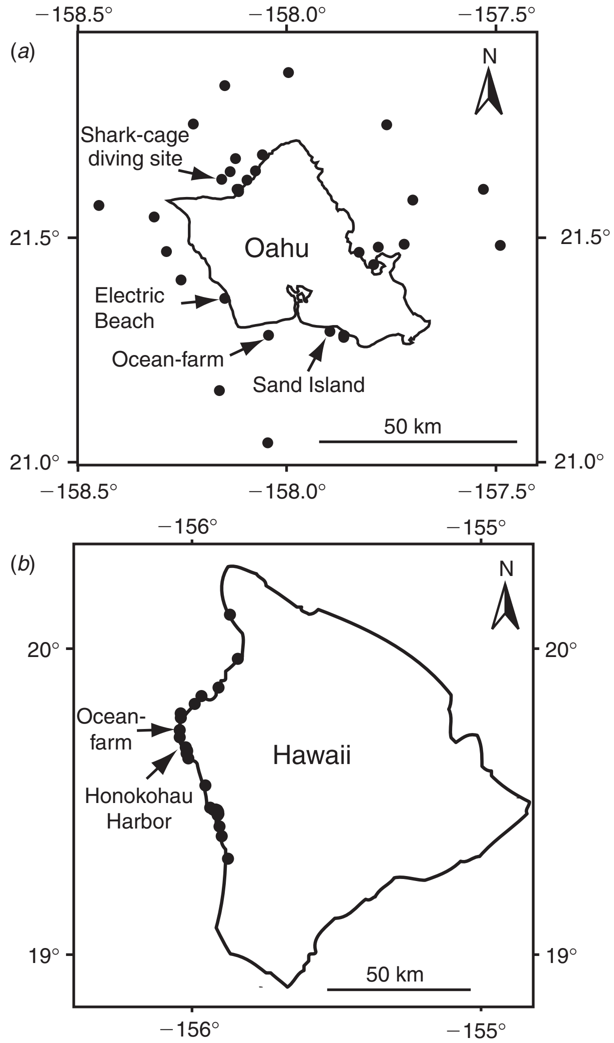

Fig. 1. The location of VR2 receivers (solid points) around (*a*) Oahu and (*b*) along the Kona coast, Hawaii. The locations of the fish cages are given in addition to other important locations (see text).

sandbar sharks (total length, TL, 155–179 cm) were also tagged with V16 transmitters off Haleiwa (North Oahu, Fig. 1). Data from some of these sharks are included here.

Horizontal movements by transmitter-equipped sharks were monitored using a network of underwater receivers deployed around the island of Oahu and along the western coast of Hawaii Island. The network included VR2 receivers deployed specifically for the present study, as well as others used by a variety of researchers to quantify the movement patterns of other sharks, rays, fishes and turtles. Monitored sites included the moi fish cages off Oahu and Kona Blue Water Fish Farms, adjacent beaches popular with the public (e.g. Sand Island and Electric Beach are both ~15 km from the moi fish cages), off-shore fish-aggregating devices (FADs – located in water depths ranging from 600 to greater than 2000 m), and shark-cage diving sites off the northern shore of Oahu (Fig. 1). On the island of Hawaii, an array of 33 VR2s was deployed along 109 km of the western coast. A full description of the location of underwater receivers can be found in Meyer *et al.* (2009*b*). Divers recovered and downloaded receivers approximately every 6 months. While recovering the receivers at the moi fish cages, divers made qualitative observations of the shark and fish species present beneath the cages.

Data analyses

A shark was considered 'present' at a fish cage if there were two or more detections within a 1-h period. On the basis of this conservative estimate, we determined the number of hours per day each shark was present, and the total number of days each shark was detected. Shark site fidelity to the fish cages was quantified by dividing the number of days present by the monitoring period of the study (site fidelity index – SFI). The estimated battery life of the transmitters exceeded the monitoring period and the SFI assumes zero tag battery failure. We obtained water temperature data from the NOAA weather buoy off Honolulu (http://tidesandcurrents.noaa.gov/geo, accessed 18 December 2009). Time-series analyses were used to identify possible cyclical patterns in shark movements. Detections of each shark were first summed into hourly bins, and then analysed using a fast Fourier transformation (FFT) with hamming window smoothing. FFTs convert time series data into frequencies and then search the data for cyclical patterns, which appear as peaks in a power spectrum (see Papastamatiou *et al.* 2009). Spectral analysis was performed with Statistica ver. 7.0 (StatSoft Inc., www.statsoft.com). We used logistic regressions to predict the probability of shark species being detected at the moi fish cages over time. Detections for each species were binned over successive 2-week periods. The probability of presence was evaluated through odds ratios generated from the models, with ratios <1 signifying decreasing probabilities of presence over time (e.g. Lowe *et al.* 2009). We examined the distribution of residuals to ensure that data were normally distributed and met the assumptions of homogeneity of variance.

Because of the large number of VR2 acoustic receivers deployed along the Kona coast, we were able to examine temporal movements of tiger sharks along the coastline. We plotted the latitudinal coordinates of VR2s where sharks were detected, and arranged them in a time sequence to graphically determine whether sharks were resident around the Kona fish cages. We also determined the number of days sharks were detected at each receiver, and utilised a non-parametric Kruskal–Wallis test to compare the times spent at particular receivers.

Results

Moi fish cages

Species present

Between 12 October 2006 and 15 April 2008, we captured 19 sharks at the moi fish cages (Table 1). Nine female sandbar sharks (*Carcharhinus plumbeus*) were tagged, ranging in size from 146 to 199 cm TL. One sandbar shark was recaptured at the moi cages after a year at liberty. Ten tiger sharks (*Galeocerdo cuvier*) ranging from 92 to 430 cm TL were also caught, of which six were acoustically tagged and released at the moi cages (Table 1). With the exception of one mature male, all tiger shark releases were female. On several occasions, divers retrieving the VR2 from underneath the fish cages saw multiple adult blacktip sharks (*Carcharhinus limbatus*); however, none were caught or tagged during the study.

Sandbar sharks

The catch per unit effort (CPUE) for sandbar sharks ranged from 0 to 7.5 sharks caught per 100 hooks per hour (median 2.5). Sandbar sharks were detected at the moi cages over periods ranging from 7 to 918 days, and there was considerable variation in SFI for this species (SFI = 0.02–70.48%, mean 23.40 ± 28.14%, Table 1). Sandbar sharks could be divided into the following two broad groups: those that showed site fidelity to the moi cage area, and those that spent only short periods in proximity to the cages. Although individual sharks were detected at the fish cages over long periods, these periods also included multiple days of absence. The probability of presence for sandbar sharks decreased significantly over time ($\chi^2_1 = 176.21$, $P < 0.001$, Odds ratio = 0.998). Detection probability of sandbar sharks decreased from 65% to 50% over the first year after tagging, and was ~35% 2 years after tagging (Fig. 2*a*). While present at the cages, sandbar sharks were detected for between 1 and 24 h day^{-1} (median 5 h day^{-1}), which was significantly longer than for tiger sharks at either the moi cages (range 1–8 h day^{-1}, median 1 h day^{-1}) or Kona Blue Water Fish Farms (range 1–12 h day^{-1}, median 1 h day^{-1}, Kruskal–Wallis $H_2 = 150$, $P < 0.001$). Regularly detected sandbar sharks exhibited clear cyclical rhythms of behaviour, with FFTs yielding dominant peaks in the power spectra at 24, 12 and 8 or 6 h (Fig. 3). Sharks were predominantly associated with the moi cages during the daytime or crepuscular periods, although sporadic detections also occurred at night.

Also apparent were seasonal movements of female sandbar sharks to the west coast of Oahu (Electric Beach). All tagged females were periodically detected at Electric Beach annually, from September through October (Figs 3, 4). Sharks did not reside at Electric Beach but consistently returned to the moi cages, a distance of nearly 14 km. Seasonal visits to Electric Beach were also seen in female sandbars that were tagged at the moi cages, but rarely detected there. Furthermore, male sandbar sharks tagged off the northern coast of Oahu were detected periodically at the Electric Beach receiver, from June through to early September over a 2-year period, but never at the moi cages (Fig. 4). No tagged female sandbar sharks were ever detected at the shark-cage diving sites on the northern shore (where males are frequently detected). In general, sandbar sharks were rarely detected at locations other than the moi cages, and Electric Beach. One female sandbar shark was briefly detected at a VR2 adjacent to Sand Island (in 20 m of water, Fig. 1), and one male was detected a kilometre offshore from Sand Island, on a VR2 stationed in water 70 m deep. There were more detections of sandbar sharks when water temperatures increased, although the time of maximum number of detections tended to lag behind the time of maximum water temperature (Fig. 5).

While within the detection range of the moi cages or Electric Beach, sandbar sharks tagged with pressure-sensor transmitters spent the majority of their time between 20- and 40-m depth, rarely going shallower than 20 m (see Accessory Publication to this paper, available on the web). For example, the depth distribution (mean ± 1 s.d.) at the moi cages for SB4 was

Table 1. Detection statistics for sharks tagged at the moi fish cages on Oahu (Moi), Kona Blue fish farm on Hawaii (Kona) and Pawai Bay close to Honokohau Harbor off Kona (Pawai)
All sharks were tagged with V16 Rcode tags; ID numbers with an asterisk indicate the tags that included a pressure (depth) sensor. SFI, site fidelity index (number of actual days detected/monitoring duration). TL, total length. Periods of dominant frequencies as determined by FFT are also given. Receiver coverage was lost for 234 days at the moi cage; these days were not included in SFI calculations

Species	ID #	Location	TL (cm)	Sex	Date tagged	Date first detected	Date last detected	Duration detected (days)	No. of days detected (days)	SFI	No. of detections	Dominant peaks
Sandbar	SB4*	Moi	199	F	26/2/2007	7/3/2007	2/9/2009	918	469	59.1	26 875	24,12,8
Sandbar	SB1	Moi	167	F	19/10/2006	2/11/2006	1/10/2008	700	445	48.2	24 146	24,12,8,6
Sandbar	SB8	Moi	161	F	15/4/2008	5/12/2008	18/12/2009	379	268	70.5	9462	24,12,8,6
Sandbar	SB6*	Moi	186	F	4/2/2008	12/2/2008	29/1/2009	353	82	18.2	2137	24,12,8
Sandbar	SB9	Moi	146	F	15/4/2008	8/11/2008	19/2/2009	311	44	11.6	796	24,12,8
Sandbar	SB5*	Moi	185	F	27/9/2007	1/10/2007	16/10/2007	15	14	2.4	6	–
Sandbar	SB2	Moi	175	F	19/10/2006	1/2/2007	24/5/2009	844	3	0.03	21	–
Sandbar	SB7	Moi	156	F	4/2/2008	4/2/2008	19/2/2008	67	2	0.44	13	
Sandbar	SB3	Moi	171	F	19/10/2006	12/12/2006	19/12/2006	7	2	0.02	4	–
Tiger	T4	Moi	430	F	27/9/2007	–	–	–	–	–	–	–
Tiger	T12	Kona	328	F	5/10/2008	–	–	–	–	–	–	–
Tiger	T6	Moi	333	M	19/2/2008	–	–	–	–		–	–
Tiger	T13	Kona	315	M	1/10/2008	27/10/2008	17/1/2009	83	36	10.4	1118	24
Tiger	T7	Kona	360	F	5/10/2008	3/12/2008	26/7/2009	236	23	6.7	632	None
Tiger	T8	Kona	330	M	4/10/2008	31/3/2009	2/8/2009	125	21	6.1	467	None
Tiger	T11	Pawai	393	F	2/10/2008	20/1/2009	23/7/2009	185	19	5.6	147	None
Tiger	T1	Moi	276	F	2/2/2007	7/3/2007	16/1/2009	682	15	1.8	221	–
Tiger	T5	Moi	201	F	4/2/2008	8/2/2008	17/3/2008	39	12	2.3	80	None
Tiger	T9	Pawai	376	F	3/10/2008	24/2/2009	29/7/2009	156	5	1.5	30	
Tiger	T10	Kona	428	F	5/10/2008	29/11/2008	15/12/2008	17	5	1.5	40	
Tiger	T2	Moi	335	F	27/9/2007	11/12/2008	5/10/2009	299	3	0.52	30	–
Tiger	T3	Moi	312	F	27/9/2007	1/10/2007	22/12/2007	83	1	0.17	8	None

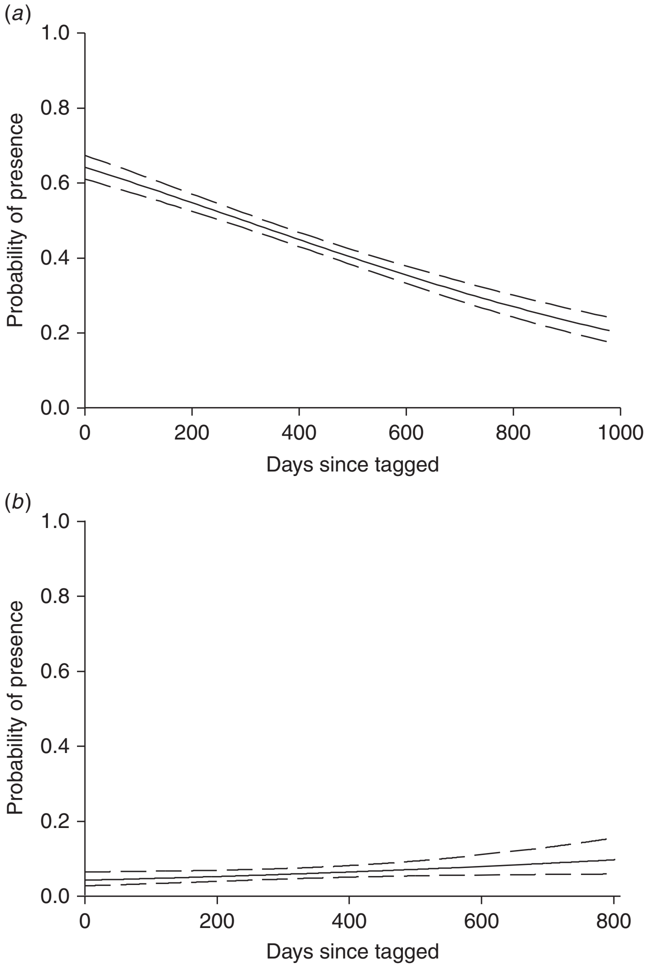

Fig. 2. Predicted probability (±95% confidence intervals) of tagged (*a*) sandbar and (*b*) tiger sharks, being detected at the moi cages after tagging. Probabilities were calculated using a logistic regression.

34 ± 8 m, and 35 ± 11 m for SB6. SB5 was detected at Electric Beach at a depth of 27 ± 12 m. All sharks appeared to utilise deeper depths during the day than at night, with sharks occasionally being detected as deep as 100 m during the day.

Tiger sharks

Moi cages Tiger shark CPUE ranged from 0 to 7.5 sharks per 100 hooks h^{-1} (median 5). We detected four tiger sharks (67%) at the moi cages over periods of 39–682 days, although sharks were only present for brief periods (1–15 days) during that time (SFI = 0.17–2.3%, mean 1.20 ± 1.02%, Table 1). Typically, tiger sharks were detected at the moi cages and other sites only over periods of days to weeks. There was a marginally significant increase in the probability of detection at the moi cages over time ($\chi^2_1 = 4.7$, $P = 0.044$, Odds ratio = 1.001). Detection probability was low, ranging from 5 to 10% 800 days after tagging (Fig. 2*b*). Unlike sandbar sharks, there were no observed cyclical patterns in behaviour, with no dominant peaks in power spectrums produced via FFTs (Fig. 6*a*, *c*). The exception was one tiger shark that showed distinct seasonal presence at the moi cages in January. Tiger sharks were wider-ranging than sandbar sharks, and were briefly detected on receivers close to Sand Island, Electric Beach, and also on offshore FADs.

Kona Blue Water Fish Farms

Five tiger sharks, ranging in size from 280 to 428 cm TL, were caught around the Kona fish cage between 1 and 7 October 2008 (Table 1). We tagged an additional two tiger sharks at Pawai Bay (next to Honokohau Harbor), which were subsequently detected at the cages. Six tiger sharks (86%) were detected over a duration of 17–236 days; however, they spent only a short period of time associated with the cage (SFI = 1.5–10.4%, mean 5.3 ± 3.4%, Table 1). There were no significant differences in the number of days sharks were detected at VR2s along the western Hawaii coast (Kruskal–Wallis, $H_{11} = 14.6$, $P = 0.19$). However, when compared with those tagged in nearby Pawai Bay, sharks tagged around the cages spent more time within detection range of the cage (Fig. 7). Sharks T13 and T8 were detected at the cages on multiple days over a duration of 4–5 months (Fig. 7). Sharks T7 and T11 moved more extensively up and down the Kona coast, and spent multiple days over several weeks when their movements were localised around the cages (Fig. 7). However, even sharks regularly associated with the cages eventually moved on, with shark T13 being subsequently detected by receivers off Maui Island. Similar to tiger sharks captured off Oahu, most individuals showed no periodicity to their movements (e.g. diel shifts), except T13 which showed diel movements associated with the Kona fish cage, being detected primarily during the day (Fig. 6*e*, *f*).

Discussion

Fish farms in Hawaii appear to attract a large number of top predators, which is in stark contrast to farms in other locations where sharks are rarely seen (e.g. Boyra *et al.* 2004; Sanchez-Jerez *et al.* 2008). During diving and fishing operations around fish cages, we regularly caught or observed tiger, sandbar and blacktip sharks, as well as carangids (amberjacks, blue trevally, *Caranx melampygus*) and potential prey (e.g. *Decapterus macarellus*). While diving on the moi cages, occasionally >20 sharks and schools of >100 amberjack were observed.

Sandbar sharks

Previous fishing surveys conducted during the 1960s and 1970s have suggested that sandbar sharks are one of the most abundant shark species in the main Hawaiian Islands, accounting for nearly 75% of sharks caught (Wetherbee *et al.* 1994; Papastamatiou *et al.* 2006). Approximately half of the sandbars tagged were detected at the moi cages more than 1 year after tagging, and some individuals were detected for almost 2.5 years after release. Despite this, sharks were detected for significantly shorter periods than the battery life of the transmitters. This attrition could result from transmitter failure or expulsion, or may reflect emigration from the cage site after 1–2 years. Site fidelity and the distinctive diel habitat shifts observed in the present study are common in tropical reef-associated sharks, although it is unclear as to the function of these habitat shifts or when and where feeding occurs (e.g. McKibben and Nelson 1986; Lowe *et al.* 2006; Papastamatiou *et al.* 2009). A daytime refuge area may improve navigational

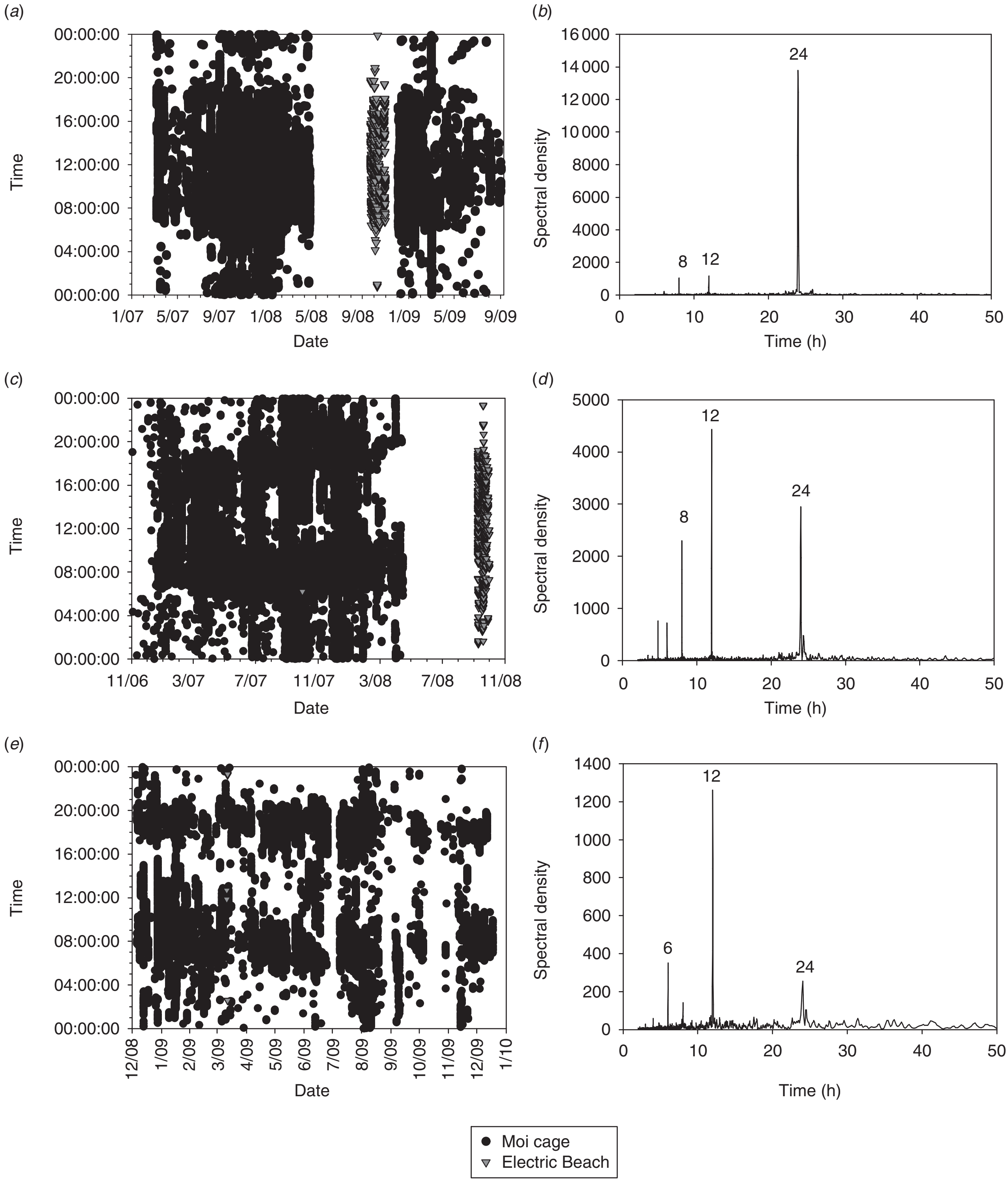

Fig. 3. Scatter plots and associated spectral analysis (fast fourier transformations) for sandbar sharks tagged at the moi fish cages. The dominant peaks in the power spectrum have been labelled. (*a*, *b*) SB4, (*c*, *d*) SB1 and (*e*, *f*) SB8. The gap in detections for SB4 and SB1 is due to loss of VR2 receiver at the moi cage during that period.

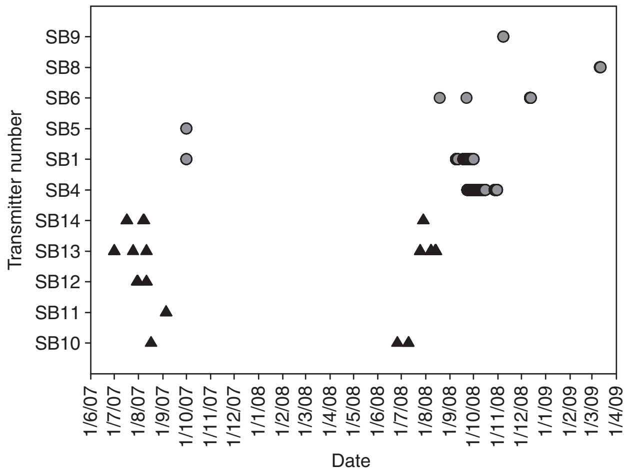

Fig. 4. Detections of acoustically tagged male (black triangles) and female (grey circles) sandbar sharks, at Electric Beach (western Oahu). Males were tagged off the northern shore, whereas females were tagged off the southern shore of Oahu.

abilities for sharks performing extended foraging searches at night (e.g. McKibben and Nelson 1986). The lag between peak water temperatures and residence times for sandbar sharks at the moi cages, suggests that peak primary productivity and the subsequent increase in forage base could be influencing shark fidelity to the cages.

On the basis of fishing records, sandbar sharks in Hawaii are thought to perform seasonal migrations, with male sharks moving inshore to shallow water during summer to mate with females (Wass 1973; Wetherbee *et al.* 1994). This approximates the seasonal movements observed in the present study. Sandbar sharks in Hawaii segregate horizontally in certain regions, with males being located off the northern coast of Oahu and females off the southern shore (Meyer *et al.* 2009*a*; the present study). The seasonal detection of both males and females at the Electric Beach site raises the possibility that the western coast of Oahu may be a location of summertime mating aggregations for sandbar sharks. However, female sandbar sharks were detected at Electric Beach right at the end of the male 'seasonal detection period'. The actual mating aggregations may be some distance away from Electric Beach, and we are only detecting sharks moving to and from the mating area. Alternatively, these seasonal movements may be linked to parturition, although juveniles are rarely caught on the western coast and are more commonly found off the eastern coast of Oahu (Wetherbee *et al.* 1994). Regardless of the function, these migrations suggest that fish farms are not disrupting the natural migratory patterns of this species. Galapagos and sandbar sharks associated with shark-cage diving operations off the northern coast of Oahu also continue to make seasonal migrations to other areas (Meyer *et al.* 2009*a*).

Historically, female sandbar sharks in Hawaii have been caught at an average depth of 46.1 ± 23 m (Wetherbee *et al.* 1994; Papastamatiou *et al.* 2006). Female sharks associated with the fish cages appear to occupy a similar vertical range, with most being recorded between 20 and 40 m. Results in the present study are biased by the bottom depths at the cages, but sharks rarely swam in waters shallower than 20 m.

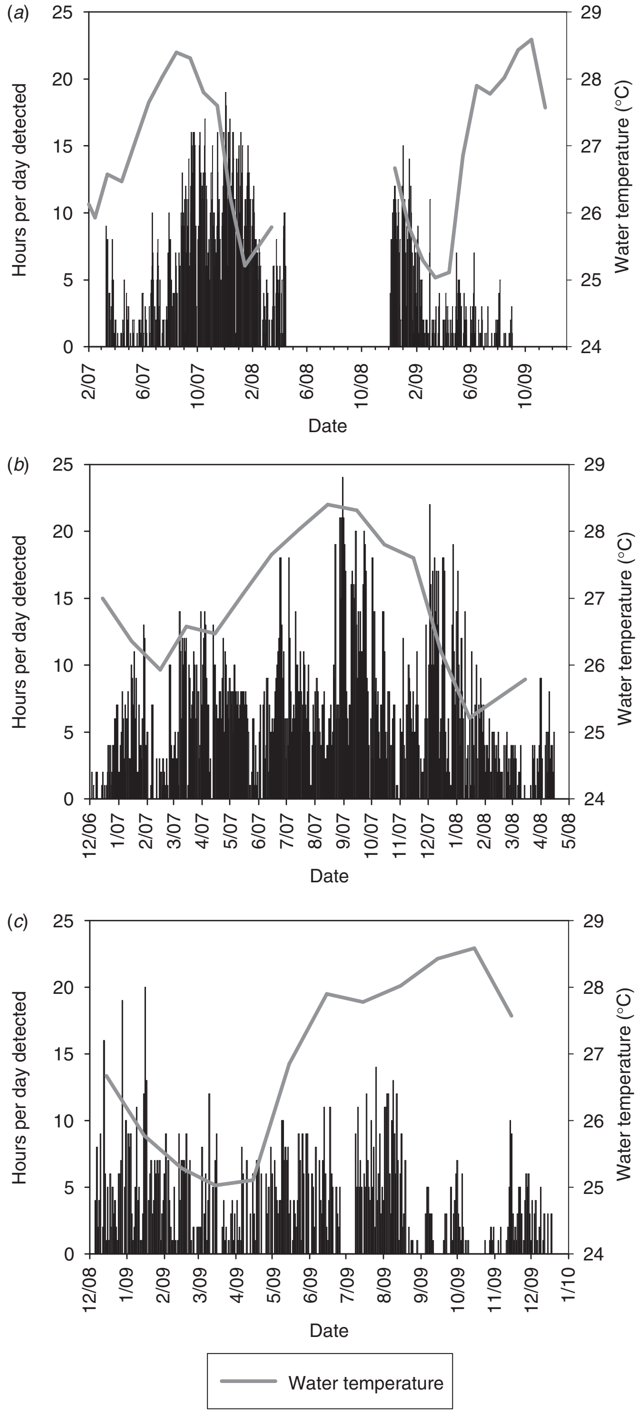

Fig. 5. Number of hours per day that sandbar sharks were detected at the moi fish cages. Grey line represents water temperature off of southern Oahu. Data are for (*a*) SB4, (*b*) SB1 and (*c*) SB8. The gap in data in (*a*) is due to loss of the VR2 receiver at the moi cage.

Tiger sharks

Tiger sharks in Hawaii have large home ranges that can span many islands within the Hawaiian archipelago, and are the species responsible for the majority of shark attacks in Hawaii (Holland *et al.* 2001; Lowe *et al.* 2006; Meyer *et al.* 2009*b*, 2010;

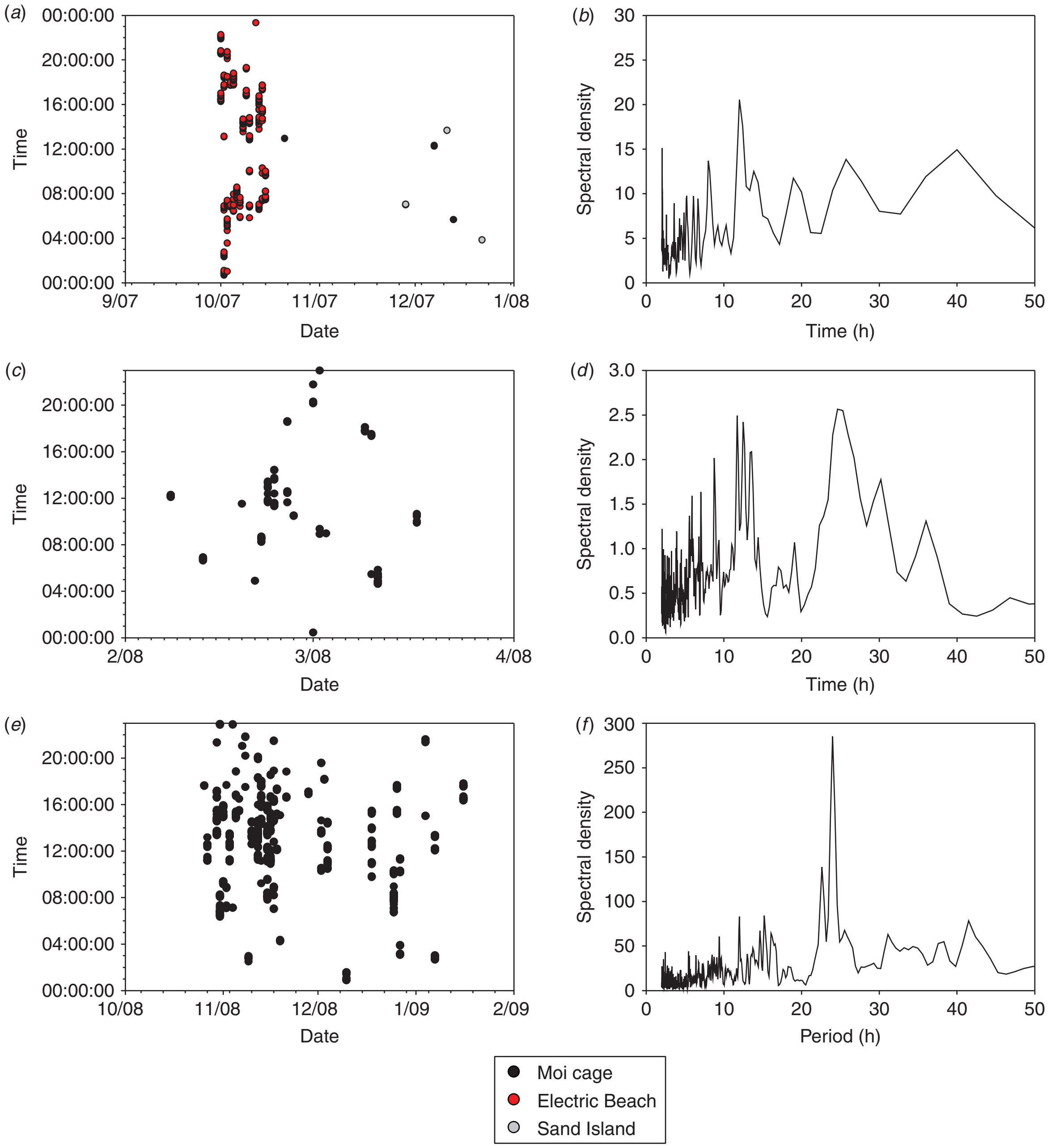

Fig. 6. Scatter plots and associated spectral analysis (fast Fourier transformations) for tiger sharks tagged by the moi cages and Kona Blue Water Fish Farms. (*a*, *b*) T3 (tagged by moi cages), (*c*, *d*) T5 (tagged by moi cages) and (*e*, *f*) T13 (tagged by Kona fish farms). Black circles in (*e*) refer to detections at the Kona fish farms.

G. Burgess, International Shark Attack File, pers. comm.). Furthermore, tiger-shark behaviour is often characterised by constant movement which results in most animals remaining in one location only for short periods of time (days to weeks), before moving to a new location, which is thought to be a predation strategy (Holland *et al.* 2001; Meyer *et al.* 2009*b*, 2010). Although numerous large tiger sharks were caught around the moi cages, the southern shore of Oahu has always had historically high tiger-shark catch rates (Wetherbee *et al.* 1994; Holland *et al.* 2001). The current data suggest that the cages may perhaps serve as 'landmarks' for tiger sharks moving along the Oahu coastline. Some individuals showed longer than expected periods of residency around the Kona Blue Water Fish farms. However, tiger sharks have shown extended periods of residency to other areas of the Kona coast (e.g. Puako, Honakahao Harbor) and a few individuals show diel and seasonal movements which may have nothing to do with anthropogenic attractants (Meyer *et al.* 2009*b*). The inter-island movement of

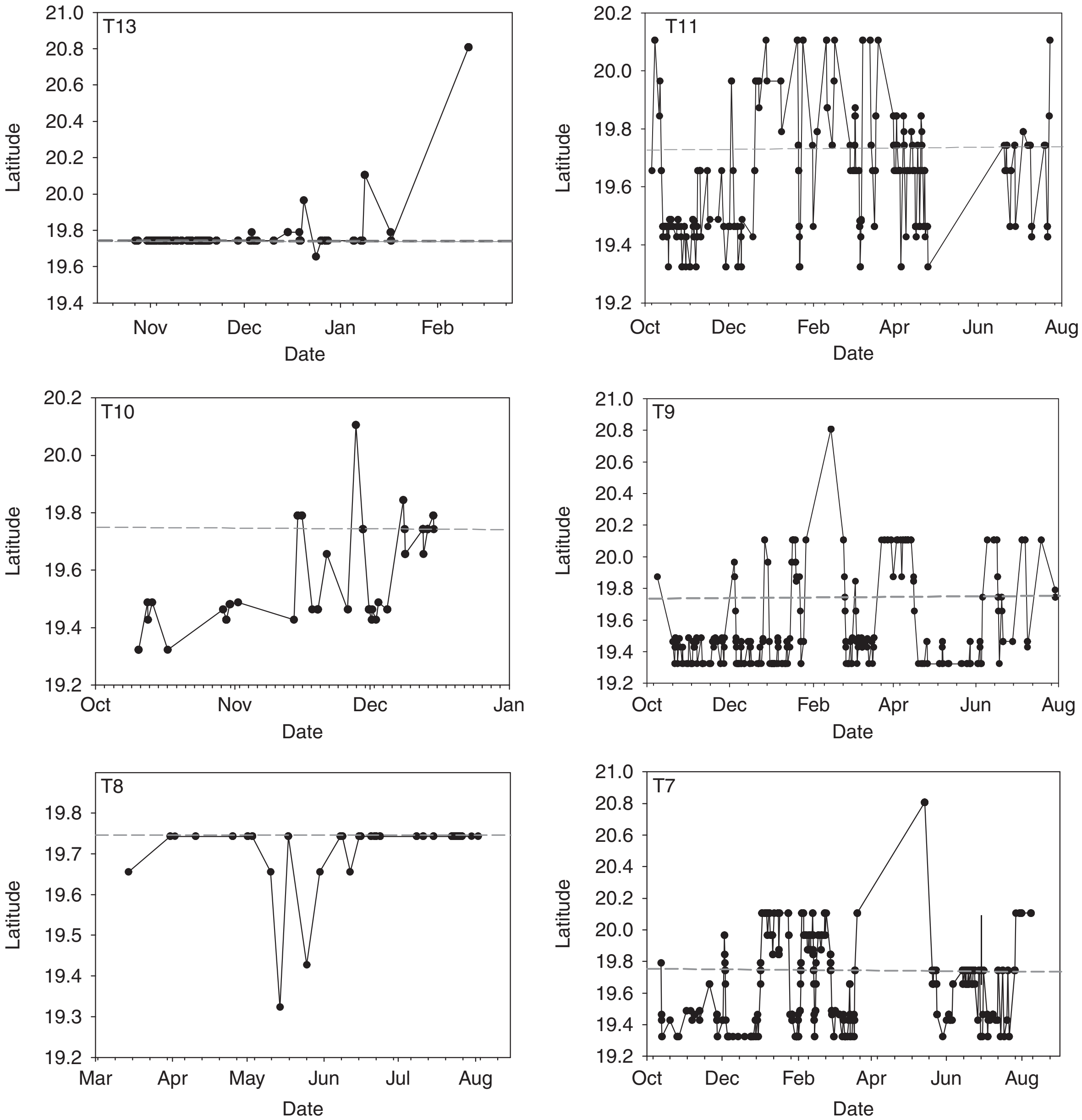

Fig. 7. Latitudinal movements of six tiger sharks tagged along the Kona coast (Hawaii). Points in figure indicate location of VR2s where tigers were detected. T11 and T9 were tagged at Pawai Bay close to Honakahau Harbor. All other tiger sharks were tagged by the Kona Blue Water Fish Farms. The grey dashed line indicates the location of the Kona fish farms.

one individual associated with the Kona Blue Water Fish Farm suggests that long-term entrainment (e.g. years) of tiger sharks is unlikely.

Public safety and ecological impacts

We cannot unequivocally determine whether or not ocean fish farms attract or aggregate sharks because we do not know how sharks in the area behaved before the deployment of the cages. However, on the basis of the telemetry results from the present study and others, and from fishing and diving in many areas around Oahu and Kona (e.g. Friedlander and DeMartini 2002), we believe ocean fish cages aggregate sandbar sharks, whereas tiger sharks only 'visit' these sites. It may be prudent for recreational water users to avoid the areas directly surrounding the ocean fish cages, although we found no evidence of farming operations having an impact on public safety on adjacent beaches; however, our monitoring coverage of popular beaches was limited. Large stretches of heavily utilised coastline lacked receiver coverage, raising the possibility of tagged tiger sharks visiting those locations undetected.

The ecological impacts of the cages are more difficult to assess. Although natural seasonal migrations may not be disrupted, there may be other effects that we are not able to quantify. If the cages are removing sharks from other locations, then the potential exists for shifts in behaviourally and density-mediated interactions and subsequent trophic cascades associated with predator displacement (e.g. Dill *et al.* 2003). Predator effects may be further reduced if sharks are foraging on biomass or left-over fish food associated with the cages. Future studies should determine the potential impacts the cages may have on the foraging ecology of sandbar sharks associated with the cages, and how this may affect prey communities in the local ecosystem. If aquaculture operations are found to provide a significant source of additional forage to sharks, some consideration should be given to regulating the density of ocean-farming operations.

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