


Residency and diel movement patterns of the endangered scalloped hammerhead *Sphyrna lewini* in the Revillagigedo National Park

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Abstract

This study is the first description of the residency and diel movements of *Sphyrna lewini* at the Revillagigedo National Park, Mexico. Eleven adult scalloped hammerheads of total length 200–300 cm were monitored using acoustic telemetry during 2013–2015 at four sites at San Benedicto Island. Diel and residency patterns were described based on 58,055 detections by four autonomous receivers. The sharks displayed high daytime residency in two of the four sites, with movements away into the pelagic environment at night. This study generates a baseline for effective monitoring to improve the conservation and management of an iconic but endangered species at this marine reserve.

KEYWORDS

conservation, Eastern Tropical Pacific, endangered species, site fidelity, telemetry

The scalloped hammerhead *Sphyrna lewini* (Griffith & Smith 1834) is a critically endangered coastal pelagic shark (Rigby et al., 2019) known to aggregate at seamount and oceanic islets throughout its distribution (Gallagher & Klimley, 2018). In the Mexican Pacific, studies have focused mostly on the analysis of dead animals captured by the fisheries department (Bejarano-Álvarez et al., 2011). These studies have shown that *S. lewini* prefers bony fishes and cephalopods (Flores-Martínez et al., 2017) and has a moderate growth ($k = 0.13$ per year) and a size of

180 and 220 cm total length (TL) for males and females, respectively, at onset of sexual maturity (Anislado-Tolentino & Robinson-Mendoza, 2001; Bejarano-Álvarez et al., 2011). Early studies describing the movements of this species were carried out by Klimley (Klimley, 1987; Klimley et al., 1988; Klimley et al., 1993; Klimley & Nelson, 1981, 1984) using acoustic telemetry in the Gulf of California.

More recently, archival and acoustic tags were deployed on juvenile scalloped hammerheads for a study on nursery areas of this

species on the west coast of Mexico (Hoyos-Padilla *et al.*, 2014; Rosende-Pereiro & Corgos, 2018). An adult scalloped hammerhead tagged with a pop-up archival tag was shown to move out of the Gulf of California and while doing so dive into the anoxic layer of the water column (Jorgensen *et al.*, 2009). Nonetheless, other than this there is little information regarding the movements of adult *S. lewini*, especially in pelagic ecosystems such as the Revillagigedo National Park (RNP). The aim of this study was to report the first observations of the residency and diel movements of *S. lewini* at the RNP to provide general insights into its key areas for monitoring and conservation.

The RNP is considered the largest marine reserve in North America, which includes four volcanic islands—Socorro, San Benedicto, Roca Partida and Clarion—spanning 148,000 km² (CONANP, 2017). Scientific expeditions were carried out at the RNP where an array of 12 acoustic receivers (VR2W, VEMCO Ltd., Nova Scotia, Canada) were installed around the four volcanic islands between 2009 and 2013 (Figure 1a). Four receivers were installed at sites known as Boiler, Canyon, Lava Flow and Cuevitas at San Benedicto Island (SBI; 19° 18' 32" N; 110° 48' 44" W; Figure 1b) in 20–40 m depth. At this island, 11 mature scalloped hammerheads were tagged in 2013 by scuba and free diving. Ultrasonic transmitters with unique identifying codes (VEMCO V16, 69.0 kHz) on a stainless-steel barb and tether were attached externally to the dorsal musculature of each shark. Ethics and tagging procedures followed an animal care protocol

(Protocol number 16022, UC Davis Institutional Animal Care and Use Committee). Divers reported the approximated size and sex by the presence of claspers in males and the absence of these structures in females (Compagno *et al.*, 2005).

Residency index was calculated for each of the tagged sharks by dividing the number of days on which a shark was detected with the number of days elapsed from tagging to the last detection. A value of 1 indicates that sharks were always present, whereas 0 indicates periods of absence from the study site (Espinoza *et al.*, 2015). Circular diagrams were generated to describe diel patterns between daytime (06.00–19.00 hours) and night-time (19.00–06.00 hours). In addition, a Rao's spacing test was applied to describe data uniformity throughout the day (Batschelet, 1981; Lund & Agostinelli, 2007).

Nine female and two male hammerheads, with size 200–300 cm TL, were tagged (Table 1). Shark activity was recorded by all four receivers deployed at SBI, but not by the eight receivers deployed around the other islands of the archipelago.

A total of 58,055 acoustic detections were recorded for all tagged sharks. The minimum number of detections per male shark was 368 in 12 days, whereas the maximum number for a female was 23,957 in 807 days (Table 1). The Canyon site reported 72.46% of the detections ($n = 42,066$), followed by Lava Flow 22.27% ($n = 12,926$), Boiler 5.08% ($n = 2950$) and Cuevitas 0.35% ($n = 203$).

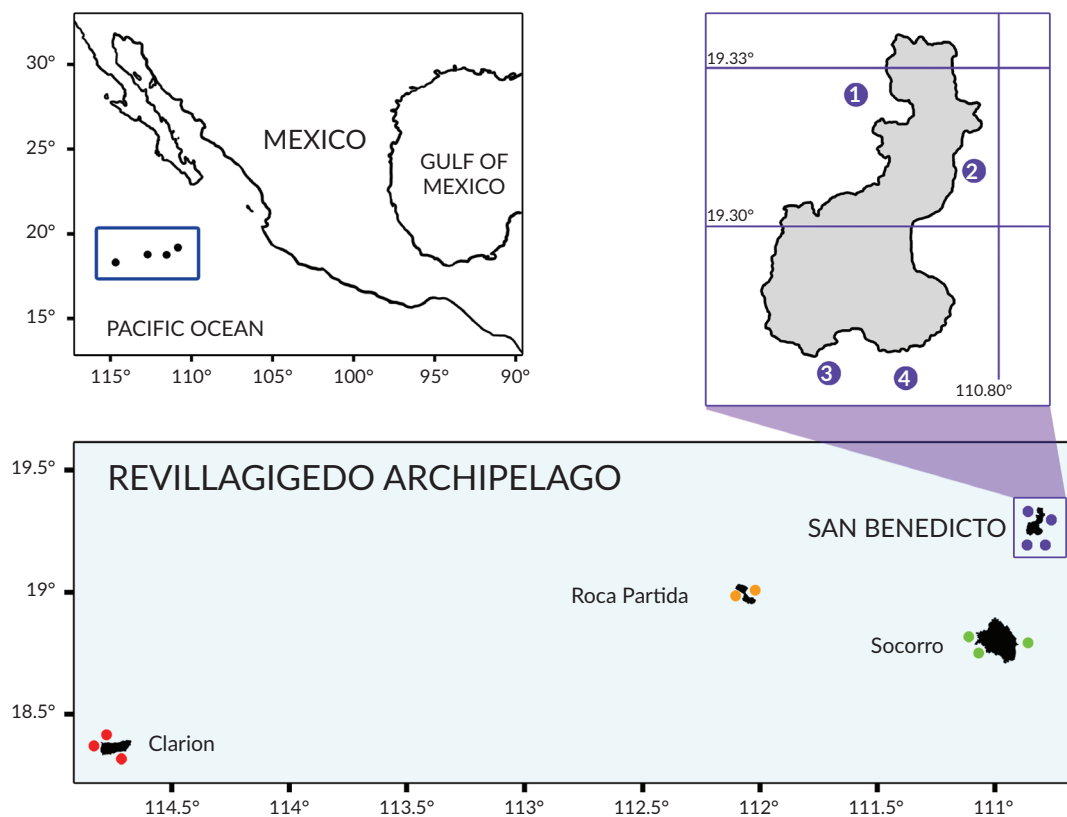


FIGURE 1 (a) Revillagigedo National Park (boundary given as blue rectangle). (b) The four Revillagigedo islands with black dots indicating the locations of the acoustic receivers (see solid coloured circles) for each island, with an inset showing San Benedicto Island with higher spatial resolution with the locations of the four acoustic receivers: (1) Boiler, (2) Cuevitas, (3) Canyon and (4) Lava Flow

TABLE 1 Acoustic detections and biological data of the 11 adult scalloped hammerhead sharks tagged in San Benedicto Island during 2013–2014

ID	Sex	TL	Tagging day	Detections	Initial date	Final date	Days detected	Days monitored
HH1	F	300	1 July 2013	797	9 January 2013	5 February 2013	27	802
HH2	F	300	1 August 2013	3690	8 January 2013	27 April 2013	109	803
HH3	F	300	1 September 2013	4612	4 January 2013	25 March 2014	445	807
HH4	F	200	1 October 2013	3638	9 January 2013	2 January 2014	358	802
HH5	F	200	1 October 2013	797	8 January 2013	19 February 2013	42	803
HH6	F	270	1 November 2013	2475	11 January 2013	15 May 2013	124	800
HH7	M	270	1 November 2013	413	10 January 2013	25 January 2013	15	801
HH8	F	250	1 December 2013	23,957	12 January 2013	23 September 2014	619	799
HH9	F	220	1 December 2013	14,136	11 January 2013	22 March 2015	800	800
HH10	M	250	1 December 2013	368	12 January 2013	24 January 2013	12	799
HH11	F	280	3 July 2013	3172	8 March 2013	3 November 2013	240	744

TL, total length (cm).

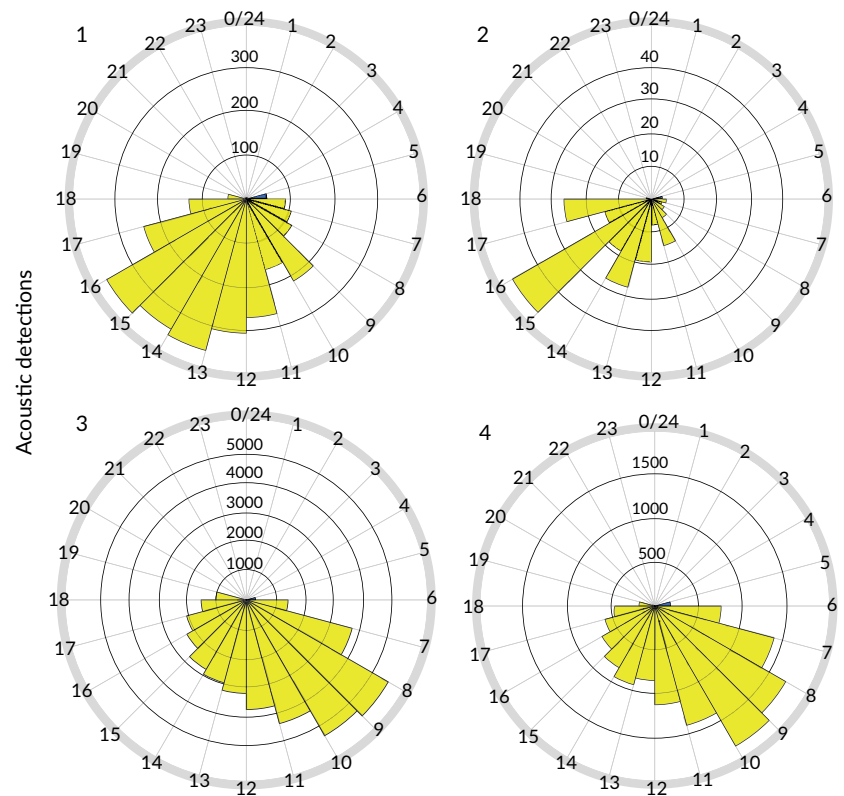


FIGURE 2 Number of acoustic detections per hour of 11 scalloped hammerhead sharks tagged in San Benedicto Island, Mexico: (1) Boiler ($n = 2950$), (2) Cuevitas ($n = 203$), (3) Canyon ($n = 42,066$) and (4) Lava Flow ($n = 12,926$). ■ Day, ■ Night

The hammerheads spent most of the day within range of the receiver locations. A higher number of detections were observed during the morning, 06.00–12.00 hours, in Canyon and Lava Flow, and during the afternoon, 12.00–18.00 hours, in Boiler and Cuevitas. Overall, a significantly lower number of detections were observed by the four receivers during the night (test, $P < 0.01$; Figure 2).

The sharks remained in the area for 1–27 months, with a mean of 8.9 months (s.e. ± 2.7). Residency index at the four sites ranged from 0.08 to 0.73, with a mean of 0.38 (s.e. ± 0.29 ; Figure 3). Residency

was significantly higher at Canyon, with values ranging from 0.01 to 0.57, and at Lava Flow, from 0.00 to 0.38, than at Boiler and Cuevitas, with values ranging from 0.00 to 0.01 and from 0.00 to 0.04, respectively (Figure 3).

The scalloped hammerhead shark is one of the most important species in commercial fisheries, as well as in ecotourism activities in the Mexican Pacific (Bejarano-Álvarez *et al.*, 2011; Ketchum *et al.*, in press; Cisneros-Montemayor *et al.*, in press). Nonetheless, the lack of full protection policies and insufficient regulations in some key areas, such as seamounts or oceanic environments, have significantly

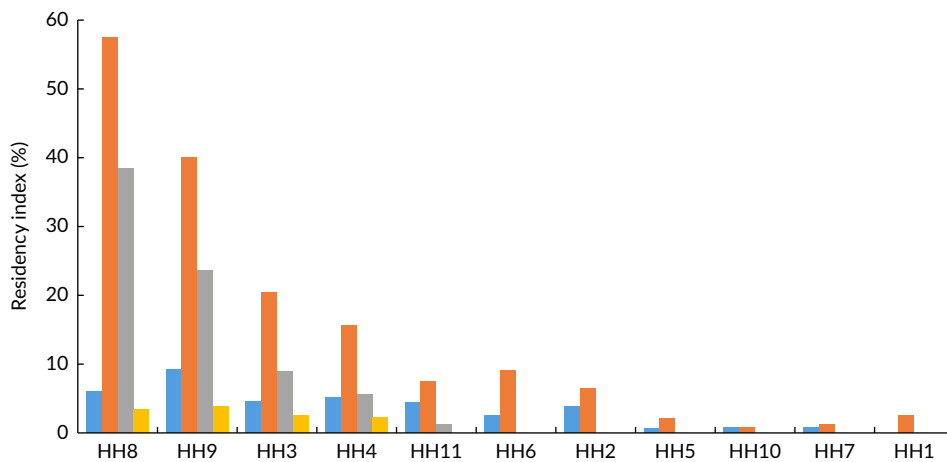


FIGURE 3 Residency index of the 11 scalloped hammerhead sharks analysed according to the locality in San Benedicto Island, Mexico. Boiler, Canyon, LavaFlow, Cuevitas

reduced their populations (Klimley et al., 2005; Hoyos-Padilla et al., 2014; Ketchum et al., in press). Although there is published information regarding the residency of this species in the Gulf of California (Klimley & Nelson, 1984; Klimley et al., 1988), the present study constitutes the first observations of its residency and movement patterns in the RNP.

The present study was focused mostly on adult females. These results may be related to a preference of *S. lewini* to SBI, especially for the southern area of this island where the highest number of detections was observed; this might be related to the proximity of some offshore seamounts where they feed.

The high residency of female hammerheads in the southern area of SBI constitutes an important refuge as shown for this species at a seamount in the Gulf of California (Klimley & Nelson, 1984), which may relate to the magnetic properties of the site (Klimley, 1993) as well as the occurrence of cleaning stations (Bessudo et al., 2011; Ketchum et al., 2014a). In the southern area of SBI, the strong currents could allow low-energy swimming for the scalloped hammerheads during their aggregation in schools, as it has been suggested in other localities like Malpelo (Bessudo et al., 2011), Galapagos (Hearn et al., 2010; Ketchum et al., 2014a) or Cocos (Nalesso et al., 2019).

In addition, the residency of *S. lewini* during the day could be related to the presence of cleaning stations, where blacknose butterflyfish *Johnrandallia nigrirostris*, the Mexican hogfish *Bodianus diplotaenia* and the endemic Clarion angelfish *Holacanthus clarionensis* have been observed by the co-authors (J.T.K. and E.M.H.). This behaviour has been observed in many other areas such as the Gulf of California and several islands in the Eastern Tropical Pacific such as Cocos, Galapagos and Malpelo.

Females of the species within schools compete for males (Klimley, 1985), resulting in pairing and mating socially during the day at these sites (Salinas-de-León et al., 2017). Thus, the insular habitat, recognizable by its bathymetry and magnetic nature, can serve as a refuge, where social interaction occurs, and a staging location to move into the pelagic environment to forage (Klimley, 1993; Klimley et al., 1993; Hearn et al., 2010; Ketchum, et al., 2014a).

The scalloped hammerheads remain at SBI during the day, whereas at night the lower number of detections may be due to the

movement of sharks to offshore areas. This pattern has been suggested as part of the feeding behaviour and diel movements of *S. lewini* in other areas of the Eastern Tropical Pacific (Hearn et al., 2010; Ketchum et al., 2014a,b; Nalesso et al., 2019).

This long-term, high site fidelity suggests that in terms of conservation, SBI may be considered an important aggregation site for this endangered species. Future research on hammerheads at the RNP should include oceanographic and geomagnetic surveys performed *in situ*, especially at depths where the scalloped hammerheads usually are found. Additional work should be performed on cleaning stations, particularly behavioural studies on the cleaning interactions for scalloped hammerheads and other species of sharks.

Aggregations of *S. lewini* like those observed at SBI can indicate that certain populations are small, highly localized and in shallow water (<30 m depth). This makes hammerheads highly vulnerable because their direct capture, especially near the ocean surface (Ketchum et al., 2009), could lead to their decline affecting the recruitment of the species (Baum et al., 2003; Baum & Myers, 2004), particularly if most sharks are adult females.

The establishment of the RNP as a large-scale no-take in 2017 may be an effective tool for the protection of the scalloped hammerhead, considering the occurrence of aggregation sites at SBI as well as at other islands such as Socorro and Roca Partida (author's personal observation). Nevertheless, other conservation and management tools are critical for the protection and recovery of this endangered species in the Gulf of California and the Mexican Pacific.

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