Shark movements and the design of protected pelagic environments within and beyond the Galapagos Marine Reserve

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Abstract

The Galapagos Archipelago is one of the last outposts where large numbers of sharks and other marine predators still remain in the eastern tropical Pacific. The Galapagos Marine Reserve (GMR) offers some protection, but its effectiveness is limited because the movements of marine predators were not considered in the general layout of the reserve. We intend to alleviate this management problem by incorporating the spatial distribution of sharks in the design of protected pelagic environments. Satellite and shipboard tracking at the Galapagos Islands have led to the description of the movements of scalloped hammerhead and Galapagos sharks on insular (< 50 km), inter-island (50-400 km) and oceanic (> 500 km) spatial scales. This implies 1) a high degree of use of areas bordering islands, 2) inter-island connectivity within the GMR, and 3) the likelihood of migratory corridors between the Galapagos and open ocean regions beyond the reserve either adjacent to the GMR 40-mile limit or further offshore. Our work demonstrates that hotspots vary in scale, from small-scale hotspots along the coast to large-scale hotspots encompassing Darwin and Wolf islands. These findings have profound implications in the shaping of marine reserves.

Introduction

Marine predators such as sharks exhibit a whole range of behaviors and occupy a diversity of habitats, reflected in their movements occurring at different spatial and temporal scales. However, these movement patterns are far from understood. The efficacy of the Galapagos Marine Reserve (GMR) in protecting marine predators is limited and an oceanic zonation scheme has yet to be proposed. The original design of the GMR includes a zonation scheme; however, management has focused on the coastal zone (Heylings et al. 2002). This is preliminary and subject to change based on long-term surveys (Edgar et al. 2004). In this study we determine movement patterns of sharks, describe their diel movement patterns and degree of residency, and elucidate environmental preferences to suggest an approximation, in shape and extent, of a pelagic marine reserve, and propose that movement patterns of coastal-pelagic predators be included in an improved zonation system within the GMR.

Methods

Six cruises were carried out between 2006 and 2009 to place satellite and ultrasonic tags on scalloped hammerhead sharks (*Sphyrna lewini*) and Galapagos sharks (*Carcharhinus* *galapagensis*) and to perform shipboard tracking at Darwin and Wolf Islands. In July 2006, we placed SPOT and PAT tags on 12 Galapagos sharks, and from November 2007 to March 2009, we tagged eight hammerhead sharks with similar tags. The sharks were caught by hook and line, placed on a canvas sling and lifted to the deck of a boat. Here the tags were bolted to the dorsal fin, and the PAT tags affixed to the dorsum by inserting a titanium dart into the musculature. Six hammerheads and one Galapagos sharks were tagged by free diving with ultrasonic transmitters (V22TP) equipped with sensors and then followed from a small boat for periods of 24 to 72 hrs. Transmissions from the satellite tags were acquired and processed by ARGOS, and transmissions from ultrasonic tags were received and recorded with an on-board acoustic hydrophone and receiver. We used different software (e.g. WGP suite, DAP, SATPAK) to decode the data transmitted from satellite tags, and performed further analyses using ArcGIS and Animal Movement 2.0 extension for ArcView.

Results

Our studies using satellite and ultrasonic telemetry at the Galapagos Islands show movements of scalloped hammerhead (HH) and Galapagos sharks (GS) at different spatial scales: insular (<50 km), inter-island (50-400 km) and oceanic (> 500 km) (Fig. 1). Insular movements are associated to 'hotspots' around islands, inter-island movements are directional and non-directional within the archipelago, whereas oceanic ones are more directional to other offshore regions. The movements imply connectivity within the archipelago and the likelihood of migratory corridors between the Galapagos and other islands or seamounts. Both species of sharks demonstrated site fidelity. GS exhibited site fidelity to a specific location in the southeast end of Darwin Island (Fig. 2a). HH showed site fidelity to a large area around Darwin and Wolf Islands indicated by the kernel of the home range calculated using a random walk simulation of 1000 iterations (Fig. 2b). Analysis of insular movements of HH demonstrated a high degree of habitat use in the east and southeast of Wolf Island, and a lower level of usage in an area 3-5 km east of the island (Fig. 3). A home range analysis of satellite tracks described different levels of habitat use within and outside the archipelago. GS showed a high degree of habitat use around Darwin Islands and at a lesser level in Bahia Cartago (Isabela) (Fig. 4a). A low to medium degree of habitat utilization was evident along an oceanic ridge west of the archipelago. The home range extent for GS was generally small. In contrast, HH exhibited high levels of habitat usage but covering a larger area surrounding both Darwin and Wolf Islands, followed by Cabo Marshall (Isabela) and at a lower level in two offshore locations northwest and northeast of Darwin (Fig. 4b), hence, home range extent for HH was relatively large.

Discussion & Conclusions

Shark movements in the Galapagos Islands show great complexity. The Galapagos archipelago is composed of many islands, islets, rocks and seamounts isolated from each other by deep water (Houvenaghel 1984), and spread across the equator in a unique oceanographic setting (Banks 2002). The expansive oceanic habitat available with temporally varying elevated levels of primary productivity in different parts of the archipelago (Banks 2002), sustains large amounts of prey inshore along the coast of the islands and offshore near the seamounts. At insular scales, HH and GS concentrate their habitat utilization in the southeastern sides of Wolf and Darwin islands, or localized hotspots, occupied by multiple species of jacks, tunas, and sharks. HH make movements to nearby offshore locations to forage at night and returning in early hours of the day in a similar fashion of movement as observed for HH in the Gulf of California (Klimley 1993). Nevertheless, the two shark species differed in site fidelity and habitat utilization, with HH requiring a larger habitat than GS, extending around Wolf and Darwin. The home ranges of both species stretch out beyond the 40-mile limit of the GMR. Does the zonation of the GMR, chosen through socio-political negotiations (Edgar et al. 2004), protect the complete range of [shark] habitats? Based on our results, the answer is "no". The protection of sites such as Wolf and Darwin where large numbers of sharks occur was effectively negotiated by tourism operators but, having a socio-political decision shaping a marine reserve seems ineffective for conserving these species. For example, we observed HH foraging several kilometers east of Wolf, however, this habitat is not part of the current zonation scheme. Furthermore, we found that as HH and GS move into oceanic waters beyond the reserve they swim near the surface, hence they are vulnerable to fishing just outside the GMR. Considering the potential of top marine predators as conservation tools (Sergio et al. 2008) and their relevance in structuring marine ecosystems (Steneck & Sala 2005), we suggest a modification of the current shape and extent of the GMR around the far northern islands and propose a new zonation of the GMR based in the movements of marine predators.

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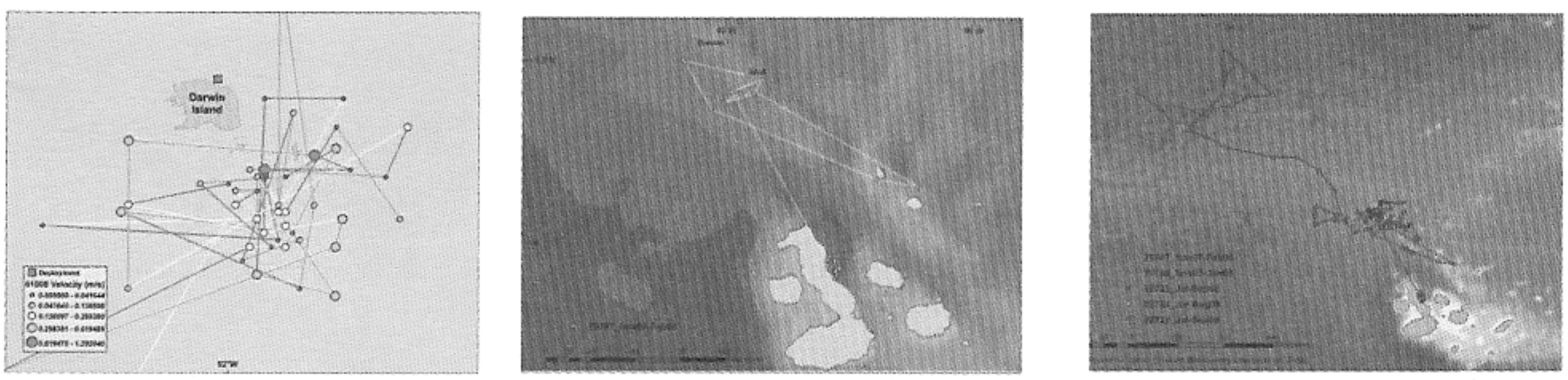
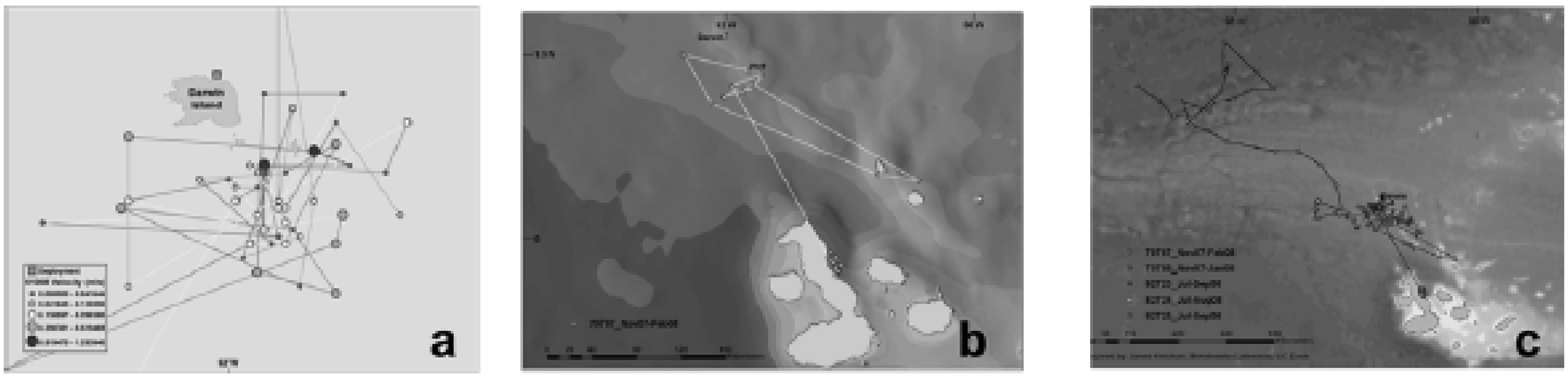


Figure 1. Movements of sharks at different scales. Insular (a), inter-island (b), and oceanic movements (c).



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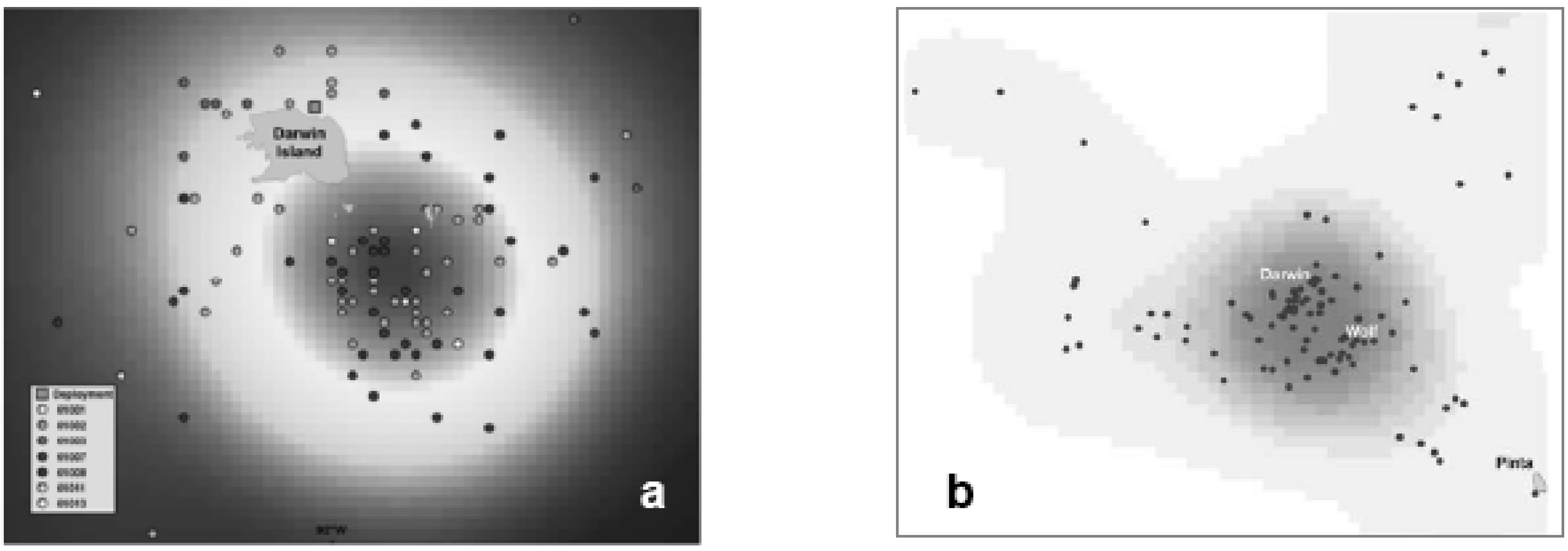

Figure 2. Home range kernels and site fidelity for Galapagos (a) and hammerhead (b) sharks. The darker color towards the center means higher probability of habitat utilization. Dots denote locations of sharks transmitted by satellite tags.

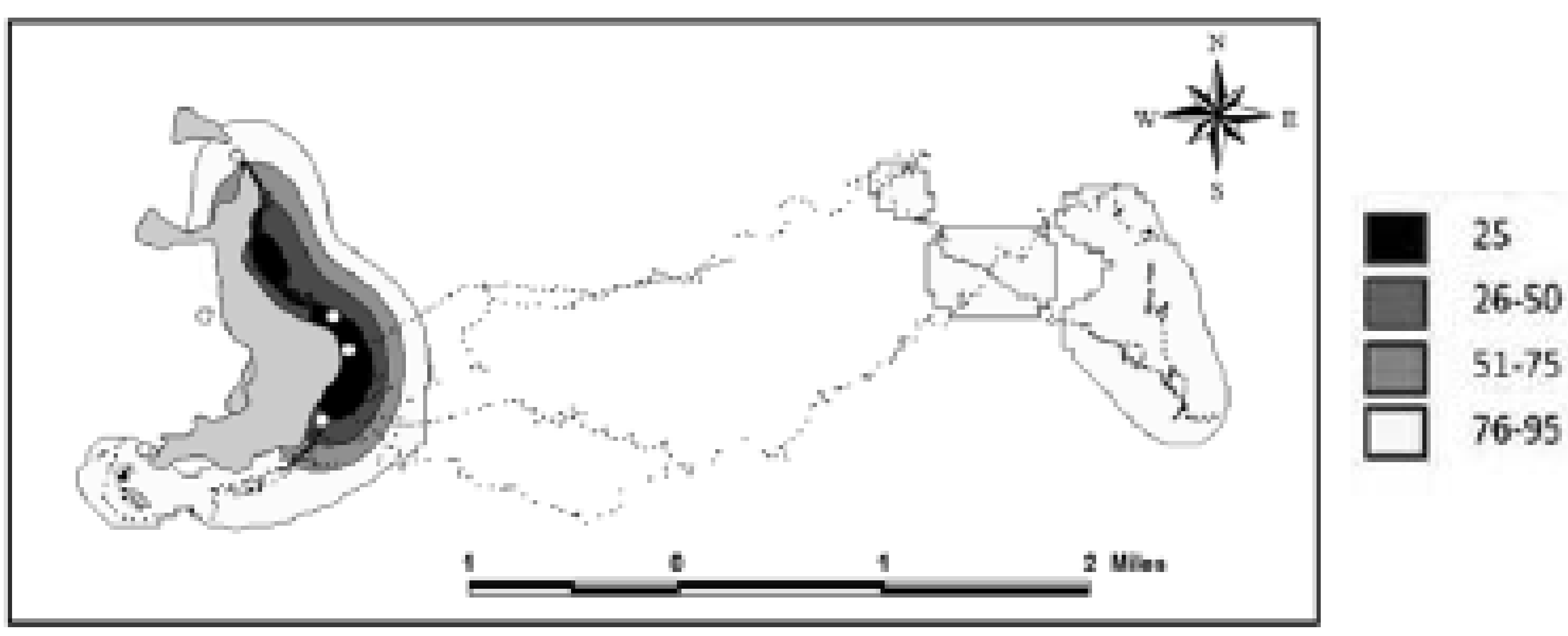

Figure 3. Home range extent for hammerhead sharks at Wolf Island.

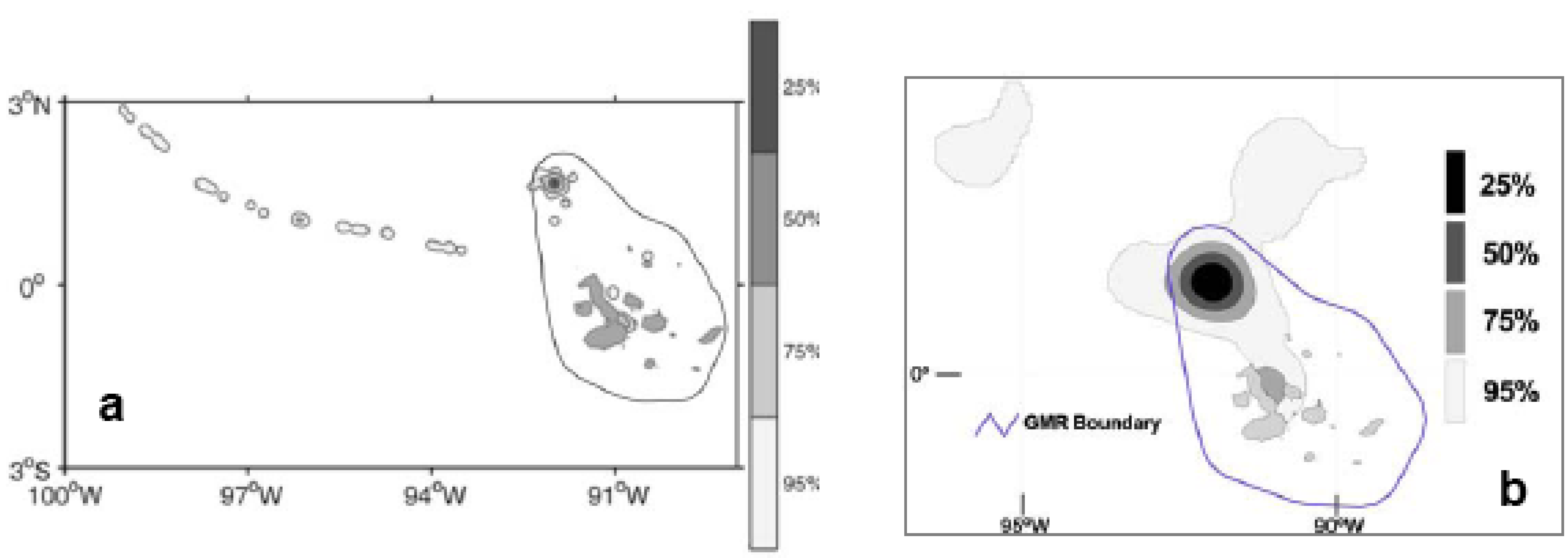

Figure 4. Home range extent for 12 Galapagos sharks (a) and 8 hammerhead sharks (b), showing the 40-mile boundary of the GMR.