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Reef shark movements relative to a coastal marine protected area

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HIGHLIGHTS

- We monitored the use of a protected area by three species of reef sharks.
- Adult reef sharks had larger activity spaces than juvenile reef sharks.
- Juveniles are likely better protected than adults due to limited movements.
- Residency ranged between 12 and 96%; many individuals were resident year round.
- We observed a migration of 275 km made by a female blacktip reef shark.

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ABSTRACT

Marine protected areas (MPA) are one management tool that can potentially reduce declining shark populations. Protected-area design should be based on detailed movements of target animals; however, such data are lacking for most species. To address this, 25 sharks from three species were tagged with acoustic transmitters and monitored with a network of 103 receivers to determine the use of a protected area at Mangrove Bay, Western Australia. Movements of a subset of 12 individuals (*Carcharhinus melanopterus* [$n = 7$]), *C. amblyrhynchos* [$n = 2$], and *Negaprion acutidens* [$n = 3$]) were analysed over two years. Residency for all species ranged between 12 and 96%. *Carcharhinus amblyrhynchos* had $<1\%$ of position estimates within the MPA, compared to *C. melanopterus* adults that ranged between 0 and 99%. Juvenile sharks had high percentages of position estimates in the MPA (84–99%). Kernel density activity centres for *C. melanopterus* and *C. amblyrhynchos* were largely outside the MPA and mean activity space estimates for adults were 12.8 km^2 ($\pm$3.12 SE) and 19.6 km^2 ($\pm$2.26), respectively. Juveniles had smaller activity spaces: *C. melanopterus*, 7.2 $\pm$1.33 km^2; *N. acutidens*, 0.6 km^2 ($\pm$0.04). Both *C. melanopterus* and *C. amblyrhynchos* had peaks in detections during daylight hours (1200 and 0900 h, respectively), whereas *N. acutidens* had a peak in detections at 0200 h. Long-distance movements were observed for adult *C. melanopterus* and *C. amblyrhynchos*, the longest being approximately 275 km. These migrations of *C. melanopterus* might be related to reproductive behaviours, because they were all observed in adult females during the summer months and provide links between known in-shore aggregation and possible nursery areas. The MPA at Mangrove Bay provided some protection for juvenile and adult reef sharks, although protection is likely greater for juveniles due to their more restricted movements.

1. Introduction

Marine protected areas (MPA) are one of the many approaches currently employed to manage and conserve fish populations. Some consider protected areas to be superior to other

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management techniques such as bag limits because a well-defined protected area is easier to monitor and enforce (Holland et al., 1996). However in reality, the effectiveness of designated protected areas also depends *inter alia* on placement, size and use of relevant biological knowledge of the organisms targeted for protection (Roberts, 2000). Although protected areas often have positive effects on biomass (Roberts, 2000), the magnitude and extent of most benefits depend on the rate and scale of animal movement in relation to reserve size (Kramer and Chapman, 1999). If the rate of movement from protected into non-protected areas is high, then effectiveness is compromised (Holland et al., 1996). Consequently, how much time targeted organisms spend within protected-area boundaries (Heupel and Simpfendorfer, 2005) is one of the most important criteria for reserve design; for this reason, such information is of great value for management.

One method to collect these data is through the use of acoustic telemetry, which can quantify movement patterns and estimate home range size. For example, this approach has been used to estimate spatial habitat use by several species of teleosts (Holland et al., 1996; Afonso et al., 2009; Wetherbee et al., 2004). It is essential that data on long-term (>1 year) patterns of movement and habitat use by many individuals of a target species are collected. Acoustic monitoring, where a network of underwater receivers are placed to capture seasonal shifts in movement (e.g. Egli and Babcock, 2004), is useful in this regard.

There has been a persistent global decline in many populations of tropical reef sharks (Ward-Paige et al., 2010; Robbins et al., 2006; Friedlander and DeMartini, 2002; Ferretti et al., 2010; Field et al., 2009), and marine parks have been suggested as one potential solution to slow this process at local scales (e.g., Bond et al., 2012). However, there have only been a few quantitative assessments of the effectiveness of protected areas for this role because the necessary movement data are generally only available for a few species and size classes (e.g. Heupel and Simpfendorfer, 2005, Bond et al., 2012, Chapman et al., 2005, Garla et al., 2006, Knip et al., 2012, da Silva et al., 2013 and Barnett et al., 2011). Studies suggest that reef sharks typically restrict their movements to within a range of <100 km^2 and show fidelity to specific sites (Chapman et al., 2005; Garla et al., 2006; Speed et al., 2010; Field et al., 2011; Speed et al., 2011; Papastamatiou et al., 2009; DeAngelis et al., 2008; Gruber et al., 1988; Chapman et al., 2009). In some instances, larger movements have been observed by smaller species (<2 m length) such as grey reef (*Carcharhinus amblyrhynchos*) and blacktip reef sharks (*Carcharhinus melanopterus*) (e.g. Heupel et al., 2010 and Chin et al., 2013), although such movements are common in large species (>4 m) such as tiger sharks (*Galeocerdo cuvier*) (Heithaus et al., 2007; Meyer et al., 2009).

Benefits of marine protected areas are likely to be greater for juvenile sharks because these life stages tend to have smaller home ranges and show greater site fidelity than adults (Garla et al., 2006; Gruber et al., 1988; Chapman et al., 2009; Heupel et al., 2010), and home range generally increases with body size (Speed et al., 2010). However, patterns in habitat use are not necessarily constant. For example, both the juveniles and adults of some species can spend more time in refugia during the day before moving more widely at night (Garla et al., 2006; Speed et al., 2011; Papastamatiou et al., 2009; McKibben and Nelson, 1986; Klimley and Nelson, 1984; Barnett et al., 2012), while grey reef sharks can be present on the reef both day and night at isolated atolls (Field et al., 2011). In a more connected network of habitats, the same species can move routinely between patches of reef over scales of 30–40 km, and can even make large movements of up to 134 km (Heupel et al., 2010). The ability of adult sharks to move over these broad spatial scales suggests that no single reserve is likely to be of sufficient size to offer complete protection throughout all life stages (Dale et al., 2011). However, designing reserves to reduce negative impacts on the most vulnerable life history stages is still possible. To optimise this process, we require data on the movement and residency patterns of reef sharks across spatial and temporal scales.

Ningaloo Reef is the largest fringing reef in Australia (260 km long) and is protected by the multiple-use Ningaloo Marine Park established in 1987 (DEC, 2005). Commercial fishing is prohibited and there are 18 marine protected areas that cover 34% of the park's area (combined protected areas = 883.65 km^2). Although many species of reef sharks are common within the park, including *C. melanopterus*, *C. amblyrhynchos*, whitetip reef *Triaenodon obesus*, and sicklefin lemon *Negaprion acutidens* sharks (Stevens et al., 2009), the zoning plan for the park was not developed with the sole aim of conserving populations of these animals. Therefore, it is not known to what extent spatial management of the reef aids the conservation of these species.

This study addresses the lack of data currently available for reef shark management and conservation planning. The overlap of shark movement patterns with the spatial coverage of a protected area (Mangrove Bay Sanctuary) within Ningaloo Marine Park was determined. The hypotheses of the study are: (1) juveniles have a smaller range of movement than adults and will therefore be afforded more protection by the MPA; (2) due to increased nocturnal movement rates, sharks should be detected within the Mangrove Bay array more frequently during the day than at night, provided they are resident to the area; and (3) the range of movements of *C. amblyrhynchos* should be larger than *C. melanopterus* and juvenile *N. acutidens* given their larger body size.

2. Material and methods

2.1. Study area

Data were collected at Ningaloo Reef between November 2007 and August 2010 (Fig. 1). The primary study site was at Mangrove Bay (21° 58′ 14″S, 113°56′ 34″E), although extensive work was done in a parallel study at Coral Bay (23° 7′ 36″S, 113° 46′8″E) (Speed et al., 2011). Both Mangrove and Coral Bay encompass protected areas within them and are managed under the Ningaloo Reef Marine Park by the Western Australia Department of Parks and Wildlife. Mangrove Bay can be characterised as an open, sandy lagoonal habitat that encompasses small mangrove-lined inlets and creeks.

2.2. Acoustic monitoring and shark tagging

Acoustic receivers (VR2W and VR3, Vemco©, Halifax, Canada) were deployed along the reef to record long-term movements of tagged individuals. The network of receivers consisted of three curtains that ran at right angles to the reef towards the edge of the continental shelf, and two main arrays, one of which was in Coral Bay and the other in Mangrove Bay (Fig. 1). The southern curtain consisted of 18 receivers; the central curtain had 13, and the northern curtain had seven. The Coral Bay array had nine receivers, while the Mangrove Bay array had 56. Receivers were fixed in position with either with steel pickets, or tyres filled with cement (Speed et al., 2011). Approximate mean maximum detection range of receivers was 300 m (Speed et al., 2011).

Sharks were tagged with V13-1H (dB 153) and V16-5H (dB 165) coded transmitters (VEMCO©, Halifax, Canada), which were inserted into the peritoneal cavity (Speed et al., 2011). Due to comparatively lower output strength of the V13 tags compared to V16 tags, the detection range would be slightly reduced for sharks fitted with V13 tags, although V13 tags have been found to be comparable in previous tests at Ningaloo (Speed et al., 2009). As part of a parallel study, sharks were also tagged at Coral Bay