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Assessing the effectiveness of a large marine protected area for reef shark conservation

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ABSTRACT

Large marine protected areas (MPAs) have recently been established throughout the world at an unprecedented pace, yet the value of these reserves for mobile species conservation remains unclear. Reef shark populations continue to decline even within some of the largest MPAs, fueling unresolved debates over the ability of protected areas to aid mobile species that transit beyond MPA boundaries. We assessed the capacity of a large MPA to conserve grey reef sharks - a Near Threatened species with a widespread distribution and poorly understood offshore movement patterns - using a combination of conventional tags, satellite tags, and an emerging vessel tracking technology. We found that the 54,000 km^2 U.S. Palmyra Atoll National Wildlife Refuge in the central Pacific Ocean provides substantial protection for grey reef sharks, as two-thirds of satellite-tracked sharks remained within MPA boundaries for the entire study duration. Additionally, our analysis of >0.5 million satellite detections of commercial fishing vessels identified virtually no fishing effort within the refuge and significant effort beyond the MPA perimeter, suggesting that large MPAs can effectively benefit reef sharks and other mobile species if properly enforced. However, our results also highlight limitations of place-based conservation as some of these reef-associated sharks moved surprising distances into pelagic waters (up to 926 km from Palmyra Atoll, 810 km beyond MPA boundaries). Small-scale fishermen operating beyond MPA boundaries (up to 366 km from Palmyra) captured 2% of sharks that were initially tagged at Palmyra, indicating that large MPAs provide substantial, though incomplete, protection for reef sharks.

1. Introduction

Marine protected areas (MPAs), which restrict fishing in order to aid conservation and fishery production, have become increasingly common in coastal waters over the last several decades (Lubchenco et al., 2003; Gaines et al., 2010; McCauley et al., 2015). A new pattern of MPA design has recently emerged: the creation of large, remote, pelagic MPAs (Lubchenco and Grorud-Colvert, 2015). The rapid establishment of these large MPAs, some spanning over one million km^2, has nearly doubled the total area of protected ocean on Earth in just five years (McCauley, 2014). Surrounding this unprecedented and fast-moving trend in global ocean management, there is considerable uncertainty about which species will benefit from MPAs of this size (De Santo, 2013; Pala, 2013).

The advantages of large MPAs for highly mobile species are particularly unclear, as the movements of many marine mammals, turtles, sharks, tunas, and other pelagic fish can dwarf even the largest MPAs (Game et al., 2009; Block et al., 2011; Sibert et al., 2012; Dueri and Maury, 2013). The presumed ecological importance of large and more mobile marine predators to marine ecosystem functioning (Bouchard and Bjorndal, 2000; Ferretti et al., 2010; Estes et al., 2011; McCauley et al., 2015) makes it essential to determine their relationship to large MPAs. To assess the benefits of large MPAs for mobile species, it is critical to determine both the proportion of time that individuals spend outside MPA boundaries, and the severity of mortality risks that occur beyond these boundaries (Graham et al., 2012; Rosenbaum et al., 2014). While spillover of populations from MPAs to adjacent waters may benefit nearby fisheries (Roberts et al., 2001; Halpern et al., 2009), under some conditions anthropogenic impacts outside an MPA can outpace reproduction and recruitment inside an MPA, resulting in population declines (Moffitt et al., 2009). Incomplete protection of an individual's activity space may be especially detrimental to shark

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species due to their low fecundity, late age at sexual maturity, and high susceptibility to fishing pressure (Cortés, 2000; Dulvy et al., 2014). Recent shark population declines within some large MPAs have fueled uncertainty about the efficacy of these reserves for mobile species and the ability of nations to reduce fishing effort across such vast regions (Graham et al., 2010; White et al., 2015).

Despite the fact that reef shark conservation is an explicit goal of many large MPAs (Koldewey et al., 2010; Davidson, 2012; Dulvy, 2013), the offshore movement patterns of some species are not well resolved and anthropogenic impacts surrounding large MPAs are rarely quantified, so it remains unclear how much protection they will truly receive from these measures. Here, we assessed the effectiveness of a large MPA for conserving one of the most historically abundant sharks in Indo-Pacific coral reef ecosystems: the grey reef shark (*Carcharhinus amblyrhynchos*). Grey reef sharks can comprise up to 46% of upper trophic level biomass in unfished reef ecosystems (Stevenson et al., 2007; Friedlander et al., 2014). However, grey reef sharks have experienced severe population declines across some of their Indo-Pacific distribution and are listed as Near Threatened in the International Union for Conservation of Nature's (IUCN) Red List of Threatened Species (Robbins et al., 2006; IUCN, 2015). Grey reef shark movements have been studied within individual atolls and coastal regions using acoustic telemetry (McKibben and Nelson, 1986; Heupel et al., 2010; Barnett et al., 2012; Espinoza et al., 2015a; Espinoza et al., 2015b) - a method that records the presence of tagged individuals when they approach nearshore acoustic receivers - but their broader, offshore movements when away from stationary receivers remain poorly understood. Stable isotope analysis of grey reef shark tissue has revealed heavy reliance on pelagic prey (McCauley et al., 2012), but it is unclear if this putative trophic subsidy reflects the movements of the sharks to pelagic habitats or movement of pelagic prey into nearshore habitats.

We conducted our investigation of large MPA effectiveness on the northern Line Islands archipelago in the central Pacific Ocean. Within this archipelago, the U.S.-managed Palmyra Atoll National Wildlife Refuge (approximately 54,000 km^2, fishing fully prohibited) is located several hundred kilometers from three inhabited and fished atolls that partially comprise the nation of Kiribati (Fig. 1). Protected reefs in this region host large populations of grey reef sharks and other mobile predators, while the fished reefs of Kiribati host dramatically lower predator densities (Sandin et al., 2008). The boundaries of the protected area at Palmyra Atoll have been expanded multiple times since 2001, and similarly the boundaries of the Papahānaumokuākea Marine National Monument in the Northwestern Hawaiian Islands were substantially expanded in August 2016, making discussions of reserve design in this area relevant and timely.

The specific goals of this study were to 1) determine the amount of time that grey reef sharks spend outside of historical and contemporary MPA boundaries by deploying conventional tags and satellite tags on this species at Palmyra Atoll, 2) assess the interaction dynamics between grey reef sharks and both commercial and small-scale fishermen by recovering conventional tags from fishermen and quantifying commercial fishing effort via recently-developed remote sensing capabilities, and 3) evaluate how locally relevant changes in MPA size may shape a species' exposure to risk. The combination of both satellite telemetry and conventional tagging provides us with unique insight into the oceanic movements and potential conservation strategies for this key species.

An important additional aim of this work was to demonstrate the value of cross-evaluating data on the spatial ecology of large marine predators obtained via animal tracking with newly available data on the spatial ecology of human predators (i.e. fishermen) obtained via vessel tracking. Historically, such comparisons have been limited as high-resolution fishing vessel data have either not been available or have been kept private by regional management authorities (but see Queiroz et al., 2016). The recent release of publically accessible data on fishing vessel activity and the development of new behavioral filtering algorithms to interpret these vessel tracks (McCauley et al., 2016) opens the door to novel analytical opportunities. Using information derived from the Automatic Identification System (AIS), a globally abundant vessel transmitting system, we generated a spatially explicit quantification of industrial fishing effort throughout the region where we tracked grey reef sharks. We evaluated how fishing effort density related to the boundaries of the focal MPA in our study region and examined interactions between shark behavior and the behavior of fishermen. Collectively these diverse forms of insight into how coastal sharks use space, combined with spatially explicit views of how fishermen use some of the same ocean space, empowers us to make much more informed decisions about how best to tailor marine management tools to meet conservation objectives.

2. Materials and methods

2.1. Study area

We tracked the movements of grey reef sharks and fishermen in relation to an MPA in the central Pacific Ocean (1–11°N, 152–167°W). This study focused on four atolls within the northern Line Islands. Palmyra Atoll is located within a large, no-take marine protected area (54,126 km^2) that is federally managed by the U.S. Fish and Wildlife Service, while Teraina, Tabuaeran, and Kiritimati are fished islands within the Republic of Kiribati (Fig. 1). Palmyra Atoll is uninhabited except for a small number (<20) of visiting researchers, research station staff, and wildlife refuge employees. The area within a 12 nautical mile (NM; 22.2 km) radius of Palmyra Atoll was first established as a National Wildlife Refuge (NWR) in 2001. In 2009, the boundaries of Palmyra Atoll NWR were expanded to 50 NM (92.6 km) through the establishment of the Pacific Remote Islands Marine National Monument (PRIMNM). PRIMNM consists of Palmyra Atoll and 6 other remote atolls, all protected out to 50 NM from fishing and other extractive activities. In 2014, the MPA boundaries were expanded out to 200 NM (370.4 km) at 3 of those 7 atolls (Jarvis and Wake Island and Johnston Atoll), bringing the total protected area to nearly 1.3 million km^2. Though Palmyra's boundaries were considered for an extension to 200 NM, its boundaries remained fixed at 50 NM. This 200 NM boundary is the extent of the U.S. exclusive economic zone (EEZ), and as such it is the maximum MPA limit that any nation can independently manage under current international law. Expansions of this scale are currently underway at other locations in the Pacific Ocean; the August 2016 expansion of the Papahānaumokuākea Marine National Monument's boundaries from 50 NM to 200 NM brought its total protected area to over 1.5 million km^2, making it the world's largest MPA at the time.

In contrast with the protected areas of PRIMNM, the islands of Teraina, Tabuaeran, and Kiritimati are respectively inhabited by 1690, 1960, and 5586 people (Tekaieti, 2012). Teraina, Tabuaeran, and Kiritimati are located a distance of 223 km, 366 km, and 665 km from Palmyra Atoll (113 km, 255 km, and 548 km from the MPA boundary). The residents of these islands are heavily dependent upon fishing for subsistence and economic opportunity (Tekaieti, 2012). Small-scale shark fisheries and the shark fin trade operate on all three of these islands, though the origins and biomass of sharks that are captured in these fisheries are currently unknown. Line Islands small-scale fishermen primarily operate out of 4–5 m aluminum skiffs and wooden canoes. Since Kiribati fishermen generally do not leave sight of their islands due to a lack of navigational equipment and limitations in gasoline availability, these fishermen do not have the range to make the 446 km to 1330 km round-trip journey to illegally fish at Palmyra Atoll.

2.2. Conventional tagging and small-scale fisheries mortality

In order to measure the movements and observe mortality of grey reef sharks from Palmyra NWR to the small-scale fisheries operating beyond the MPA boundary, we deployed 262 numbered dorsal fin tags