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How robust are estimates of coral reef shark depletion?

Justin R. Rizzari [a,b,c,*,1], Ashley J. Frisch [a,1], Sean R. Connolly [a,b]

[a] Australian Research Council Centre of Excellence for Coral Reef Studies, James Cook University, Townsville, Queensland 4811, Australia
[b] School of Marine and Tropical Biology, James Cook University, Townsville, Queensland 4811, Australia
[c] AIMS@JCU, Australian Institute of Marine Science, James Cook University, Townsville, Queensland 4811, Australia

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ABSTRACT

On coral reefs, diver-surveys of shark abundance indicate that populations are severely depleted, even in no-take zones with low-levels of illegal fishing, but are protected by strictly enforced no-entry zones. These findings have been questioned, on the grounds that diver-surveys overestimate shark abundance. We evaluated whether divers encounter sharks at higher rates when they first enter the water, and whether these effects vary among reefs that are subject to different levels of human interaction due to management zoning. We also examined the consistency of abundance estimates derived from multiple survey methods. For timed-swim, towed-diver, and baited-remote-underwater-video (BRUV) surveys, encounter rates were constant over time. For audible-stationary-count (ASC) surveys, encounter rates were elevated initially, then decreased rapidly, but the extent of upward bias did not differ between management zones. Timed-swim, BRUV, and ASC surveys produced comparable estimates of shark density, however, towed-diver-surveys produced significantly lower estimates of shark density. Our findings provide no evidence for biases in diver-surveys: encounter rates with sharks were not elevated when divers first entered the water; behavioural responses of sharks were consistent across management zones; and diver-surveys yielded abundance estimates comparable to other stationary methods. Previous studies using underwater counts have concluded that sharks are vulnerable to low levels of illegal fishing in no-take management zones, and that additional measures are needed to protect species, which, like sharks, have demographic characteristics that make them vulnerable to low levels of exploitation. Our results support the robustness of the abundance estimates on which those conclusions have been based.

1. Introduction

Apex predators are large carnivores that occupy the top trophic level of food webs. They are typically characterized by conservative life history traits, such as slow growth rates, late sexual maturity, and low fecundity. These traits make them particularly susceptible to over-harvesting, and apex predators often are preferentially targeted by humans for food or game (e.g. Myers and Worm, 2003). Consequently, apex predators are typically the first to become extinct or locally extirpated. This loss of apex predators may have extensive, adverse effects on ecosystem structure and function. In terrestrial, marine and freshwater systems, for example, changes in apex predator abundance have affected herbivore populations, with substantial flow-on effects to plant communities that provide the primary production and habitat structure that support biodiversity in these ecosystems (Estes et al., 2011).

In marine food webs, sharks are common apex predators, and also are socio-economically valuable resources (Heithaus et al., 2008). This is most apparent in tropical ecosystems, such as coral reefs, where reef sharks are believed to play an important role in ecosystem resilience (e.g. Ruppert et al., 2013), and they generate ~$1billion USD annually from ecotourism and fisheries (Cisneros-Montemayor et al., 2013). However, recent surveys of sharks of the Red Sea (Berumen et al., 2013), the Great Barrier Reef (GBR; Hisano et al., 2011; Robbins et al., 2006), the Indian Ocean (Graham et al., 2010), the Pacific Ocean (Nadon et al., 2012) and the Caribbean (Ward-Paige et al., 2010b) indicate substantial declines compared to estimated baseline populations, which have been primarily attributed to increased fishing pressure. Given the putative ecosystem functions provided by sharks, the need for accurate assessments of population status is crucial for effective coral reef management and to sustain the livelihoods of people who depend on their ecosystem goods and services.

* Corresponding author at: Australian Research Council Centre of Excellence for Coral Reef Studies, James Cook University, Townsville, Queensland 4811, Australia. Tel.: +61 450551087.
E-mail address: justin.rizzari@my.jcu.edu.au (J.R. Rizzari).
[1] These authors contributed equally to the research.

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Currently, the severity of shark population declines on coral reefs is disputed (e.g. Heupel et al., 2009). Differences in survey method selection are commonly cited as a potential cause for discrepancies in abundance estimates (e.g. Graham et al., 2010; Ruppert et al., 2013; Ward-Paige et al., 2010a). Sharks may respond variably to different stimuli such as noise, bait, divers, and boats, which are employed in different ways in different types of surveys (Cubero-Pardo et al., 2011; Fitzpatrick et al., 2011; Ward-Paige et al., 2010a). In addition, some methods, particularly diver-based counts, have been criticized for potentially producing biased estimates of differences in shark abundance along gradients of human interaction (Ward-Paige et al., 2010a). If sharks are less accustomed to people at unfished or remote locations, they may be more likely to approach divers, leading to over-estimates of abundance in those locations, relative to areas with more human activity (Graham et al., 2010).

Recent studies have concluded that reef shark populations in fished areas are severely depleted, and that low levels of poaching render no-take marine reserves much less effective than strictly enforced no-entry zones (Ayling and Choat, 2008; Robbins et al., 2006). Because estimates of population status in these studies have relied heavily on relative abundances from diver-based surveys, resolving the controversy about the validity of these approaches is crucial for evaluating the effectiveness of no-take marine protected areas for protecting apex predators with low intrinsic population growth rates, such as reef sharks, and for determining how best to assess the status of such populations. In particular, for estimates of baseline shark densities to be unbiased, sharks should neither actively avoid, nor approach, divers conducting surveys. Consequently, estimates of population depletion based on relative abundances estimated in fished and unfished areas, will be compromised if any such biases differ in magnitude in areas with different levels of fishing pressure. To date, the only study to investigate the performance of survey methods for sharks was undertaken at a single remote location (Palmyra Atoll, Line Islands) where sharks may be naïve towards humans (McCauley et al., 2012). Thus, an assessment of sharks' responses to alternative survey methods across a gradient of human interaction, and the responses' implications for estimates of absolute and relative abundance, is needed to assess the robustness of recent conclusions about the status of reef shark populations and their vulnerability to poaching in no-take marine reserves.

Here, we address this issue by comparatively evaluating four visual survey techniques that are commonly used for estimating shark abundance: (1) timed-swim, (2) towed-diver, (3) stationary-point-count (SPC), and (4) baited-remote-underwater-video (BRUV). In addition, we trialed a novel survey method, (5) audible-stationary-count (ASC), which uses low frequency sound to attract sharks to a stationary point. During each replicate survey, we recorded any observed behavioural response of sharks to divers, as well as the time at which each shark was observed. If sharks are attracted to divers, then we expect encounter rates with new individuals to be high when divers first enter the water to commence counting, and to decrease thereafter. Conversely, if sharks respond neutrally to divers, encounter rates should not increase or decrease over the course of a survey time. Each method was repeated across a gradient of human interaction in order to quantify whether any such biases vary, depending on the prevalence of human activity on the reef. To achieve this, we conducted our study in the Great Barrier Reef Marine Park (GBRMP), a system of spatial zoning that includes: (1) no-entry zones, which are strictly enforced exclusion areas; (2) no-take zones, which are conservation areas where fishing is prohibited, but non-extractive activities (e.g. diving) are allowed and where low levels of illegal fishing have been recorded (Davis et al. 2004); and (3) fished zones, which are general use areas that allow fishing and other extractive activities. Finally, we converted all shark counts to density estimates, and we tested for any differences between survey methods in shark abundance estimates, allowing for potential interactive effects with management zone and habitat type.

2. Methods

2.1. Study sites and species

Surveys were performed at Rib Reef (fished zone), Little Kelso Reef (no-take zone) and Bandjin Reef (no-entry zone) in the central Great Barrier Reef (GBR), and Northwest Reef (fished zone), Tryon Reef (no-take zone) and Wreck Reef (no-entry zone) in the southern GBR (Fig. 1). At each reef, zone boundaries are a minimum of 1–2 km from the reef edge. All six reefs are comparable in morphology and distance from shore, with a well-developed reef slope, reef flat and back reef, and each reef has an intact faunal community that is typical of reefs in the GBR (Done, 1982; Frisch et al., 2014; Newman et al., 1997). More than 4000 recreational vessels, >200 commercial line-fishing vessels and dozens of dive-charter vessels operate in the central and southern GBR (Lunow and Holmes, 2011; Taylor et al., 2012). During the course of this study, up to ten boats were observed fishing at Rib and Northwest Reefs at one time, while up to three boats were observed (anchored) at Little Kelso and Tryon Reefs at one time, and no boats were observed at Bandjin or Wreck Reefs at any time. This steep gradient of human presence is typical for these reefs and occurs year-round (J. Aumend, surveillance unit, Great Barrier Reef Marine Park Authority, pers. comm.). Thus, fished, no-take and no-entry reefs represent a steep gradient in the frequency of shark-human interactions. Estimates of abundance were recorded for whitetip reef sharks, *Triaenodon obesus,* grey reef sharks, *Carcharhinus amblyrhynchos* and blacktip reef sharks, *C. melanopterus*, as they are the dominant shark species on Indo-Pacific coral reefs (Ceccarelli et al., 2014; Robbins et al., 2006; Sandin et al., 2008). Multiple previous studies have demonstrated that the majority of all three reef shark species exhibit a high level of site fidelity, typically remaining on single reefs for long periods of time (Speed et al., 2011, 2012; Whitney et al., 2012; Vianna et al., 2013). Although reef sharks are capable of moving large distances in relatively short periods of time, only a small proportion of individuals move between reefs (Barnett et al., 2012; Field et al., 2011; Heupel et al., 2010; Whitney et al., 2012). This supports our assumption that inter-reef movements are sufficiently infrequent to establish and maintain a strong gradient in the frequency of human interactions experienced by sharks in the different management zones.

2.2. Survey methodology

Survey methods consisted of timed-swims, towed-diver, SPC, ASC, BRUV (described below). Fourteen to 24 surveys were performed per method per reef, except for the towed-diver method, which entailed five to eight surveys per reef due to the large size of each replicate tow ($\sim$1.5 km) relative to the size of each reef and the need for spatial separation between replicate tows. For all survey methods, replication was stratified across three habitat types (reef slope, reef flat, back reef); however, shark counts on the reef flat were too low (<8% of total sharks observed) to allow parameter estimation in our encounter rate and generalized linear model analyses, so we focus our analysis on the slope and back reef data only. When a shark was observed, we recorded the time (to the nearest second), species, and other identifying characteristics such as estimated total length (TL), colour patterns, and scars, to minimize the risk of multiple-counting of the same individuals.