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Oceanic manta rays aggregating near a major population center have far higher injury rates than at an offshore protected area

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ABSTRACT: The oceanic manta ray *Mobula birostris* is an Endangered species facing numerous anthropogenic threats that have led to population declines worldwide. Although oceanic manta rays are fully protected in Mexico, this species is still threatened by bycatch and vessel collisions, which jeopardize the population's stability and recovery. This study compares the prevalence and types of injuries observed in oceanic manta rays between the remote Revillagigedo Archipelago National Park and Bahía de Banderas, an area of high vessel traffic and small-scale fisheries in Mexico. Using visual censuses and photo-identification techniques conducted from 2014 to 2022 for Bahía de Banderas and from 1978 to 2020 for the Revillagigedo Archipelago, we found significant disparities in injury rates between the 2 regions. The overall injury rate was substantially higher in Bahía de Banderas (31.7%) than in the Revillagigedo Archipelago (5.2%), with a notable proportion of injuries attributed to anthropogenic causes, particularly vessel collisions and fishing gear entanglement. Moreover, the severity and types of injuries varied significantly, with a higher incidence of major injuries in Bahía de Banderas. These findings highlight the importance of marine protected areas for oceanic manta rays and emphasize the critical importance of implementing targeted conservation measures, especially in coastal regions with high maritime activity, to safeguard oceanic manta ray populations from further decline. We encourage the community and stakeholders to implement conservation actions urgently to preserve the vulnerable oceanic manta ray population in Bahía de Banderas and other coastal areas inhabited by this species.

KEY WORDS: *Mobula birostris* · Conservation · Revillagigedo · Bahía de Banderas · Population threats · Bootstrapping

1. INTRODUCTION

The oceanic manta ray *Mobula birostris* is an Endangered species (Marshall et al. 2022), with extremely low intrinsic population growth rates, making it highly susceptible to declines in response to anthropogenic impacts (Dulvy et al. 2014). The species faces threats related to human activities world-

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wide, with direct and incidental capture in fisheries having the greatest impact on populations (Croll et al. 2016, Stewart et al. 2018). In addition to these primary sources of mortality, sub-lethal impacts (i.e. non-fatal but harmful effects) on manta ray populations are increasingly being recognized as secondary threats to individual health and population viability. The incidence of sub-lethal injuries in populations can be an indicator of the relative magnitude of stressors such as fishing and vessel traffic (Strike et al. 2022).

In the Pacific region of Mexico, there are 2 proposed subpopulations of oceanic manta rays — one that visits the Revillagigedo Archipelago (hereafter referred to as Revillagigedo), 450 km from the southern tip of the Baja California peninsula, and 700 km west of mainland Mexico, and one that visits Bahía de Banderas, at the southern limit of the Gulf of California (Stewart et al. 2016a). The species is protected in Mexico by national environmental laws that prohibit targeted fishing or retention of bycaught individuals (DOF 2007). Despite these management efforts, entanglement in fishing gear and boat strikes have been noted as having significant impacts on the oceanic manta population in Bahía de Banderas (Domínguez-Sánchez et al. 2023). In contrast to this heavily trafficked and fished coastal area, Revillagigedo is remote, far from human settlements, and is protected by the largest no-take marine protected area in North America, limiting the potential impact of anthropogenic stressors on oceanic manta rays and other vulnerable marine species (Favoretto et al. 2023).

Within Bahía de Banderas, the southern coast of the bay has been identified as an aggregation zone for oceanic manta rays (Fonseca-Ponce et al. 2022), which probably take advantage of upwelling dynamics in the area to feed in productive deeper waters on vertically migrating prey at night and then bask near the surface during the day to recover body temperature (Domínguez-Sánchez et al. 2023). The fishing villages along this southern coastline are connected to the major human population center of Puerto Vallarta primarily through high-speed water taxis. These water taxis and the intensive commercial and recreational boat traffic in the area pose a significant vessel strike risk to manta rays in this feeding hotspot and thermoregulation area (Stewart et al. 2016a). Additionally, local fishers use gill nets and other fishing gear that may entangle manta rays in the area, placing them at risk of injury and potential mortality through exposure to vessel traffic and fishery bycatch.

The objective of this work is to compare the proportion of natural and human-caused injuries in manta rays observed in Revillagigedo and Bahía de Banderas in order to estimate exposure to anthropogenic threats and thus provide relevant information for future management measures of the species in Mexico as well as assessments of the conservation status of the species at regional and global levels.

2. MATERIALS AND METHODS

Between 2014 and 2022, we conducted visual censuses of oceanic manta rays along the southern Bahía de Banderas coast from a boat, approximately 100 m offshore. Onboard observers (2–3 individuals) searched for manta rays and, upon sighting an individual, 1 or 2 observers entered the water to capture photos and videos of the manta ray's ventral surface for individual identification (Fonseca-Ponce et al. 2022). We analyzed photographs collected through this active monitoring program as well as photographs submitted to Proyecto Manta (https://www.mantatrust.org/proyecto-manta-pacific-mexico-affiliate-project) by tourists and divers from the region. Additionally, we conducted a thorough review of a database of oceanic manta rays sighted in Revillagigedo. All pictures were taken and given voluntarily to the Pacific Manta Research Group (PMRG; https://pacificmantaresearchgroup.org/) by researchers and tourists from liveaboard and recreational vessels frequenting the area from November through June 1978 to 2020. We identified each individual manta ray by coloration and spot patterns on the ventral surface (Marshall & Pierce 2012).

Furthermore, if there were signs of injury, we recorded the origin of the injury as well as the specific cause, severity, and type of injury. We defined the origin of the injury as wounds or scars caused by anthropogenic, natural, or undetermined factors. Natural wounds on oceanic manta rays are commonly caused by predator bites, such as sharks or odontocete whales (Marshall & Bennett 2010, Higuera-Rivas et al. 2023). These injuries usually occur on the posterior edge of the pectoral fins, resulting in a distinctive half-moon-shaped wound or scar (Fig. S1E in the Supplement at www.int-res.com/articles/suppl/n055p037_supp.pdf), whereas anthropogenic wounds are typically clean, deep, and straight cuts that can occur on any part of the animal's body (McGregor et al. 2019). The specific cause of the injury refers to the factor that caused the wound, such as collisions with vessels, fishing gear, or predator bites. We divided the severity of the injury into 2 categories: 'major' and 'minor' (Figs. S1 & S2). We defined major injuries as those wounds that could potentially affect the fitness of the individual (Speed et al. 2008), such as the absence of cephalic lobes, which could impact feeding efficiency. Minor injuries are wounds or scars that most likely do not affect the fitness of the individual but provide relevant information about the threats faced by individuals in the region, such as small clean cuts that are likely indicators of interactions with fishing gear (Speed et al. 2008). Lastly, we defined the type of injury as the form of the wound, including amputations, dysfunctions, lacerations, bites, abrasions, notches, and healed major and minor injuries (Figs. S1 & S2).

To analyze the rate of body injury in oceanic manta rays from Bahía de Banderas and Revillagigedo, we employed the bootstrapping resampling method (Fieberg et al. 2020). We determined the overall proportion of individuals with injuries, the proportion of individuals with injuries of natural and anthropogenic origin, and the severity of the injuries using the total number of identified individuals in each region. Additionally, we calculated the proportion of each type of injury and analyzed the proportion of injuries specifically caused by vessel collisions and fishing gear.

We performed a resampling with 10 000 repetitions to estimate the accuracy of the injury rate in each population. We subsampled 80% of the larger data set with no replacement and calculated the rate of body injury for each sample. From these samples, we generated 95% confidence intervals (CIs) for the rates of injury in each population. This allowed us to evaluate the variability and uncertainty associated with the observed injury rates.

Finally, the rate of injuries was compared between the 2 populations to determine if there were significant differences, using the resampling results from the bootstrapping method for each type of injury. We subtracted the bootstrapped distributions of each injury type in Bahía de Banderas from the corresponding injury type in Revillagigedo and considered the proportion of bootstrapped differences greater than 0 to be the probability that manta rays in Bahía de Banderas had more injuries of that type than manta rays in Revillagigedo, analogous to the handling of Bayesian posterior distributions. We used a threshold of >95% of the bootstrapped differences being greater than 0 for statistical significance.

3. RESULTS

We identified 926 oceanic manta rays in Revillagigedo between 1978 and 2020 and 397 individuals in Bahía de Banderas from 2014 to 2022. We observed a significant difference in the proportion of injured manta rays between the 2 regions (100% of bootstrap draws at Bahía de Banderas were higher than bootstrap samples at Revillagigedo). In total, 31.7% (CI: 29.2–34%) of the oceanic manta rays in Bahía de Banderas displayed some form of injury, while only 5.2% (CI: 4.4–5.8%) of the individuals in Revillagigedo had injuries. This indicates that the population at Bahía de Banderas sustained 6 times more injuries than the population at Revillagigedo. Moreover, 27.4% (CI: 25–29%) of the oceanic manta rays in Bahía de Banderas exhibited anthropogenic injuries compared to only 3.2% (CI: 2.5–3.7%) in Revillagigedo, representing an 8.5 times higher incidence of human-caused injuries in Bahía de Banderas than in Revillagigedo (100% of bootstrap draws at Bahía de Banderas were higher than bootstraps samples at Revillagigedo). Interestingly, the proportions of natural injuries were similar between the regions, with 3.8% (CI: 2.8–4.7%) in Bahía de Banderas and 2.3% (CI: 1.8–2.8%) in Revillagigedo. Analyzing the categories of injuries, we found that approximately 14.8% (CI: 13.2–16.6%) of the oceanic manta rays in Bahía de Banderas had major injuries and 16.1% (CI: 14.1–17.9%) had minor injuries, while in Revillagigedo, only 1% (CI: 0.6–1.2%) of the individuals showed major injuries and 4.6% (CI: 3.9–5.25%) had minor injuries (Fig. 1).

In terms of the type of injury, we observed that damage to the cephalic fins, including cephalic amputation and cephalic dysfunction, accounted for 9.3% (CI: 7.86–10.7%) of the injuries in Bahía de Banderas and 0.4% (CI: 0.1–0.5%) in Revillagigedo. Interestingly, lacerations were absent in Revillagigedo but

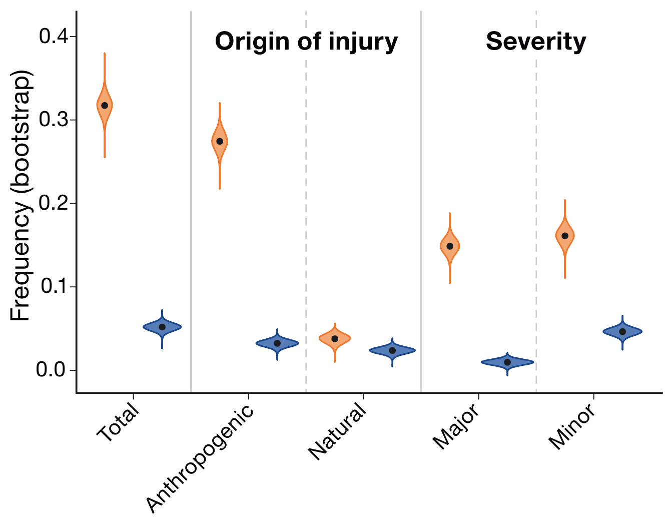

Fig. 1. Proportion of injuries on oceanic manta rays in Bahía de Banderas (orange) and Revillagigedo (blue). Points represent the observed proportion, and violin intervals represent the 95% bootstrap intervals from the resampling analysis

present in 4.7% (CI: 3.7–5.6%) of the population in Bahía de Banderas. Additionally, we identified healed major injuries in 4% (CI: 2.8–5%) of the Bahía de Banderas population. Although we did not observe healed major injuries in Revillagigedo, we found healed minor injuries in 0.7% (CI: 0.4–0.9%) of the population. The occurrence of injuries from bites was relatively low in both regions, comprising 3% (CI: 2.2–3.7%) in Bahía de Banderas and 1.2% (CI: 0.8–1.4%) in Revillagigedo. In contrast, the proportion of abrasions was higher in Bahía de Banderas (2.8%, CI: 1.8–3.4%) compared to Revillagigedo (0.8%, CI: 0.5–1%) (Fig. 2).

Finally, we conducted a comparison of the proportion of injuries attributed to fishing gear (specifically fishing nets and fishing lines) and boat collisions. Our findings revealed that approximately 12.3% (CI: 10.6–13.8%) of the injuries observed in oceanic manta rays in Bahía de Banderas were the result of boat strikes, while 11.8% (CI: 10–13.2%) were attributed to fishing gear. In contrast, in Revillagigedo, only 2% (CI: 1.6–2.4%) of the injuries were caused by boat collisions and 1.3% (CI: 0.9–1.6%) were associated with fishing gear (Fig. 3).

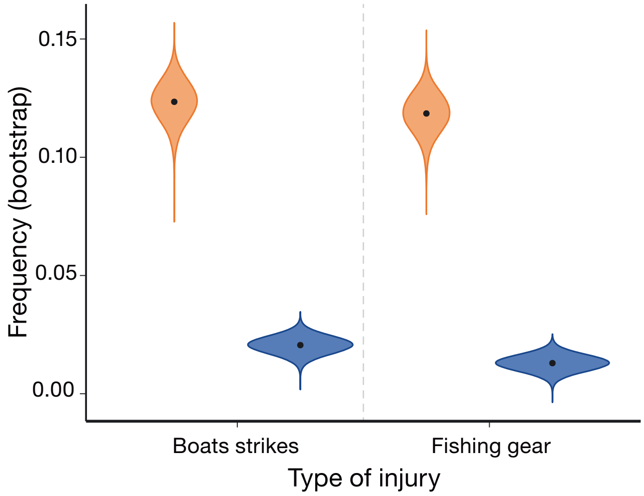

Fig. 3. Proportion of anthropogenic injuries on oceanic manta rays in Bahía de Banderas (orange) and Revillagigedo (blue). Violin plots as in Fig. 1

4. DISCUSSION

We observed significant differences in the incidence of injuries in oceanic manta rays between Revillagigedo and Bahía de Banderas. In particular, we found that the Bahía de Banderas region has a considerably higher proportion of injuries compared to Revillagigedo, with an approximately 6-fold difference in the total proportion of injuries. These findings underscore the importance of marine protected areas as refugia for oceanic manta rays and other large, mobile marine species. An attribute that provides greater protection to Revillagigedo is its geographical isolation (an aspect not shared by all protected areas), which dramatically reduces the incidence of maritime transport, industrial fishing (Favoretto et al. 2023), and coastal activities within the protected boundaries. As such, the major reduction in injuries exhibited by the subpopulation of manta rays that spends time at Revillagigedo could be due to either the protected status of the region or the much greater distance from major population centers compared to the subpopulation of manta rays visiting Bahía de Banderas.

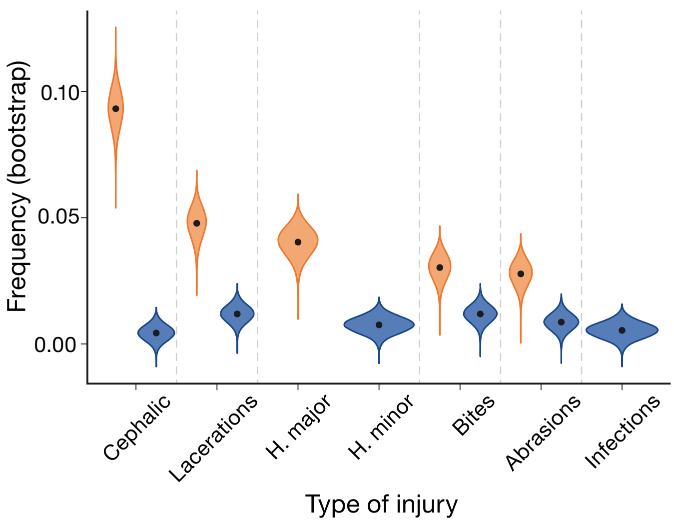

Fig. 2. Proportion of injuries per type on oceanic manta rays in Bahía de Banderas (orange) and Revillagigedo (blue). H. major and H. minor: healed major and minor injuries, respectively. Violin plots as in Fig. 1

Of anthropogenic injuries, collisions with vessels were the most frequent in both regions, followed by injuries from fishing gear. According to studies conducted in Bahía de Banderas (Fonseca-Ponce et al. 2022, Domínguez-Sánchez et al. 2023), the presence of oceanic manta rays in the southern part of the bay has been frequently observed. This area is known for its high maritime traffic, as it lies on the navigation routes of tourist vessels, sport fishing, and passenger transportation to and from Puerto Vallarta, the main port in this region, as well as nearby fishing communities. Oceanic manta rays spend considerable time at the surface to assist with thermoregulation after making deep dives into cold waters to feed (Stewart et al. 2016b), making them particularly vulnerable to collisions with vessels. Furthermore, due to their proximity to the coast in this area, oceanic manta rays are also exposed to risks associated with artisanal fishing vessels, which use fishing nets and lines in the areas they frequent.

Oceanic manta rays were protected under Mexican law in 2007 (DOF 2007; NOM-029-PESC-2006), which prohibited their capture, retention, or trade. In 2019, they were added to the NOM-059-SEMARNAT-2010 list as 'subject to special protection' (DOF 2019), highlighting the need for measures to promote their recovery and conservation. Despite these regulations, our results indicate that factors such as maritime traffic and incidental capture continue to be the major challenges facing oceanic manta rays in Mexico, which could jeopardize population stability in the coming years.

Although reef (*Manta alfredi*) and oceanic manta rays have a high capacity for tissue regeneration (McGregor et al. 2019), it remains unclear whether severe injuries, such as amputation or dysfunction of the cephalic lobes, directly impact their health or physical condition. The absence of these lobes or damage to pectoral fins could potentially reduce feeding or swimming efficiency, leading to increased energy expenditure, reduced body condition, or greater vulnerability to predators.

The proportion of injuries caused by predators (i.e. bites) in the 2 studied regions is substantially lower than in other areas worldwide. Strike et al. (2022) observed that in the Maldives, where both species of manta rays are found, the proportion of predator bites was 10% for oceanic manta rays and 15% for reef manta rays. In contrast, research conducted on reef manta rays in Mozambique revealed that 76% of individuals had predator bites in 2010 and 68% had bites in 2020 (Marshall & Bennett 2010, Venables 2020). In Hawaii, 33% of manta rays had bites (Deakos et al. 2011), while in eastern Australia, it was 23% (Couturier et al. 2014). Although Revillagigedo is characterized by the presence of high shark richness and abundance (Becerril-García et al. 2020), the only species of shark found frequently within the archipelago that is also a documented predator of manta rays is the tiger shark *Galocerdo cuvier* (Couturier et al. 2012). According to Klimley et al. (2022), tiger sharks in the Revillagigedo Archipelago do not permanently remain within the marine protected area boundaries and may forage outside of the archipelago. This behavior could potentially reduce the frequency of encounters with manta rays, thus possibly lowering the immediate risk of predation and the prevalence of predation-related injuries. In contrast, there are no modern reports of the presence of tiger sharks in Bahía de Banderas. Killer whales *Orcinus orca* are another documented predator of manta rays in the region (Higuera-Rivas et al. 2023), although killer whale abundance in the region is low and they are likely to be only a sporadic predator of oceanic manta rays. We suggest that the very low observed rates of predatory injuries in manta rays in the Mexican Pacific may be explained by the generally low densities of their predators in this region compared to other populations of manta rays globally. Last, the abrasions on the manta rays could be caused by the contact between the seabed and ventral region including cephalic fins due to sea bottom feeding (Stevens 2016), or by hitchhiker species such as the remora *Remora remora*, which uses its adhesive disc to adhere itself to its host (Nicholson-Jack et al. 2021). The abrasions could cause infections if the continuous damage persists.

In this study, we highlight the influence of both protected areas and proximity to major human settlements on the rates of anthropogenic injuries in oceanic manta rays. Despite legal protection, this Endangered species is still vulnerable to threats such as incidental fishing and high maritime traffic, and our high observed rates of anthropogenic injuries in Bahía de Banderas suggest that these impacts may have both sub-lethal (observed) and lethal (unobserved) consequences for the regional populations. The findings from this research provide valuable insights for improving conservation and management measures for oceanic manta rays in the region. We urge decision-makers and researchers to work closely with local communities and the general public to propose effective conservation strategies such as temporary fishing gear restrictions, vessel speed reductions, and other forms of spatial protection that could reduce impacts on manta rays in regional hotspots and during periods of high occupancy, benefitting both these species and the communities that share their habitat.

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