Natural or Anthropogenic: Threats faced by Maldivian Manta Rays

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Disclaimer

I hereby declare that the work and analysis reported in this dissertation is my own, except where otherwise stated (here, and under acknowledgements). Typical input, advice, support and discussion were provided Guy Stevens of the Manta Trust and Dr Julie Hawkins. I am grateful to Guy and the Manta Trust for the provision of data and photographs, and for help with photographic review before analysis.

I declare this piece of work to be 4894 words, excluding title page, report title, acknowledgements, figures and legends, reference list and this disclaimer.

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Abstract

Manta rays are globally listed as vulnerable, and understanding threats posed to their populations can help aid conservation measures. Manta rays in the Maldives are not directly exploited by fisheries. However, they still bear scars of injuries from both natural and anthropogenic causes. Using data from the Maldivian Manta Ray Project (MMRP) database, obtained from over 30,000 sightings in the past decade, photographic-identification was used to review details of injury observed on individual *Manta alfredi* and *Manta birostris*. Through examination of injuries sustained by these individuals, this study has determined the origin of permanent injuries in the Maldivian populations of mantas. Of the 3715 identified *M. alfredi* individuals in the Maldives, 23% showed signs of permanent injury, whereas 21% of the 169 known *M. birostris* that were injured. Adult *M. alfredi* had significantly more injuries than subadults or juveniles (67%, 3%, 30%, respectively: $X^2 = 66.4$, df = 2, $p < 0.001$). Similarly, injuries were more likely to result from threats of natural (n = 471) rather than anthropogenic (n = 338) origin ($X^2 = 10.7$, df = 1, $p = 0.00108$). By understanding the threats faced by local populations of manta rays, this analysis of the MMRP database can provide the Maldivian government with an evidence base of which to develop informed management strategies to help preserve them.

Introduction

Effective species conservation and management is reliant on scientists having a thorough understanding of the target's fundamental ecology and biology (Deakos et al., 2011). This is especially important for animals, such as manta rays, which have long and complex life histories that make them particularly vulnerable to depletion (Deakos et al., 2011). Manta ray populations face a number of natural and anthropogenic threats (Marshall et al., 2009; Couturier et al., 2012). By exploring these risks, essential management can be applied to conserve these iconic species which are of significant importance to countries whose waters host them as they generate substantial economic gain, particularly in coastal and developing areas (Anderson et al., 2010). The work reported here examines if manta ray populations in the Maldives are more affected by anthropogenic or natural threats, with the aim of allowing more informed guidance to be developed for management strategies specific to local aggregations and the risks they face.

The low-lying coral islands of the Maldives are situated in the Indian Ocean (07^{o}07'N to 00^{o}42'S and 72^{o}32'E to 73^{o}46'E), south-west of Sri Lanka and India (Kutier, 1998). Composed of 26 geographically distinct atolls, the archipelago is comprised of approximately 1,190 coral reef islands (McClanahan and Muthiga, 2014). The nation is near to the equator and rarely experiences severe weather, apart from two seasonal monsoons; Halhangu and Iruvai, which strongly influence the waters surrounding the Maldives (Anderson et al., 2011; Stevens, 2011a). Hulhangu, the southwest monsoon, runs May-October and typically drives currents east. Iruvai, the northeast monsoon, runs December-May and results in westward flowing currents (Anderson et al., 2010; Anderson et al., 2011; Stevens, 2011a). The Maldivian atolls rise from 2,000m below sea level and act as natural barriers to monsoonal currents. They force water upwards, resulting in deep-water upwelling around the islands (Stevens, 2011a). As currents pass over the atoll ridges, the nutrient-rich waters mix with shallow water in the lagoons, thus promoting mass phytoplankton blooms (Stevens, 2011a). This productivity peak on the leeward side of the atolls results in an elevated biomass of zooplankton - the primary food of manta rays (Anderson et al., 2011). As a result, the largest known single population of reef manta rays in the world are supported year round (Stevens, 2011a), making Maldivian waters a unique location to view and study these animals (Anderson et al., 2011).

In 2009, Marshall et al., split the monotypic genus *Manta*, of the family *Mobulidae*, into two distinct species; the reef manta (*Manta alfredi*) and the oceanic manta (*Manta birostris*). Both species are circumglobally distributed (Kitchen-Wheeler et al., 2012) and listed as vulnerable on the International Union for the Conservation of Nature (IUCN) Red-List (Marshall et al., 2011a; Marshall et al., 2011b). The larger and more migratory species, *M. birostris*, is widely observed in subtropical, tropical and temperate waters, whereas *M. alfredi* is more frequently found in subtropical and tropical waters (Kashiwagi et al., 2011). Predictable aggregations of both species of manta rays are generally witnessed around island groups, productive coastlines and in areas with elevated primary productivity (Marshall et al., 2011a; Marshall et al., 2011b), as they come inshore to feed and clean (Couturier et al., 2011). As mentioned, the productive waters of the Maldives support populations of both *M. alfredi* and *M. birostris*, which in turn help support the local economy (Couturier et al., 2011).

Manta rays are economically valuable to countries around the world, via fisheries and tourism (O'Malley et al., 2013). Populations of mantas are targeted by fisheries around the world for use in the gill plate market, particularly in Mozambique, India, Sri Lanka, Peru and China (Heinrichs et al., 2011). Highly sought after for use in Chinese medicine, gill plates tend to be marketed as a tonic to treat a number of conditions, and the industry generates an estimated US$5 million a year (O'Malley et al., 2013). In the Maldives, however, it is illegal for fisheries to directly target manta rays (Kitchen-Wheeler et al., 2012). These species are more lucrative alive than dead, and their value to local economy was recognised by the Maldivian government in 1995 when exportation of all ray products was banned. Subsequently, in 1996, trading of all ray skins was also banned (Anderson et al., 2010). Implementation of the export ban before the recent boom in gill trade stalled the establishment of a destructive fishery in the country (Anderson et al., 2010; Kitchen-Wheeler., 2010). However, the risk that a targeted fishery would develop in the Maldives prevailed until 2014 when a new law inadvertently eradicated it. The Maldivian government passed legislation making the capture, containment or harm of any type of ray species illegal (Murray, 2014).

Globally it is estimated that manta ray watching tourism generates about US$140 million annually, making the species highly valuable to the countries where they occur (O'Malley et al., 2013). In the Maldives, the most recent estimate of the value of manta tourism was made by Anderson et al., in 2010, and suggested that the activity generates US$8.1 million a year in direct revenue from scuba diving and snorkelling. While manta ray tourism has without doubt helped promote conservation of mantas in the Maldives, largely driven by economic incentives, it can also result in a number of indirect detrimental effects on the species (Deakos et al., 2011).

Manta species, although protected by legislation in the Maldives, still face a number of threats there, both natural and anthropogenic (Couturier et al., 2012; Ward-Paige et al., 2013). Due to their large size and flattened body structure (Stevens, 2011b) mantas have few natural predators, but are prone to attack from large sharks such as bull (*Carcharhinus leucas*), tiger (*Galeocerdo cuvier*), great hammerhead (*Sphyrna mokarran*) and great white (*Carcharodon carcharias*) (Marshall and Bennett, 2010a; Stevens, 2011b; Couturier et al., 2012). There have also been reports of orca (*Orcinus orca*), false killer whale (*Psuedorca crassidens*) and other cetaceans attacking *M. birostris* (Fertl et al., 1996; Visser and Bonoccorso, 2003). Despite not being targeted by fisheries, lost or discarded fishing gear poses an indirect threat to manta populations. Nets and broken fishing lines can wrap around an animal, and easily slice through their skin with varying degree of severity (Stevens, 2011c). Serious injury from entanglement, such as cephalic fin amputation or gill damage, could prevent an affected manta from feeding, reproducing and breathing, and increase its susceptibility to natural predation (Marshall and Bennett, 2010a). Manta rays also face threats from mooring lines and boat propellers that result in injuries which can leave permanent disfigurements, and are associated with loss of fitness (Deakos et al., 2011).

Manta rays worldwide bear signs of injury in the form of scars, deformities, amputations and bite marks (Heithaus, 2001a; Marshall and Bennett, 2010a). By analysing these scars, the origin of threats afflicting manta rays can be determined (Speed et al., 2008), and effective conservation management strategies then made to address them (Germanov and Marshall, 2014). Past studies have analysed scars and injuries observed on populations of *M. alfredi* in Mozambique (Marshall and Bennett, 2010a) and Hawaii (Deakos et al., 2011), but none have examined populations of *M. birostris*. Furthermore, no comprehensive study has been conducted on both natural and anthropogenic injuries observed on manta rays. Marshall and Bennett (2010a) conducted an in-depth study of natural threats to *M. alfredi* in Mozambique, reporting that many injuries have negative repercussions, and a limited analysis was conducted on threats faced by an Hawaiian population (Deakos et al., 2011). Whilst studies on manta rays in the Maldives have focused on population estimates and individual identification, it is yet to be established if these aggregations face greater threat from natural or anthropogenic sources (Kitchen-Wheeler 2010; Kitchen-Wheeler et al., 2012).

Since populations of manta rays in the Maldives are considered to be relatively pristine due to heavy protection and the lack of targeted fishing (Kitchen-Wheeler et al., 2012), it has been suggested that they could provide good baselines of healthy populations with which to study the threats they face. By using a decade of data collected on both species of manta ray in the Maldives, the origins of permanent injuries and scars were explored.

This study is the first to quantify the threats encountered by these aggregations. Specifically, the following was examined: (1) what proportion of each species is injured, and at what frequency; (2) is one type of injury more likely to affect a particular population than another; (3) are injuries equally distributed between the sexes; (4) are adults more likely to be harmed than juveniles or subadults; (5) is there a difference between the type of injury sustained between the two manta species; and (6) how has the accumulation of fresh injuries, from any origin, changed over time in the *M. alfredi* population?

Methodology

Manta rays are permanent residents of the Maldives, forming predictable aggregations (Couturier et al., 2012) as they move around the archipelago with seasonal shifts in food abundance (Anderson et al., 2011). This provides opportunities for regular encounters and, for the past 10 years, the Maldivian Manta Ray Project (MMRP) has photographically documented over 30,000 sightings of both species of manta ray. As a result, an electronic database of over 3,700 known individual *M. alfredi* has been produced. The MMRP has also established a database containing almost 170 *M. birostris*, a population that less frequently visits the Maldives.

Identification

The underlying methodology of the MMRP is photographic-identification (photo-ID), which can easily be completed post-hoc of the encounter (Marshall et al., 2011c). Photo-ID is a minimally invasive, effective and efficient way to individually identify animals in a population (Marshall and Pierce, 2012). Manta rays are ideal candidates for this method of ID; having unique spots and colouration on the ventral surface of their bodies (Fig. 1), comparable to human fingerprints (Couturier et al., 2011; Marshall and Pierce, 2012). These markers are present at birth and have been shown to remain unchanged over time (Deakos et al., 2011; Marshall et al., 2011c; Couturier et al., 2012).

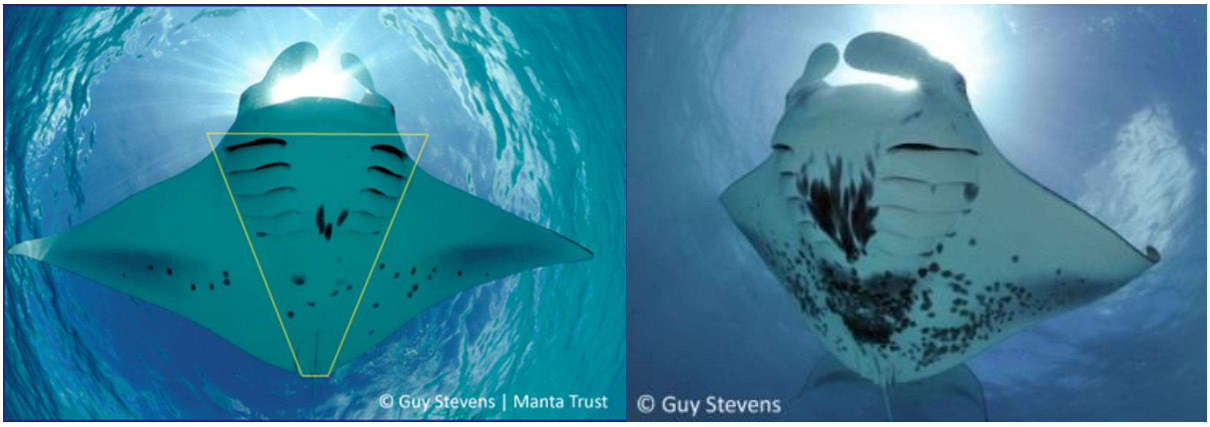


Figure 1: Distinctive ventral spot markings used in individual manta ray identification. The primary ID area used is highlighted. Photographs courtesy of Manta Trust.

Photographs taken during encounters between January 2005 and April 2015 were uploaded to a computer. Using IDtheManta software, which highlights a manta's unique spot pattern and matches it to animals on a global database through use of automated animal recognition technology (Manta Trust, 2015), all manta rays photographed were identified as either a known or a new individual (Deakos et al., 2011). Scars and injuries were also used to aid identification, however they were not used in isolation as they can change and disappear in time depending on their level of severity (Kitchen-Wheeler, 2010; Marshall et al., 2011c). Information gathered on each individual manta included, but was not limited to; sex, age class, maturity, size, atoll where sighted, any injury observed and the anatomical placement of the observed injury. Sex was determined by the presence of claspers (the male reproductive organ) in mal mantas, and the absence of them in females (Deakos et al., 2011). Individuals were classified as adults if they were considered to be sexually mature. In females, this was when mating scars were observed on the dorsal side of their pectoral fin, and/or a pregnancy bulge was visible (Marshall and Bennett, 2010b). For male males, maturity was identified by calcification of claspers and extension of them past the pelvic fins (Deakos et al., 2011).

Injury Identification

Along with the MMRP project founder, Guy Stevens, the author reviewed all photographs taken of known manta rays. These were cross-checked against the MMRP database to ensure information of each individual was correct and up-to-date. Categories checked were sex and maturity, to enable sex- and maturity-specific analysis of injury frequency (Marshall and Bennett, 2010b), and permanent injury. Ongoing observations in the field have shown that some injuries remain with mantas for life, usually in the form of scars and/or missing tissue (Marshall and Bennett, 2010a). These injuries, for the purpose of this study, were regarded as permanent. Small cuts and scrapes, observed to heal as mantas were re-sighted during the study period, were not counted in this analysis. Individual injuries were recorded as natural, anthropogenic or unknown in origin. Natural injuries were largely in the form of bites, and presumed to be a result of failed predation attempts. These were generally distinctive semi-circle injuries, with tissue missing from the trailing edge of the manta's pectoral fin (Fig. 2a, b), and occasionally tooth scrapes were observed. Some bites were healing or healed and therefore covered by scar tissue (Fig. 2c), however the indicative shape attributable to predatory attack could still be distinguished (Deakos et al., 2011). Anthropogenic injuries were categorised by anything derived from human activity. For example, fishing lines leave distinctive straight edge cuts where they sever the skin (Deakos et al., 2011), while fishing nets do this in a very regular pattern (Fig. 2d, e). Some animals had hooks embedded in their skin, or were visibly trailing monofilament line (Fig. 2f), and injuries from boat strikes or propellers could be identified as obvious lacerations on the dorsal surface of mantas (Fig. 2g). The origin of some injuries could not be determined because tissue regeneration had occurred to such an extent that markers used to determine specific causes of damage had been obscured. Such wounds were categorised as unknown.

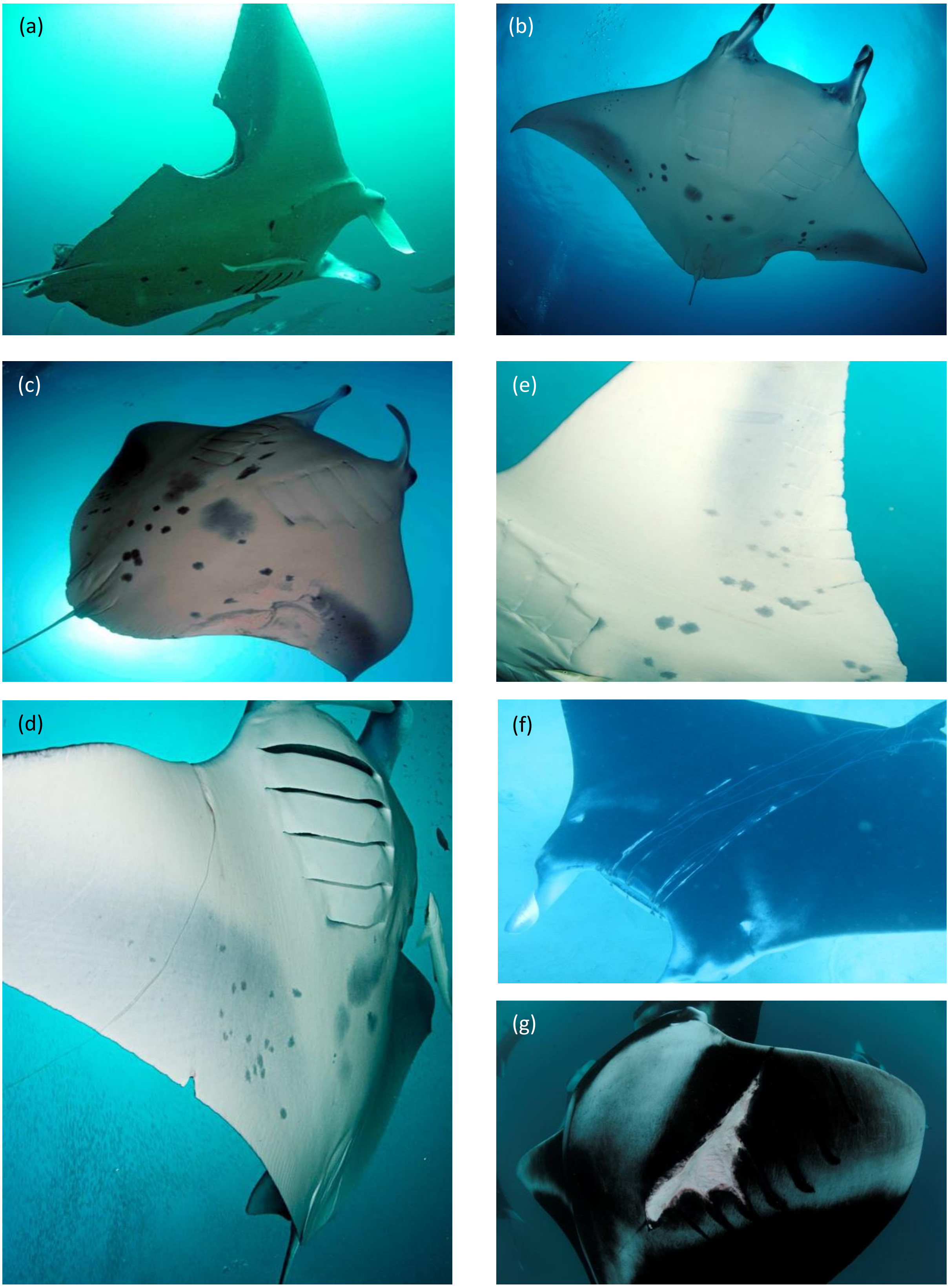


Figure 2: (a-b) predatory bites resulting in chunks of tissue missing from trailing edge of pectoral fins; (c) healed predatory bite with substantial scar tissue; (d) fishing line slices on leading and trailing edge of pectoral fin, with line still embedded; (e) distinctive net scarring on trailing edge of pectoral fin, slicing at regular intervals; (f) fishing line wrapped around manta ray body; (g) fresh propeller laceration to dorsal surface of manta ray. Photographs courtesy of Manta Trust.

Information about freshness of injury was also recorded on the MMRP's database of individual manta rays. Injuries were considered to be fresh if the wound was red, unhealed, bleeding, or open with no evidence of scar tissue (Fig. 3a, b). Healed injuries were distinguished by the presence of scar tissue, or where pink or red flesh was no longer present (Fig. 3c) (Marshall and Bennett, 2010a). Through analysis of the database, yearly accumulation of fresh injuries by *M. alfredi* was examined, and data were normalised by dividing the total number of fresh injuries observed per year by the total number of individual rays sighted in the same year (Marshall and Bennett, 2010a).

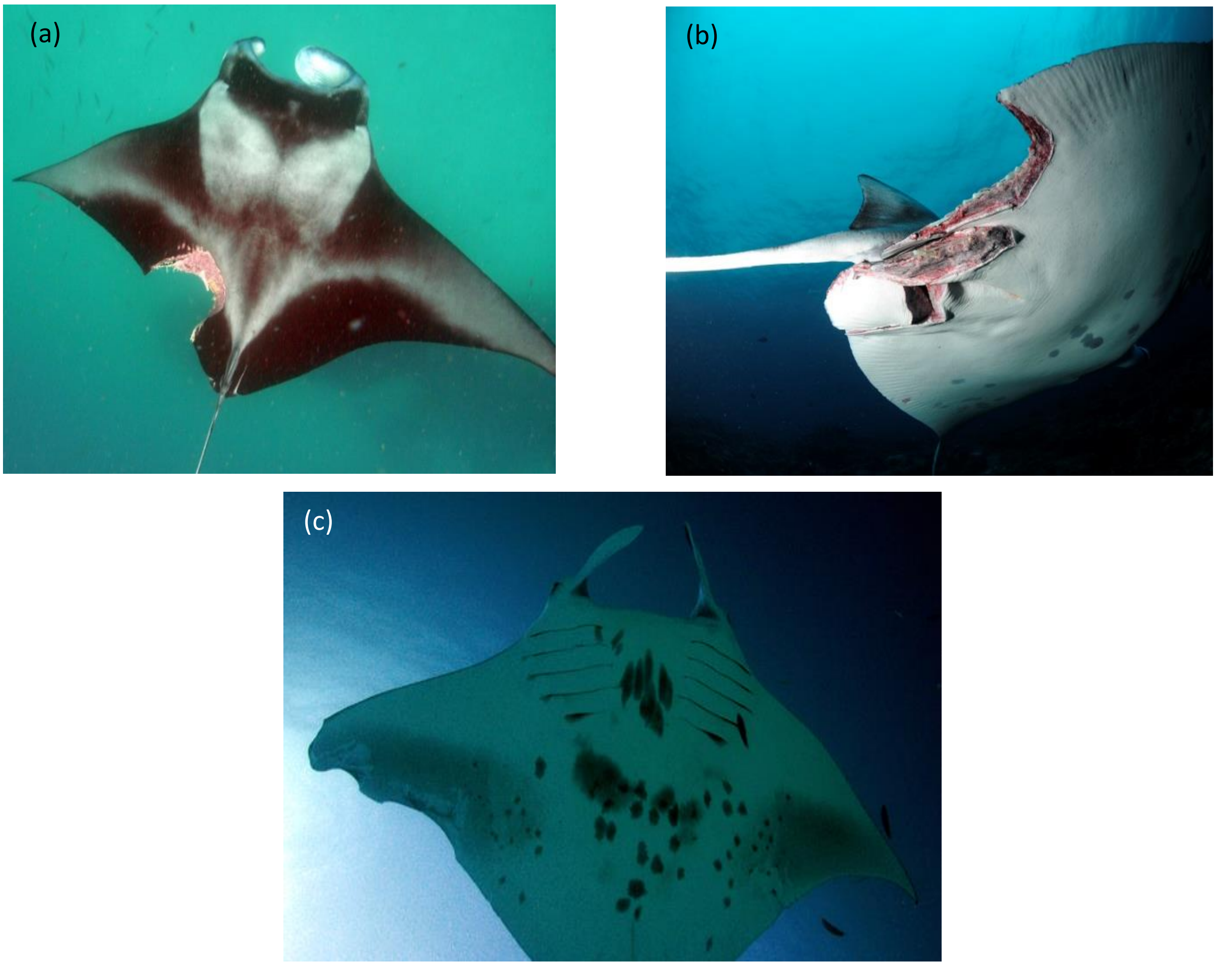


Figure 3: Photographs of manta rays with injuries considered to be: (a-b) Fresh - wounds open, red and unhealed; (c) healed – evident formation of scar tissue on trailing edge of right pectoral fin. Photographs courtesy of Manta Trust.

Statistical Analysis

The number and origin of scars were examined with respect to sex and maturity level. Individuals of unknown sex or maturity, and injuries of unknown origin were excluded from the analyses in question. Chi-square (X^2) tests were used to compare the occurrence of scars between manta rays of different sex and maturity, and Yate's correction factor was applied to all X^2 tests with one degree of freedom to reduce the risk of Type I error (Zar, 1996). In analyses where one or more expected frequencies were five or less, a Fisher's exact test was carried out. Significance was accepted at $p < 0.05$. All analyses were conducted using the statistical package R, version 3.1.1.

Results

Population Demographics

Manta alfredi

The database of *M. alfredi* contained 3715 photographed individuals, comprised of 1859 (50%) female and 1807 (49%) male rays. The remaining 49 (1%) animals were of unknown sex, and were not included in further analysis. Of the 3666 sexed individuals, 55% were adult, 40% juvenile and 5% subadult. Females accounted for 38% of the adult population, and males 62%, whereas amongst juveniles 74% were female. All the subadult population were male.

Manta birostris

The population of photographed *M. birostris* in the database contained 169 individuals, of which 85 (50%) were female, 71 (42%) male and 13 (8%) of unknown sex. As for *M. alfredi* individuals of unknown sex were excluded from further analysis. Of the 156 rays of known sex, 72.8% were adults and 20.7% juvenile, with the remaining 6.5% of unclassifiable maturity. Of the population of known maturity and sex, 78% were adults and 22% juvenile. The adult population was exactly split between males and females. The juvenile population was predominantly female (71%).

Injury Occurrence

Manta alfredi

A total of 3715 individually identified *M. alfredi* were examined for injury related scarring, of which 23.4% (n = 856) exhibited permanent scarring. For the latter, the number of injuries per individual, in both males and females, ranged from one to three. The frequency of the all individuals with two or more injuries was 1.35% (50/3715). The proportion of injured rays bearing two or more injury related scars was 5.84% (50/856).

In total, 909 separate injuries were recorded in the *M. alfredi* population. Of these, 37% were identified as anthropogenic in origin and 52% as natural, with the remaining 11% of unknown origin. Scars from injuries of unknown origin were not considered in further analysis. Manta ray injuries were significantly more likely to be due to natural (n = 471) causes than anthropogenic (n = 338: $X^2 = 10.7$, df = 1, $p = 0.00108$).

Of the 807 discernible injuries on manta rays of known sex, no significant difference was observed between males (48%) and females (52%) ($X^2 = 0.387$, df = 1, $p = 0.534$). Similarly, the type of injury did not appear to be associated with sex, as natural injuries affected 56% of males and 61% of females, while anthropogenic injuries affected 44% of males and 39% of females ($X^2 = 1.90$, df = 1, $p = 0.169$).

In the injured population, the ratio of Adult:Subadult:Juvenile was 67%:3%:30%, whereas the ratio for this in the overall *M. alfredi* population was 54%:5%:41%, respectively. Injury appeared to be related to maturity level in *M. alfredi* ($X^2 = 66.4$, df = 2, $p < 0.001$). Natural injuries affected 57% of the injured adult population while anthropogenic injuries affected 43%. In juveniles and subadults, 63% and 44% had natural injuries, respectively. Anthropogenic injury accounted for 37% of juvenile and 56% of subadult injuries. Whilst injury occurrence was related to maturity, the type of injury did not appear to be associated with maturity ($X^2 = 4.81$, df = 2, $p = 0.0903$).

Manta birostris

Of the 169 *M. birostris* in the MMRP database, 36 (21%) showed permanent scars from injury. Of these animals, the number of injuries per individual, both in males and females, was one.

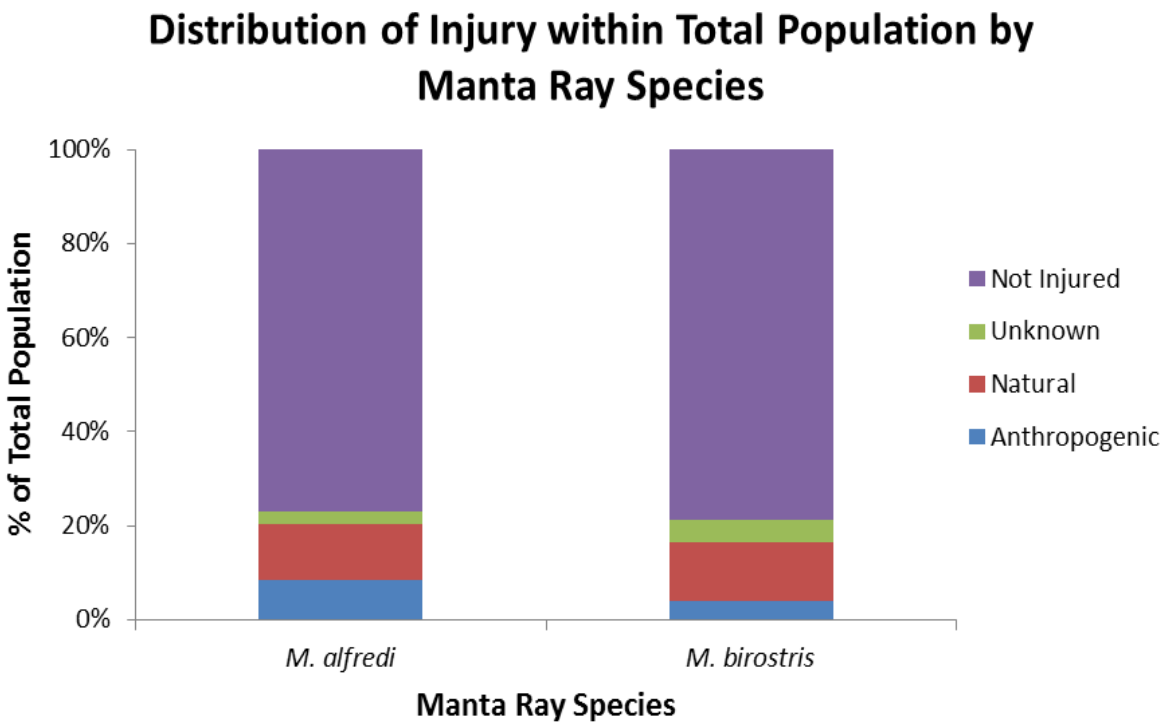
Of the injured animals, 58.33% had scars thought to be natural in origin, with the remaining 19.44% and 22.22% classified as anthropogenic and unknown, respectively. The scars of unknown origin were excluded from further analysis. There was no evidence of any difference in the rate of injury between natural versus anthropogenic origin ($X^2 = 2.74$, df = 1, $p = 0.0977$).

Of the 25 discernible injuries on manta rays of known sex, there was no significant difference in the proportion of males (44%) and females (56%) affected ($X^2 = 0.201$, df = 1, $p = 0.887$). Likewise, there appeared to be no relationship between injury type and sex (Fisher's exact test, p = 0.661) as natural injuries were observed in 71% of females and 82% of males, while 29% of females had anthropogenic injuries, as did 18% of males.

In the injured population, maturity distribution (Adult:Juvenile) was 78%:22%; this compares with the overall *M. birostris* population distribution of 79%:1%, respectively. Injury was not related to maturity level in oceanic manta rays (X^2 = 0, df = 1, p = 1). Similarly, the type of injury did not appear to be related to maturity level. All injuries on juveniles were natural, as were 70% of those on adults, with the remaining 30% of adults bearing scars from anthropogenic injury (Fisher's exact test, p = 0.280).

M. alfredi vs M. birostris

The number of injuries observed in *M. alfredi* compared to *M. birostris* were not significantly different (X^2 = 0.278, df = 1, p = 0.598) (Fig. 4a). Similarly, there was no relationship between the type of injury and the species of manta (X^2 = 2.491, df = 1, p = 0.115) (Fig. 4b).



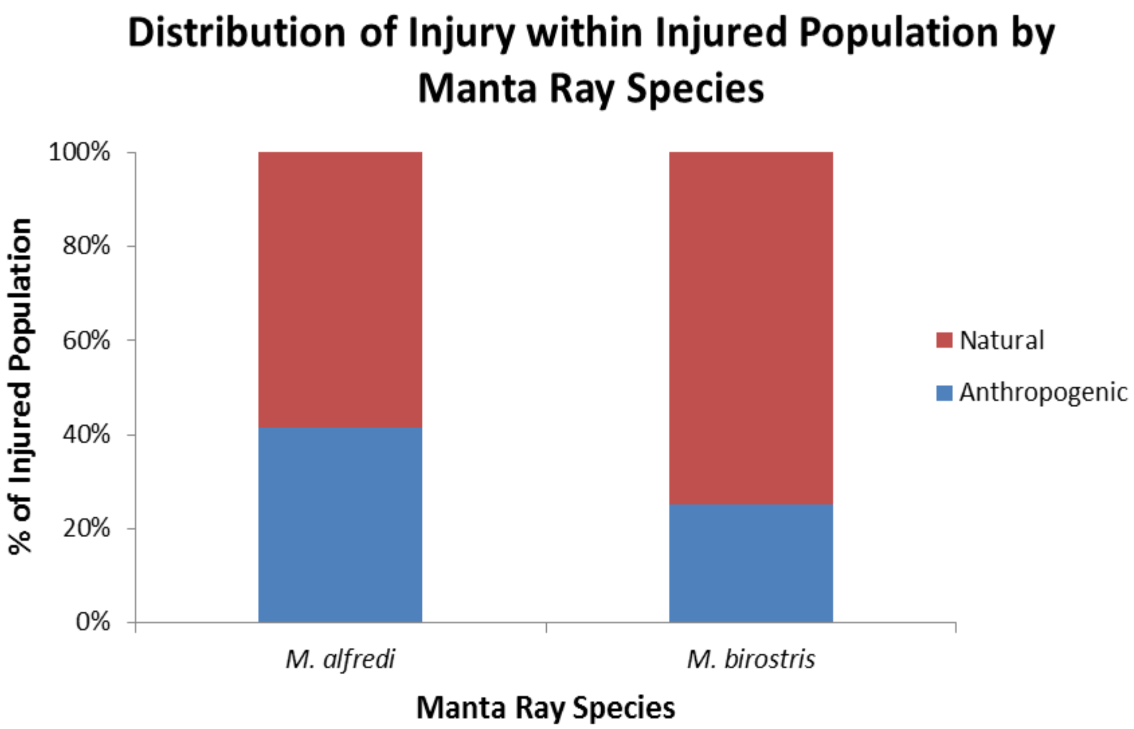


Figure 4: Distribution of injury by species: (a) proportion of total population with injury: Not Injured, Anthropogenic, Natural and Unknown; (b) distribution of Anthropogenic and Natural injuries within injured population.

Fresh Injury Accumulation in M. alfredi

Overall, the proportion of fresh injuries observed annually in *M. alfredi* more than doubled between 2005 and 2014, increasing from 1.14% (176/240) to 2.46% (1626/5675), respectively. The percentage of fresh injuries of anthropogenic origin sighted each year on *M. alfredi* remained largely constant over the same time period: 1.14% of 176 individuals in 2005 bore fresh anthropogenic scars, rising only to 1.17% (n = 1626) of individuals in 2014. By contrast, fresh injuries of natural origin increased from zero in 2005, to 1.29% in 2014. The trend in fresh injuries observed over the ten year study period was consistent, apart from in 2012. In 2011, 2012 and 2013, the proportion of fresh injuries sighted on *M. alfredi* fluctuated from 2.52%, 1.38% to 2.83%, respectively. This decline was largely due to a decrease in fresh anthropogenic injuries, which affected 1.46% of individuals in 2011, 0.32% in 2012, and 1.24% of *M. alfredi* sighted in 2013 (Fig. 5).

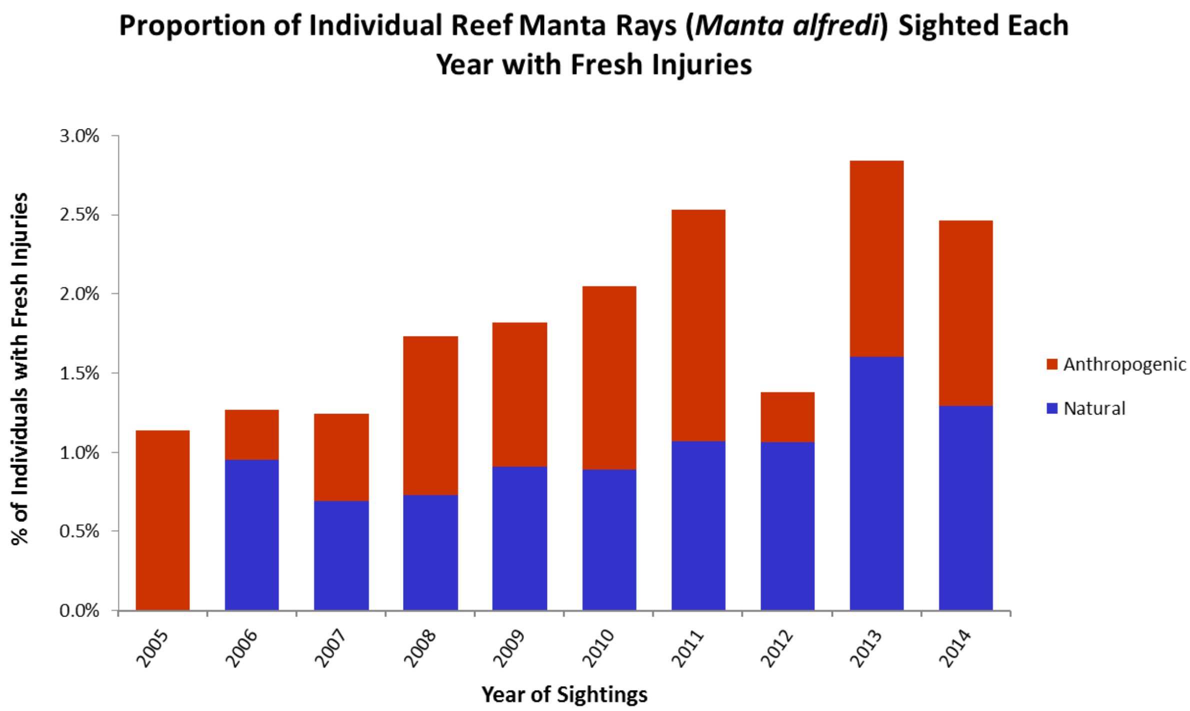


Figure 5: Normalised occurrence of individual *M. alfredi* observed with fresh injuries by year. The proportions of fresh injuries of anthropogenic and natural origin are shown.

Discussion

Occurrence of injuries in manta rays

The MMRP has established databases of individuals of both *M. alfredi* and *M. birostris* which, over the past decade, have visited the waters of the Maldives. Individuals of both species exhibited injuries, many of which can be established as either natural or anthropogenic in origin.

In contrast to a study of *M. alfredi* in Mozambique, where natural injuries affected 76% of individuals (Marshall and Bennett, 2010a), this study only found 13% of the *M. alfredi* in the MMRP's database of photographs to have injuries of natural origin. Amongst these, male and female manta rays were equally likely to possess an injury of either natural or anthropogenic origin. Injury frequency was, however, related to manta maturity. This is not surprising as adults, that showed noticeably more injuries than subadults or juveniles, have led longer lives and have therefore been exposed to injury and predation for longer (Deakos et al., 2011). Adult rays are also larger and, with a greater wingspan than their younger counterparts, they are better suited to withstand attack or entanglement. These results also reinforce previous findings that young manta rays adapt their behaviour in response to threat by geographically placing themselves in areas where they are less prone to predation (Deakos et al., 2011). This analysis is limited by the inability to quantify fatal injuries in manta rays of any maturity, as these incidents are rarely observed in the field (Deakos et al., 2011). Additionally, only injuries that left an external mark could be considered by this study. Internal damage caused by attack or entanglement, and the repercussions of this, warrants further investigation.

For the study conducted and reported here on *M. birostris,* no difference was observed between injury and manta sex or maturity, however since sample sizes were small there is a possibility of Type 2 errors (a false negative). By conducting a sensitivity analysis accurate results would be reiterated. Also, more observations of *M. birostris* would provide greater confidence in the results.

Accumulation of fresh injuries

One of the key aggregation sites of *M. alfredi* in the Maldives is Hanifaru lagoon, which is an important cleaning and feeding station for mantas, located in Baa atoll (Kitchen-Wheeler et al., 2012). In January 2012, scuba diving was prohibited here when the atoll was designated as an UNESCO World Biosphere Reserve in the latter part of 2011 (BRO, 2012). In the year following implementation rangers who monitored tourism, and enforced stringent regulations on activities such as fishing, were seen on a daily basis within the reserve. This success in management failed to be replicated in 2013, as an increase in rule infraction by locals and visitors alike was observed (MMRP, 2013). This resulted in an increase in fishing and diving activity, and therefore boat traffic, within the Marine Protected Area (MPA) (MMRP, 2013). These fluctuations in enforcement and management could account for the decline in observations of fresh injuries on individual *M. alfredi* found by this study as the reduction in injuries observed in 2012, and the subsequent rise in 2013, were largely of anthropogenic origin (Fig. 5). This finding confirms that protection of manta rays, particularly against human threat, is successful when adequately managed.

Injury effects on local *Manta* populations

The prevalence and origin of injuries on known manta rays in the Maldives show that activities other than direct fishing pose a threat to *Manta* species worldwide, which is consistent with results reported by Speed et al., (2008) of injures to whale sharks in the Indian Ocean.

Although delayed mortality from injury is unknown, it has been suggested that overall fitness of an injured manta will decline due to redirection of energy from foraging and reproduction to wound healing (Marshall and Bennett, 2010a). Injured manta rays are known to frequent cleaning stations more often than uninjured individuals (Heithaus, 2001b; Marshall, 2009). Increased time spent at these sites ultimately decreases the time mantas can spend foraging, as can severe injuries. Of the *M. alfredi* population studied, 7% had non-functioning or amputated cephalic fins, comparable to a value of 10% found in a study of this species in Hawaii (Deakos et al., 2011). These injuries, largely from monofilament fishing line entanglement, likely impact an individual's feeding efficiency as the function of cephalic fins is to funnel food into the manta's mouth (Deakos et al., 2011; Stevens, 2011d; Couturier et al., 2012).

Whereas most injuries to the head, dorsal and leading edge of mantas pectoral fins appeared to be anthropogenic in origin, the majority of injuries to the posterior pectoral and pelvic fins were identified as natural. This is consistent with results of populations studied in Mozambique (Marshall and Bennett, 2010a) and Hawaii (Deakos et al., 2011). Natural injuries are expected to be located here due to instinctive behaviour of the manta, causing it to speed away when attacked. If a predator had successfully caught hold of part of the animal's wing, then flesh would be removed in distinctive shapes, as observed in several mantas in the Maldives (Stevens, 2011b). Sometimes these non-fatal attacks can damage mantas' sex organs, potentially inhibiting reproductive success and, in extreme cases preventing it (Marshall and Bennett, 2010a). Reproductive gain can also be lost due to the stress of being entangled in fishing gear, observed to cause instant abortion in pregnant females (Marshall and Bennett, 2010b). Furthermore, serious trauma may delay the mean age of when a female manta will first mate (Harris, 1989). By monitoring growth and reproductive success over time, research into how missing reproductive organs and cephalic fin deformities impair overall fitness of manta rays can be completed (Kitchen-Wheeler, 2010; Deakos et al., 2011).

Anthropogenic activity is thought to influence manta ray behaviour, however the extent to which this occurs, regardless of the animals physical state, is unknown. Increasing tourism at key manta aggregation sites could cause animals to alter their natural behaviour as they opt to avoid loud, overcrowded sites where tourists go to scuba dive and snorkel. This could potentially result in increased predation attacks if the animal spends more time out at sea than on the reefs. The risk of entanglement increases as tourism grows. Visitors participate in recreational fishing which in turns leads to an increase in broken or discarded gear. Despite these negative aspects of tourism with regards to manta rays, some positives have been observed between human and manta interaction: animals trailing fishing lines, nets and/or hooks have approached humans and allowed the gear to be removed (Stevens, 2011c), hence increasing chances of survival. Furthermore, swim-with-manta programmes are becoming more popular (Deakos et al., 2011) and, if properly regulated, could educate the public whilst increasing their awareness on the value of the species.

Conclusions

Manta rays in the Maldives are protected by law and as a result of their seasonal occurrence, 5 of the country's 32 MPAs are specifically designated to safeguard the species (Anderson et al., 2010). The MMRP is working hard with the Maldivian government and local stakeholders to implement specific conservation and management plans for manta rays. It is hoped that findings from this study can be used to provide scientifically informed guidance on the best strategies to adopt. Ongoing monitoring of individuals is crucial to enable evaluation of applied management and protection measures (Knowlton and Kraus, 2001).

Further studies could try to quantify the long-term survival of animals with injuries and the likelihood of survival after serious injury. Since manta rays are highly valuable to the Maldives, preservation of this vulnerable species is vital. By understanding threats to manta rays, risks faced by local populations can be minimised in light of proper protection.

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