Trends in sightings of the stingrays of southern Mozambique

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Abstract. Understanding the drivers that influence abundance and distribution of marine species is essential to predict future trends in abundance and inform conservation efforts. This is vital in the largely unregulated coastline of Mozambique, where stingrays are afforded no protection by law and are caught by small-scale fishers. During SCUBA dives from 2012 to 2018, trained citizen scientists recorded 11 environmental, spatial and temporal variables along with the count of four stingray species (*Megatrygon microps*, *Taeniurops meyeni*, *Neotrygon indica* and *Pateobatis jenkinsii*) in the Inhambane region of Mozambique. By constructing bubble plots and generalised additive mixed models (GAMMs), we analysed the relationship between the probability of sightings of each species with the 11 variables. It is evident that the sightings for each of these four stingrays of the Inhambane region differ spatially and seasonally. The key findings include that *T. meyeni* and *M. microps* were found to increase in sighting frequency in different seasons (winter and summer respectively) at similar dive sites typically further from shore. *Neotrygon indica* commonly occupied the areas closer to shore. Identifying key habitats, and temporal and environmental conditions, is conducive to implementing effective conservation strategies in the region, such as, in this instance, all stingrays could be provided with a refuge in the same area.

Summary. This paper investigated the relationship among the sightings of four stingray species and environmental and temporal variables in southern Mozambique. This included the smalleye stingray (*Megatrygon microps*), which is severely unknown to science. We compared trends among the species, discussing overlap and niche partitioning. We identified an area where all stingrays are found, lending itself to future studies and conservation. Last, we outline the training necessary for reliable, long-term data collection by citizen scientists.

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Introduction

Chondrichthyans have the greatest percentage of threatened species in any taxonomic class of marine organisms (Hoffman *et al*. 2010), and batoids have generally received less conservation attention (Dulvy *et al*. 2017). Major research gaps in the south-western Indian Ocean, along with heavy and unregulated fishing pressure, have resulted in this area hosting some of the most at-risk (and data deficient) batoid species in the world (Temple *et al*. 2019). Little or no information on life-history parameters, such as reproductive biology, movement patterns, feeding ecology and population genetics, has meant that legal fisheries protection is lacking for some of the most at-risk (or data deficient) batoid species.

Most batoids are mesopredators within the marine food web throughout their range (Stevens *et al*. 2000; Navia *et al*. 2016; Flowers *et al*. 2021), have been shown to modify their physical and biological habitats through foraging and predation (O'Shea *et al*. 2012) and are considered indicators of habitat quality (Dulvy *et al*. 2014). The majority of studies investigating the role of mesopredator abundance have been focussed on anthropogenic factors, such as overfishing (Barker and Schluessel 2005; Frisk *et al*. 2005; Dulvy *et al*. 2014) and habitat degradation (Coll *et al*. 2012). Studies concerned with the effect of the abundance of predators and trophic cascading on mesopredator abundance often exclude the physical aspects of the environment, such as habitat structure that creates refuges, the availability of prey and foraging opportunity, which may more significantly influence the abundance of mesopredators (Desbiens *et al*. 2021). The physical characteristics of the environment are therefore crucial to consider, given that they may affect species assemblages and composition and, thus, mediate the structure of food webs. Failing to consider these factors can lead to misinterpretation of results.

A lack of basic information about how environmental and temporal conditions affect abundance of stingrays means that local and regional population assessment and management is more difficult for many species within the Dasyatidae family. For example, an indication as to the ideal environmental conditions for optimal stingray abundance will better inform management decisions over time (seasonally) and space (hotspot areas).

Non-anthropogenic causes of variability in elasmobranch abundance include drivers that vary over short (i.e. hours–days) time scales (e.g. tidal movements, lunar phases and oceanic currents; Couturier *et al*. 2011; Jaine *et al*. 2012), long-term (i.e. years–decades) changes (e.g. climate shifts; Albouy *et al*. 2014), subannual changes (e.g. seasonal temperature change and the Indian Ocean dipole; Rohner *et al*. 2013; Hameed 2018) and effects that can be considered invariant on the scale of a stingray's lifespan (e.g. depth at sea floor, rugosity and substratum; Parra *et al*. 2006; Ward-Paige *et al*. 2010). Biotic variables such as the presence of another stingray, competitive or commensal interactions (Last and Stevens 2009), and predator and prey abundance (Heupel and Hueter 2002), can also affect stingray abundances. Given the metabolic and osmoregulatory requirements of ectothermic sharks and rays, ambient sea temperature can directly influence their movements (Bernal *et al*. 2012; Rohner *et al*. 2013). Temporal factors include intra-annual variation in elasmobranch abundance, which has been related to reproduction behaviours and seasonal shifts in prey abundance (Marshall *et al*. 2008; O'Shea *et al*. 2013). Annual variation in elasmobranch abundance has previously been attributed to an increase in fishing effort and habitat degradation in the western Indian ocean (van der Elst and Everett 2015; Davidson and Dulvy 2017).

Overfishing is undoubtedly a contributing driver of diminished abundance of all marine megafauna in the south-western Indian ocean, including species within Dasyatidae (Temple *et al.* 2019). Large-bodied, shallow-water species are known to be most at risk because they are most accessible to all fishing gears (Dulvy *et al.* 2014). Small-scale fishers, mostly via drift and bottom-set gill-netting (Temple *et al.* 2019), are catching stingrays along the Mozambique coastline at an unregulated rate because no species in the family Dasyatidae are afforded protection by law in Mozambique (National Institute for Fisheries Research 2020). We aim to establish whether environmental and temporal variables affect the abundance of four stingray species via dive-log data collected by trained citizen scientists for broad application across their range. By also constructing bubble plots demonstrating relative abundance of each species across the local dive sites, we hope to inform future research and contribute towards management decisions to avoid the overfishing of these species locally.

The four stingray (family: Dasyatidae) species selected for analysis were *Pateobatis jenkinsii*, *Taeniurops meyeni*, *Neotrygon indica* and *Megatrygon microps. Pateobatis jenkinsii* and *T. meyeni* have been classified as '*Vulnerable*' by the International Union for the Conservation of Nature (IUCN) with a decreasing population trend (Kyne and White 2015; Manjaji-Matsumoto *et al.* 2016). These species are primarily benthic, although both species have been regularly observed swimming in mid-water (Last and Stevens 2009; Cerutti-Pereyra *et al.* 2012). *Neotrygon indica* was formally described by Pavan-Kumar *et al.* (2018), making it 1 of 11 genetically distinct species formerly known as *N. kuhlii*. *Neotrygon* spp. primarily occupy open sandy areas adjacent to rocky reefs (O'Shea *et al.* 2012; Gauthier *et al.* 2018). Pavan-Kumar *et al.* (2018) stated that considerable sampling effort is necessary for an investigation of the phylogeographic structure of this newly described *Neotrygon* species set. *Neotrygon indica* had not been evaluated by the IUCN at the time of writing. *Megatrygon microps* is classified as '*Data Deficient*' by the IUCN (Fahmi *et al.* 2016) and currently only two areas are known throughout its range where it is possible to observe *M. microps* during SCUBA dives. These two sites are along the Inhambane coastline of Mozambique (Pierce *et al.* 2008a) and the southern coastline of Queensland, Australia (Meekan *et al.* 2016). It is possible to use citizen scientist-collected photo-identification images to individually identify *M. microps* (Keeping *et al*. 2019). Photo ID has been used to track the broad-scale movement of *M. microps* along the Inhambane coastline of Mozambique, showing that these individuals are very rarely sighted, or indeed re-sighted, capturing only 70 individuals despite a 15-year-long dataset (Boggio-Pasqua *et al.* 2019). There is a call for further research concerning population size, distribution and demography, life history and ecology, fisher use and threats of all the classified stingrays by the IUCN. This information, although globally critical, is more efficiently tackled regionally, informing national governments about the populations of threatened species under their jurisdiction.

Materials and methods

Study site

SCUBA surveys of *M. microps*, *N. indica*, *P. jenkinsii* and *T. meyeni* were completed in the coastal waters adjacent to the village of Praia do Tofo in the Inhambane province of Mozambique (23.52°S, 35.23°E; Fig. 1). Survey dives were conducted between January 2012 and December 2018 at 16 sites, spanning 30 km of the coastline. Dive sites consisted of 'rocky reefs' that covered areas between 150 and 250 m^2. These reefs are predominantly rock but include some areas of sand. Between the rocky reefs were larger expanses of sand (these areas were not surveyed). Water temperatures were recorded at the maximum depth by a dive computer carried on the wrist of the researcher. The same computer model was used throughout the study (Suunto).

Data collection

Dives were conducted on a commercial dive boat, with no more than 11 divers in the group. Each dive group had two guides (non-researchers) and one staff researcher from the citizen-science organisation All Out Africa (AOA) as a minimum. The remainder of the group contained a variable number of trained citizen-science researchers from AOA, and recreational divers. AOA staff trained and accompanied citizen scientists *in situ* during data collection. Collectively, the contributors of data to this study are, henceforth, referred to as 'researchers'. To understand whether individual researchers had any influence on the sightings of each stingray species, the researcher designated to collect stingray data was recorded for each dive as the *source* variable. All researchers were trained before their data contribution was accepted. Training included techniques to identify each of the stingray species, estimation of underwater visibility and data entry. Dive sites were selected daily according to accessibility, influenced by the weather conditions and diver qualification levels. One trained researcher was assigned to record the stingray sightings during the dive, which they must have witnessed themselves, to avoid double-counting. Researchers followed a specific and consistent route for each of the dive sites. For analysis, the count of stingrays of each species was recorded, along with 11 predictor variables for each dive (Table 1). *Tide height* was sourced from NASA's Horizon website (http://ssd.jpl.nasa.gov/horizons.cgi).

Data analysis

The proportion of sightings for each dive site was calculated by dividing the number of stingrays seen by the total number of minutes spent diving at that site (stingray min^{-1}). The percentage of sightings for each dive site was represented in a bubble plot to give an overview of site-by-site abundance for each species.

The *temperature* variable was taken from dive computers of the same manufacturer (Suunto), although these were not calibrated against a thermometer, nor tested for drift over time. These temperature data are recorded to the nearest whole number to negate any small differences among dive computer units.

A generalised additive mixed model (GAMM) was applied to observations of each stingray species by using the GAMLSS package (Stasinopoulos 2007) in R software (ver. 3.4.4, R Foundation for Statistical Computing, Vienna, Austria). GAMMs were used to examine the relationship between the count of stingray sightings and a suite of 11 predictor variables (Table 1). A pairplot matrix of all the variables was constructed to ensure that there was no collinearity among the predictor variables (Zuur *et al*. 2009). For the full models (which included all predictor variables), *day of the year* (Julian date) was fitted with a cyclic penalised β-regression spline to ensure that the last and first values of the year were the same. *Dive time*, representing the total number of minutes spent at the reef during each dive, was offset in all the models to normalise the data to account for diving effort. *Dive site* was set as a random effect variable in all the GAMMs, allowing for a lack of independence among data points. We opted to used ecologically meaningful environmental variables for broader application outside of this diving area. Therefore, we included *underwater temperature*, *maximum depth*, *underwater visibility* and *tide height*, all of which were fitted using the non-parametric smoothing p-spline function 'pb()' (Stasinopoulos and Rigby 2017). The best-fitting distribution was selected from among the Poisson, negative binomial, zero-inflated Poisson and zero-inflated negative binomial distributions on the basis of fit to the full model (Zuur *et al*. 2009). The best-fitting model in each case was selected using the Akaike information criterion (AIC), where the lowest score indicated the better fit. The quantile residuals were also plotted against index to ensure that no patterning was shown by the residuals. Predictor variables were then selected by backward selection using the stepGAIC function via the GAMLSS package (Stasinopoulos and Rigby 2017). *P*-values for each variable were interpreted as approximations as to their respective significance (Halsey *et al*. 2015), and variables with $P < 0.05$ were retained to produce the minimum adequate model (MAM). Model assumptions were verified by plotting quantile residuals *v*. fitted values, quantile residuals *v*. every covariate in the MAM and quantile residuals *v*. every covariate not included in the MAM. Quantile residuals were checked to be centred at ~0 with a density estimate plot of the residuals, and homogeneity (no pattern) was ensured by plotting residuals against fitted values. A graphical output of each variable retained in the final model was produced to provide a visual representation of the relationship between each predictor variable and the response (the sightings count of each stingray).

Results

Data collection effort

In total, 1808 dives (1319 h) were recorded by 403 different citizen scientists between January 2012 and December 2018. Annual diving effort was lowest in 2012 (110.5 h) and highest in 2017 (387.7 h). Annual variability in total survey duration per day throughout each year of the study was high, because most data collection dives (50%) and encounters (60%) occurred in 2017 and 2018 (Fig. 2). The 16 dive sites had maximum depths between 8.6 and 32.9 m (mean = 22.0 m). Survey dives ranged between 12 and 90 min in duration (mean = 31.6 min). Underwater visibility varied from 2 to 35 m (mean = 13.7 m). Temperatures fluctuated between 17 and 29°C (mean = 24.1°C).

Total numbers of stingrays encountered were 355 individuals of *Neotrygon indica*, 160 of *Taeniurops meyeni*, 147 of *Pateobatis jenkinsii* and 68 of *Megatrygon microps* over the study period.

No significant collinearity was found among variables (Pearson's correlation $P > 0.05$, Appendix 1). Removing *source* improved the AIC of all the final models, implying that there was no meaningful effect of researcher identity on the number of stingrays observed.

Trends in stingray sightings

Day of the year was the only variable to be retained in all four stingray models (Fig. 3a, 4a, 5a, 6a). The day of the year trend for N. indica indicates a peak in the autumn season, with a dip in abundance occurring in spring. The P. jenkinsii model retained only two significant predictor variables, namely, day of the year and year. More P. jenkinsii individuals were seen through the first half of the year than the second. The year variable in both P. jenkinsii and N. indica models, the only two models to retain this variable, showed a general increase in abundance from 2012 through to 2018.

The count of stingrays was not explained by either the *current* or *surge* predictor variables for any of the four species studied. All species except *P. jenkinsii* retained *underwater visibility* as a predictor variable in the final models (Table 2). In each of these cases, sightings generally increased with an increasing horizontal underwater visibility (Fig. 3*b*, 4*b*, 6*b*). *Tide height* was also retained in three of the four models, implying an important but complex relationship with each of these stingrays. Notably, abundance in *M. microps* increases slightly at spring low and spring high tide heights. For both *T. meyeni* and *N. indica*, abundance tends to decrease with an increasing *tide height*.

Dive site was used as a 'random effect' variable to cater for the lack of independence between data points. Locally, however, it is interesting to note which stingrays are seen most often at which sites. Therefore, we constructed a bubble plot to show these data.

Although they have been seen at the same site simultaneously through the study period (n = 13), the *day of the year* variable for *M. microps* and *T. meyeni* displayed opposite trends. *Megatrygon microps* and *T. meyeni* abundances increased at approximately the third quarter (Fig. 3*a*) and the first quarter (Fig. 4*a*) of the year respectively. Maximum groups of up to five individuals of *T. meyeni* were sighted simultaneously and four *M. microps* individuals during these respective seasons. *Taeniurops meyeni* and *M. microps* also have a similar distribution throughout the study area (Fig. 7). This distribution agrees with the relationship that *maximum depth* showed in the models, describing *M. microps* and *T. meyeni* both to be observed more often at greater depths (Fig. 3*d*, 4*d*). Conversely, *N. indica and P. jenkinsii* were observed throughout the range of studied depths.

The physical and biological characteristics of specific underwater environments can influence the abundance of stingrays (O'Shea *et al*. 2013), and the characteristics in the dive site 'Giants'

(Appendix 2) seemed to appeal to all four of the studied rays. 'Giants' was the only dive site of the 16 surveyed to have accumulated more than one sighting of all the stingray species each year between 2012 and 2018. 'Giants' has a mean depth of 30.2 m, located near to the Praia do Tofo bay (Fig. 1). *Pateobatis jenkinsii* is seen to have a large proportion (59.3%) of sightings on 'Reggies' dive site (Fig. 7*c*), whereas *N. indica* has more sightings in near-shore dive sites (Fig. 7*d*), regardless of depth. Further investigation of the raw data showed that most (93%) of all *N. indica* sightings were recorded on the seven most proximal dive sites to the bay of Praia do Tofo (Fig. 7*d*).

Discussion

Seasonal changes in elasmobranch abundance have been linked to reproductive behaviour, ontogenetic habitat shifts and changing abundances of prey and predator species (Chaikin *et al.* 2020; Le Port *et al*. 2012; Schlaff *et al.* 2014). *Megatrygon microps* and *T. meyeni*, although sighted throughout the year, peak in abundance in opposite seasons, when they can be seen in groups of up to four and five individuals respectively. Boggio-Pasqua *et al.* (2019) also found a peak in sightings of *M. microps* between July and September each year in the same study area. It therefore seems reasonable that these seasonal abundances may be driven by reproductive behaviour, ontogenetic habitat shifts or changing prey and predator abundances, potentially making the Inhambane coastal region critical for the preservation of these species. Further specific information about fishery threats, population genetics, reproductive and feeding ecology, small-scale movements and distribution of these species is required for optimal management between these dive sites and throughout their range.

Characteristics of the underwater environment influence the abundance of stingray species, and each species will favour different aspects of a habitat (Flowers *et al*. 2021; O'Shea *et al*. 2013). *Current* and *surge* were not retained in any of the final models, suggesting that these variables are not contributing to the abundance of the stingray species in this diving region. However, wave action and current velocity were seen to affect mesopredatory teleost fish abundance in the northern Great Barrier Reef (Desbiens *et al*. 2021). Three of the four stingray species in this study are primarily found resting on the seafloor; so, we suggest that energetic conditions underwater do not affect stingray abundances as they would mid-water teleost fishes. Intuitively, *underwater visibility* was retained in all except one model, demonstrating that with an increasing visibility, stingray detection increases. This was also the case in the study region for manta ray and turtle detectability (Rohner *et al*. 2013; Williams *et al*. 2017). *Maximum depth* was retained for two stingray species (*T. meyeni* and *M. microps*), which agrees with the similar use of dive sites (Fig. 7).

Most of *P. jenkinsii* observations were made at the dive site 'Reggies', which is likely to be due to the large rocky overhangs with sandy floors where *P. jenkinsii* was usually found (Manjaji-Matsumoto *et al*. 2016; J. Keeping, pers. comm.). However, more information on reef structure, substrata and prey availability will show more information about the ideal habitat for *P. jenkinsii*. On the contrary, *Neotrygon indica* was observed on near-shore sites, regardless of depth. These species differ greatly in size (Pavan-Kumar *et al.* 2018; Manjaji-Matsumoto 2016, tail spine characteristics (Schwartz 2007), visual acuity (Garza-Gisholt *et al*. 2015) and other ways; thereby, it is unsurprising their fine-scale distribution differs greatly. However, both species can be seen simultaneously on the dive site 'Giants'.

The dive site 'Giants' has been highlighted as the only dive site where all the stingray species in this study were observed multiple times in each year of study. How each of these stingrays divides resources within 'Giants', and to understand what conditions make 'Giants' unique among the 16 studied dive sites, requires further investigation. Information such as rugosity, slope, substratum, abundance of prey and predator species and fishing pressure could help understand which variables within each dive site provide ideal habitat for each species.

Day of the year was the only variable retained in all the models, whereas *temperature* was retained in only two. These variables did not present any collinearity, suggesting that there are other seasonal variances driving these abundances of stingrays in this region. Underwater temperatures can be influenced by large-scale oceanographic movement, such as the dynamic eddies and upwellings found off the coast of Inhambane (Saetre and Silva 1984; Rohner *et al.* 2018). The productive coastal waters adjacent to Praia do Tofo have also been linked to the abundance of surface-feeding *Rhincodon typus*, which are found to frequent this area throughout the year in accordance with plankton blooms (Rohner *et al*. 2018).

Tide height has a difficult relationship with stingray abundance to interpret. We can imply that some relationship is held between the increasing tide height and higher abundances of *P. jenkinsii* and *N. indica*. A relationship between the spring high and low tides and an increase in *M. microps* abundance was also observed. Higher abundances of *Mobula alfredi* and *Rhincodon typus* were seen 6 h after high tide in the same study area (Rohner *et al*. 2013). Further investigation to understand these relationships is required.

The predictor variables included in the models are not exhaustive, and other variables are likely to be important in explaining the remaining variance in stingray abundances in this region (Saetre and Silva 1984; Le Port *et al*. 2012; Rohner *et al*. 2013, 2018). For example, fishing effort in the study area and the abundance of predator and prey species were not measured and are potentially key variables influencing stingray abundance. Including these variables might help in designing effective conservation strategies. Analysing more fine-scale environmental and ecological variables (e.g. current velocity, reef rugosity, substrate cover, behavioural observations) will give a more specific understanding of where and how each stingray species uses different parts of the reef. The dive site 'Giants' could provide an ideal opportunity for this type of investigation, providing efficient data collection because it contains a diversity of habitats containing all studies stingray species.

This study utilised recreational diving tour companies and trained citizen scientists, proving to be an effective method in which to provide long-term, meaningful ecological data on the four stingray species observed in the coastal area of Praia do Tofo. However, it is important to point out that the variable number of divers and researchers in the diving group could affect the number of stingrays detected per diving trip. Collecting observational data while near to a commercial dive group of mixed diving experience could negatively influence the sightings of stingrays, because they could be disturbed and swim away from a novice diver before being seen by a researcher (Stamoulis *et al.* 2020). Also, it could be assumed that with a larger dive group, it would be more likely that stingrays would be sighted. The effect of dive group size was not considered in this study and further investigation into detection rate and stingray avoidance behaviours induced by dive group size is required to fully understand dive group effect on stingray counts.

Small-scale fishers are catching stingrays along the Inhambane coastline at an unregulated rate because no dasyatids are afforded protection by law (National Institute for Fisheries Research, 2020). Comprehensive monitoring of the frequency of stingray catches along the Mozambican coastline, including gears used, could provide important information about the level of threat to stingrays and their population status (Pierce *et al.* 2008b; Temple *et al.* 2019). Manta rays (family Mobulidae) are a major tourism attraction to the Inhambane province of Mozambique, creating an economic impact (including associated tourism expenditures) of up to US$34.0 million annually (Venables *et al.* 2016). All mobulid species known to occur in Mozambique are now protected under the latest Mozambican fisheries legislation (Boletim Da República 2020), and along with sawfish (family: pristidae), are the only batoids included in the legislation. The occurrence of *Megatrygon microps* is extremely rare globally, being seen while diving in only two regions in the world (Pierce *et al.* 2008a; Last and Stevens 2009). With little known about this species currently, but catches being reported in Mozambique (Boggio-Pasqua *et al.* 2019; J. Keeping, pers. comm.) and seasonal peaks in observations, it would seem that this region is both important to their life cycle and has potential to create a tourism draw akin to manta rays. It therefore seems wise to also place *M. microps* under official fisheries protection in Mozambique.

Comments on the contribution of citizen scientists

Citizen scientists have provided the funding essential for long-term data collection while also themselves collecting data, demonstrating the efficacy of citizen scientists in contributing towards meaningful scientific investigations (Chin *et al*. 2018 Kosmala *et al*. 2016. The careful management of volunteers in this citizen-science program by the programs' staff, both in data collection and expectation, has undoubtedly been the crux of its success. The staff running the program were retained on a long-term basis and adequately remunerated to foster a low staff turnover. Staff had a minimum of 2 years of experience in diving in the region and a minimum of a biology-based undergraduate degree. Volunteers were trained in stingray identification by a presentation and in-water training. All stingray counts were verified by a supervising staff member, who was also present during dives. One volunteer per dive was allocated to count the number of each stingray species during the dive, recording the dive metadata and stingray counts in the program database. It was made clear during training that all data collected by volunteers were the property of the organisation running the program, and volunteers would be thanked collectively in the acknowledgements of any subsequent publication.

Chin and Pecl (2018) outlined the issues that can arise in using citizen scientists in place of trained scientists to collect data, such as accuracy, which will vary depending on training, experience and supervision. Kosmala *et al*. (2016) stated that datasets produced by citizen scientists can be of questionable quality despite training, because the accuracy of individual citizen scientists varies. Kosmala *et al*. (2016) suggested mitigating methods to increase data accuracy to include volunteer training and testing, expert validation, replication across volunteers and statistical modelling of potential bias. In the study presented here, testing of stingray identification was introduced only in 2018, whereas expert validation was used throughout the study period. There was adequate replication across multiple volunteers, equating to 1808 dives recorded by 403 different volunteers between 2012 and 2018. Observer bias was tested in these data by recording the *source* variable, noting which allocated volunteer researcher recorded the stingray data for each dive. None of the models retained this variable, indicating that there was no significant, consistent effect of any individual researcher on the recorded sightings. We therefore support the notion that training for citizen scientists by competent, long-term staff to identify and record counts of marine species can yield reliable results.

Conclusions

Monitoring the trends in stingray sightings has given us an insight into the variables influencing their abundance and distribution in the Inhambane region of Mozambique. We have identified seasonal trends and relationships with depth, tide height, temperature and year with each stingray species' abundance. We have also identified a reef area where all the studied stingray species occur. These data will assist in both future stingray-focussed studies and highlight 'Giants' as an ideal reef to provide refuge for all of the studied stingray species.

Local fishers in this area have been known to catch stingray species, which is entirely legal in Mozambique. Future studies ought to address this factor and its potential effect to stingray population trends in both the Inhambane region of Mozambique and the greater western Indian Ocean.

Megatrygon microps, *N. indica*, *P. jenkinsii* and *T. meyeni* globally are afforded limited protection throughout their respective ranges, with special note to *Megatrygon microps*, where extremely little information is known about this large, potentially migratory species. The IUCN have called for information on population size, distribution and trends, life history, ecology and harvest of all four studied species. The continued inclusion of a citizen-science research program will enable consistent and reliable means for long-term data collection of all the stingrays included in this study.

Conflicts of interest

The authors declare that they have no conflicts of interest.

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Table 1. Environmental, temporal and spatial variables collected by researchers during dives

NASA tide data were sourced from NASA's Horizons website (http://ssd.jpl.nasa.gov/horizons.cgi)

Smoother type	Unit	Category	Source	Description	Variable Type	
	(Integer)	(Count)	(Researcher)	-	(Response)	Count of each stingray species observed on a dive
Pbc()	Integer	Continuous	Researcher	–	Predictor	Day of the year
–	Year	Categorical	Researcher	Year the dive took place	Predictor	Year
Pb()	°C	Continuous	Dive Computer	Water temperature at the max depth	Predictor	Underwater temperature
Pb()	m	Continuous	Dive Computer	–	Predictor	Maximum depth
Pb()	m	Continuous	Researcher	Estimation of horizontal underwater visibility	Predictor	Underwater visibility
Pb()	m	Continuous	NASA	Height of the tide at the time of the dive	Predictor	Tide height
–	1/0	Binary	Researcher	Presence or absence of directional water movement at depth	Predictor	Current
–	1/0	Binary	Researcher	Presence or absence of back-and-forth motion of water at depth	Predictor	Surge
–	–	Categorical	Researcher	An identification to the AOA staff on the dive	Predictor	Source
–	–	Categorical	Researcher	The site the dive took place	Random	Dive site
–	Min	Continuous	Dive computer	The time (in min) spent surveying the dive site	Offset	Bottom time

Table 2. Summary of the generalised additive mixed model (GAMM) for assessing the influence of each predictor to the relative sightings of stingrays *Megatrygon microps*, *Taeniurops meyeni*, *Neotrygon indica* and *Pateobatis jenkinsii*

Only predictor variables with a *P*-value of <0.05 was retained in each model

Term added to model	*N. indica*		*P. jenkinsii*		*T. meyeni*		*M. microps*	
	d.f.	$P(c^2)$	d.f.	$P(c^2)$	d.f.	$P(c^2)$	d.f.	$P(c^2)$
Day of the year	7	–	1	–	1	–	10	–
Year	11	0.008	4	0.01	–	–	–	–
Maximum depth	–	–	–	–	9	$6.42E^{-13}$	1	$3.30E^{-09}$
Underwater visibility	8	0.022	–	–	1	0.0002	1	0.004
Tide height	2	$<2E^{-16}$	–	–	2	0.03	13	0.05

Underwater temperature	–	–	–	–	1	0.003	2	0.0002
Full model	**30**		**17**		**12**		**32**	

Fig. 1. The study region of Praia do Tofo in southern Mozambique, indicating the 16 dive sites at which stingrays were sighted.

Fig. 2. Number of minutes of diving per day of the year from 2012 to 2018, including days with zero minutes.

Fig. 3. Term plots for each of the predictor variables retained in the best-fitting GAMM for *Megatrygon microps*. Each plot describes the relationship of the predictor variable against abundance of *Megatrygon microps* sightings considering the response of the other predictor variables retained in the GAMM (denoted by 'partial(predictor variable)'). The 'rug' across the *x*-axis of each graph indicates the number of data points across *x*.

Fig. 4. Term plots for each of the predictor variables retained in the best-fitting GAMM for *Taeniurops meyeni*. Each plot describes the relationship of the predictor variable against abundance of *Taeniurops meyeni* sightings considering the response of the other predictor variables retained in the GAMM (denoted by 'partial(predictor variable)'). The 'rug' across the *x*-axis of each graph indicates the number of data points across *x*.

Fig. 5. Term plots for each of the predictor variables retained in the best-fitting GAMM for *Pateobatis jenkinsii*. Each plot describes the relationship of the predictor variable against abundance of *Pateobatis jenkinsii* sightings considering the response of the other predictor variables retained in the GAMM (denoted by 'partial(predictor variable)'). The 'rug' across the *x*-axis of each graph indicates the number of data points across *x*.

Fig. 6. Term plots for each of the predictor variables retained in the best-fitting GAMM for *Neotrygon indica*. Each plot describes the relationship of the predictor variable against abundance of *Neotrygon indica* sightings considering the response of the other predictor variables retained in the GAMM (denoted by 'partial(predictor variable)'). The 'rug' across the *x*-axis of each graph indicates the number of data points across *x*.

Fig. 7. Size of circles denote the percentage of sightings of (*a*) *Megatrygon microps*, (*b*) *Taeniurops meyeni*, (*c*) *Pateobatis jenkinsii* and (*d*) *Neotrygon indica* at each dive site, adjusted for SCUBA diving effort (min).

Appendix 1. A pairplot matrix to identify collinearity between predictor variables

Bivariate scatter plots are below the diagonal, histograms on the diagonal and the Pearson correlation above the diagonal. The closer the Pearson correlation is to 1 or –1, the more correlated the two variables

Appendix 2. Dive site metadata

Site	Number of dives on the site	Minimum and maximum depth (m)	Average depth (m)	Proximity from shore (m)	Average bottom time (min)	*P. jenkinsii* (*n*)	*N. indica* (*n*)	*T. meyeni* (*n*)	*M. microps* (*n*)
Amazon	25	24.7–30.4	27.2	14934	27.3	0	0	8	3
Office	121	22.8–30.8	25.3	10014	32.6	22	0	27	3
Reggie’s	116	24.0–30.4	27.5	9214	29.8	73	1	27	3
Mike’s	116	10.0–18.2	15.6	583	47.2	0	83	0	0
Fingers	93	13.5–17.6	15.0	714	38.5	2	29	1	0
Salon	293	12.8–18.1	15.3	728	41.1	0	131	0	0
Tabletop	13	26.5–32.3	30.4	2899	26	0	6	2	2
Sherwood	54	23.0–31.9	29.5	2844	27.0	2	10	9	0
Giants	312	22.0–32.9	30.2	2390	23.9	20	49	58	44
Clownfish	180	8.6–16.1	10.1	166	33.9	0	1	2	0
Simon’s Town	65	14.2–19.8	18.2	650	50.0	3	8	2	1
Marble Arch	22	17.0–19.9	18.4	642	48.2	0	9	0	0
Chamber	1	16.5-18.6	18.6	629	54	0	1	0	0
Rob’s	36	18.6–30.8	27.6	1804	28.7	0	0	2	1
Manta Reef	259	21.0–29.8	24.8	1857	36.9	22	27	0	5
Outback	102	25.9–32.0	28.7	2049	28.3	3	0	22	6