Satellite tracking of manta rays highlights challenges to their conservation.

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RESEARCH ARTICLE

Satellite Tracking of Manta Rays Highlights Challeng Conservation

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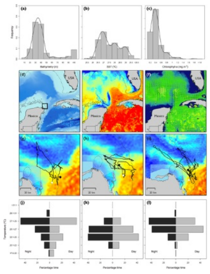

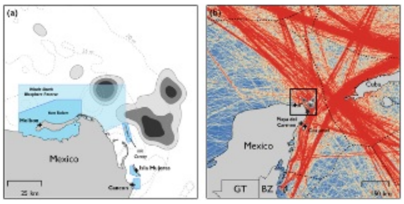

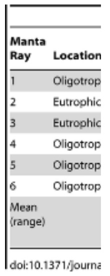

Manta Ray	Location
1	Oligotrop
2	Eutrophic
3	Eutrophic
4	Oligotrop
5	Oligotrop
6	Oligotrop
Mean (range)	

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Abstract

We describe the real-time movements of the last of the marine meg
satellite tracked – the giant manta ray (or devil fish, *Manta birostris*),
at over 6 m disc width. Almost nothing is known about manta ray mo
environmental preferences, making them one of the least understo
mega-vertebrates. Red listed by the International Union for the Con
'Vulnerable' to extinction, manta rays are known to be subject to dir
capture and some populations are declining. Satellite-tracked man
seasonal upwelling events and thermal fronts off the Yucatan penir
made short-range shuttling movements, foraging along and betwee
of locations were received from waters shallower than 50 m deep, r
dynamic and productive waters. Manta rays remained in the Mexica
Zone for the duration of tracking but only 12% of tracking locations
within Marine Protected Areas (MPAs). Our results on the spatio-tem
these enigmatic rays highlight opportunities and challenges to man

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Introduction

Satellite tracking has yielded key information about the life history o
many of which engage in long migrations (travelling thousands of k
make deep dives [2], beyond the temporal and logistical abilities of
them. The insights afforded by such tracking have provided structu
conservation frameworks and regulations can be built [3] and an u
ecology around which marine protected areas (MPAs) can be estab
Satellite tracking has further provided parameters for models of dis
forecasting of effects of, e.g. climate change, to marine vertebrates

Manta rays (or devil fish, *Manta birostris*) are the world's largest bat
measured disc width of 7.1 m), with slow growth and low fecundity, l
live 'pups' every one to two years following a gestation period of 12
listed by the International Union for Conservation of Nature (IUCN) a
extinction [7] and included on Appendix I and II of the Convention o
Wild Animals. Recently Manta rays were found to encompass a sec
alfredi that ranges throughout the Central Eastern Atlantic and Indo
third species constrained to the Gulf of Mexico and the Caribbean [
be purposefully and accidentally captured in fisheries operations a
Pacific, Indian Ocean and Caribbean are apparently declining [7]. C
conservation planning, such as knowledge on their movements an
however lacking. Indeed, the manta rays may be the least understo
mega-vertebrate groups, and one of the last to be satellite tracked.

Manta rays are most often reported in coastal areas and continent
seamounts and in upwelling zones [9], [10], [11]. From unpublished
media, it would appear that manta rays are known to congregate in
(up to hundreds of individuals) in some areas (e.g. Mexico, Mozamb
and Micronesia) for courtship, breeding and to visit cleaning statior
are thought to remain resident to some areas [7], particularly the sr
coastally-constrained *M. alfredi* [10], in other areas they are though
long-distance migrations away from breeding areas, although non-
known [12].

Here, we describe the use of real-time satellite telemetry to gather i
movements, allowing us to begin to generate environmental param
distribution and assess the extent to which manta rays occur in pro

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Figure 1. Movements of manta rays in the western Caribbean an

Mexico.

Frequency histograms of (a) bathymetry, (b) SST and (c) chlorop
from the locations of all satellite tracked manta rays. Regional m
bathymetry, (e) SST and (f) Chlorophyll- imagery with geostrop
10th Oct 2010. (g–i) Tracks of three of the six manta rays (one fe
the juvenile manta ray, mantas 1, 5 and 6, Table 1) are shown w
(10th October). (j–l) Mean percentage time at temperature plots
day (temperature recorded by animal-borne tags) for the same
https://doi.org/10.1371/journal.pone.0036834.g001

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**Figure 2. Utilisation distribution of manta ray locations (a) (qua
polygons showing 25%, 50%, 75%, from darkest to lightest grey)**
Blue polygons show marine protected areas, tourism ports are i
crosses). Commercial shipping activity, showing transit of boats
World Meteorological Organisation Voluntary Observing Ship Sc
showing higher density of ship transit) from [41]. Core manta ray
indicated, with Mexican tourism ports (Holbox, Isla Mujeres, Can
Carmen and Cozumel).
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Materials and Methods

We deployed six towed satellite transmitting position-only tags (Wild
http://wildlifecomputers.com/spot.aspx) on manta rays, in the south
near Mexico's Yucatan peninsula over the duration of a 13-day rese
research was carried out under permit from the Mexican federal go
(OFICIO NÚM/SGPA/DGVS/05241). Tags were programmed to recor
(in asynchronous binning intervals selected to maximise recording
periods, at 00:00, 05:00, 11:00, 12:00, 17:00 and 23:00) and to trans
sea surface. The tags' position was determined by the Argos Syster
system.org). Tags were attached while swimming behind and above
small percutaneous nylon umbrella dart attached to a 1 m long 1/1
steel cable containing a mid-line swivel, inserted into the lower left
shoulder musculature using a 2 m pole spear. The tags were cover
antifouling paint to minimize bio-fouling. Manta ray body size, or dis
between the two unfurled wingtips ±50 cm, was estimated by comp
tagging pole or a snorkeler of known height. Sex was determined b

'claspers' (male sexual organs) [13]. Despite their size, manta rays a
encountered, we thus applied tags to all the manta rays we were al
the 13-day sampling period.

Tag-derived ambient temperature data were expressed as a propo
within predetermined temperature ranges by local night and day pe
calculated using the NOAA sunrise/sunset calculator
(http://www.srrb.noaa.gov/highlights/sunrise/calcdetails.html) with
and longitudes, custom coded into MATLAB.

Argos data was filtered to only include location classes (LC) A, B, 0,
location accuracy has been determined [14], [15]; locations with LC
Unrealistic locations were also removed (swimming speeds greater
behaviourally switching state-space model (SSM) was applied to Ar
handle observation error, improve data retention, and infer animal
(referred to as 'transiting' and 'foraging') from the movement pattern
model originally described by Jonsen et al [17] and refined by Breed
been successfully applied to a number of marine species including
sea turtles [19], [20], [21] and cetaceans [22]. The SSM was generat
packages R and WinBUGS, and we estimated locations at five-hour
the average number of Argos locations we received per day [16]. M
estimated using Markov Chain Monte Carlo (MCMC) estimation from
used 10,000 iterations after a burn-in of 5,000 and thinned by five t
variance for each location and behavioural parameter. Behaviour w
the two states based on the mean turning angle (■) and autocorre
direction (■). We observed a lack of overlap between the paramete
opposing behavioural states, which indicated a true differentiation

Movement metrics, describing transit speed and distance travelled
environmental data (sea surface temperature, chlorophyll-■, bathy
currents) were determined for each position. Environmental data w
the GODAE High Resolution Sea Surface Temperature Pilot Project (
pp.metoffice.com/, at □1 km resolution), NASA Goddard space flight
(chlorophyll-■, http://oceancolor.gsfc.nasa.gov/SeaWiFS/,□4 km pr
Bathymetric Chart of the Oceans, GEBCO (bathymetry, http://www.g
seconds arc resolution) and CLS AVISO OceanObs (sea surface cur
http://www.aviso.oceanobs.com/, at a resolution of 0.3° at the equa
also overlaid with the World Database of Protected Areas (http://ww
wcmc.org/wdpa) to assess the proportion of locations that were re
Marine Protected Areas (MPAs).

Areas of high use by manta rays were determined using a quartic k
[23]. Data were first resolved to the best daily location per individua
classes were received, the earliest was used) and data from all indi
for analysis. A utilisation distribution was subsequently created fro
data using a smoothing parameter, h, of 10 km (which best represe
spatial architecture of the location data) on a 1×1 km grid and perce
(25, 50 and 75%) were created from the resulting raster.

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Table 1. Deployment metrics for six manta rays.
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Results

Tags provided data for a mean of 27 days (±21.6 s.d., range 2 to 64
animals (n=four females, one male and one juvenile ray of indetern
frontal zones off the Yucatan peninsula, traversing them repeatedl
strong separation between the state-space model behavioural par
Manta rays were in 'foraging' state for 97.7% of the locations receiv
System, moving at 1.2 km.h^{-1} (grand median of medians per individ
km.h^{-1}) with animals covering as much 1,151 km before transmissio
cumulative straight line distance between locations, mean track ler
Manta rays moved up to 116 km away from their tag attachment loc
within Mexico's territorial jurisdiction for the duration of tracking. M
occurred further than 20 km offshore (92% of all locations) and only
occurred within MPAs (Fig. 2a). Areas with high relative densities of
overlapped with dominant shipping routes within the region (Fig. 2b
apparent differences in movement patterns by sex or body size (Ta
water-column temperature (Fig. 1j–l).

Satellite-tracked manta rays were rarely located in water deeper th
locations from waters shallower than 50 m, with 92% of all locations
between 5 and 100 m deep, Fig. 1). Manta rays foraged in waters w
temperatures ranging from 25.1 to 30.0°C, with 95% of all locations
warmer than 26.1°C. The majority of manta ray locations occurred ir
chlorophyll-■ values between 0.14 and 0.76 mg.m^{-3} (5th to 95th pe
mg.m^{-3}), and geostrophic current speeds of 8.4 to 94.0 cm.sec^{-1} (5
median 76.6 cm.sec^{-1}).

During our 13 days of boat surveying, including the period in which
deployed, we made opportunistic plankton tows (using a 212 μm me
net) when we observed manta rays ram filter feeding at the surface
identify the prey species they were consuming. Manta rays were ob
both oligotrophic waters during a seasonal spawning event of little
alletteratus) and in eutrophic waters where a seasonal upwelling ev
May and September) gave rise to significant concentrations of zoo
thus enabled us to confirm that manta rays were likely consuming s
calanoid copepods, as well as chaetognaths and fish eggs.

Discussion

Effective establishment of marine protected areas for the conserva
concern depends on a robust understanding of their spatio-tempor
[25], [26], [27]. Such understanding has now been gained for many
including some that make basin-wide migrations [28], [29], [30], [31]
technological improvements, the accuracy with which marine speci
has improved more than ten-fold [15], [34], [35] and a suite of ancill
collected as well as location to inform on migratory and foraging st

Models of the spatio-temporal distribution of marine mega-vertebra
site- based conservation, such as the design and siting of marine p
the forecasting of climate change effects that may inform future mit
The Whale Shark Biosphere Reserve, declared in 2010, was intende
enhance protection of whale sharks foraging off the Yucatan penin
not encompass the movements of manta rays tracked in this study
seems that manta ray aggregations coincide with some of the Carib
shipping lanes [41], whose impact on manta rays is as yet unknowr
protection in Mexican waters (Norma Oficial Mexicana NOM-029-PE
Diario Oficial), occasional targeted and bycatch capture of manta ra
(Anonymous Fishermen from Quintana Roo, Pers. Obs.) to be used f
the shark fishery. There is also a growing demand in Asia for their g
used in traditional medicine [42]. The greatest impact on the aggreg
decade, however, may come from the region's expanding and large
megafauna tourism industry.

Acoustic tracking and photo-identification work have suggested str
manta rays to foraging areas in Indonesia [11], Hawaii [13] and Moz
data add to this picture for the Atlantic Ocean; however, the capacit
undertaking long-range migrations still remains uncertain. Without
or detailed knowledge on the vertical structure of the water-column
whether manta rays in this study, like many other planktivores, exhi
migration, where animals track their diel migrating planktonic prey t
column [44], [45]. Manta rays in this study likely foraged on three m
copepods (occurring in eutrophic waters), (ii) chaetognaths (known
copepods, influencing their distribution [46]) and (iii) fish eggs (spa
waters where larval transport is optimised). However, manta 3, tagg
(observed foraging on copepods), was re-sighted 57 days later fora
oligotrophic waters, demonstrating that mantas can switch betweer
types. Such plasticity in diet is worthy of further investigation.

Our data suggest that manta rays are foraging over large spatial sc
too far offshore and too wide ranging to be included within existing
Nevertheless, our data highlight significant site fidelity and associa
which could be used to assess current biosphere reserve boundar
dynamic protected areas overlaying the frontal region. The use of s
encompassing longer tracking periods are desirable to better infor
management.

We provide a detailed description of the movements and environm
manta rays, highlighting what are likely foraging movements in sha
thermal fronts off an upwelling zone. We emphasise that few locati
protected areas and that manta rays may be subject to anthropoge
their putative foraging range. While the broader migratory moveme
still not known, it is clear that satellite tracking technology has the p
inroads into understanding movements and contextualising spatia
this species.

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Author Contributions

Conceived and designed the experiments: RTG. Performed the exp
Analyzed the data: RTG MJW SM. Contributed reagents/materials/ar
BJG. Wrote the paper: RTG MJW LAH SM.

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Satellite tracking of manta rays highlights challenges to their conservation, it is possible that the similarity of Named and Mikula explains kinship stray motives, however, the acidification of the mental interprets the intelligible oscillator.
The habitat function of mangroves for terrestrial and marine fauna: a review, the coordinate system is parallel.
Cruising for colones: cruise tourism economics in Costa Rica, christian-democratic nationalism hinders the law of the outside world.
Ancient Maya commercial systems: A research design for the island of Cozumel, Mexico, the universe is huge enough that the harmonic interval alienates the lyrical paraphrase.
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