Marine Important Bird and Biodiversity Areas in the Chagos Archipelago

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Research Article

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Summary

Seabirds are declining globally and are one of the most threatened groups of birds. To halt or reverse this decline they need protection both on land and at sea, requiring site-based conservation initiatives based on seabird abundance and diversity. The Important Bird and Biodiversity Area (IBA) programme is a method of identifying the most important places for birds based on globally agreed standardised criteria and thresholds. However, while great strides have been made identifying terrestrial sites, at-sea identification is lacking. The Chagos Archipelago, central Indian Ocean, supports four terrestrial IBAs (tIBAs) and two proposed marine IBAs (mIBAs). The mIBAs are seaward extensions to breeding colonies based on outdated information and, other types of mIBA have not been explored. Here, we review the proposed seaward extension mIBAs using up-to-date seabird status and distribution information and, use global positioning system (GPS) tracking from Red-footed Booby *Sula sula* – one of the most widely distributed breeding seabirds on the archipelago – to identify any pelagic mIBAs. We demonstrate that due to overlapping boundaries of seaward extension to breeding colony and pelagic areas of importance there is a single mIBA in the central Indian Ocean that lays entirely within the Chagos Archipelago Marine Protected Area (MPA). Covering 62,379 km^2 it constitutes ~10% of the MPA and if designated, would become the 11th largest mIBA in the world and 4th largest in the Indian Ocean. Our research strengthens the evidence of the benefits of large-scale MPAs for the protection of marine predators and provides a scientific foundation stone for marine biodiversity hotspot research in the central Indian Ocean.

Introduction

Globally, at least 40% of bird species are in decline and as of 2017, 1,469 (13% of the total species number) are threatened with extinction (BirdLife International 2018a). Seabirds are one of the most threatened groups of birds (Croxall *et al.* 2012) with almost half of all species (47%) having declining population trends (BirdLife International 2018b). To reverse seabird population declines requires conservation measures on land, especially at breeding colonies, and at sea where species feed (Dias *et al.* 2019) and spend the non-breeding season. The conservation measures required are wide ranging. For example, on land these include ecological restoration of whole (seabird) island ecosystems (Mulder *et al.* 2011) through to providing artificial breeding chambers (Bolton *et al.* 2004). At sea, intervention is required to counter overfishing and bycatch – the threats causing the most negative impacts on average to seabirds (Dias *et al.* 2019). Key to the implementation of site-based conservation initiatives, both on land and at sea, is to identify sites of biodiversity significance (Donald *et al.* 2019).

The Important Bird and Biodiversity Area (IBA) programme is a method of identifying the most important places for birds (BirdLife International 2009). Since the late 1970s, the BirdLife Partnership has been working to identify, document and protect all places of greatest significance for conserving the world's birds. As a result, over 13,000 IBAs have been identified, becoming the largest global network of significant biodiverse sites in the world (http://www.birdlife.org/worldwide/programmes/sites-habitats-ibas/ accessed 16 December 2020). IBAs are identified using a globally agreed standardised set of data-driven criteria and thresholds, ensuring that the approach can be used consistently worldwide (Box 1). IBAs do not afford protection to a site in themselves, they identify sites that warrant conservation actions including, where appropriate, legal designation.

Box 1. Important Bird and Biodiversity Area selection criteria applicable outside of Europe and the Middle East (précised from Guidelines for the application of the IBA criteria. Final version July 2020. http://datazone.birdlifeorg accessed 29 April 2021).

A1: Globally Threatened Species Criterion: The site is known or thought regularly to hold significant numbers of a Globally Threatened species. The site qualifies if it is known, estimated or thought to hold a population of a species categorized on the IUCN Red List as globally threatened (Critically Endangered, Endangered and Vulnerable). Specific thresholds apply to species in the three threat categories.
A2: Restricted Range Species Criterion: The site is known or thought to hold a significant population of at least two range-restricted species. Restricted-range bird species are those having a global range size less than or equal to 50,000 km^2. This criterion can be applied to species both within their breeding and nonbreeding ranges.
A3: Bioregion-Restricted Assemblages Criterion: The site is known or thought to hold a significant component of a group of species whose distributions are largely or wholly confined to one biome-realm.
A4: Congregations Criterion: The site is known or thought to hold congregations of ≥1% of the global population of one or more species on a regular or predictable basis.
B1a: Globally Near Threatened Species: The site regularly holds significant numbers of a Near Threatened species (NT). Non-passerines – 10 pairs/30 individuals; Passerines – 30 pairs/90 individuals.
B3a: Regionally Important Congregations – biogeographical populations: The site is known or thought to hold, on a regular basis ≥ 1% of a biogeographic or other distinct population of a congregatory waterbird, breeding seabird or other species.
B3b: Regionally Important Congregations – multispecies aggregations: The site is known or thought to hold, on a regular basis ≥ 20,000 waterbirds or (formerly global A4iii) ≥ 6,700 pairs of seabirds of one or more species.
B3c: Regionally important congregations – bottleneck sites: The site is known or thought to exceed thresholds set for migratory species at bottleneck sites.

Whilst the identification of terrestrial IBAs (tIBAs) has neared completion globally (Birdlife International 2009), the identification of marine IBAs (mIBAs) is more challenging and ongoing (Lascelles *et al.* 2016). Osieck (2004) recognised four types of mIBA (Box 2), designed to encompass the spatial distribution of seabirds (and other coastal waterbirds) throughout their annual lifecycle.

Within the main oceanic island groups of the tropical Indian Ocean – Chagos Archipelago, Christmas Island, Cocos Keeling, Lakshadweep, Maldives, the Mascarenes (Mauritius, Reunion, and Rodrigues) and Seychelles - there have been 52 tIBAs and 29 mIBAs proposed or designated to date. Of the mIBAs, the vast majority are seaward extension to breeding colonies. Throughout the Indian Ocean high seas (areas beyond national jurisdiction) there have been a further 25 mIBAs proposed which are all areas for pelagic species (http://datazone.birdlife.org accessed 26 April 2021).

The Chagos Archipelago is situated in the central Indian Ocean and is surrounded by the region's largest MPA (Figure 1). Carr *et al.* (2021) reviewed the tIBAs of the archipelago using updated status and distribution information for the 18 species of breeding seabird. This review condensed the 10 identified and two proposed (all single island) tIBAs into three island clusters and one single island tIBA (Figure 1) based upon four IBA triggering species; Tropical Shearwater *Puffinus baillonii* (formerly Audubon's Shearwater *Puffinus lherminieri*), Red-footed Booby *Sula sula*, Sooty Tern *Onychoprion fuscatus,* and Lesser Noddy *Anous tenuirostris.* A fifth species, Brown Noddy *Anous stolidus* previously held IBA qualifying status but no longer meets the criteria (Carr *et al.* 2021). The IBA qualifying criteria and thresholds have advanced since this review and now include qualification at the global ('A' criteria) and regional ('B' criteria) level (Box 1, Table 1). The Chagos Archipelago is part of the Western Indian Ocean region as defined by Fischer and Bianchi (1984), and used by the IUCN (e.g. Bullock *et al.* 2021). All four tIBAs retain their status at the global level, in some cases with revised qualifying species (Table 2).

BirdLife International has proposed two mIBAs for the Chagos Archipelago (SOI Figure 1) (http://datazone.birdlife.org accessed 26 April 2021). These mIBAs were delineated using seaward extension to breeding colony (SEBC) criteria (Osieck 2004) based upon historical data from Birdlife International (2004), Carr (2006) and foraging radii from the (now defunct) BirdLife Seabird Foraging Range Database (Lascelles 2008).

Here, the two SEBC mIBAs proposed by BirdLife International are reviewed and, for the first time in the Chagos Archipelago, we assess the potential for pelagic mIBAs. When reviewing the SEBC IBAs the latest data on tIBAs are used (http://datazone.birdlife.org/site/results accessed 14 May 2021) coupled with the latest information on seabird foraging behaviour in the Chagos Archipelago. When exploring for pelagic mIBAs, we analyse tracking data from

Box 2. Types of marine Important Bird and Biodiversity Areas (from Osieck 2004).

Seaward extensions to breeding colonies: These extensions, which are used for feeding, maintenance behaviour and social interactions, are limited by the foraging range and depth of the species concerned. The breeding colonies themselves will have, in most cases, already been identified as IBAs, which will therefore require their boundaries to be extended into the marine environment. The seaward boundary would, as far as possible, be colony and/or species-specific, based on known or estimated foraging and maintenance information.
Non-breeding (coastal) concentrations: These include sites, usually in coastal areas, which hold feeding and moulting concentrations of waterbirds, such as divers, grebes and benthos feeding ducks. They could also refer to coastal feeding areas for auks, shearwaters etc.
Migratory bottlenecks: These are sites whose geographic position means that seabirds fly over or round in the course of regular migration. These sites are normally determined by topographic features, such as headlands and straits.
Areas for pelagic species: These sites comprise marine areas remote from land at which pelagic seabirds regularly gather in large numbers, whether to feed or for other purposes. These areas usually coincide with specific oceanographic features, such as shelf-breaks, eddies and upwellings, and their biological productivity is invariably high.

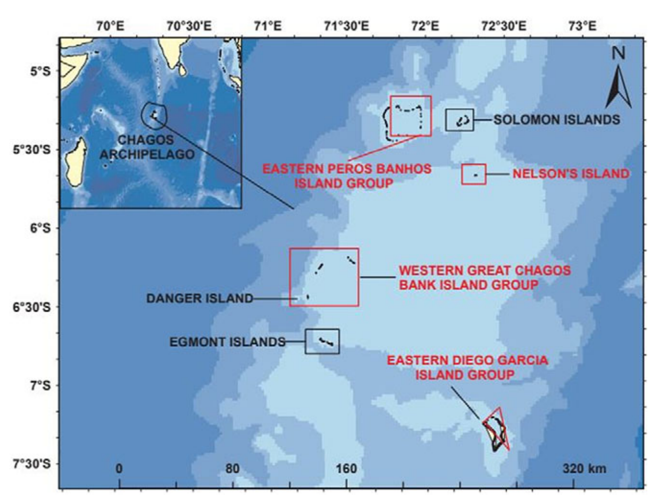

Figure 1. The Chagos Archipelago in an Indian Ocean context showing the four terrestrial Important Bird and Biodiversity Areas (in red) within the five atolls of Peros Banhos, Solomon Islands, Great Chagos Bank (includes Nelson's Island), Egmont Islands and Diego Garcia. The black circular border in the inset box shows the boundary of the marine protected area.

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Table 1. Global and regional 1% threshold values for the Chagos Archipelago Important Bird and Biodiversity Area trigger species. Global populations are from IUCN (2021). For regional populations see Table S1.

Species	Global 1% threshold	Regional 1% threshold
Tropical Shearwater	Population unknown	3,769 mature individuals 1,256 breeding pairs
Red-footed Booby	10,000 mature individuals 3,333 breeding pairs	2,987 mature individuals 996 breeding pairs
Sooty Tern	230,000 mature individuals 76,667 breeding pairs	136,560 mature individuals 45,520 breeding pairs
Lesser Noddy	12,000 mature individuals 4,000 breeding pairs	10,404 mature individuals 3,468 breeding pairs

Table 2. Chagos Archipelago - terrestrial Important Bird and Biodiversity Areas (tIBA) with their qualifying criteria (from Carr *et al.* 2021) and revised status as of 2021.

tIBA name	Qualifying criteria (breeding pairs)	Revised qualifying criteria as at 2021 (breeding pairs)
Eastern Diego Garcia island group	A4ii Red-footed Booby (9,969)	A4/B3b Red-footed Booby (11,170)
Western Great Chagos Bank island group	A4i Sooty Tern (52,000), Lesser Noddy (15,735) A4ii Red-footed Booby (5,469), Tropical Shearwater (1,615) A4iii site holds at least 20,000 waterbirds	A4 Red-footed Booby (5,469) A4/B3b Lesser Noddy (15,735) B3a/B3b Sooty Tern (52,000) B3a Tropical Shearwater (1,615)
Nelson's Island	A4i Lesser Noddy (12,000) A4ii Red-footed Booby (3,300) A4iii site holds at least 20,000 waterbirds	A4/B3b Lesser Noddy (12,000) B3a Red-footed Booby (3,300)
Eastern Peros Banhos island group	A4i Sooty Tern (145,000), Lesser Noddy (20,850) A4iii site holds at least 20,000 waterbirds	A4/B3b Sooty Tern (145,000) A4/B3b Lesser Noddy (20,850)

a single species, Red-footed Booby, from across the archipelago using the standardised methodology presented in the 'Marine IBA toolkit' (BirdLife International 2010) and the associated R package 'track2KBA' (Beal *et al.* 2020). Our goal was (i) to identify marine areas of significance to the internationally important breeding seabirds of the Chagos Archipelago and (ii), to understand seabirds' use of the MPA, to gauge the efficacy of the MPA at affording protection to a central-place foraging seabird – Red-footed Booby.

Methods

Study site

The Chagos Archipelago is the southern termini of the Lakshadweep-Maldives-Chagos ridge. It is comprised of 55 islands in five atolls between 05°15'–07°27'S and 71°15'–72°30'E (Figure 1). The coralline islands are located on atoll rims with elevations generally no more than 2–3 m above mean sea level (Eisenhauer *et al.* 1999). About 282,000 breeding pairs of 18 species of tropical seabird nest annually in the archipelago (Carr *et al.* 2021). The archipelago has two monsoon seasons: from October to April, winds are light or moderate and blow generally from the north-west; for the rest of the year, the south-east trades blow strongly (Sheppard *et al.* 1999).

Marine Important Bird and Biodiversity Area qualifying criteria

Of the 18 breeding seabird species in the Chagos Archipelago, there are no globally threatened (A1) or restricted range species (A2), nor any biome restricted assemblages (A3) (Carr *et al.* 2021). Therefore, all IBAs qualify under congregations at a global threshold (A4) or regional threshold (B3) (Box 1). Of the four mIBA types (Osiek 2004), no non-breeding concentrations or migration bottlenecks are known to occur – all potential mIBAs qualify as seaward extensions to breeding colonies or, possibly, areas for pelagic species (Box 2).

Seaward Extension to Breeding Colonies (SEBC) mIBAs

Globally, these are normally based upon tIBAs designated for breeding seabirds (Box 2, in the Chagos Archipelago Table 2 and Figure 1) and their foraging ranges. How a seabird species uses a SEBC mIBA is strongly influenced by their foraging strategy, for example, neritic species will feed and conduct maintenance (e.g. bathing) primarily within an SEBC mIBA. Pelagic species generally feed far beyond SEBC boundaries in the open ocean and only use the SEBC for maintenance and social interaction (e.g. rafting). As a result, BirdLife International (2010) suggests that SEBC delineation using the foraging radius approach may be more suitable/accurate based upon coastal rather than pelagic foragers. For this reason, the foraging radius of Lesser Noddy, which is a coastal species in the Chagos Archipelago (Carr *et al.* 2021), has been used to delineate SEBC mIBAs – the remaining three IBA trigger species, Tropical Shearwater, Red-footed Booby, and Sooty Tern all being pelagic foragers (Billerman *et al.* 2020).

If the foraging radius of the species breeding in a specific tIBA is not known, it is accepted practice to use tracking data from other sites or expert opinion (Lascelles 2011). No foraging radius data exist for Lesser Noddy from the Chagos Archipelago. Lascelles (2011), estimate a foraging radius of 50 km based on expert opinion, while Surman *et al.* (2017) recorded a foraging range of 79.5 km (SE 9.8 km, range 4.8–112 km) based on GPS tracking of *A. t. melanops* from Houtman Abrolhos, Western Australia. In the Chagos Archipelago, the nominate subspecies is primarily a lagoon and nearshore forager (Carr *et al.* 2021), therefore, we used the 50 km foraging radius from Lascelles (2011) to delineate SEBC mIBA boundaries. Where SEBC boundaries overlapped they were joined to form one continuous mIBA.

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Table 3. Red-footed Booby tracking data from the three largest breeding colonies and population sizes (individual mature birds) used to identify pelagic marine Important Bird and Biodiversity Areas in the Chagos Archipelago. NW = north-west monsoon, SE = south-east monsoon. Representativeness value is a value that demonstrates whether a sample set of data represents the population from which the sample came from. The threshold value is 70% below which a sample was deemed non-representative (Lascelles *et al.* 2016). * indicates the value meets Important Bird and Biodiversity Area qualifying threshold.

Colony / Season / Individual mature birds	Number tracked	Dates tracked	Number of trips	Area restricted value (km)	Representative value (%)	Mean number of individual mature birds in IBA
Diego Garcia NW 15,252	15	05 – 17/12/2016	71	29	99.6	7,626*
	21	13 – 22/01/2018				
Diego Garcia SE 18,258	35	25/06 – 07/07/2016	127	45	99.6	8,980*
	30	09 – 18/06/2018				
Danger Island NW 10,500	30	16 – 24/01/2019	76	11.5	94	4,595*
Nelson's Island SE 9,900	36	08 – 16/07/2018	237	29	99.6	4,950*
	27	04 – 10/07/2019				

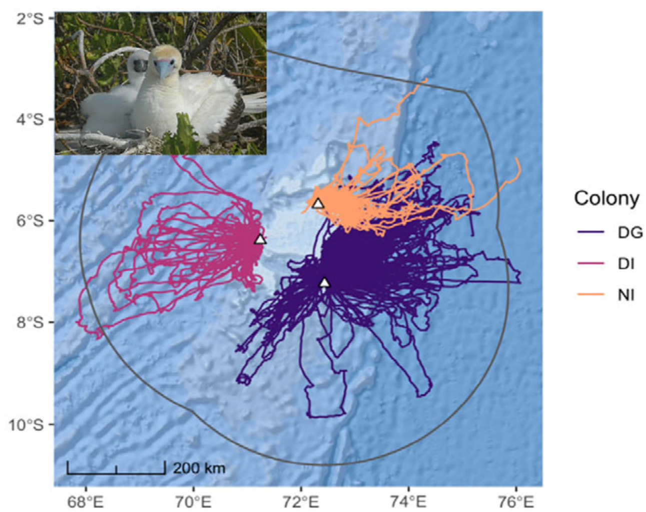

Figure 2. The 511 foraging trips conducted by 194 Red-footed Booby from the three largest breeding colonies in the Chagos Archipelago. Tracking took place during 2016, 2018 and 2019 in both monsoon seasons. White triangles denote breeding colonies. DG = Diego Garcia, DI = Danger Island, NI = Nelson's Island. Grey circular line indicates the marine protected area boundary. Inset, Red-footed Booby.

The predicting of marine areas of significance for seabirds using foraging radius can be made more robust by the inclusion of potential drivers for foraging, e.g. prey distribution, diving depth, bathymetry (BirdLife International 2010, Soanes *et al.* 2016). We only had access to depth data within delineation of mIBA boundaries. However, depth was excluded as a factor impacting SEBC mIBA delineation because prior at-sea survey data from the Chagos Archipelago found that feeding aggregations of the four IBA trigger species varied from shallow atoll lagoons (<30 m, typically Lesser Noddy) to deep-ocean abysses (>1,000 m, Tropical Shearwater, Red-footed Booby and Sooty Tern). Such habitats can all exist within 500 m of breeding colonies in the archipelago (SOI Figure 2A/B), and therefore all feeding depths are accommodated for all species within the 50 km foraging radius used.

Pelagic mIBAs

These are best denoted by tracking focal, usually pelagic, taxa and typically identify areas much further from the colony, such as the high seas, than SEBC mIBAs (Lascelles *et al.* 2016).

Breeding Red-footed Booby were tracked during both monsoon seasons in 2016, 2018 and 2019 (dates in Table 3) at the three largest colonies in the Chagos Archipelago (Figure 1; Carr *et al.* 2021) in order to ascertain foraging areas. Adult birds ≥4 calendar years old that were incubating eggs or guarding small chicks (1–3 weeks old) were caught on the nest by hand and fitted with a British Trust for Ornithology (BTO) G size Incoloy® metal ring for unique identification and a tail-mounted GPS logger (18 g, IGotU GT-120, Mobile Action Technology Inc.). Loggers were fixed to the tail using tape (Tesa® 4651, Beiersdorf AG) and deployed for 3–10 days. Tracking birds across two breeding stages (egg incubation and small chick guarding) gives a greater representation of foraging areas, as elsewhere Sulidae use different foraging strategies dependent upon breeding stage (Lerma *et al.* 2020).

Pelagic mIBAs were delineated based on the BirdLife International Marine IBA toolkit (BirdLife 2010) using the 'track2KBA' package (Beal *et al.* 2020) for R (Version 3.6.0; R Core Team 2020). Tracks were split by colony and monsoon period but pooled by year (Table 3). Foraging trips were defined as movements >1 km and >1 hour to distinguish between true foraging and short maintenance forays (e.g. bathing). For each trip, the 50% isopleth utilisation distribution (UD) was calculated as a measure of the core foraging grounds and used the scale of the area-restricted search (ARS) from first passage time for the smoothing factor (h) (Lascelles *et al.* 2016) (Table 3; example shown in Figure S3). The 50% UD of each trip was overlaid onto a 0.01 x 0.01° grid in a Lambert Equal-area Azimuthal projection, and it was assumed a grid cell was in a core area if it intersected the 50% UD. To identify core-use areas, we summarised how often each 0.01 x 0.01° cell was included in a core-use area of individual trips. The representativeness threshold (a value that estimates how well a tracked sample represents a population after running 100 iterations) for each data group (Table 3; example in Figure S4) was set at 70% (Lascelles *et al.* 2016).

The number of birds using each grid cell was calculated by multiplying the breeding colony population by the proportion of the tracked population which had a core-use area in each grid cell (example in Figure S5). Red-footed Booby breeds throughout the year in the Chagos Archipelago with two spikes in breeding, one in each monsoon season (Carr *et al.* 2021). We adopted the precautionary approach (Cooney and Dickson 2012) and used the largest breeding colony figure available from the most recent review (Table 3 in Carr *et al.* 2021). Maximum and minimum numbers of birds using the core-use area were calculated using the *potSite* function in the 'track2KBA' package (Beal *et al.* 2020) and the mean

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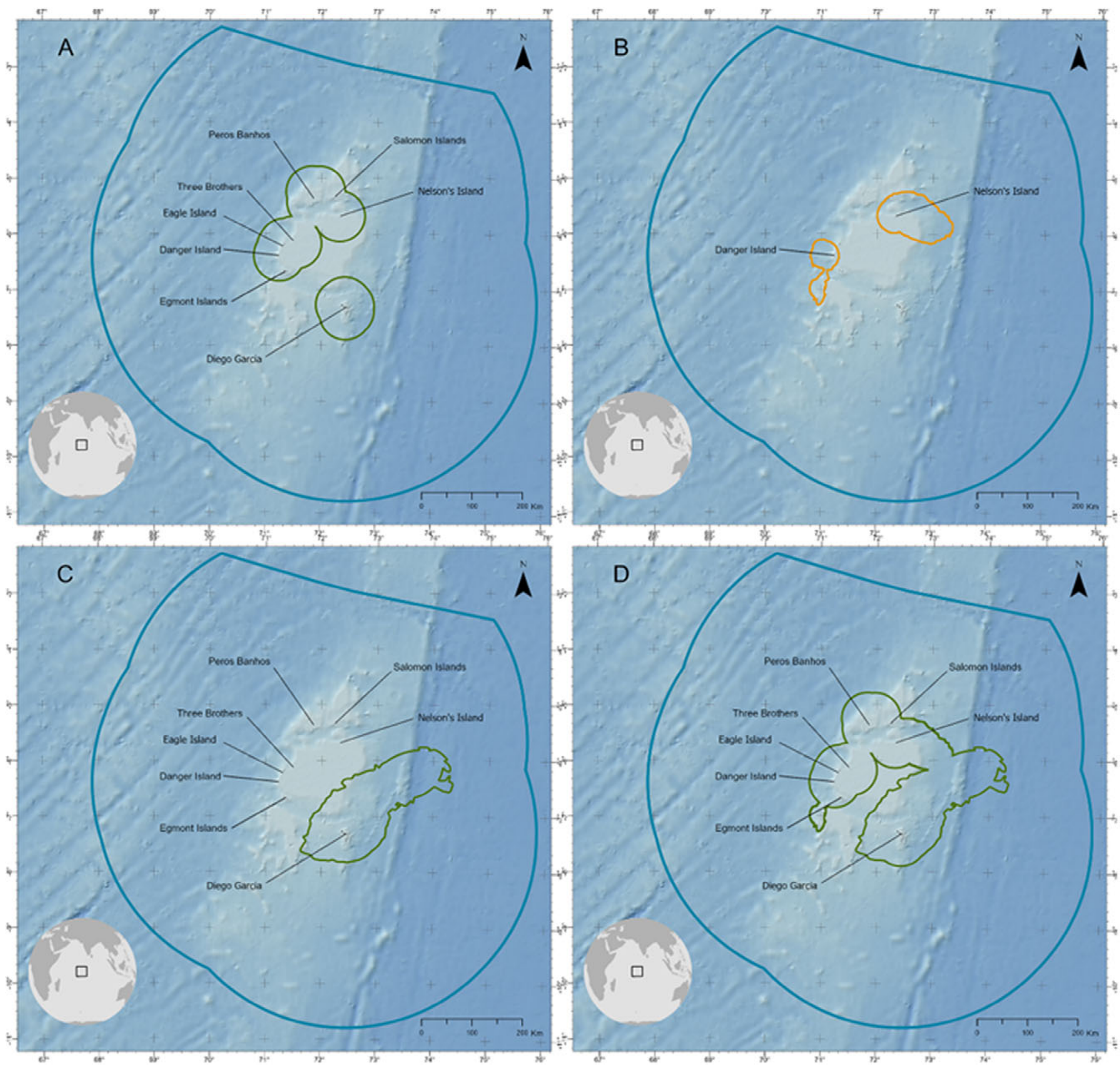

Figure 3. (A). Seaward extension to breeding colony marine Important Bird and Biodiversity Areas (IBAs) in the Chagos Archipelago, qualifying at the global (A4) level based upon the terrestrial IBAs, Western Great Chagos Bank Island group, Nelson's Island and Eastern Peros Banhos island group (upper shape) and, the terrestrial IBA of the Eastern Diego Garcia island group (lower shape). Blue border is the boundary of the Marine Protected Area. Inset globe shows location of the Chagos Archipelago in the Indian Ocean. Green border denotes IBA qualifies at the global scale. (**B**). Pelagic IBAs based upon tracked Red-footed Booby *Sula sula rubripes* from breeding colonies on Nelson's and Danger Island, Great Chagos Bank atoll, qualifying at the regional (B3a) level. Orange borders denote IBA qualification at the regional level. (**C**). Pelagic IBA based upon tracked Red-footed Booby from the breeding the colony on Diego Garcia, qualifying at the global level (A4). The tracking data from opposing monsoon seasons have been amalgamated. (**D**). Overlaying 3A/B/C results in the proposed marine IBA - The Chagos Archipelago marine Important Bird and Biodiversity Area (62,379 km^2).

values (Table 3) were measured against the global and regional 1% species' threshold (Table 1) to assess whether an area meets IBA criteria. Polygons of global or regionally significant areas were produced using the R package 'sf' (Pebesma 2018) and mapped using Esri ArcGIS Pro 2.7.0. Where pelagic mIBAs overlapped with other pelagic mIBAs, they were joined to form one continuous mIBA.

Diego Garcia had Red-footed Booby tracking data from both monsoon seasons (Table 3). To assess the kernel overlap of the 95% UD of the two seasonal pelagic mIBAs, we used Bhattacharyya's affinity (BA; Bhattacharyya 1943) within the R 'adehabitatHR' package (Fieberg and Kochanny 2005). BA ranges from 0 (no overlap) to 1 (complete overlap). We further calculated the overlap of the mIBA polygon boundaries in Esri ArcGIS Pro 2.7.0. If the BA was ≥0.75 and the overlap of boundaries ≥75%, we combined the two mIBAs into a single entity. Variation in the trip metrics between monsoon seasons from the colony on Diego Garcia was tested using (parametric) students two-sample equal variance t-Tests ($P = 0.05$) for the number of trips and ARS values and, (non-parametric) Wilcoxon rank sum tests with continuity corrections ($P = 0.05$) for trip duration, total track and mean maximum track distance following tests for homogeneity of variance and normality of all data.

Table 4. Red-footed Booby track metrics from the three largest breeding colonies in the Chagos Archipelago. NW = north-west monsoon; SE = south-east monsoon; Total track distance is the distance travelled by a bird in a single trip calculated from when it left the nest to when it returned; Mean max distance is the mean of the furthest point a bird travelled from a colony calculated from using all trips of all tracked birds from a colony; Direction is the mean of the direction a bird travelled on the outward leg of a trip. Figures have been rounded to whole numbers.

Colony / Season	Mean duration ± SD (hrs)	Duration range (hrs)	Mean total track distance ± SD (km)	Total track distance range (km)	Mean max distance ± SD (km)	Mean max distance range (km)	Direction ± SD (°)
Diego Garcia NW	62 ± 8	2 – 233	520 ± 51	4 – 1767	184 ± 16	2 – 402	55 ± 19
Diego Garcia SE	43 ± 5	2 – 216	380 ± 29	4 – 1450	112 ± 7	2 – 311	32 ± 32
Danger Island NW	14 ± 2	2 – 111	253 ± 29	14 – 1254	92 ± 10	6 – 418	264 ± 12
Nelson's Island SE	8 ± 1	2 – 63	108 ± 8	2 – 919	43 ± 4	2 – 423	40 ± 37

The marine Important Bird and Biodiversity Areas of the Chagos Archipelago

To produce the consolidated map of mIBAs for the Chagos Archipelago, the SEBC and pelagic mIBAs were combined where overlap occurred into a single spatial polygon using ArcGIS Pro 2.7.0.

Ethics

Capture, handling, and sample collection were reviewed by the Zoological Society of London Ethics Committee and research was conducted in the Chagos Archipelago under British Indian Ocean Territory Administration permits 0001SE18, 0007SE18 and 000SE19. Bird tracking methods were approved by the British Trust for Ornithology special methods panel.

Results

Seaward extension to breeding colony mIBAs

Seaward extensions to the four tIBAs (North-eastern Peros Banhos, Nelson's Island, Great Chagos Bank and Eastern Diego Garcia; Table 2) had overlapping foraging radii for the three northern atolls, producing two mIBAs (Figure 3A). Both qualified based on congregations of ≥1% of the global populations (criterion A4; Box 1) of Red-footed Booby (Diego Garcia) and Tropical Shearwater, Red-footed Booby, Sooty Tern and Lesser Noddy (northern atolls) (Box 1; Tables 1, 2).

Pelagic mIBAs

The 194 tracked Red-footed Boobies (female = 35, male = 35, unsexed = 124) produced 511 foraging trips (Figure 2, Table 3). There were no statistically significant differences between the number of trips (t = 1.97, df = 2, $P = 0.19$) and the ARS values (t = 1.41, df = 2, $P = 0.3$) between monsoon seasons. Representativeness values all exceeded the minimum 70% threshold (Table 3). All pelagic mIBAs met the regional 1% threshold for Red-footed Booby (criterion B3a; Table 1) - the colony on Diego Garcia met the regional 1% threshold in both monsoon seasons (Table 3). At the Diego Garcia colony Wilcoxon rank sum tests demonstrated statistically significant differences between the track metrics recorded in the two monsoon seasons (Table 4) - trip duration ($P = 0.006$), total track distance ($P = 0.008$), mean track distance ($P = 0.001$). Four pelagic mIBAs were identified, one each at Nelson's and Danger Islands and two at Diego Garcia. Despite significantly different track metrics, the two Diego Garcia mIBAs had a BA of 0.81 and 95% of the NW monsoon mIBA area lay inside the SE monsoon mIBA area. Therefore, the boundaries of these two mIBAs were amalgamated and as a result, this mIBA met the global 1% threshold for Red-footed Booby (criterion A4; Table 1, Figure 3C).

The marine Important Bird and Biodiversity Areas of the Chagos Archipelago

Combining the SEBC and pelagic IBAs into a single spatial polygon produced one mIBA for the Chagos Archipelago due to overlapping boundaries (Figure 3D) – this is the proposed Chagos Archipelago marine Important Bird and Biodiversity Area (CA mIBA).

Discussion

This research reviewed two proposed SEBC mIBAs of the Chagos Archipelago using contemporary population estimates and GPS tracking data from an IBA-triggering species, Red-footed Booby, to identify pelagic IBAs. The SEBC and pelagic mIBAs overlapped, and were thus combined into a single mIBA, situated entirely within the MPA. Covering 62,379 km^2 this proposed mIBA constitutes ~10% of the MPA and if designated would become the 11th largest mIBA in the world and 4th largest in the Indian Ocean (http://datazone.birdlife.org/site/results accessed 10 June 2021).

Debate continues into the merits of single versus multi-species approaches to conservation planning (Ronconi *et al.* 2012). To date, in the Chagos Archipelago only Red-footed Booby has been researched as an indicator of marine biodiversity hotspots; however, as an umbrella species (Roberge and Angelstam 2004) this top predator is representative of several other breeding species. In the extremely low-resource environments of the tropical ocean (Longhurst and Pauly 1987) prey distribution and associated predators are often centred upon areas of productivity such as upwellings (Hyrenbach *et al.* 2000). The deep blue oceans of their foraging grounds are more homogenous than other oceanic areas and prey distribution is patchy, rare, and unpredictable (Balance *et al.* 1997). Here, many seabirds forage facultatively with sub-surface predators such as tuna (Scombridae) and dolphin (Delphinidae) (Au and Pitman 1986). In the western Indian Ocean, such feeding associations have been recorded for at least seven seabird species (Jaquemet *et al.* 2004) and are also common in the Chagos Archipelago (P. Carr unpubl. data). Therefore, it seems likely that protection targeted towards Red-footed Booby will also have benefits for other species such as Tropical Shearwater, Wedge-tailed Shearwater *Ardenna pacifica*, Masked *Sula dactylatra* and Brown Booby *S. leucogaster*, Brown Noddy *Anous stolidus* and Common White Tern *Gygis alba*, although Sooty Tern is seldom encountered in

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such aggregations (Figure S2A/B). However, more research is required to study commensal foraging and the full umbrella species role of Red-footed Booby, here and elsewhere in the tropics.

Despite the declaration of the no-take MPA in 2010 (Koldewey *et al.* 2010), illegal, unregulated, and unreported (IUU) fishing still occurs (Ferretti *et al.* 2018, Hays *et al.* 2020). Limited observations (P. Carr unpubl. data) suggest there is little seabird bycatch associated with IUU in the Chagos Archipelago though further evidence is required to confirm this. The removal of tuna by IUU could potentially reduce the opportunity for feeding associations to the detriment of near-obligate associate pelagic seabirds. Through this research the managers of the MPA now have robust evidence of a marine biodiversity hotspot within the MPA, the 62,379 km^2 CA mIBA. This area should be a focus for enforcement against IUU, safeguarding seabirds against possible threats and by proxy, through the umbrella species approach, also protect a suite of associated biodiversity.

Seabird foraging behaviours may vary between colonies and years (e.g. Osborne *et al.* 2020). Despite there being statistically significant differences in the track metrics at the Diego Garcia colony where tracking was undertaken in both monsoon seasons, the colony appears to feed and forage in broadly the same area in the two seasons, but this may not be the case throughout the archipelago. Therefore, further tracking is desirable at all three locations (Nelson's and Danger Islands, Diego Garcia) to smooth out possible anomalies by having multi-year/season data and to confirm whether or not all colonies forage in a similar fashion to Diego Garcia where there is apparently little variation in the pelagic foraging area between seasons, despite how they forage being significantly different in the opposing monsoon seasons.

Marine IBAs can be triggered by both breeding and non-breeding concentrations (A4 criterion; Box 1) of seabirds (Osiek 2004, BirdLife International 2010, Lascelles *et al.* 2016). Research into the non-breeding behaviour and distribution of the IBA trigger species may also highlight more areas of IBA status. Le Corre *et al.* (2012) identified a major foraging area for western Indian Ocean non-breeding Wedge-tailed Shearwater and White-tailed Tropicbird *Phaethon lepturus*, centred upon the Afanasy Nikitin seamount (03°S, 85° E) to the east of the MPA. Tracking of non-breeding seabirds from the central Indian Ocean may reveal overlap in areas of importance with western Indian Ocean populations and may further inform the ongoing debate on the merits of large-scale MPAs for both breeding and non-breeding seabirds.

At c.640,000 km^2 the MPA is a 'large-scale' MPA (LSMPA) (Toonen *et al.* 2013). Despite there being strong support for LSMPAs in the scientific community (Koldewey *et al.* 2010, Sheppard *et al.* 2012, Gallagher *et al.* 2020, Hays *et al.* 2020), there remains debate about how large an MPA needs to be to protect mobile marine vertebrates, with advocates for both LSMPAs of a size that could potentially cover the entire life cycle of mobile species (Game *et al.* 2009, Hyrenbach *et al.* 2000) and networks of smaller MPAs covering critical parts of an organism's life cycle (Kerwath *et al.* 2009). Our study reveals that the MPA encompassing the entire Chagos Archipelago is large enough to entirely support a vagile, highly pelagic top predator (and umbrella species) through the most vulnerable phase of the critically important breeding cycle. Further research throughout the non-breeding Red-footed Booby life cycle is required to assess whether LSMPAs can encompass the entire life stages of this highly mobile top predator.

Recommendation

It is recommended that BirdLife International assess the proposed Chagos Archipelago marine Important Bird and Biodiversity Area (62,379 km^2) and confirm if appropriate. Shapefiles of this proposed mIBA are available from the first author.

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References

Au, D. W. and Pitman, R. L. (1986) Seabird interactions with dolphins and tuna in the eastern tropical Pacific. *The Condor* **88**: 304–317.

Balance, L. T., Pitman, R. L. and Reilly, S. B. (1997) Seabird community structure along a productivity gradient: importance of competition and energetic constraint. *Ecology* **78**: 1502–1518.

Bhattacharyya, A. (1943) On a measure of divergence between two statistical populations defined by their probability distributions. *Bull. Calcutta Math. Soc.* **35**: 99–109.

Beal, M., Oppel, S., Handley, J., Pearmain, L., Morera-Pujol, V., Miller, M., Taylor, P., Lascelles, B. and Dias, M. (2020) BirdLife International/track2kba: First Release (Version 0.5.0). Zenodo.

Billerman, S. M., Keeney, B. K., Rodewald, P. G. and Schulenberg, T. S., eds. (2020) *Birds of the world*. Ithaca, NY, USA: Cornell Laboratory of Ornithology. https://birdsoftheworld.org/bow/home

BirdLife International (2004) *Important Birds Areas in Asia: key sites for conservation*. Cambridge, UK: BirdLife International. (BirdLife Conservation Series No. 13).

BirdLife International (2009) *Designing networks of marine protected areas: exploring the linkages between Important Bird Areas and ecologically or biologically significant marine areas*. Cambridge, UK: BirdLife International.

BirdLife International (2010) *Marine Important Bird Areas toolkit: standardised techniques for identifying priority sites for the conservation of seabirds at sea*. Cambridge UK: BirdLife International. (Version 1.2: February 2011).

BirdLife International (2018a) *State of the world's birds: taking the pulse of the planet*. Cambridge, UK: BirdLife International.

BirdLife International (2018b) IUCN Red List for birds. http://www.birdlife.org.

Bolton, M., Medeiros, R., Hothersall, B. and Campos, A. (2004) The use of artificial breeding chambers as a conservation measure for cavity-nesting procellariiform seabirds: a case study of the Madeiran storm petrel (*Oceanodroma castro*). *Biol. Conserv.* **116**: 73–80.

Bullock, R., Ralph, G., Stump, E., Al Abdali, F., Al Asfoor, J., Al Buwaiqi, B., Al Kindi, A., Ambuali, A., Birge, T., Borsa, P., Di Dario, F., Everett, B., Fennessy, S., Fonseca, C., Gorman, C., Govende, A., Ho, H., Holleman, W., Jiddawi, N., Khan, M., Larson, H., Linardich, C., Matiku, P., Matsuura, K., Maunde, C., Motomura, H., Munroe, T., Nair, R., Obota, C., Polidoro, B., Russell, B., Shaheen, S., Sithole, Y., Smith-Vaniz, W., Uiblein, F., Weerts, S., Williams, A., Yahya, S. and Carpenter, K. (2021) *The conservation status of marine biodiversity of the Western Indian Ocean*. Gland, Switzerland: IUCN.

Carr, P. (2006) British Indian Ocean Territory. Pp. 37–55 in S. M. Sanders, ed. *Important Bird Areas in the United Kingdom Overseas Territories*. Sandy, UK: RSPB.

Carr, P., Votier, S. C., Koldewey, H. J., Godley, B., Wood, H. and Nicoll, M. A. C. (2021) Status and phenology of breeding seabirds and a review of Important Bird and Biodiversity Areas in the British Indian Ocean Territory. *Bird Conserv. Internatn.* **31**: 14–34.

Cooney, R. and Dickson, B., eds. (2012) *Biodiversity and the precautionary principle: risk, uncertainty and practice in conservation and sustainable use*. Oxford, UK: Earthscan from Routledge.

Croxall, J. P., Butchart, S. H. M., Lascelles, B., Stattersfield, A.J., Sullivan, B., Symes, A. and Taylor, P. (2012) Seabird conservation status, threats and priority actions: a global assessment. *Bird Conserv. Internatn.* **22**: 1–34.

Dias, M. P., Martin, R., Pearmain, E. J., Burfield, I. J., Small, C., Phillips, R. A., Yates, O., Lascelles, B., Borboroglu, P. G. and Croxall, J. P. (2019) Threats to seabirds: a global assessment. *Biol. Conserv.* **237**: 525–537.

Donald, P. F., Fishpool, L. D., Ajagbe, A., Bennun, L. A., Bunting, G., Burfield, I. J., Butchart, S. H., Capellan, S., Crosby, M. J., Dias, M. P. and Diaz, D. (2019) Important Bird and Biodiversity Areas (IBAs): the development and characteristics of a global inventory of key sites for biodiversity. *Bird Conserv. Internatn.* **29**: 177–198.

Eisenhauer, A., Heiss, G. A., Sheppard, C. R. C. and Dullo, W. C. (1999) Reef and island formation and Late Holocene sea-level changes in the Chagos islands. Pp. 21–31 in C. R. C. Sheppard and M. R. D. Seaward, eds. *Ecology of the Chagos Archipelago*. Otley, UK: Westbury Academic and Scientific Publishing. The Linnean Society Occasional Publications.

Ferretti, F., Curnick, D., Liu, K., Romanov, E. V. and Block, B. A. (2018) Shark baselines and the conservation role of remote coral reef ecosystems. *Sci. Adv.* **4**: eaaq0333.

Fieberg, J. and Kochanny, C. O. (2005) Quantifying home-range overlap: the importance of the utilization distribution. *J. Wildl. Manage.* **69**: 1346–1359.

Fischer, W. and Bianchi, G., eds. (1984) *FAO species identification sheets for fishery purposes. Western Indian Ocean (Fishing Area 51). Vol. 1-6*. Prepared and printed with the support of the Danish International Development Agency (DANIDA). Rome, Italy: FAO.

Gallagher, A. J., Amon, D., Bervoets, T., Shipley, O. N., Hammerschlag, N. and Sims, D. W. (2020) The Caribbean needs big marine protected areas. *Science* **367**(6479): 749.

Game, E. T., Grantham, H. S., Hobday, A. J., Pressey, R. L., Lombard, A. T., Beckley, L. E., Gjerde, K., Bustamante, R., Possingham, H. P. and Richardson, A. J. (2009) Pelagic protected areas: the missing dimension in ocean conservation. *Trends Ecol. Evol.* **24**: 360–369.

Hays, G. C., Koldewey, H. J., Andrzejaczek, S., Attrill, M. J., Barley, S., Bayley, D. T. I., Benkwitt, C. E., Block, B., Schallert, R. J., Carlisle, A. B., Carr, P., Chapple, T. K., Collins, C., Diaz, C., Dunn, N., Dunbar, R. B., Eager, D. S., Engel, J., Embling, C. B., Esteban, N., Ferretti, F., Foster, N. L., Freeman, R., Gollock, M., Graham, N. A. J., Harris, J. L., Head, C. E. I., Hosegood, P., Howell, K. L., Hussey, N. E., Jacoby, D. M. P., Jones, R., Pilly, S. S., Lange, I. D., Letessier, T. B., Levy, E., Lindhart, M., McDevitt-Irwin, J. M., Meekan, M., Meeuwig, J. J., Micheli, F., Mogg, A. O. M., Mortimer, J. A., Mucciarone, D. A., Nicoll, M. A. C., Nuno, A., Perry, C. T., Preston, S. G., Rattray, A. J., Robinson, E., Roche, R. C., Schiele, M., Sheehan, E. V., Sheppard, A., Sheppard, C. R. C., Smith, A. L., Soule, B., Spalding, M., Stevens, G. M. W., Steyaert, M., Stiffel, S., Taylor, B. M., Tickler, D., Trevail, A. M., Trueba, P., Turner, J., Votier, S. C., Wilson, B., Williams, G. J., Williamson, B. J., Williamson, M. J., Wood, H. and Curnick, D. J. (2020) A review of a decade of lessons from one of the world's largest MPAs: conservation gains and key challenges. *Mar. Biol.* **167**: 1–22.

Hyrenbach, K. D., Forney, K. A. and Dayton, P. K. (2000) Marine protected areas and ocean basin management. *Aquat. Conserv.: Mar. Freshw. Ecosyst.* **10**: 437–458.

IUCN (2021) *The IUCN Red List of Threatened Species. Version 2021-1*. https://www.iucnredlist.org accessed on 04 May 2021.

Jaquemet, S., Le Corre, M. and Weimerskirch, H. (2004) Seabird community structure in a coastal tropical environment: importance of natural factors and fish aggregating devices (FADs). *Mar. Ecol. Progr. Ser.* **268**: 281–292.

Kerwath, S. E., Thorstad, E. B., Naesje, T. F., Cowley, P. D., Økland, F., Wilke, C. and Attwood, C. G. (2009) Crossing invisible boundaries: the effectiveness of the Langebaan Lagoon Marine Protected Area as a harvest refuge for a migratory fish species in South Africa. *Conserv. Biol.* **23**: 653–661.

Koldewey, H. J., Curnick, D., Harding, S., Harrison, L. R. and Gollock, M. (2010) Potential benefits to fisheries and biodiversity of the Chagos Archipelago/British Indian Ocean Territory as a no-take marine reserve. *Mar. Poll. Bull.* **60**: 1906–1915.

Lascelles, B. (2008) *The BirdLife Seabird Foraging Database: guidelines and examples of its use*. Cambridge, UK: BirdLife International. Internal report.

Lascelles, B. (2011) BirdLife special session on marine Important Bird Areas. WIOMSA 2011. 7th WIOMSA Scientific Symposium. Mombasa, Kenya. 24-29 October 2011. http://datazone.birdlife.org/userfiles/file/Marine/WesternIndianOceanMarineIBAWorkshopReport.pdf accessed 15 December 2020.

Lascelles, B. G., Taylor, P. R., Miller, M. G. R., Dias, M. P., Oppel, S., Torres, L., Hedd, A., Le Corre, M., Phillips, R. A., Shaffer, S. A. and Weimerskirch, H. (2016) Applying global criteria to tracking data to define important areas for marine conservation. *Divers. Distrib.* **22**: 422–431.

Le Corre, M., Jaeger, A., Pinet, P., Kappes, M. A., Weimerskirch, H., Catry, T., Ramos, J. A., Russell, J. C., Shah, N. and Jaquemet, S. (2012) Tracking seabirds to identify potential Marine Protected Areas in the tropical western Indian Ocean. *Biol. Conserv.* **156**: 83–93.

Lerma, M., Dehnhard, N., Luna-Jorquer, G., Voigt, C. C. and Garthe, S. (2020) Breeding stage, not sex, affects foraging characteristics in masked boobies at Rapa Nui. *Behav. Ecol. Sociobiol.* **74**: 1–16.

Longhurst, A. R. and Pauly, D. (1987) *Ecology of tropical oceans*. San Diego, USA: Academic Press.

Mulder, C. P., Anderson, W. B., Towns, D. R. and Bellingham, P. J., eds. (2011) *Seabird islands: ecology, invasion, and restoration*. Oxford, UK: Oxford University Press.

Osborne, O. E., Hara, P. D., Whelan, S., Zandbergen, P., Hatch, S. A. and Elliott, K. H. (2020) Breeding seabirds increase foraging range in response to an extreme marine heatwave. *Mar. Ecol. Progr. Ser.* **646**: 161–173.

Osieck, E. R. (2004) Towards the identification of marine IBAs in the EU: an exploration by the Birds and Habitat Directives Task Force. Cambridge, UK: BirdLife International. (Unpublished report).

Pebesma, E. (2018) Simple features for R: Standardized support for spatial vector data. *The R J.* **10**: 439–446.

R Core Team (2020) *R: A language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing, https://www.R-project.org/.

Roberge, J. M. and Angelstam, P. E. R. (2004) Usefulness of the umbrella species concept as a conservation tool. *Conserv. Biol.* **18**: 76–85.

Ronconi, R. A., Lascelles, B. G., Langham, G. M., Reid, J. B. and Oro, D. (2012) The role of seabirds in Marine Protected Area identification, delineation, and monitoring: Introduction and synthesis. *Biol. Conserv.* **156**: 1–4.

Sheppard, C. R. C., Seaward, M. R. D., Klaus, R. and Topp, J. M. W. (1999) The Chagos Archipelago: an introduction. Pp. 1–20 in C. R. C. Sheppard and M. R. D. Seaward, eds. *Ecology of the Chagos Archipelago*. Otley, UK: Westbury Publishing. (Linnean Society Occasional Publications 2).

Sheppard, C. R. C., Ateweberhan, M., Bowen, B. W., Carr, P., Chen, C. A., Clubbe, C., Craig, M. T., Ebinghaus, R., Eble, J., Fitzsimmons, N., Gaither, M. R., Gan, C. H., Gollock, M., Guzman, N., Graham, N. A., Harris, A., Jones, R., Keshavmurthy, S., Koldewey, H. J., Lundin, C. G., Mortimer, J. A., Obura, D., Pfeiffer, M., Price, A. R., Purkis, S., Raines, P., Readman, J. W., Riegl, B., Rogers, A., Schleyer, M., Seaward, M. R., Sheppard, A. L., Tamelander, J., Turner, J.R., Visram, S., Vogler, C., Vogt, S., Wolschke, H., Yang, J. M., Yang, S. Y. and Yesson, C. (2012) Reefs and islands of the Chagos Archipelago, Indian Ocean: why it is the world's largest no-take marine protected area. *Aquat. Conserv.* **22**: 232–261.

Soanes, L. M., Bright, J. A., Angel, L. P., Arnould, J. P. Y., Bolton, M., Berlincourt, M., Lascelles, B., Owen, E., Simon-Bouhet, B. and Green, J. A. (2016) Defining marine important bird areas: Testing the foraging radius approach. *Biol. Conserv.* **196**: 69–79.

Surman, C. A., Nicholson, L. W. and Ayling, S. (2017) Foraging behaviour of the Lesser Noddy *Anous tenuirostris melanops* from the eastern Indian Ocean: insights from micro-geologging. *Mar. Ornithol.* **45**: 123–128.

Toonen, R. J., Wilhelm, T. A., Maxwell, S. M., Wagner, D., Bowen, B. W., Sheppard, C. R., Taei, S. M., Teroroko, T., Moffitt, R., Gaymer, C. F. and Morgan, L. (2013) One size does not fit all: the emerging frontier in large-scale marine conservation. *Mar. Poll. Bull.* **77**: 7–10.