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Dugong abundance and distribution in the Bazaruto Archipelago, Mozambique

KP Findlay[1]*, VG Cockcroft[2] and AT Guissamulo[3]

[1] Department of Oceanography, University of Cape Town, Private Bag, Rondebosch 7701, South Africa
[2] Centre for Dolphin Studies, Department of Zoology, PO Box 77000, Nelson Mandela Metropolitan University, Port Elizabeth 6031, South Africa
[3] Universidade Eduardo Mondlane, Museu de História Natural, PO Box 257, Maputo, Mozambique
** Corresponding author, e-mail: kenfin@mweb.co.za*

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Despite the distribution of dugongs *Dugong dugon* ranging across nearshore waters of the tropical and subtropical regions of the Indian Ocean and western Pacific Ocean, their distribution in the western Indian Ocean is highly fragmented and appears to be declining. The population of the Bazaruto Archipelago is believed to comprise the only viable population in the region. In all, 27 surveys were flown over the Bazaruto Bay area to define the distribution and estimate the abundance of the species in the area. A total of 9 052 nautical miles of survey effort was flown during the surveys, from which there were 355 sightings of 760 dugongs. Two core areas of distribution were apparent within the surveyed area; a northern core area spread within the 10 m isobath between the Save River mouth and Ponta Bartolomeu Dias (21°24′ S), and a southern core area aligned with the shallow sandbanks to the north and south of Santa Carolina Island. Group sizes recorded in the Bazaruto Archipelago were comparable to group sizes recorded in other regions where dugongs occur, although few large (>20) groups of dugongs were seen in this study. Line transect analyses of each survey showed dugong densities were considerably lower than densities recorded in surveys in Australian waters or in the Arabian Gulf, with a population estimate of 247 dugongs (CV = 34.1) when all surveys were considered, and 359 dugongs (CV = 38.2) when only the surveys that were carried out under adequate sighting conditions were included.

Keywords: abundance, Bazaruto, distribution, *Dugong dugon*, Mozambique, western Indian Ocean

Introduction

Dugongs *Dugong dugon* have an extensive range in nearshore tropical and subtropical coastal and island waters of the Indo-Pacific from southern Mozambique in the west to between Vanuatu and Japan in the east (Marsh et al. 2002). This geographical distribution extends across an estimated 140 000 km of coastline from approximately 27° N to 27° S, and may be limited by water temperatures of less than about 18 °C (Preen 1992, Marsh et al. 1994). The dugong is currently listed as Vulnerable by IUCN, although quantitative population estimates have been made in only three regions, namely Australia, the eastern Red Sea, and the Arabian Gulf (Bayliss and Freeland 1989, Preen 1989, Marsh and Saalfeld 1990, Marsh et al. 1994, Preen et al. 1997, Marsh and Lawler 2001, Marsh et al. 2002).

Marsh et al. (2002) noted that the dugong is declining or extinct across a third of its range but that the status of the species over a large proportion of its range is unknown, particularly within the western Indian Ocean. Historically, the geographical distribution of dugongs within the western Indian Ocean extended from Somalia in the north, through Kenya, Tanzania, Mozambique and farther east off the Comoros Islands, the Seychelles, Madagascar and Mauritius. Information from both the qualitative and quantitative surveys (Marsh et al. 2002) show that current dugong distribution may be summarised as patchy across the western Indian Ocean region, including Kenya, Tanzania, Madagascar, the Seychelles, Mayotte and Mozambique (Cockcroft 1993, 1995, Muir et al. 2003). Dugongs possibly still occur in the Comoros (at Moheli Island) and off the Somalia coast, but their current status is unknown. Marsh et al. (2002) reported that dugongs have become extinct from Mauritius and the Maldives and appear to have vagrant status in the Seychelles, although more recently Hermans and Pistorius (2008) confirmed that there are resident animals at Aldabra atoll. According to Marsh et al. (2002), extinction of the dugong in the western Indian Ocean region is inevitable without immediate and effective conservation measures, but although dugongs are protected across the range of all the western Indian Ocean states, enforcement is currently limited by both capacity and resources.

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Dugong distribution within Mozambique

Based on a survey along the Mozambican coastline in 1969, Hughes (1971) reported that dugongs were common at Maputo Bay, Chidenguele, Inhambane Bay, Bazaruto Bay, Mozambique Island and Pemba Bay (see Figure 1). The author also speculated (based on the existence of suitable habitat) that dugongs might occur in the Quirimbas Archipelago, but their status in this area was unknown (Hughes 1971, Smithers and Lobão Tello 1976). Smithers and Lobão Tello (1976) observed dugongs in Maputo Bay (8–10 animals), Inhambane Bay (2–4 animals), Ponta Bartolomeu Dias (20 animals) and along the coast between Bazaruto Bay and Save River where they were reported to be common. Elsewhere, smaller groups were observed at Angoche, Mozambique Island, Matimbane Bay and Pemba where they were thought to be abundant until 1970. These reports suggested a hiatus in the distribution of dugongs between the Save River mouth and Angoche (Hughes and Oxley-Oxland 1971), although the lack of survey effort within this area (coupled with the generally high water turbidity resulting from river discharge in this area, and the consequent difficulty in visual surveys) should be noted.

The status and distribution of dugongs along the Mozambique coast are believed to have altered significantly since Hughes's (1969) survey, with results of recent aerial and vessel-based surveys indicating a considerable decline in dugong abundance across Mozambican waters. In the mid-1970s, dugong herd sizes of 8–10 individuals were reported for Inhaca Island (Guissamulo and Cockcroft 1997). Guissamulo and Cockcroft (1997) further assessed the distribution and relative abundance of dugongs in Maputo Bay during 1992, when dugongs were sighted in the eastern quarter of the bay, in the vicinity of Inhaca Island (Guissamulo 1993). This area was subsequently thought to support only 2 or 3 individuals (Cockcroft and Young 1998). Two individuals were sighted in Maputo Bay in 2007 (N Rabe, *in litt.*) and four individuals were seen (ATG pers. obs.) in 2008. Two (possibly three) individuals were taken from this isolated population by an artisanal fisher in 2010.

During a boat survey in Inhambane Bay in October 1994, dugongs were observed throughout the bay (ATG unpublished data), although an aerial survey in 2001 recorded only a single dugong observed outside the bay, during a low spring tide (Mackie 2001). No dugongs were recorded during a survey in 2007 (AGT unpublished data).

The Bazaruto Archipelago area is reported to support the largest dugong population along the East African coast (Dutton 1994). An aerial census of this area (including the Bazaruto National Park [Bazaruto, Santa Carolina, Benguerra, Magaruque and Bangue islands]) conducted by WWF in May 2001 found dugongs distributed throughout the northern, central and south central parts of the Archipelago between Bazaruto Island and the mainland (Marsh et al. 2002). Estimates based on strip-transect sightings in 1992 suggested a local population of 130 dugongs in Bazaruto Bay (Guissamulo and Cockcroft 1997). However, when maximum counts of 21 animals per aerial survey were obtained during surveys in the 1990s, it was suggested that the population was declining (Dutton 1998). It should be noted that the past series of surveys carried out across the Bazaruto Archipelago in the 1990s and early 2000s were inconsistent, both in terms of effort and methodology, so that resulting estimates cannot provide population trend indices.

No dugongs were recorded in aerial surveys of the area between Pemba and Mtwara in northern Mozambique (Cabo Delgado Province) in 2007 (ATG unpublished data). A local fisher reported seeing a lone dugong in 2001 near Quilalea Island in the Quirimbas National Park (Motta 2001, in WWF 2004). Although no dugongs appear to have been reported from this area since an individual drowned in a net in the Quirimbas National Park in November 2003 (WWF 2004), an incidental sighting of a lone individual in 2009 was subsequently reported (KPF unpublished data). The intensification of large-mesh gillnetting from 1976 onwards (sometimes directed at dugongs), coupled with lack of law enforcement, is thought to have been the principal cause of the perceived decline of the dugong population in Mozambique. Such fishing pressure is further compounded by seine-netting, commercial trawl operations and palisade fish traps. WWF (2004) suggested that habitat destruction of seagrass beds (through increased levels of riverine sedimentation and from natural cyclone and flood events), and increased anthropogenic disturbance through exposure to vessel noise (particularly tourism vessels), are further threats to dugong populations in Mozambique.

This paper reports on a series of aerial surveys carried out in 2006 and 2007 to define the current distribution and abundance of dugongs within the Bazaruto Archipelago and surrounding waters.

Material and methods

Study area

The Bazaruto Archipelago is a series of five islands (Bazaruto, Benguerra, Magaruque, Bangue and Santa Carolina) situated in a general north–south linear orientation in the vicinity of 21° S on the central coastline of Mozambique, although Santa Carolina lies to the west of the others (Figure 1). Bazaruto Bay is a shallow (generally <30 m deep) protected bay of some 1 000 km^2, lying between the four outer islands of the Bazaruto Archipelago and the mainland. This large bay has extensive seagrass beds and consequently provides suitable habitat for dugongs. There are two distinct basins in this bay, one to the north of Santa Carolina Island (maximum depth 33 m) and one in the central section of the bay (maximum depth 24 m). The southern section of the bay comprises vast areas of tidal flats, which often dry out during spring low tides.

The main feature of water circulation within the bay is the strong tidal currents (mean spring tidal range is approximately 3 m during normal spring tides) during the flood and ebb phases, and wave action is largely restricted to the seaward side of the islands. Such strong tidal flows maintain the deep channels on the landward side of the islands. The physical and chemical characteristics of the water masses of Bazaruto Bay exhibit spatial and temporal variability by season as rainfall is highly variable both within and between years. In the dry season, the bay has a marine character, with a uniform salinity ranging from 35 to 36. However, in the wet season the bay becomes more estuarine, exhibiting a lower overall average salinity (33–35) compared with the dry season. Water temperatures for the Bazaruto area range annually between 24 and 28 °C (McClanahan et al.

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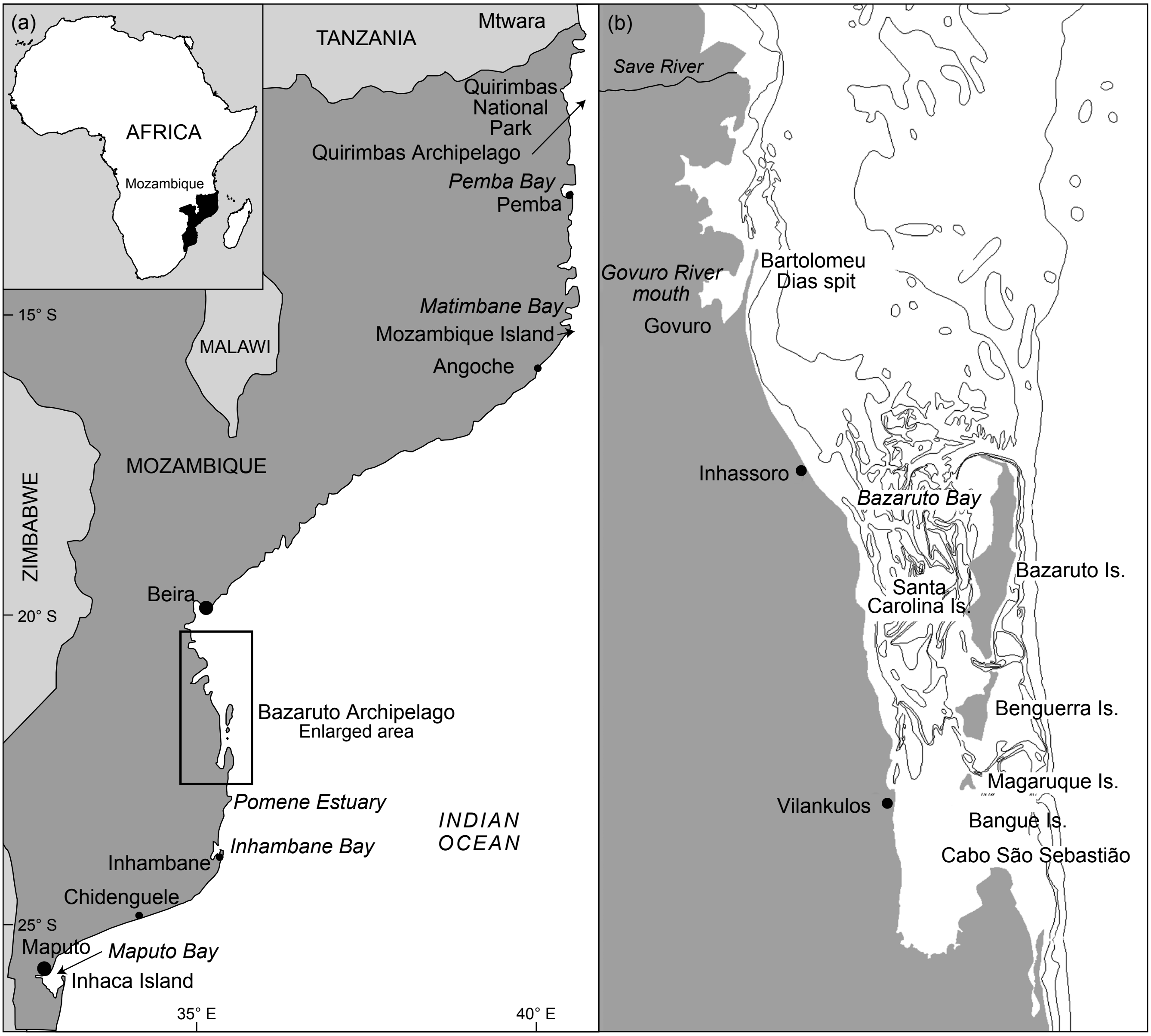

Figure 1: (a) Coast of Mozambique and (b) Bazaruto Archipelago showing positions of locations referred to in the text

2000). The Bazaruto Archipelago lies within a high-risk region for tropical cyclones.

As a shallow tropical bay, Bazaruto Bay contains a number of important seagrass meadows or beds. Prior to this project, the information on seagrass species composition, extent and distribution was only known for the southern extent of the bay. Within the Inhassoro and Cabo São Sebastião areas, seagrass cover an area of approximately 88 km^2 of the shallow intertidal and subtidal waters inside the 5 m isobath. Nine species of seagrass were recorded there (ATG unpublished data), namely: *Thalassondendron ciliatum*, *Cymodocea rotundata*, *Cymodocea serrulata*, *Thalassia hemprinchii*, *Halophila ovalis*, *Nanozostera capensis*, *Halodule uninervis*, *Halodule wrightii* and *Siringodium isoetifolium*. Seagrass meadows also occur north of Inhassoro and off the Govuro River estuary and westward of the Bartolomeu Dias area, where it is suspected that *N. capensis*, *H. uninvervis* and *C. rotundanta* dominate the meadows.

Two major marine protected areas occur in the vicinity of Bazaruto Archipelago, namely the Bazaruto Archipelago National Park and the total protection zone of the Cabo de São Sebastião.

Aerial sighting surveys

Field methods

Aerial surveys between March 2006 and October 2007 (Table 1) were flown over the Bazaruto Bay area from Cabo São Sebastião in the south to north of the Save River mouth, and between the coast and the 30 m isobath (extending seawards of the Bazaruto Archipelago islands in the south). Surveys were flown as a series of east to west or west to east transects in a progressive north to south

Table 1: Survey effort and sightings of dugongs made during aerial surveys carried out during the study

Date	Number of transects flown	Distance surveyed (nautical miles)	Sightings of groups: primary/secondary	Sightings of animals: primary/secondary	Sightings of calves	Comment
31 March 2006	22	282.36	12	22	3	
1 April 2006	22	282.36	11/2	16/2	2	
2 April 2006	22	282.36	12/3	41/4	1	
18 November 2006	17	225.07	8	18	4	
16 December 2006	20	222.15	8/2	9/9	0	
13 January 2007	25	333.85	15/3	61/4	5	Optimal sighting conditions
14 January 2007	3	5.33	2	2	0	Survey aborted due to poor weather conditions
28 January 2007	36	455.39	14/1	22/2	2	
6 February 2007	36	424.14	31/1	53/1	4	
15 February 2007	32	366.34	13/2	28/7	5	
15 April 2007	26	337.75	21	30	2	
26 April 2007	30	420.35	21	40	0	
17 May 2007	31	432.33	28/1	52/1	5	Optimal sighting conditions
9 June 2007	32	408.41	19/6	34/8	5	
19 June 2007	32	405.01	12	20	2	
26 June 2007	32	410.03	15/1	19/2	0	
8 July 2007	34	420.73	12	42	1	
17 July 2007	32	402.39	11	30	2	
4 August 2007	32	407.98	3	3	0	
20 August 2007	32	408.05	14/1	68/1	5	Optimal sighting conditions
26 August 2007	0					Survey aborted due to poor weather conditions
17 September 2007	26	129.95	2	3	0	Survey aborted due to poor weather conditions
20 September 2007	30	385.65	8/1	24/1	3	
6 October 2007	32	402.71	5	8	1	Optimal sighting conditions
14 October 2007	32	398.33	8	33	3	Optimal sighting conditions
29 October 2007	31	406.15	11	16	3	Twin-platform survey
29 October 2007	30	396.83	15	24	4	Twin-platform survey
Total	729	9 052.01	331/24	718/42	62	

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direction. All transit time *en route* from Vilankulos airport to the start of survey in the north, between transects and *en route* from the end of survey to Vilankulos airport were not regarded as effort. Sightings made while in transit were recorded as secondary sightings, whereas sightings made during transects were recorded as primary sightings. Secondary sightings were excluded from abundance estimation or density analyses. Transects were flown at an altitude of 450 ft (137 m) and a speed of approximately 80 knots, in two types of aircraft; a Cessna 210 with six seats and high-wing configuration (ZS SPV) was used in the flight of 18 November 2006, whereas four different single-engine Cessna 182 or 185 aircraft (ZS IGR, ZS EPO, D-EOVC and C9 JSH) were used for the remainder of the surveys. The number of transects flown per survey was not constant, being influenced by fuel capacity, available observer time or weather conditions. Because surveys were generally flown from north to south, such limitations prevented the southern end of the survey area from being covered on all occasions. However, all survey transects that were flown over this southern area of the bay (dark shaded area; Figure 2) were eventually excluded from the analyses (see Results for explanation).

All survey transects were flown following the aircraft's Global Positioning System (GPS). Line spacing between transects was 2 nautical miles. The lengths of the transects were variable depending on the coastal orientation and water depth. In the northern area, between Inhassoro and the Save River, the eastern limit of the survey was limited by the 20 m isobath, whereas within the Bazaruto National Park, surveys were carried out between the islands and the mainland, although surveys extended beyond the islands in the southern area where shallow banks extended to the east of the islands. The greater part of each survey was carried out in passing mode. However, when large groups were observed or suspected, or in cases in which identification or group size estimation was not certain, the aircraft would be diverted from the survey track line for confirmation of the sighting. Other sightings of dugongs made during confirmation were considered secondary sightings and recorded, but not used for estimation of dugong numbers.

The survey crew consisted of a pilot, two observers and a data recorder. A single observer searched the entire visual observation area (outwards from the most vertical perspective that could be gained) from the rear seats on each side of the aircraft. The data recorder, seated in the forward starboard position, logged flight paths, altitude, survey effort, sighting parameters and weather conditions, and also directed the pilot. Positions of effort and sightings were recorded using a handheld GPS. On making a sighting, the

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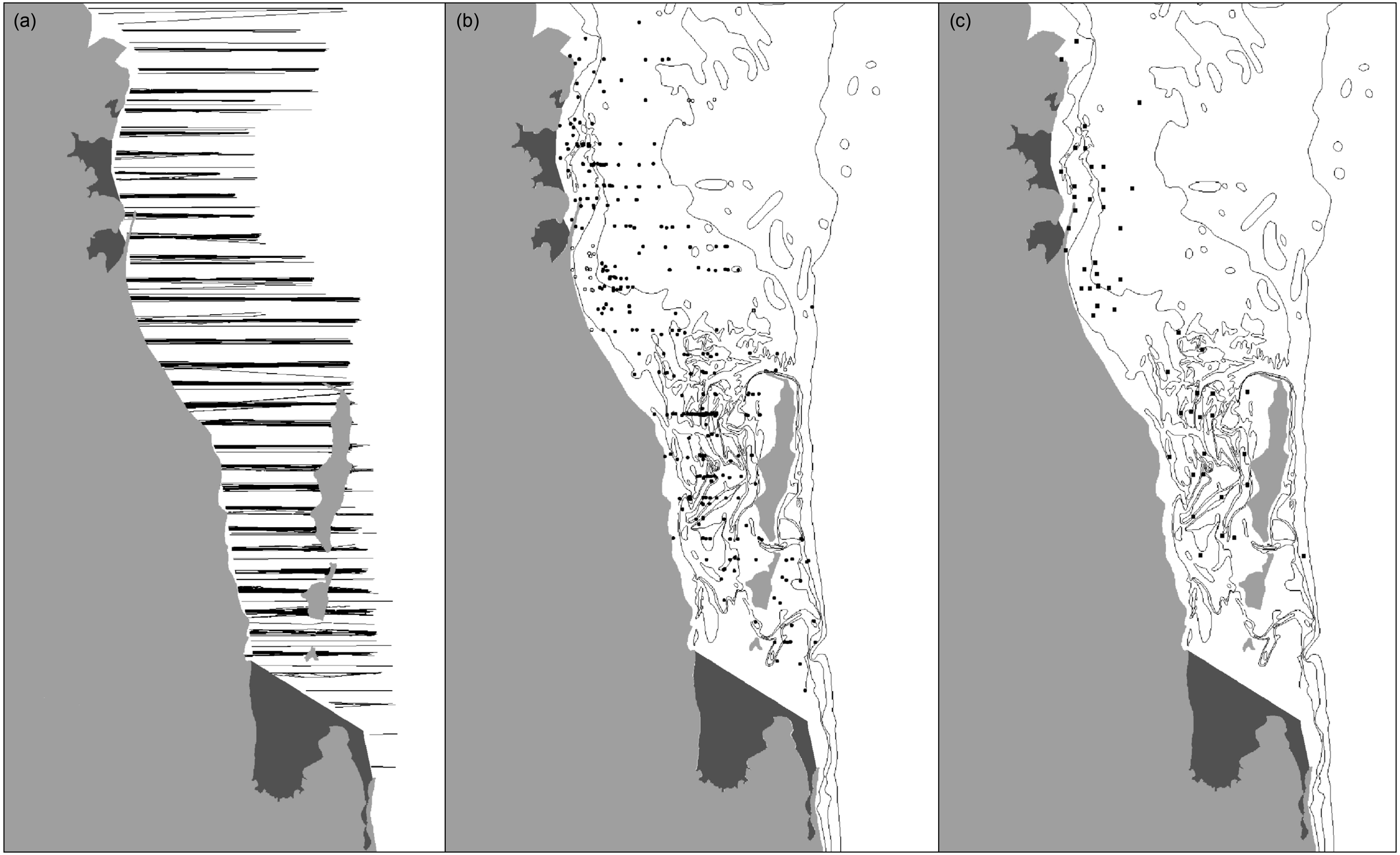

Figure 2: Distribution of (a) aerial survey search effort (transects) and of sightings of dugongs for (b) all groups and (c) groups containing a calf observed during surveys of the Bazaruto Archipelago. The dark shaded areas were excluded from analyses due to shallow depths precluding dugong distribution

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observer measured the perpendicular distance from the survey track line to the dugong sighting using an inclinometer to measure the dip azimuth angle to the group (surveys after 16 December 2006), or by assigning sightings to distance bins marked by tape on the aircraft wing-strut (surveys prior to and including 16 December 2006). All information on a dugong sighting (including the number of animals, occurrence of calves in groups, and the sighting angles) was immediately relayed by the observer to the data recorder, who operated the GPS and recorded sighting data. Data and associated GPS positions were immediately downloaded on completion of each of the surveys, and entered into spreadsheets for initial verification analyses.

Data analyses

Perpendicular distances of dugong groups from the track line were calculated for sightings as $d.\tan(\theta)$, where d was the aircraft altitude at the time of sighting and θ was the horizon minus the dip azimuth angle of the sighting from the horizon (measured at the time of sighting abeam by handheld inclinometer).

The Distance software programme (Thomas et al. 2006) was used to fit a hazard-rate model (Buckland 1985) to the perpendicular distances grouped into 0.05 nautical mile intervals to give the sighting probability density function $f(0)$ and its variance $V[f(0)]$. All the perpendicular distances of sightings, left-truncated at 0.1 nautical miles due to the low detection probabilities directly under the aircraft, were used. This pooled sighting probability density function was initially applied to all surveys combined, to estimate abundance over the entire series of surveys. Given that the application of a generic effective search width will bias results of the individual surveys (upwards under good sighting conditions and downwards under poor sighting conditions), a further set of analyses was performed on the data collected during the five surveys carried out under optimal sighting conditions (see Table 1).

The entire area that was surveyed was calculated as the extent of the area between the coastline and the eastern limit of the survey transects, excluding the land area of islands or the area shaded in Figure 2 (see Results for explanation).

Assumptions of the abundance analyses

Estimates of dugong abundance across the survey area require a number of assumptions to be met including:

- The area surveyed represents the entire range of the population. The current range limits of the Bazaruto Archipelago dugong population are unknown. Anecdotal reports of individuals within the Pomene Estuary and published historic records of individuals in Inhambane Bay suggest a possibly broader range than the area surveyed. However, the association of these animals with the Bazaruto Archipelago population is unknown and it is assumed for the purpose of this study that such groups are discrete and no migration occurs in and out of the surveyed area. It is further assumed that the entire Bazaruto Archipelago population is found within the area surveyed. This assumption may bias the abundance estimate downwards if animals are present outside of the area surveyed (e.g. to the south of Cabo São Sebastião or to the north of the Save River mouth).
- The probability of detection of groups of animals on the track line $g(0)$ is assumed to be 1 (that all groups distributed on the track line will be detected with certainty) and the probability of detection decreases with distance from the survey track line.

  A number of authors (e.g. Marsh and Sinclair 1989, Gales et al. 2004, Preen 2004) have reported on detection bias of animals that are missed by observers in strip transect surveys. Such bias may result from (a) availability bias where animals are not near the surface and consequently not available to observers as potential sightings, and (b) perception bias that results from visible animals being missed by the observers. The assumption that all groups on the track line will be detected with certainty is unlikely to be met and will bias the abundance estimate downwards.

  An estimate of the number of groups available as potential sightings may be carried out by analysis of the sightings from independent sighting platforms using a capture–recapture Petersen model. A twin-platform survey was carried out on 29 October 2007, when two aircraft surveyed the area independently. The standard survey aircraft (the primary aircraft) completed the survey followed by an independent second survey aircraft flying the same transects some 5–7 minutes behind the primary aircraft. The available groups were determined using Chapman's modified Petersen model (Chapman 1951, in Seber 1982).

$$N = (n_1 + 1)\,(n_2 + 1)/(m + 1) - 1 \qquad (1)$$

  where n_1 is the number of sightings made from the primary aircraft, n_2 is the number of sightings made independently from the second aircraft and m is the number of sightings made by both aircraft. However, a number of assumptions are required to be met for this model to be valid including:

  (a) the population of groups is closed (that no immigration or emigration of groups, or splitting or merging of groups occurs, between the two independent surveys);

  (b) all groups are equally likely to be sighted in each survey, and;

  (c) all groups, and only groups sighted by both aircraft, are recognised as such.
- The entire surveyed area represents dugong habitat and dugongs are randomly distributed throughout this habitat with respect to survey transects. Two aspects of this assumption require consideration: (1) uneven distribution of survey effort in relation to animal distribution is likely to bias results if density estimates from high or low density areas are spread across the entire survey area; and (2) dugong habitat within the survey area is likely to be fragmented by shallow sandbanks, with such fragmentation varying by tidal cycle.

Results

Aerial sighting surveys

In all, 27 surveys were flown during this study. Particulars of each survey are presented in Table 1 and the distribution of total survey effort and sightings are shown in Figure 2. No survey was flown between 15 February and 15 April 2007

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due to the extensive damage received to the chartered aircraft (ZS IGR) during Cyclone Favio on 22 February 2007, and delays encountered in sourcing a replacement aircraft. No surveys were attempted on 5 May, 25 May, 25 July, 26 August and 5 September of 2007 due to inclement weather, and on 14 January, 26 August and 17 September, surveys were abandoned after initiation due to high winds and sea state and poor sighting conditions. A total of 9 052 nautical miles of survey effort was flown during the 27 surveys. There were 331 primary and 24 secondary sightings comprising 718 and 42 individuals respectively (Table 1).

Distribution, size and composition of dugong groups

The distribution of sighted dugong groups by depth interval is shown in Figure 3. Although not adjusted for survey effort or by tidal levels at the time of the survey, the results suggest that dugongs occur out to the 20 m isobath. However, the inshore or shallow-water distribution limit remains unknown and is likely to vary with the tidal cycle. No dugongs were sighted to the south of the line between Vilankulos and Cabo São Sebastião (Figure 2). This area appears to comprise a number of tidally inundated sandbanks and is possibly too shallow to be utilised by dugongs. Consequently, it was excluded from analyses of abundance. Within the surveyed area, two core areas of distribution are apparent from Figure 2. The northern core area of distribution was spread across the inshore and offshore area to approximately the 10 m isobath between the Save River mouth and 21°24′ S. The southern core area, situated within Bazaruto Bay and inshore of Bazaruto, Benguerra and Magaruque islands, appeared to be aligned with the shallow sandbanks to the north and south of Santa Carolina Island. The prominence of these core areas was increased when the distribution of individuals rather than groups was reviewed, in that such core areas often contained large groups.

The mean group size (primary sightings made during full survey effort) was 2.22 (SE 0.191) (Figure 4). No seasonal pattern in group size was evident (single-factor ANOVA; F = 0.4895, p = 0.6897, df = 354). A total of 62 (8.1%) of the 760 sighted dugongs in the Bazaruto Archipelago were calves (Figure 2). The proportion of calves per survey ranged between 0 (December, April, June and August) and 22.2% (November) (Table 1). Despite higher proportions of calves being observed in spring (September–November), no significant difference in the proportion of calves in the population were observed between seasons (single-factor ANOVA; F = 2.11634, p = 0.128597, df = 24). As with the distribution of all groups, that of calves appears to be centred on the two core areas.

Abundance estimation

Data from 23 survey flights were used for dugong abundance estimation. The three aborted flights on 14 January 2007, 26 August 2007 and 17 September 2007 were excluded due to incomplete survey coverage, and the survey carried out on 16 December 2006 was excluded due to uncertainty in the recorded positions of the track lines (which were recorded to the aircraft GPS and appeared to be in error). All of the remaining flights were assumed to be of equal-sighting probability with respect to environmental

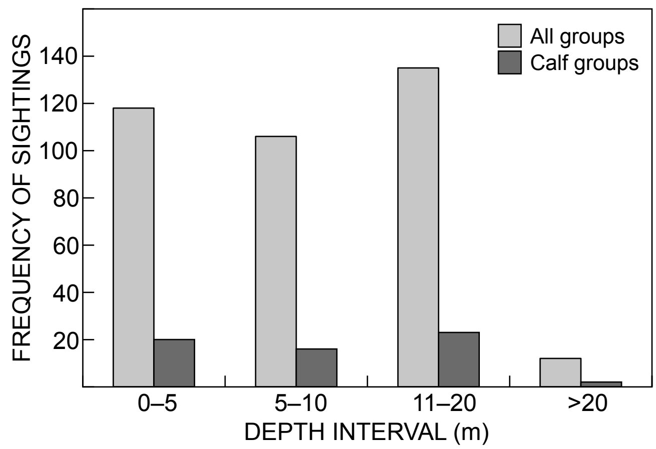

Figure 3: Distribution of dugong groups (all groups and groups containing a calf) recorded by depth interval during aerial surveys of the Bazaruto Archipelago

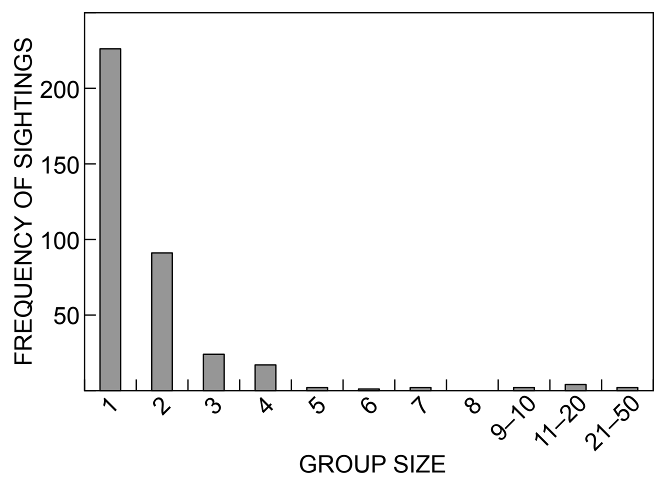

Figure 4: Frequency of dugong group sizes recorded during aerial surveys of the Bazaruto Archipelago

conditions. A total of 8 824 nautical miles of survey effort were flown during the remaining 23 survey flights, during which 319 primary sightings were made (see Table 1). Nine sightings had no associated distance data and were excluded from analyses.

The total survey area defined by the limits of each of the surveys was calculated at 1 211 square nautical miles. This area was defined by the coast in the west and the outer limits of the transect lines in the east, with the shallow sandbank area to the south-east of Vilankulos excluded (Figure 2). Dugong distribution across the total surveyed area is shown in Figure 2. In order to increase the available sample size, the estimation of the sighting probability density function $f(0)$ was carried out using distance data pooled from all surveys. The distribution of sightings by perpendicular distance from the track line is shown in Figure 5. The inability of observers to detect dugong groups below the aircraft is clearly apparent in these data. Consequently, two analyses of sighting probability density

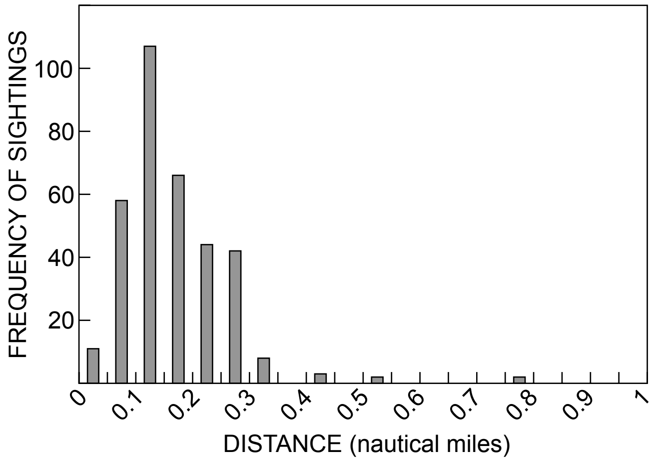

Figure 5: Distribution of all primary sightings of dugongs with perpendicular distance from the track line observed during surveys of the Bazaruto Archipelago

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function were carried out: the first using all sightings to define the sighting probability density function, and the second using a left truncation at 0.1 nautical miles so that only sightings seen outside of a distance of 0.1 nautical miles were used. Figure 6 shows the hazard rate modelled $f(0)$ to each of these options respectively. Given the paucity of sightings below the aircraft, the truncated distance model was selected as the most robust. Table 2 lists parameters of the sighting probability density functions calculated using the hazard rate model in the Distance analysis. No significant correlation was found between sighting distance and group size ($r^2 < 0.001$, $p = 0.93$), which suggests detection was independent of group size. The abundance estimated from all 23 surveys (Table 2) was 247 dugongs (CV = 34.1).

The density of dugongs recorded from the aerial surveys across the Bazaruto Archipelago, using the effective strip width calculated with the truncated distance data, was 0.058 per km^2 for all surveys, and 0.123 per km^2 when only the five optimal surveys were considered. During the only twin-platform survey that was carried out, the primary aircraft (D-EOVC) made 11 primary sightings of dugongs, whereas the secondary aircraft (ZS EPO) made 15 primary sightings (Table 3). Six sightings were considered as common to both platforms on the basis of their positions and their time of sighting. The capture–recapture Petersen model estimated a total 'population' of 31 groups available for sighting within the search width during this survey. Sightings of 11 groups by the primary observation platform and 15 groups by the secondary observation platform suggest that 35.5% and 48.4% of dugong groups were sighted by these platforms respectively. The high proportions of missed sightings during the twin-platform survey are presumed to have resulted from the poor sighting conditions under which it was conducted. This suggests that surveys conducted under suboptimal conditions will underestimate abundance. The estimate pooled across the five optimal sighting condition surveys of 359 (CV = 38.2) is therefore considered to be the most robust estimate of dugong abundance from this study.

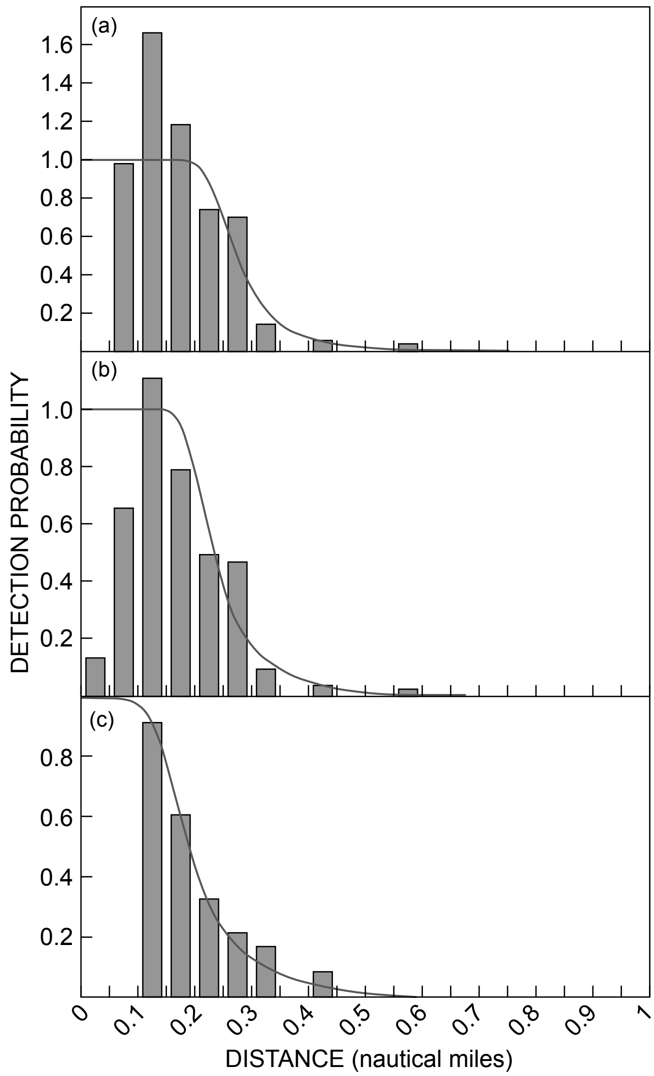

Figure 6: Detection probability function of dugong groups sighted during aerial surveys of the Bazaruto Archipelago fitted to (a) the frequencies of perpendicular distances of all primary sightings in 0.05 nautical mile distance bins, (b) the frequencies of perpendicular distances of all primary sightings in 0.05 nautical mile distance bins outside of 0.01 nautical miles, and (c) the frequencies of perpendicular distances of primary sightings made in the five optimal sighting condition surveys in 0.05 nautical mile distance bins outside of 0.01 nautical miles

Discussion

The aerial surveys identified that dugongs occur throughout the shallow area inshore of the 20 m isobath from the Save River mouth to Cabo São Sebastião of the Bazaruto Bay area. Two distinct core areas of distributional abundance were apparent from the sighting records, a northern core area offshore of the Govuro River mouth and the Bartolomeu Dias spit, and a core area in the vicinity of Santa Carolina Island, where a number of large dugong groups were recorded. The fact that the second core area has little seagrass cover suggests that animals utilise this area for

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reasons other than feeding. Dugongs use distinct habitats for various activities, and shallow waters such as tidal sandbanks and estuaries have been reported as sites for calving (Hughes and Oxley-Oxland 1971, Marsh et al. 1984). The use of these areas may be a strategy to minimise the risk of shark predation to calves (Anderson 1981) and more time might be allocated to safe but lower-quality feeding microhabitats when the likelihood of encountering sharks is increased (Wirsing et al. 2007).

The group sizes recorded in the Bazaruto Archipelago were comparable to group sizes recorded in other regions of dugong abundance, although few very large groups of dugongs (of >20 individuals) were seen in the Bazaruto Archipelago compared to other regions. For example, Preen (2004) recorded a maximum group size of 674 dugongs in the Arabian Gulf. The proportion of groups with calves was also lower within the Bazaruto Bay region. Preen (2004) reported proportions of dugong calves in the western and southern Arabian Gulf in 1986 as 14.5%, compared with 18.7% in the southern Gulf in 1999, and noted that these figures were typical of the proportions recorded on other surveys (Marsh et al. 1994).

Of the two core areas of calf distribution, the high density within Bazaruto Bay is expected in terms of water clarity, decreased exposure to predation and water movement. However, the high density of calf sightings in the northern core area is unexpected given the poor water clarity often encountered in this area. The reason for the hiatus in calf distribution between these two areas is unknown, but may be related to water movement in and out of the bay, the distribution of suitable calf habitat or to anthropogenic influences of seine-net fishing in the region (and the impact this may have on habitat). Surprisingly, two calf groups were sighted offshore of the islands, where both wave action and exposure to potential shark predation could be high.

The population numbers of dugongs in the Bazaruto Archipelago estimated in this study is probably the most robust population estimate of this population to date. Abundance estimates from previous surveys have suggested a smaller population than that recorded in this study, although it should be noted that the different estimates are not directly comparable on account of different survey methods and survey area limits. Guissamulo and Cockcroft (1997) estimated a local population of 130 dugongs in the bay based on strip transect sightings, although their survey area was smaller than that covered in our study and consequently a smaller proportion of the local population was likely to be surveyed. Whereas Dutton (1998) suggested that the population was declining because no more than 21 animals were counted per survey during aerial counts conducted during the 1990s, these count data were not subjected to abundance analyses and were most likely underestimates of abundance. Furthermore, the extent of the survey area covered by Dutton (1998) is unknown. An aerial census in May 2001 found dugongs distributed throughout the northern, central and south central areas of the Archipelago between Bazaruto Island and the mainland and based on aerial counts (of between 25 and 130 individuals) between 1990 and 2002, WWF (2004) suggested that this population was declining. In 1990, a single survey revealed

Table 2: Parameters used in the population estimates for the survey region with left truncation at a perpendicular distance of 0.1 nautical miles

Number of groups sighted (n)	Length of transect (nautical miles)	Area (square nautical miles)	$f(0)$ (SE)	Effective search width (SE)	Mean group size (SE)	Density of groups (SE)	Density of animals (SE)	Population (CV)
All surveys pooled								
247	8 824.56	1 211	6.537 (0.447)	0.153 (0.010)	2.227 (0.22)	0.091 (0.009)	0.204 (0.281)	247 (34.1)
Five optimal sighting condition surveys								
5	398.33	845.98	9.115 (2.578)	0.110 (0.31)	5.00 (2.05)	0.057 (0.029)	0.286 (0.186)	242 (65.60)
5	402.71	855.84	9.115 (2.578)	0.110 (0.31)	1.60 (0.24)	0.566 (0.021)	0.091 (0.491)	77 (54.18)
8	333.85	861.20	9.115 (2.578)	0.110 (0.31)	6.75 (3.45)	0.109 (0.049)	0.737 (0.503)	635 (68.29)
8	408.85	867.75	9.115 (2.578)	0.110 (0.31)	5.87 (4.17)	0.089 (0.039)	0.525 (0.438)	456 (83.40)
26	432.33	938.74	9.115 (2.578)	0.110 (0.31)	1.92 (0.24)	0.274 (0.098)	0.527 (0.199)	495 (37.78)
Mean								359 (38.20)

Table 3: Results of the independent twin-platform aerial survey carried out on 29 October 2007 as per the modified Petersen model (Equation 1)

Platform	Model parameter	Value
D-EOVC	Capture (n_1)	11
ZS EPO	Recapture (n_2)	15
D-EOVC and ZS EPO	Common sightings (m)	5
	N	31
D-EOVC	Proportion sighted	35.4%
ZS EPO	Proportion sighted	48.4%

a count of 92 dugongs in the area between Bazaruto, Benguerra and Magaruque islands and the mainland, from the northern tip of Bazaruto to Vilankulos (VGC and ATG, unpublished data). Although these data have not been analysed and the extent of the survey areas may not be directly comparable, the high raw counts recorded on the 1990 survey suggest higher densities than those recorded during the current surveys.

Little is known about the human-induced changes in the habitat of dugongs in the Bazaruto Archipelago over the past 40 years, although increased human pressure, including increased vessel traffic and associated noise and potential vessel-strike effects, increased beach seine-net fishing which may heavily alter seagrass structure through disturbance, and increased pollution loading, suggest that habitat quality may have declined over this period. The greatest current impact on adult survivorship appears to be the commercial fishery for shark fins in the Bazaruto Archipelago. This fishery uses 40 cm stretch size gillnets set for extended periods (unattended overnight) in known dugong habitats and has resulted in many dugong mortalities (Cockcroft et al. 1994, Dutton 1994, Guissamulo and Cockcroft 1997). There is also evidence that the catch of dugongs has developed into a directed fishery in Bazaruto Bay (Guissamulo and Cockcroft 1997, Cockcroft and Young 1998), where nets are set at night. Fishers do not openly admit to taking dugongs; however, its meat is prized (Cockcroft et al. 1994). Due to the illegal nature of the activity, the extent of mortality to the Bazaruto Archipelago dugong population from hunting remains unknown. However, it is believed to be in the order of 4–6 individuals per year (VGC pers. obs.). Other anthropogenic and natural stressors to the population include vessel activity (including potential strikes and vessel noise). Such stressors are of particular concern due to both the inherently low reproductive rates of dugongs and the role played by stochastic or episodic events such as the impacts of tropical cyclones or floods on seagrass bed habitat (Heinsohn and Spain 1974).

The densities of sightings recorded in the Bazaruto Archipelago area, although high compared with the rest of East Africa, are low compared with populations in Australia and the Arabian Gulf, where densities observed from aerial strip surveys ranged from 0.21 km^{-2} (SE 0.05) in 1986 in the southern Arabian Gulf, 0.08 km^{-2} in the eastern Red Sea (Preen 1989) to 0.71 km^{-2} in Shark Bay, Australia (Preen et al. 1997). Given that the local Bazaruto Archipelago dugong population might be viewed as the only viable population within the western Indian Ocean metapopulation (which has clearly declined over the past 30–40 years), it should be afforded the highest possible conservation efforts. Preen (2004) has suggested that the long-term survival of the dugong in the western Indian Ocean will depend on the establishment of an adequate network of protected areas where the impacts of human activities can be minimised.

Furthermore, the Bazaruto Archipelago dugong population must be viewed in the context of a seed or source population for the western Indian Ocean metapopulation. Whereas daily movements of dugongs are dependent on tidal amplitude, dugongs may move considerable distances, as detected during tracking studies using VHF and satellite telemetry equipment in Australian waters (Marsh and Rathbun 1990, Gales et al. 2004, Sheppard et al. 2006). Several studies have shown that dugongs appear to move seasonally (or at least during winter) in response to water temperature thresholds of 17–19 °C (Anderson 1986, Preen 1992, 2004, Marsh et al. 1994, Sheppard et al. 2006). Movements of dugongs into or out of the Bazaruto area are largely unknown. North of the Chiloane Islands, the water visibility is often extremely poor, even in the 'dry' season when river discharge is reduced. This poor visibility extends out to at least 15 nautical miles offshore, as far as the aircraft used in our study was permitted to fly. Although areas north of Sofala were not explored, a preliminary examination of satellite photographs suggests that there is little dugong habitat between the Chiloane Islands and about 600 km to the north, which may provide a natural barrier to northward dispersion by Bazaruto dugongs. South of Cabo São Sebastião, the continental shelf is narrow and probably does not provide adequate habitat for dugongs, other than for transient movements. Inhambane, which about 10 years ago was known to accommodate at least 16 dugongs, now appears to have suffered from human activity. Dugongs were not seen during an exploratory survey in 2007 and the density of fishing boats and fish traps observed during this survey suggests that dugongs may well have been all but extirpated from the area.

Despite the reported decline in dugongs in the Bazaruto Bay area (Dutton 1994), the importance of this area to dugongs is particularly evident in the context of the limited dugong populations within the western Indian Ocean. The Bazaruto population probably represents the most viable (and possibly the only viable) population of dugongs in the western Indian Ocean south of the Arabian Gulf. The long-term conservation and recovery of this species within the western Indian Ocean may well be dependent on the 'seeding' of the region by individuals from the Bazaruto population (and their subsequent survival after 'reseeding' within areas that have shown recent population declines). Consequently, it is recommended that the dugongs of the Bazaruto Archipelago area be afforded the strongest conservation priorities and that a dedicated and integrated management plan for dugong conservation in the area is implemented immediately. Such a management plan should address dugong bycatch concerns as a matter of priority.

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References

Anderson PK. 1981. The behaviour of the dugong (*Dugong dugon*) in relation to conservation and management. *Bulletin of Marine Science* 31: 640–647.

Anderson PK. 1986. Dugongs of Shark Bay, Australia – seasonal migration, water temperature, and forage. *National Geographic Research* 2: 473–490.

Bayliss P, Freeland WJ. 1989. Seasonal distribution and abundance of dugongs in the western Gulf of Carpentaria. *Australian Wildlife Research* 16: 141–149.

Buckland ST. 1985. Perpendicular distance models for line transect sampling. *Biometrics* 41: 177–195.

Cockcroft VG. 1993. A preliminary assessment of the status of Madagascar's coastal resources, with special reference to marine mammals and reptiles. Final report for United Nations Environment Programme, South African Department of Foreign Affairs and African Wildlife. December 1993.

Cockcroft VG. 1995. Aerial survey in Kenya finds few dugongs. *Sirenews* 24 [newsletter of the IUCN/SSC Sirenian Specialist Group].

Cockcroft VG, Salm RV, Dutton TP. 1994. The status of dugongs in the western Indian Ocean. In: First International Manatee and Dugong Research Conference, 11–13 March 1994, Gainesville, Florida.

Cockcroft VC, Young DD. 1998. An investigation of the status of coastal marine resources along the west coast of Madagascar. Unpublished report, Worldwide Fund for Nature (WWF), Gland, Switzerland.

Dutton P. 1994. Past and present status of dugong *Dugong dugon* in the Bazaruto Archipelago and other known habitats on the Mozambique Coast. In: First International Manatee and Dugong Research Conference, 11–13 March 1994, Gainesville, Florida.

Dutton P. 1998. East African dugongs disappearing. *Sirenews* 29 [newsletter of the IUCN/SSC Sirenia Specialist Group].

Gales NJ, McCauley RD, Lanyon J, Holley DK. 2004. Changes in abundance of dugongs in Shark Bay, Ningaloo and Exmouth Gulf, Western Australia: evidence for large-scale migration. *Wildlife Research* 31: 283–290.

Guissamulo AT. 1993. Dolphins and dugongs distribution in Maputo and Bazaruto Bays: an assessment of interaction with artisanal and semi industrial trawling fisheries. Unpublished report to UNEP, July 1993.

Guissamulo AT, Cockcroft VG. 1997. Dolphin and dugong occurrence and distribution and fisheries interactions in Maputo and Bazaruto Bays, Mozambique. Paper SC/49/SM24 presented at the 49th meeting of the International Whaling Commission, London, September 1997.

Heinsohn GE, Spain AV. 1974. Effects of a tropical cyclone on littoral and sub-littoral biotic communities and on a population of dugongs (*Dugong dugon* (Muller)). *Biological Conservation* 6: 143–152.

Hermans A, Pistorius PA. 2008. Marine mammal diversity in the remote waters of Aldabra Atoll, Southern Seychelles. *Atoll Research Bulletin* 564: 1–7.

Hughes GR. 1969. Dugong status survey in Mozambique. *In: World Wildlife Yearbook*. Switzerland: World Wildlife Fund. pp 137–139.

Hughes G[R]. 1971. Preliminary report on the sea turtles and dugongs of Mozambique. *Veterinária Moçambicana* 4: 45–62.

Hughes GR, Oxley-Oxland R. 1971. A survey of dugongs (*Dugong dugon*) in and around António Enes, northern Moçambique. *Biological Conservation* 3: 299–301.

Mackie C[S]. 2001. Aerial census of dugongs, dolphins and turtles in the Bazaruto National Park, WWF Eastern African Marine Ecoregion Programme. Report to the Directorate of Forestry and Wildlife, Ministry of Agriculture, Mozambique.

Marsh H[D], Heinsohn GE, Marsh LM. 1984. Breeding cycle, life history and population dynamics of the dugong, *Dugong dugon* (Sirenia: Dugongidae). *Australian Journal of Zoology* 32: 767–788.

Marsh H[D], Lawler I. 2001. Dugong distribution and abundance in the southern Great Barrier Reef Marine Park and Hervey Bay: results of an aerial survey in October–December 1999. Research Publication No. 70. Great Barrier Reef Marine Park Authority, Townsville.

Marsh H[D], Penrose H, Eros C, Hugues J. 2002. Dugong status reports and actions plans for countries and territories. Nairobi: UNEP.

Marsh H[D], Prince RIT, Saalfeld WK, Shepherd R. 1994. The distribution and abundance of the dugong in Shark Bay, Western Australia. *Wildlife Research* 21: 149–161.

Marsh H[D], Rathbun GB. 1990. Development and application of conventional and satellite radio tracking techniques for studying dugong movements and habitat use. *Australian Wildlife Research* 17: 83–100.

Marsh HD, Saalfeld WK. 1990. The distribution and abundance of dugongs in the Great Barrier Reef Marine Park south of Cape Bedford. *Australian Wildlife Research* 17: 511–524.

Marsh H[D], Sinclair DF. 1989. Correcting for visibility bias in strip transect aerial surveys of aquatic fauna. *Journal of Wildlife Management* 53: 1017–1024.

McClanahan TR, Sheppard CRC, Obura DO (eds). 2000. *Coral reefs of the Indian Ocean: their ecology and conservation.* USA: Oxford University Press.

Muir CE, Sallema A, Abdallah O, De Luca DW, Davenport TRB. 2003. The dugong (*Dugong dugon*) in Tanzania: a national assessment of status, distribution and threat. Unpublished threat to the Wildlife Conservation Society, New York.

Preen A. 1989. Technical report, dugongs, Volume 1: the status and conservation of dugongs in the Arabian Region, Saudi Arabia. Meteorological and Environmental Protection Administration [MEPA] Coastal and Marine Management Series, Saudi Arabia.

Preen A. 1992. Interactions between dugongs and seagrasses in a subtropical environment. PhD thesis, James Cook University of North Queensland, Townsville, Australia.

Preen AR. 2004. Distribution, abundance and conservation status of dugongs and dolphins in the southern and western Arabian Gulf. *Biological Conservation* 118: 205–218.

Preen AR, Marsh H, Lawler IR, Prince RIT, Shepherd R. 1997. Distribution and abundance of dugongs, turtles, dolphins and other megafauna in Shark Bay, Ningaloo Reef and Exmouth Gulf, Western Australia. *Wildlife Research* 24: 185–209.

Seber GAF (ed.). 1982. *The estimation of animal abundance*. New York: Macmillan Publishing.

Sheppard JK, Preen AR, Marsh H, Lawler I, Whiting SD, Jones R. 2006. Movement heterogeneity of dugongs, *Dugong dugon* (Müller), over large spatial scales. *Journal of Experimental Marine Biology and Ecology* 334: 64–83.

Smithers RHN, Lobão Tello JLP. 1976. Checklist and atlas of the mammals of Mozambique. Museum Memoir No. 8, Trustees of the National Museums and Monuments of Rhodesia, Salisbury.

Thomas L, Laake JL, Strindberg S. Marques FFC, Buckland ST, Borchers DL, Anderson DR, Burnham KP, Hedley SL, Pollard

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JH, Bishop JRB, Marques TA. 2006. Distance 5.0. Release "x"1. Research Unit for Wildlife Population Assessment, University of St. Andrews, UK. Available at http://www.ruwpa.st-and.ac.uk/distance/ [accessed February 2008].

Wirsing AA, Heithaus MR, Dill LM. 2007. Living on the edge: dugongs prefer to forage in microhabitats that allow escape from rather than avoidance of predators. *Animal Behaviour* 74: 93–101.

WWF (World Wildlife Fund). 2004. Towards a Western Indian Ocean dugong conservation strategy: the status of dugongs in the Western Indian Ocean region and priority conservation actions. WWF Eastern African Marine Ecoregion programme, Dar es Salaam, Tanzania.

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