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Focused and inclusive actions could ensure the persistence of East Africa's last known viable dugong subpopulation

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Abstract

Although the dugongs of Mozambique's Bazaruto Archipelago are the last known viable subpopulation along the East African coast, they remain threatened by a variety of anthropogenic and natural pressures that must be addressed to ensure their persistence. We aimed to establish recent trends in dugong abundance through a series of aerial surveys carried out between 2017 and 2021 over the Bazaruto seascape. We also assessed hotspots of dugong distribution in this region where targeted conservation measures may prove most effective. Finally, we modeled dugong population growth and mortality rates under varying scenarios to better understand the level of risk to anthropogenic mortality. We derived a total abundance of 325 SD 145 dugongs. While the estimates from this study and those from surveys in 2006–2007 (359 SD 137) suggest that dugong abundance has not changed significantly over the past 15 years, the confidence intervals of these estimates are too wide to detect potentially small changes relative to the subpopulation's size. The distribution of dugong sightings within the Bazaruto seascape over the 5-year period indicates two core zones, one of which occurs outside the limits of established conservation areas. Population viability analyses demonstrated variability around rates of unnatural mortality that would cause long-term decline in abundance. Together, these results provide strong motivations for higher level conservation actions such as the expansion and management of formal marine protected areas in the region and the listing of the East African dugong subpopulation within the IUCN Red List of Threatened Species. Our study also highlights the importance of developing alternative livelihoods and sustainably managing small-scale fisheries in collaboration with local communities and other stakeholders in order to reduce the prevalence of fishing equipment and anthropogenic activities that directly or indirectly threaten dugongs in the Bazaruto seascape.

KEYWORDS

abundance, critically endangered, dugongs, East Africa, seagrass

1 | INTRODUCTION

Dugongs (*Dugong dugon*), long-lived marine mammals that occur in the Indian and western Pacific Oceans, are threatened by a variety of factors throughout their shallow coastal range (Marsh & Sobtzick, 2019). Currently listed globally as vulnerable on the International Union for Conservation of Nature (IUCN) Red List of Threatened Species, dugongs occur in their highest numbers in the Torres Strait, located between Papua New Guinea and Australia, and the Persian/Arabian Gulf but are severely depleted in most other regions (Marsh & Sobtzick, 2019). Along the coast of East Africa, dugongs have largely been extirpated, probably due to the widespread use of particular types of fishing gear that ensnare and drown dugongs, such as gill nets (Marsh et al., 2011; Pilcher et al., 2017). Gill nets are inexpensive, simple to use, and can be highly efficient—all attractive qualities for artisanal fishers in developing countries seeking food security. Dugongs in East Africa are also threatened by the broader loss of crucial habitat such as seagrass meadows due to coastal development and pollution (Marsh & Sobtzick, 2019; Dunic et al., 2021).

The Bazaruto seascape in Mozambique, East Africa, which includes two marine protected areas (MPAs), is home to a dugong subpopulation that has survived despite these pressures (Figure 1; Cockcroft et al., 1994; Dutton, 1994; Findlay et al., 2011). These animals, henceforth referred to as the Bazaruto subpopulation, are the last known viable group of dugongs along the East African coast and are thus of significant biological, economic and cultural value (Findlay et al., 2011). Indeed, the East Africa dugong subpopulation, which includes the Bazaruto subpopulation, is geographically isolated from the nearby Red Sea subpopulation and is genetically distinct from subpopulations around western Indian Ocean islands, such as Madagascar (Marsh et al., 2011; Plön et al., 2019). Despite its enduring presence, the Bazaruto subpopulation remains threatened by the aforementioned pressures that were responsible for declines elsewhere in East Africa (Findlay et al., 2011).

Conserving dugongs is confounded by their cryptic nature, which makes them difficult to locate, study and monitor (Marsh, 1995; Marsh & Sinclair, 1989; Pollock et al., 2006). The most recent published assessment from 2006–2007 estimated the total abundance of dugongs at 359 SD 137 across the Bazaruto seascape (Findlay et al., 2011). At that time, Findlay et al. (2011) estimated that approximately four to six dugongs were dying of unnatural causes per annum. However, potential biological removal (PBR), a frequently used and conservative metric for evaluating the sustainability of marine mammal stocks, suggests that as little as a single individual per annum dying of unnatural causes could be unsustainable for the Bazaruto subpopulation (Findlay et al., 2011; Hagihara et al., 2016; Wade, 1998). These results suggest that more dugongs may be dying each year than the subpopulation can sustain.

In this study, we utilize two aerial survey techniques to assess the total abundance and distribution of dugongs throughout the Bazaruto seascape. We then quantitatively and qualitatively compare our results with historical data to evaluate trends in dugong abundance and long-term performance, which are important for informing appropriate conservation actions (Norton-Griffiths, 1978). We also analyze distribution data, which can be used to infer how a population selectively occupies its range, to help plan and prioritize new conservation areas (or modify existing ones) and to identify hotspots where targeted management initiatives may be most valuable. Additionally, we made use of the distribution data to assess the subpopulation's risk of local extinction—isolated and geographically restrained populations may be more vulnerable to catastrophes like extreme weather, which can destroy or damage suitable habitat. Finally, we made use of basic demographic data, such as the proportion of calves, to offer further insight into the performance of the Bazaruto subpopulation.

We hypothesized that the Bazaruto subpopulation would have declined in abundance, and that altered occupancy patterns would reflect this loss, with unprotected areas experiencing less use by dugongs. We then used population modeling to simulate different mortality scenarios and explore viability under a variety of different conditions.

By understanding trends in abundance and occupancy patterns over the past two decades, we aimed to determine the Bazaruto subpopulation's vulnerability and extinction risk. Additionally, we intended to provide an updated assessment of the status of dugongs in the Bazaruto seascape and offer specific targets and recommendations for conserving this unique and globally important subpopulation.

2 | METHODOLOGY

2.1 | Study area

The Bazaruto seascape is located approximately halfway along Mozambique's coast between ~21°S and 22°S (Figure 1) and comprises an archipelago of five islands in the south, enclosing a shallow bay of some 1500 km^2. Named

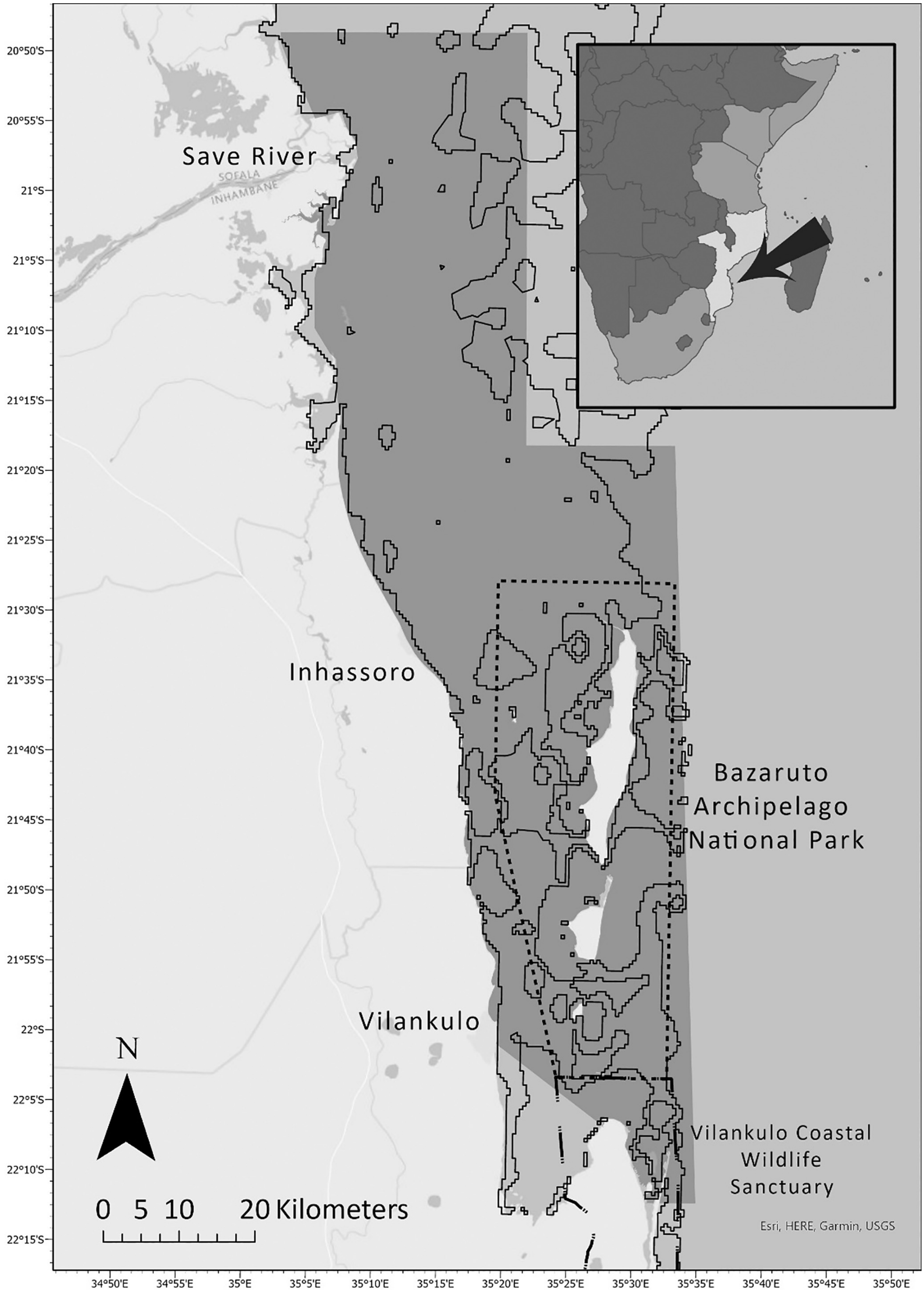

FIGURE 1 The area surveyed in the Bazaruto seascape designated in dark gray approximately corresponds with the 20-m isobaths in the north (black contour lines overlaid) and the 30-m isobaths in the south, which mostly covers the geographic distribution of dugongs throughout the area (Findlay et al., 2011).

after the largest island in the archipelago, the Bazaruto seascape hosts a wide diversity of marine species, including a variety of marine mammals, five species of sea turtle, and coral reefs (Everett & Van der Elst, 2008). Two conservation areas, Bazaruto Archipelago National Park (BANP) and the Vilanculos Coastal Wildlife Sanctuary (VCWS), were established to preserve this region's ecological diversity. However, these MPAs protect only a small portion of the Bazaruto seascape. The waters of this region are highly productive, and tens of thousands of local residents depend on marine resources for food security and livelihoods. Tourism also provides a vital source of income for communities throughout the region. Additionally, the Bazaruto seascape is an integral component of an Important Marine Mammal Area (IMMA) that was recently declared in 2020 (IUCN-MMPATF, 2020).

The survey area (approximately 3700 km^2) aligned with the boundaries of recent historical surveys (Findlay et al., 2011). It was defined by the coastline outwards toward the 30-m isobath from Cabo de São Sebastião to the northern tip of Bazaruto Island (Figure 1). To the north of the Bazaruto Archipelago, the survey area's limits were adjusted to the coastline outwards toward the 20-m isobath to just beyond the Save River's mouth (Figure 1). Coverage between years in this study was approximately similar, particularly in areas that historically had higher densities of dugongs. We treated the entire study area as a single block. While dugongs may occur in deeper waters (up to around 40 m), their presence and availability for detection in such habitats is relatively low, and the required transect lengths offshore would significantly increase safety risks (Hagihara et al., 2018; Marsh et al., 2011). Historically, few dugongs were detected in waters deeper than 20 m (Findlay et al., 2011). We therefore did not extend our surveys into areas further out in deeper waters.

2.2 | Dugong abundance estimates

We obtained dugong abundance estimates using aerial surveys flown between January 20, 2017 and May 6, 2021 (Table 1). All team members had experience with aerial surveys, and observers had previously flown dugong surveys. Team members communicated with each other through an on-board communication system. Transects were spaced two nautical miles apart, the minimum distance that allowed for the entire survey area to be studied in a single day, or approximately 5.5 h of active observing.

For each observation, rear seat observers (RSOs) reported the distance to the observation (or angle, using an inclinometer), the number of adults, and if possible the number of calves. A calf was defined as an individual less than two-thirds the size of a closely associated adult, assumed to be a cow (Sobtzick et al., 2020). The front seat observer (FSO) assessed sea state and bottom visibility of each observation for evaluation consistency (only in 2021) and recorded the location of each observation using a handheld GPS.

Surveys were only flown when the weather conditions were below or equal to Beaufort state 3 and when there was no precipitation (Fitzroy, 1839; Sobtzick et al., 2020). While dugong abundance in Australia is typically estimated using strip sampling, the earlier surveys in this study (2017–2018) collected data intended for distance sampling estimates, given that this particular methodology was previously employed for dugong abundance estimates in the Bazaruto seascape in 2006–2007 (Buckland et al., 2005; Findlay et al., 2011). During 2021, we collected sufficient data to derive estimates from both strip sampling and Distance sampling in order to assess the merits of each technique under the conditions particular to the Bazaruto seascape. Given our ability to incorporate perception and availability bias into the strip sampling estimate,

TABLE 1 Parameters of 10 aerial surveys over the Bazaruto Archipelago

Date	Aircraft	Abundance estimate methods	Active-strip width (m)	Rear-seat observers	Altitude (ft)	Overflight speed (kts)	Transect width (m)
Jan 20, 2017	Piper Tri-pacer PA-22150	Distance	3704	2	500	90–100	7408
May 20, 2017							
Oct 17, 2017							
Nov 19, 2017							
Mar 12, 2018							
Apr 16, 2018							
Apr 19, 2018							
May 4, 21	Cessna 182	Distance and strip sampling	600				
May 5, 21							
May 6, 21							

we chose to report these results as our final total abundance. However, to compare current abundance with estimates from previous surveys, we used results derived using Distance sampling to ensure comparable methodologies between 2006, 2007, 2017, 2018, and 2021.

Following all surveys, observations were analyzed using the Distance library in R (version 4.0.5). We tested a variety of models, including half-normal, hazard-rate and uniform, with various modifications such as left/right truncation and binning (Thomas et al., 2010). The models with the lowest Akaike Information Criteria (AICs) were evaluated using chi-squared tests (Akaike, 1987; Pearson, 1900). The models provided dugong abundance and density estimates for each survey, which were averaged for a final abundance estimate.

For strip sampling, all observations outside of the 100–300 m strips were removed from the dataset. We applied correction factors for availability and perception bias, which are two errors inherent to any aerial survey (Pollock et al., 2006). Availability bias quantification for this survey was based on availability probability estimates (p_a) defined by two key parameters: environmental condition index (ECI) and habitat depth (Appendix S1). Different values of p_a were derived for each combination of ECI (from 0–4) in three distinct depth ranges (0–5 m, 5–20 m, and ≥20 m) by researchers using artificial dugong models and dive profiles of tagged, wild dugongs in Northern Australia's Torres Strait (Hagihara et al., 2016, 2018). The estimates from the Torres Strait were assumed to be appropriate for the Bazaruto subpopulation (H. Marsh, personal communication). For each observation, the FSO determined the ECI by pairing in-flight evaluations of sea state and bottom visibility and evaluated depth after the survey using an open-source bathymetry model (GEBCO, 2020). Perception bias, p_d, was estimated using a modified "mark-recapture" approach designed for double observers (Ferreira et al., 2011; Seber, 1982).

To incorporate availability and perception bias (and their associated errors) into the final strip sampling abundance estimate, an initial error-adjusted estimate ($N\hat{}$) was calculated from each survey using a modified Horvitz Thompson estimator:

$$\hat{N} = \sum_{j=1}^{n} \frac{1}{p_b \hat{p}_{aj} \hat{p}_{dj}}, \tag{1}$$

where n is the total number of dugongs observed during a single survey, p_b is the probability that a strip was sampled in the study area (equivalent to the proportion of the study area sampled), $p\hat{}_{aj}$ is the probability that the animal was available for detection within the sampled area (availability bias), and $p\hat{}_{dj}$ is the probability that an animal available for detection is seen by an observer (perception bias) (Horvitz & Thompson, 1952; Pollock et al., 2006). Following each initial estimate of abundance, we used Python (version 3.8.5) to simulate 1000 surveys. We then estimated the standard error from all simulated abundance estimates (Hagihara et al., 2018; Pollock et al., 2006). Finally, we calculated the standard deviation and reported this value alongside a final abundance estimate, derived by averaging the values of N̂ from all strip-sampling surveys.

2.3 | Dugong distribution and occupancy

To generate comparable estimates of distribution between years, we mapped error-unadjusted observations using ArcGIS Pro (version 2.8.2). We then used the Kernel Density function to identify areas with higher densities of dugongs, which we interpreted as approximate occupancy patterns (Low et al., 2009; Silverman, 2018). We chose this analysis due to its ease of interpretability and its potential to practically inform marine spatial planning efforts in the future.

2.4 | Viability of the Bazaruto dugong subpopulation

In order to assess the viability of the Bazaruto subpopulation, we used the population viability analysis (PVA) software VORTEX (version 10.5.5) to model this dugong subpopulation (Lacy & Pollak, 2021). Some life history parameters, such as number of calves or reproductive intervals, were extrapolated from survey results, while others, such as lifespan or natural mortality rates, were obtained from other sirenian subpopulations (Appendix S2). In cases where no data were available for dugongs (e.g., natural mortality), these parameters were drawn from studied subpopulations of West Indian manatees (*Trichechus manatus*; Marsh et al., 2011). We ran PVA iterations 1000 times using our strip sampling-derived abundance estimate. In order to account for uncertainties around key life history characteristics of the Bazaruto subpopulation, we ran six different models assuming two different calving intervals (2.5 or 3.0 years) and three different ages of first offspring (8, 10, or 12 years; Hagihara et al., 2016; Marsh et al., 2011). By doing so, we aimed to estimate different potential growth rates to understand how the subpopulation may grow in the future under optimal conditions (no anthropogenic mortality).

We also modeled two different mortality scenarios to estimate the unnatural death rate threshold after which the subpopulation's abundance begins to decline. Our first mortality model, which assumed a more cautious scenario in which reproductive rates were as unfavorable as biologically possible, assumed an age of first offspring of 12 years and a calving interval of 3 years. Our second mortality scenario assumed an age of first offspring of 8 years and a calving interval of 2.5 years. All simulated mortality assumed that only adults were killed, and that males and females had an equal likelihood of unnatural death.

The PBR, a frequently used, conservative metric to calculate sustainable human harvest of marine mammals, was also calculated to provide a more cautious estimate of sustainable mortality rates (Hagihara et al., 2016). PBR has demonstrably captured trends in other marine mammal stocks even with uncertainties around biological parameters and relies only on an abundance estimate (Punt et al., 2020). The many assumptions that are required for VORTEX are, thus, not necessary for this calculation. We calculated PBR as

$$\mathrm{PBR} = N_{\min} \times \frac{1}{2} R_{\max} \times F_R \tag{2}$$

where $N_{\min}$ is the minimum population estimate, $R_{\max}$ is the estimated net population productivity, and F_R is a safety factor to account for additional uncertainties (Wade, 1998). $N_{\min}$ is equal to

$$N_{\min} = \frac{\hat{N}}{\exp\left(z\sqrt{\ln\left(1+\mathrm{cv}(N)^2\right)}\right)}, \tag{3}$$

where z is the standard normal variate equal to 0.842 and CV(N) is the coefficient of variation for the population estimate (Wade, 1998). For dugongs, $R_{\max}$ can be assumed as either 0.03 or 0.05 depending on whether calving ratios are every 3.0 or 2.5 years, respectively, and F_R is assumed to be 0.1 or 0.5, which is a standard value for endangered or vulnerable species, respectively (Hagihara et al., 2016; Marsh & Sobtzick, 2019). We subsequently compared PBR estimates with VORTEX-derived threshold mortality rates to provide a range of targets for management authorities and other support groups involved in conserving dugongs throughout the Bazaruto seascape.

3 | RESULTS

During the 10 surveys, we observed dugongs on 163 occasions, totaling 345 individuals (Figure 3a). Of these individuals, 42 were calves (12%). Average group size across was 2.12 SD 2.08 individuals (Appendix S3). Group size ranged from one to eight individuals (Figure 3a). Over 50% of observations were of a single dugong (n = 88), while 38% were of two to four individuals (n = 63).

3.1 | Dugong abundance estimates

Distance estimates yielded an error-unadjusted average of 422 SD 146 dugongs within the study area (Table 2).

TABLE 2 Summary of dugong population and density estimates for recent surveys using both strip and distance sampling

	Date	Number of dugongs observed	Number of calves	Abundance estimate (mean)	Density estimate (per km^2)	Abundance SD
Distance sampling[a]	Jan 20, 2017	7	1	199	0.05	97
	May 20, 2017	24	5	312	0.06	99
	Oct 17, 2017	39	2	335	0.09	113
	Nov 19. 2017	27	5	300	0.08	129
	Mar 12, 2018	40	5	880	0.24	263
	Apr 16, 2018	21	5	281	0.08	126
	Apr 19, 2018	54	4	985	0.27	350
	May 4, 2021	35	4	408	0.11	127
	May 5, 2021	23	5	265	0.07	82
	May 6, 2021	22	2	262	0.07	71
			Average	422	0.11	146
Strip sampling	May 4, 2021	11	3	315	0.09	145
	May 5, 2021	14	6	231	0.06	138
	May 6, 2021	8	1	430	0.12	151
			Average	325	0.09	145

Note: Density estimates were derived from abundance estimates.
[a]Abundance estimates unadjusted for availability or perception bias.

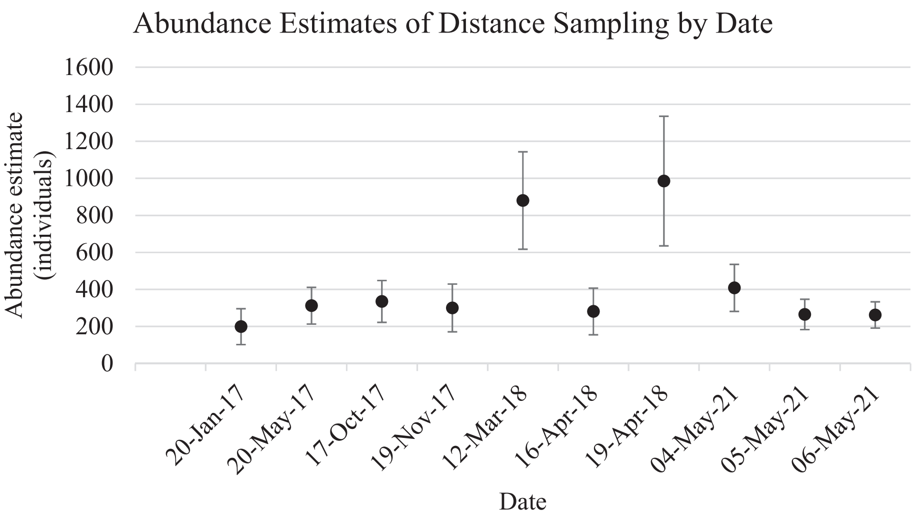

FIGURE 2 Abundance estimates of dugongs for all surveys in the Bazaruto seascape generated by distance sampling. The two surveys in early 2018 are significantly different from all others. Removing these two surveys, abundance estimates suggest that the population has remained relatively stable over the past 4 years.

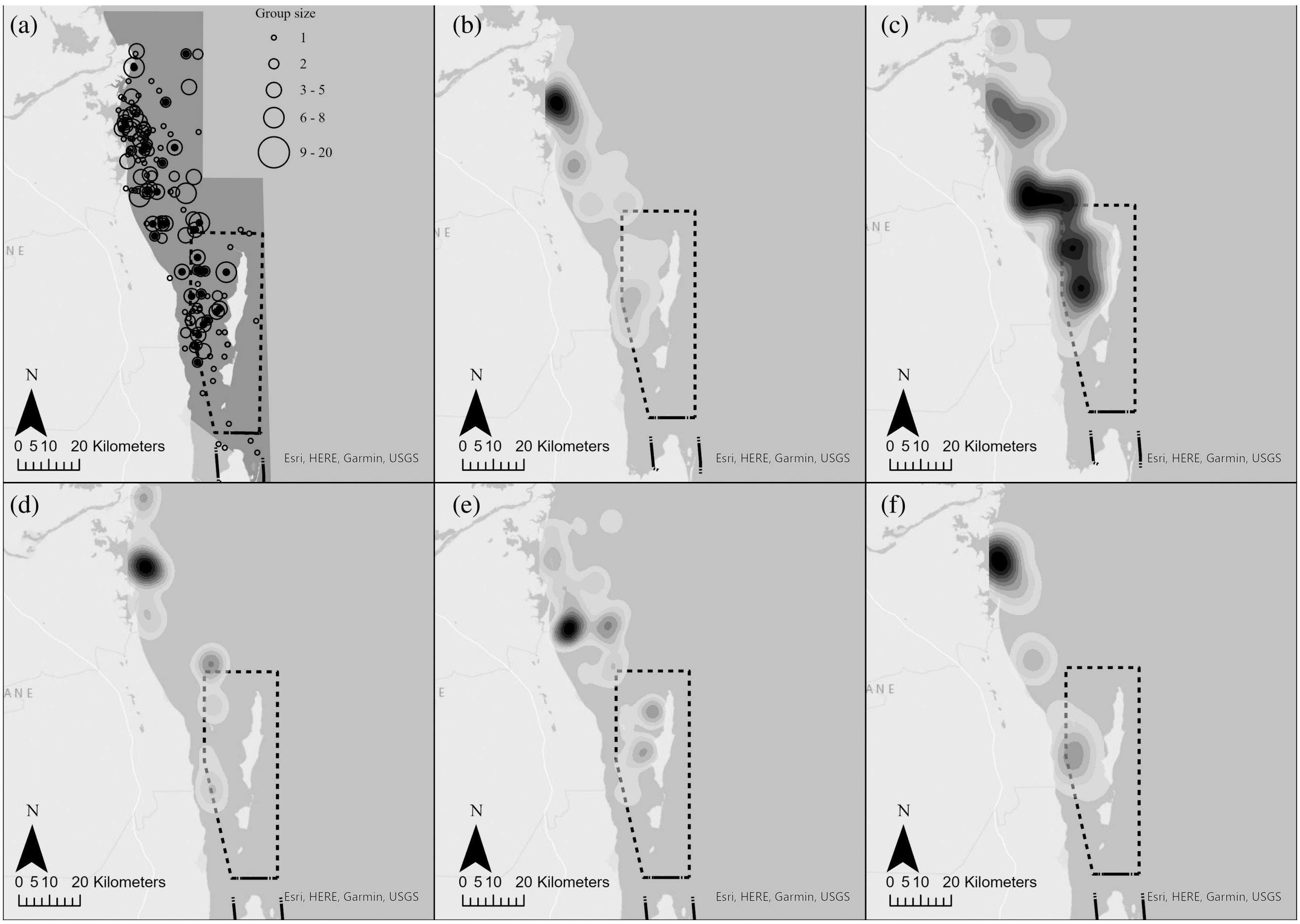

FIGURE 3 (a) Observations of dugongs throughout the study area in dark gray from all surveys from 2017 to 2021. Circles with black dots indicate observations when at least one calf was observed. (b) Kernel density map of all dugong observations throughout the study area. (c) Kernel density map of all calf observations throughout the study area. (d) Kernel density map of all dugong observations in 2017. (e) Kernel density map of all dugong observations in 2018. (f) Kernel density map of all dugong observations in 2021. *All kernel density analyses used uncorrected observations.

Estimates derived from two surveys on March 12, 2018 and April 19, 2018 were significantly larger than all other estimates (Figure 2; Table 2). Averaging abundance estimates while excluding these two outliers returned an error-unadjusted estimate of 295 SD 102 dugongs. Strip sampling yielded an average estimate of 325 SD

145 dugongs, when adjusted for availability and perception bias (Table 2).

Contrary to our expectations, our study did not find a significant change in dugong abundance throughout the Bazaruto seascape. However, this was because neither of our distance-derived abundance estimates (422 SD 146 and 295 SD 102 with or without the outlying surveys, respectively), was able to detect a significant change from the 359 SD 137 dugongs estimated by Findlay et al. (2011) in 2006–2007 due to the large confidence intervals around the abundance estimates of all of these studies. We thus cannot use these results to confirm with any certainty whether the Bazaruto subpopulation's abundance has increased, decreased, or remained stable.

3.2 | Dugong distribution and occupancy

While most observations were close to shore or in shallow water, individuals were occasionally detected over 20 km offshore or in water deeper than 30 m. Calves were also observed in these off-shore habitats, including in the highly turbid region around the Save River's mouth. Dugongs were consistently encountered at the openings of sheltered bays north of Inhassoro (Figure 3a). Kernel density analyses indicated that the entire subpopulation is clustered within two core zones in the north and south of the study area (Figure 3b,c). These two core zones were consistently distinguishable from adjacent low occupancy areas in 2017, 2018, and 2021 (Figure 3d–f). These hotspots coincided with those identified during previous surveys (Findlay et al., 2011).

3.3 | Viability of the Bazaruto dugong subpopulation

Population viability assessment models yielded an average 25-year projection of approximately 490–850 individuals, assuming an initial abundance of 325 individuals and no unnatural mortality (Figure 4).

Using the least cautious life history parameters, VOPVA indicated that the subpopulation would only decline if eight adult dugongs per year died from unnatural causes. Modeling in VORTEX with the most conservative parameters provided a similar result—the subpopulation could endure the removal of up to six adult dugongs per year before a decline would begin. PBR estimates were lower and indicated that the BANP subpopulation would remain stable if only 0.34–0.57 dugongs were killed per annum if the subpopulation is endangered and 1.70–2.84 if vulnerable.

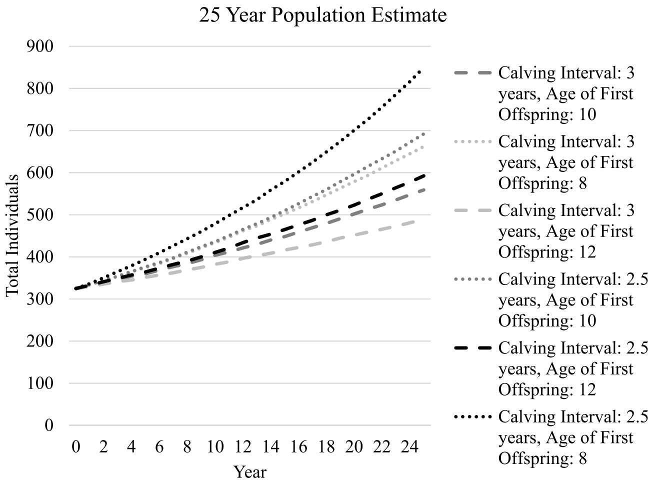

FIGURE 4 Population viability modeling for six different scenarios with various calving intervals and ages of first offspring. These two factors, which can vary amongst different dugong populations but have important implications for the rate of population growth, are unknown for the BANP subpopulation.

4 | DISCUSSION

A total of 10 surveys over the Bazaruto seascape provided an updated abundance estimate and basic demographic characteristics for a highly isolated subpopulation of dugongs along the East African coast. We used these data to also analyze this subpopulation's geographic distribution and explore scenarios conducive to viability. These surveys provide the first dugong abundance estimate since 2007 throughout the Bazaruto seascape.

4.1 | Trends in dugong abundance estimates

Despite aiming to evaluate the long-term performance of the Bazaruto subpopulation, we were unable to state with any certainty whether the abundance of this subpopulation has changed. Averaged abundance estimates of the Bazaruto subpopulation derived from Distance sampling from recent surveys were not able to indicate significant changes since surveys conducted in 2006–2007, partly due to the wide confidence intervals on both the results from 2017–2021 and historical surveys (Findlay et al., 2011).

We can, however, use the demographic results to provide further insight into the status of the Bazaruto subpopulation. Our survey found a higher percentage of calves than previously observed (Findlay et al., 2011). The current proportion of calves in the Bazaruto subpopulation is approximately comparable to that of the dugong subpopulation in the Torres Strait, a stronghold where dugong abundance is considered to be stable (Fuentes et al., 2016; Hagihara et al., 2018; Marsh et al., 2015). We also found comparable mean group sizes between our results and historical. These qualities are positive indicators of the status of the Bazaruto subpopulation.

The wide uncertainty around our abundance estimates demonstrates that aerial surveys should not be the only approach used to monitor trends in the Bazaruto subpopulation's abundance. Strip or distance sampling alone may be sufficient to manage and protect dugongs if the population in question fulfills basic assumptions of sampling, namely an even geographic distribution and relatively high abundance (Norton-Griffiths, 1978). Other aerial survey methods, namely total counts, are not viable alternatives given this seascape's vast area and dugongs' prevalence of moving based on tidal fluxes, which may result in the double counting of dugongs. Additional methods to study the BANP subpopulation are thus necessary to detect fluctuations or changes more rapidly.

Abundance estimates generated by strip sampling, which conforms to methods used to evaluate dugong subpopulations elsewhere in the world, suggest that there are only 325 SD 145 individuals left in the Bazaruto seascape (Hagihara et al., 2018; Marsh et al., 2002; Pollock et al., 2006). Surveys elsewhere in East Africa suggest severe declines in dugong abundance along the coast over the past few decades (Marsh et al., 2011). This inferred decline, the lack of other viable groups within the region and the small number of individuals in the isolated Bazaruto subpopulation should be used to inform a listing assessment of the East Africa coastal dugong subpopulation as critically endangered on the IUCN Red List of Threatened Species (IUCN Standards and Petitions Committee, 2019).

4.2 | Trends in dugong distribution and occupancy

Geographic distributions for dugongs within the Bazaruto seascape do not appear to have changed since 2006–2007 (Findlay et al., 2011). Of the two core regions confirmed by this study, the northern zone should be treated as particularly important, as there are openings to mangrove-protected estuaries where relatively high densities of dugongs were detected in both 2021 and in the early 2000s. Dugongs were often seen entering or exiting these small bays depending on tidal movements. Further highlighting this region's uniqueness, the human population in this area, unlike in the Bazaruto Bay, is relatively low, and only small fishing camps were observed by the survey team. Dugongs may rely on these sheltered habitats for a variety of reasons, as they may provide an area with seagrass where both the risk of natural predation and human fishing pressure is low. Indeed, elsewhere in Mozambique around the Primeiras and Segundas Archipelago (PSA), these types of estuaries have been noted as crucial for dugongs and reportedly used for calving (Hughes & Oxley-Oxland, 1971). In these habitats throughout the PSA, intense tidal fluxes made netting challenging, which may partially explain the observed absence of particularly dangerous net-based fishing methods in this part of our survey area. Understanding and preserving the conditions that make these refuges such an attractive habitat for dugongs should be a priority in order to protect and preserve such characteristics and properly manage the Bazaruto subpopulation.

If an environmental protected area is declared in or around the Bazaruto Seascape, the sheltered bays in the north of the study area should be afforded the highest degree of protection as soon as possible. This high-level intervention should be complemented by on-the-ground conservation actions that protect seagrass habitats and help minimize the use of dangerous fishing gear, such as gill nets, which can cause unnatural dugong mortality. We consider initiatives that shift pressure from marine resources, such as alternative livelihood development, to be critical in achieving these objectives provided that these programs are equitable and sustainable. Effective, impartial law enforcement may also help reduce the use of gill nets, which are legally banned throughout Mozambican waters. Finally, sensitization campaigns and long-term engagement with small-scale fishing communities throughout the region could help prompt positive changes in natural resource management and encourage more sustainable fishing techniques.

4.3 | Viability of the Bazaruto dugong subpopulation

The Bazaruto subpopulation remains vulnerable to unnatural mortality given our modeled estimates of threshold mortality rates and historical estimates of mortality (Findlay et al., 2011). Findlay et al. (2011) estimated that four to six dugongs per annum were dying due to unnatural causes, which would approximately align with the VORTEX-derived threshold mortality rates of six to eight adults per year. PBR estimates indicate even lower thresholds. Therefore, we suggest that management authorities responsible for the Bazaruto seascape's two MPAs, as well as support groups involved in conservation efforts, should aim for zero mortality given this dugong subpopulation's low abundance and geographic isolation.

We acknowledge the challenge of such a low unnatural mortality rate. The difficulty of remaining below this threshold is further complicated by the fact that dugong mortality may go undetected in such a vast seascape.

5 | CONCLUSIONS

The dugongs of Bazaruto remain the last known viable subpopulation along the East African coast and are estimated at only 325 SD 145 individuals. These realities suggest that the East African subpopulation may warrant significant special conservation status, including classification as critically endangered (IUCN Standards and Petitions Committee, 2019). Additional conservation areas would need to be expanded to the north of BANP to ensure that this subpopulation receives targeted management initiatives. Finally, irrespective of these high-level measures, culturally-appropriate strategies, such as alternative livelihood development, that either directly or indirectly reduce unnatural dugong mortality should also be introduced on a local level. The East African dugong subpopulation is directly dependent on the success of the last few hundred individuals living around the Bazaruto Archipelago.

AUTHOR CONTRIBUTIONS

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CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data used to support the conclusions of this article are presented in the article or supporting information material.

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SUPPORTING INFORMATION

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