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Long-term persistence of large dugong groups in a conservation hotspot around Hawar Island, Kingdom of Bahrain

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Abstract

1. Predictable aggregations of large marine mammals are valuable conservation targets, but aggregated populations can also be exposed to site-level threats.
2. The globally vulnerable *Dugong dugon* has a wide distribution but is found in large numbers mainly in Australia and the Arabian Gulf. Though Australian dugong populations are well studied, much less is known of the dugongs in the Arabian Gulf.
3. The spatial and temporal persistence of dugongs around Bahrain, with a focus on large dugong groups (>50 dugongs), was determined using an occupancy modelling framework supported by historical records, structured interviews, citizen science network reports, and small-scale boat and unmanned aerial vehicle surveys.
4. Historical records and current distributional studies confirmed that large dugong groups have been reliably sighted around Hawar Island (Bahrain) since at least 1986, forming large, clumped groups that persist almost year round. The largest recorded so far in the world, these fluid groups (maximum of ∼700 dugongs) account for ∼60% of the dugongs found in Bahrain and ∼12% of all dugongs in the Arabian Gulf.
5. The delineated occupancy core area of large dugong groups (∼145 km^2) straddles the Bahrain–Qatar border, reflecting the transboundary nature of these groups.
6. Careful management of human-induced stressors (in particular, fishing, boating, and coastal development) combined with regular monitoring of Hawar Island's large dugong groups and their seagrass habitat is critical to safeguard this globally important population.
7. The effectiveness of any conservation management is predicated on strengthening cooperation among all range states in the Arabian Gulf. A key recommendation of this study is to establish a regional network of marine protected areas encompassing core aggregation sites for dugongs, particularly the

Hawar Islands in Bahrain, the north-western waters of Qatar, Marawah Island in the United Arab Emirates in addition to the shallow waters between Saudi Arabia, Qatar, and United Arab Emirates.

KEYWORDS

Arabian Gulf, conservation, fishing, GIS, grouping behaviour, historical data, marine mammals, memory recalls, seagrass

1 | INTRODUCTION

The tendency of many large marine mammals to gather in dense aggregations at predictable locations makes these sites hotspots for conservation (Nowacek et al., 2011; Brakes & Dall, 2016; di Sciara et al., 2016). At the same time, their high abundances and clumped distribution make these populations particularly vulnerable to human-induced stresses at their aggregation sites (Anderson, 1981; Laist & Reynolds, 2005; Schipper et al., 2008; Reeves, 2009; Reynolds & Marshall, 2012; Magera et al., 2013; Brakes & Dall, 2016). The globally Vulnerable dugong (*Dugong dugon*) (Marsh & Sobtzick, 2019) shows highly variable grouping behaviour (Preen, 1992; Hodgson, 2004; Marshall et al., 2018). Described as facultative herders (Preen, 1992), dugongs are usually found as solitary individuals, mother–calf pairs, or small groups (<10 dugongs), but they occasionally aggregate in large groups of several hundred (Anderson, 1981; Preen, 1992; Hodgson, 2004; Marsh, O'Shea & Reynolds, 2011; Marshall et al., 2018; Deutsch et al., 2022; Khamis et al., 2022; O'Shea et al., 2022).

Dugongs have experienced considerable reductions across their Indo-Pacific distributional range with reported regional extinctions dating back to the 18th century (Marsh, O'Shea & Reynolds, 2011; Aragones et al., 2012b; Marsh & Sobtzick, 2019). Yet, data on their population status and distribution are still scarce in many regions, even where they are known to be abundant (Marsh et al., 1999; Marsh et al., 2002; Marsh & Sobtzick, 2019; Khamis et al., 2022). Across their range, dugongs are threatened by incidental net entanglement, direct hunting, alteration and loss of their primary seagrass habitats, boat strikes, pollution, and climate change, pushing several geographically isolated populations to the edge of extinction (Marsh et al., 2002; Reynolds & Marshall, 2012; Aragones et al., 2012b; Marsh & Sobtzick, 2019; Marsh et al., 2022; Ponnampalam et al., 2022). For instance, the dugong population in China has recently been declared functionally extinct. In addition, dugongs in Japan and East Africa are Critically Endangered, and in New Caledonia they are considered Endangered (Marsh & Sobtzick, 2019; International Union for Conservation of Nature, 2022; Lin et al., 2022a; Lin et al., 2022b).

Their slow reproduction rate and long generation times impede the rapid recovery of depleted dugong populations (Anderson, 1981; Marsh et al., 1999; Marsh et al., 2002; Marsh & Kwan, 2008; Marsh, O'Shea & Reynolds, 2011). This makes areas where dugongs aggregate in large numbers of particular significance. On the one hand, they are ideal areas to conserve the population. On the other hand, anthropogenic stressors at these key sites can disproportionally affect a large number of breeding adults as well as calves. Therefore, identifying these aggregation sites and determining how dugongs use them over space and time are important conservation priorities (Hodgson, 2004; Preen et al., 2012). However, this is often not straightforward. Dugongs are characteristically wide-ranging and elusive animals (Marsh et al., 2002; Sheppard et al., 2006; Marsh, O'Shea & Reynolds, 2011), and obtaining reliable population estimates across extensive spatio-temporal scales can be a considerable challenge for conservation planners.

Despite its vast range, spanning around 44 countries and territories across the warm tropical and subtropical Indo-Pacific waters (Marsh & Sobtzick, 2019), large groups (co) of >100 dugongs have been reported in recent times predominantly from two broad regions: Australia (e.g. Moreton Bay, Cape York, and Shark Bay) and the Arabian Gulf (e.g. Bahrain, Qatar, and United Arab Emirates) (Preen, 1992; Marsh et al., 2002; Lanyon, 2003; Hodgson, 2004; Preen, 2004; Chilvers et al., 2005; Marshall et al., 2018). Slightly smaller groups of between 50 and 100 dugongs are more common and have been regularly sighted in Australia (e.g. Moreton Bay, Cape York, Shark Bay, Hervey Bay-Tin Can Bay, Cape Flattery–Princess Charlotte Bay, and Shoalwater Bay) and the Arabian Gulf (e.g. Bahrain, Qatar, and United Arab Emirates) (Preen, 1992; Preen & Marsh, 1995; Marsh et al., 2002; Hodgson, 2004; Preen, 2004; Sobtzick et al., 2017; O'Shea et al., 2022), but have also been encountered occasionally across a broader range, including New Caledonia (Cleguer, 2015), Thailand (Hines, Adulyanukosol & Duffus, 2005), and Mozambique (Findlay, Cockcroft & Guissamulo, 2011). Across this range, however, small groups of one or two dugongs are still frequently encountered (O'Shea et al., 2022).

The Arabian Gulf hosts one of the world's largest (∼5,800) dugong populations (Preen, 2004), second only to Australia (∼155,000 dugongs; Clark, Fischer & Hunter, 2021). The Arabian Gulf's population is considered the largest in the western and northern regions of the dugong's distributional range (Marsh et al., 2002; Preen, 2004; Hodgson, 2011; Preen et al., 2012). The population is spread over a wide area, and the key to maintaining and conserving the species is identifying hotspots of dugong use, especially those occupied by large groups (Preen, 2004; Preen et al., 2012). To date, however, the management of large dugong groups (LDGs) (>50 dugongs) and their primary habitats in the Arabian Gulf has been limited by sparse information. In 1986, Preen (1989) and Preen (2004) encountered exceptionally large groups totalling ~670 dugongs in the Arabian Gulf, south east of Bahrain, repeatedly cited as the largest ever reported in the world (Preen, 2004; Hodgson, 2011; Marsh, O'Shea & Reynolds, 2011; Preen et al., 2012; O'Shea et al., 2022). After this first record from over 35 years ago, reliable reports of LDGs in the Arabian Gulf are limited to a few sightings from Bahrain and United Arab Emirates (Preen, 2004; Hodgson, 2011; Preen et al., 2012; Environment Agency-Abu Dhabi, 2014). An exception was Marshall et al. (2018) who reported five LDGs in the north-western waters of Qatar near the Bahrain-Qatar border on surveys conducted in the winter of 2015. Given the current wide knowledge gaps, it is difficult to know where LDGs are reliably found in the Arabian Gulf, how persistent they are in these areas, and whether they form seasonally or use the area throughout the year. This baseline information is essential for effective spatial management of aggregating marine mammals such as dugongs.

In this study, current and past distribution of LDGs was evaluated around Bahrain and their persistence since their first encounter in 1986 was determined. For this, a set of complementary methods was used including historical records, structured interviews, citizen science network reports as well as small-scale boat and unmanned aerial vehicle (UAV) surveys. Consequently, current critical LDG areas around Bahrain were identified and a proactive conservation approach has been discussed with a focus on strengthening the role and utility of regional cooperation in managing this globally important dugong population and associated seagrass habitat.

2 | MATERIALS AND METHODS

2.1 | Study area

The study covered the territorial waters of the Kingdom of Bahrain (25°32′–27°9′ N; 50°20′–51°7′ E) that span over ~7,500 km^2 (Al-Zayani, Zainal & Choudhury, 2009). Bahrain is an archipelago comprising more than 36 islands and islets occupying a total landmass area of 778 km^2 (General Directorate of Statistics, 2017). The archipelago is situated in the Gulf of Bahrain, an inlet of the central southern coast of the Arabian Gulf whose southern part forms a shallow bay called Gulf of Salwa (Figure 1). The Gulf of Bahrain is recognized as an Important Marine Mammal Area (IMMA), named 'Gulf of Salwa IMMA' in recognition of its international importance for marine mammals, particularly dugongs (IUCN–Marine Mammal Protected Areas Task Force, 2021). An aerial survey carried out in 2006 indicated that Bahrain has a large population of 1,164 (95% confidence interval: 530, 1,798) dugongs with an average group size of 1.5 (±0.22 *SE*) dugongs (Hodgson, 2009; Preen et al., 2012). The shallow waters surrounding Hawar Island (hereinafter around Hawar) in the south-east of Bahrain have been consistently identified as one of the most important areas for the Arabian Gulf's dugong population (Preen, 2004; Hodgson, 2009; Preen et al., 2012). The area has the highest dugong density (0.59 km^{-2}) in Bahrain (Hodgson, 2009), and most LDG sightings in the Arabian Gulf have been reported from these shallows. These include the ~670 dugongs encountered by Preen (2004) on March 5, 1986, that was in fact composed of two nearby groups of ~570 and ~100 dugongs sighted around Fasht Mu'tarid, a small reef complex situated to the north-west of Hawar (Preen, 1989; Marsh et al., 2002). In addition, Bell (2001) sighted groups of ~55, ~150, and ~250 dugongs in 2000, and Preen et al. (2012) reported ~300 dugongs in 2005 around Hawar. Hodgson (2009) also encountered an LDG in 2006 comprising >50 dugongs off Fasht Jarim (~80 km from Hawar). In 2015, Marshall et al. (2018) identified five LDGs ranging from ~170 to 510 dugongs in Qatar to the east of the Bahrain–Qatar border.

2.2 | Compilation of past and present data on LDGs

Since the definition of a 'dugong herd' is problematic (Hodgson, 2004), we prefer to use the terms 'marine mammal group' as suggested by Acevedo-Gutierrez (2009) and 'scattered dugong group' as defined by Preen (1989) to describe the dugong groups around Bahrain. We consider a dugong group comprising >50 individuals with inter-dugong distance not exceeding 20 body lengths (mean dugong body length ~2.5 m; Hodgson, 2004) to be an 'LDG'. All LDG sightings obtained by various methods were categorized according to season, following the classification of Vousden (1995) of the temporal patterns of the marine environment around Bahrain: winter (December–March), spring transition period (April), summer (May–October), and autumn transition period (November). The sightings were then plotted with geographical information system (GIS) maps using the software Quantum Geographic Information System (QGIS; Version 3.18; QGIS Association).

The persistence of LDGs around Bahrain was assessed by combining historical records, structured interview surveys, and citizen science network reports together with opportunistic small-scale boat and UAV surveys. The field surveys and structured interviews were undertaken in accordance with the environmental permit RH/24/84/2019/AA and following the guidelines of the Research Ethics Committee of the University of Barcelona, who also approved the interview schedule. The identities of interviewed people were always kept anonymous.

To identify potential LDG core areas, LDG sightings recorded by all standardized aerial surveys undertaken thus far in Bahrain were inventoried: (a) March 1986 (Preen, 1989; Preen, 2004), (b) October 1986 (Preen, 1989; Preen, 2004), (c) October 2000 (Bell, 2001), and (d) October 2006 (Hodgson, 2009). These aerial surveys covered nearly all Bahraini waters up to the 10 m isobath marking the broad-scale distribution of dugongs in the Arabian Gulf, delineated by Preen (2004), with the exception of the 2000 survey that focused only on the waters around Hawar (Figure 1).

Owing to the paucity of historical records of dugongs, the persistence of the dugong population around Bahrain was assessed,

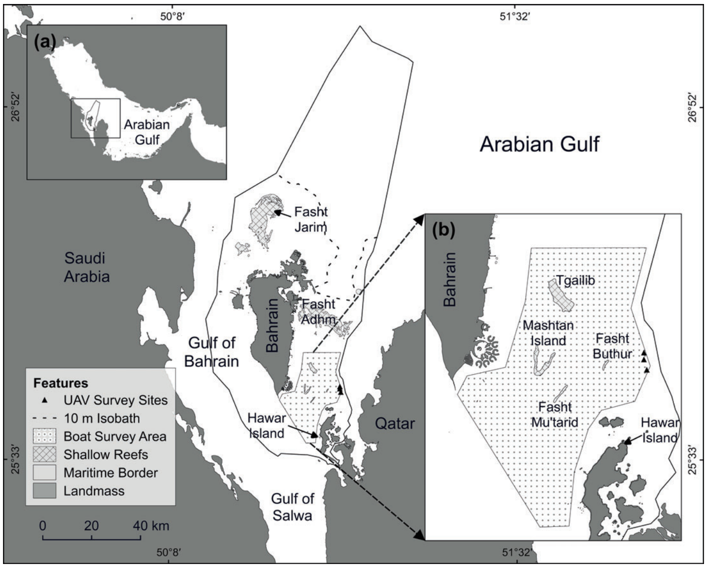

FIGURE 1 Map of the study area showing (a) the location of Bahrain in the Gulf of Bahrain and the larger context of the Arabian Gulf, and (b) major islands and shallow reef complexes (fashts), boat-based survey area, and large dugong groups (>50 dugongs) surveyed by unmanned aerial vehicles (UAVs). The dashed line represents the 10 m isobath marking the broad-scale distribution of dugongs in the Arabian Gulf delineated by Preen (2004).

with a focus on LDGs, through memory recalls. During 2020–2021, questionnaire-based structured interviews were conducted with local fishermen, tour boat operators, environmentalists, and researchers ($N = 97$). The interviewees were asked to specify important dugong areas and identify seasonal variations in dugong abundance. To obtain spatial data on dugong occurrence, knowledgeable key respondents ($n = 41$) were presented with a map of the region and requested to mark polygons representing the estimated spatial extent of all dugong sightings that they could remember encountering across all territorial waters of Bahrain. The informants were then asked to rank each polygon ($N = 149$) in terms of (a) time interval (1–3, 4–15, 16–30, and >30 years) and (b) size (1–10, 11–50, 51–100, 101–300, 301–500, and >500 dugongs) of the dugong group encountered. Sixteen key informants were chosen as members of a citizen science network and encouraged to report on all dugong sightings that they incidentally encountered across all Bahraini waters. Between October 2019 and February 2022, members of the citizen science network reported the location, timing, and group size (as the best estimated count of dugongs seen on water surface) of each dugong sighting.

A total of 61 LDG boat-based surveys were conducted between December 2019 and February 2022 around Hawar where LDGs had been reported by aerial surveys, structured interviews, and the citizen science network (Figure 1). During these trips, the boat travelled at 15–20 kn (27.8–37.0 km h^{-1}) while two observers scanned the surface, unaided or with 10×42 binoculars. Though this speed was not ideal for observing individual or paired dugongs, it allowed a large area to be covered in search of LDGs, which were the primary focus of these surveys. Although sightings of scattered dugongs were recorded whenever encountered, these records were not included in the analysis since spotting solitary or paired dugongs from a low platform in murky waters is challenging even at slower speeds.

Upon encountering a dugong group, the search was suspended and the boat slowly manoeuvred towards the animals, maintaining ~200 m from the group to minimize disturbance. The estimated geographical coordinates were then obtained with a Global Positioning System and the dugongs were observed more closely with binoculars. Since evaluating dugong abundance through boat-based surveys is challenging due to the elusive nature of dugongs and limited water visibility in their habitats (Hodgson, 2011; Aragones et al., 2012a; Keith-Diagne et al., 2022), three independent observers estimated the size of dugong groups encountered during boat surveys. First, the observers estimated the maximum number of dugongs seen on the surface using binoculars. Considering that the number of dugongs counted from a boat fluctuates over short time intervals due to the rapid changes in the predominant group behaviour (e.g. grazing or travelling), each observer continued to scan the dugong group for at least 5 min. After that, each observer estimated the group size, which was averaged across observers.

Three LDGs encountered on February 14, 15, and 16, 2021, were surveyed with two UAVs (DJI Mavic 2 Pro and DJI Inspire 2) equipped with high-resolution cameras mounted with wide-angle lenses and anti-glare polarizer filters. The UAVs were controlled from a speedboat and flown over the LDGs at a maximum height of 120 m. Still frames were then extracted from the UAV videos and carefully examined by three observers who obtained independent counts to estimate the average group size and calf proportions. The observers employed image-processing software (Adobe Photoshop) to mark (with a coloured dot) and count each shape with recognizable dugong features. The dugong group size and calf count and the proportion of the three LDGs surveyed were then averaged between observers.

Dugong group sizes were cross-verified by comparing overlapping UAV and boat-based dugong surveys on February 14, 15, and 16, 2021. This enabled an estimation to be made of the number of subsurface dugongs missed by boat-based observers at the time of counting. During all UAV flights, three observers in a nearby speedboat independently estimated the maximum number of dugongs seen near the water surface using binoculars as described earlier. On the February 15, 2021, survey, the percentage of individuals located within two dugong body lengths of nearest neighbours was also calculated. To identify habitats in key areas occupied by LDGs, six groups were observed until they moved away from their feeding spots (as indicated by their repetitive diving and the sediment plume generated by feeding; Hodgson, 2004; Marshall et al., 2018; Keith-Diagne et al., 2022) and then the benthos was visually examined by snorkelling or scuba.

2.3 | Current distribution of LDGs

The main distributional range of LDGs reported between 2019 to 2022 by the citizen science network and boat-based surveys was determined by computing kernel density estimate heatmaps using QGIS. The resultant heatmaps were then converted to percentage volume contours (PVCs) following the guidelines of MacLeod (2014) to identify where large groups were likely to occur 50% (50% PVC) and 95% (95% PVC) of the time. Shallow reef complexes (locally known as 'fashts'), marked on the habitat map produced by Al-Zayani, Zainal & Choudhury (2009), and islands were considered natural barriers and cropped from the resultant PVCs.

2.4 | Spatio-temporal trends of LDGs and dugong population

The persistence of LDGs over space and time around Bahrain was first determined visually by examining the GIS maps and observing any distinctive patterns in the spatial or temporal trends using the different methods included in the survey. These trends in persistence of LDGs were then compared with all dugongs around Bahrain to highlight any potential role of LDGs in maintaining the dugong population. To this end, a dynamic occupancy modelling framework (see Royle & Kéry, 2007) was used to estimate dugong occupancy (i.e. percentage of sites occupied), turnover (i.e. persistence), and colonization of all dugongs around Bahrain over time, based on the memory recall data reported by observers in the structured interviews, from >30 years ago to the time of data collection (i.e. 2021). It has to be noted that detectable changes in dugong occupancy, persistence, and/or colonization do not necessarily indicate corresponding changes (i.e. increase or decrease) in population size. A similar approach was also used by D'Souza et al. (2013) to estimate dugong occupancy and changes in distribution in India's Andaman and Nicobar Islands. Occupancy modelling allows for the probabilistic estimation of parameters related to species occurrence at specific sites conditional on the probability that all animals of the species may not be perfectly detected by observers. These surveys, conducted in a systematic spatial sampling framework, can prove helpful in estimating past distribution dynamics by addressing issues of imperfect detection inherent to available historical records or, in the case of this study, memory recalls. In this model, the probability of detection was estimated through spatial replicates represented by multiple informants in the same grid, who were providing memory recall information. Owing to the long intervals between the aerial surveys and the absence of any standardized dugong survey over the last 15 years, only data obtained through interviews (see earlier herein) were included in this analysis. First, the accuracy of the polygons marked by informants was verified by classifying them based on the time of sighting and dugong group size as already described herein. Then, polygons were overlaid on the historical dugong encounters recorded by corresponding aerial surveys undertaken in 1986 (Preen, 1989; Preen, 2004), 2000 (Bell, 2001) and 2006 (Hodgson, 2009) before the overlap percentage was calculated.

The territorial waters of Bahrain, confined within the Gulf of Bahrain, were partitioned into 2×2 nmi^2 ($\sim 3.70 \times 3.70$ km^2) grid cells ($N = 490$). From the 490 grids sampled, a reconfigured dataset of 151 grid cells, with three or four spatial replicates each based on proximate grids, was used across the four time intervals of memory recalls reported by interviewed informants. The northernmost waters of Bahrain were not included in the modelling as they are further offshore than the 10 m isobath cut-off, as detailed earlier herein. The data on dugong occurrence reported by memory recalls were assigned in a 1/0 format to the 151 grids. Reports of confirmed dugong sightings were assigned '1' and reports of not having seen dugongs were assigned '0' from all interviewees for that particular grid. These data represented detections and non-detections, and not true presence or absence of dugongs, as the reported sightings were conditional on (a) the interviewee's probability of encountering a dugong and correctly reporting it, (b) the interviewee's ability to accurately recall past sightings, and (c) internal consistency in reporting sightings for the four time-periods for which information was requested. Clearly, some of these detections are likely to be imperfect. It is also reasonable to expect that recent detections would have a lower uncertainty than past detections. All these caveats and assumptions lent themselves to an occupancy modelling approach. The model was run in the R software (R Core Team, 2020), using the packages 'rjags' and 'jagsUI', through the Bayesian statistical programming module JAGS (Plummer, 2014). For each model, 10,000 Markov chain Monte Carlo iterations were run in three chains and a burn-in time of 5,000 interactions was used. All model parameter estimates were checked for convergence, and their Bayesian credible intervals (95%) were reported.

2.5 | Potential transboundary movements of LDGs

To highlight likely transboundary movements of LDGs in the Arabian Gulf, LDG sightings recorded during this study that are <2 km from the maritime border of Bahrain were examined. In addition, the interval distances between the LDGs in Bahrain and those recorded earlier in Qatar (Marshall et al., 2018) and United Arab Emirates (Preen, 1989; Preen, 2004) were estimated and compared with the dugong movement ranges defined by earlier studies (e.g. Sheppard et al., 2006; Deutsch et al., 2022).

3 | RESULTS

3.1 | Current distribution of LDGs

Based on data from boat-based surveys and the citizen science network between 2019 and 2022, a number of LDGs were identified around Hawar (Figure 2a). Kernel density estimate heatmaps indicated that LDGs were distributed over 490 km^2 of the shallow waters surrounding Hawar (i.e. distributional range). These shallows encompassed an LDG occupancy area (144.6 km^2) that is composed of three PVCs indicating where LDGs spend 50% and 95% of their time. Two 50% PVCs were located to the west and north of Hawar, one around Fasht Mu'tarid of 7.9 km^2 and another off Fasht Buthur of 38.3 km^2 (~1% of the latter straddles the Bahrain–Qatar border). The longitudinal axis of the 50% PVCs around Fasht Mu'tarid measured 6.8 km and around Fasht Buthur measured 8.1 km. The linear nearest interval distance between the edges of the two 50% PVCs was 5.2 km. The 95% PVC occupied 98.4 km^2 off the western and northern coasts of Hawar, with 5.4% of its total area extending eastwards beyond the Bahrain–Qatar border. In addition, the distribution of the LDGs shows distinct spatial separation between winter and summer feeding grounds as described in the following (Figure 2b).

3.2 | Temporal and spatial trends of LDGs

Structured interviews showed a clear persistence of LDGs around Bahrain over the last three decades. A total of 35% of all respondents reported that they had encountered LDGs during their lifetime, although the size of the largest groups they sighted varied considerably (size category: 51–100 dugongs [32%], 101–300 dugongs [27%], 301–500 dugongs [19%] and >500 dugongs [22%]; maximum: 1,000 dugongs). The informants outlined a total of 25 polygons representing LDG sightings; these spanned all time intervals apart from the >30 years. The persistence of these groups in the shallow waters around Hawar was also confirmed by citizen science network reports and boat-based surveys, recording a total of 149 dugong groups, of which 64 (43%) were LDGs. The historical aerial survey records further confirmed that LDGs persisted over the period 1986–2000 within the same core areas they currently occupy (Figure 3). In addition to Hawar, both structured interviews and aerial survey records reported LDG sightings ($n = 3$) off Fasht Jarim.

Of the interviewed respondents that recorded LDGs, 27% encountered large groups in both summer and winter and 46% and 27% sighted them either in summer or winter respectively (Figure 4). The citizen science network and boat surveys provided further insight into the seasonal patterns of LDGs. The large groups around Hawar were persistently recorded in each of the 12 calendar months with the exception of April and May, although logistical constraints prevented adequate sampling of the region in April. Additionally, distinctive seasonal patterns were detected in the distribution of these groups around Hawar. In warm months (June–October), LDGs were mostly found in the 50% PVC around Fasht Mu'tarid, where they continued to be sighted until October or November. Later, most LDG sightings were encountered in the 50% PVC around Fasht Buthur, where they persisted throughout the cold winter months (December–March; Figure 2b). Occasionally, however, LDGs moved to the winter ground before the end of summer, leading to a slight overlap between the two areas. On all boat surveys, LDGs were sighted either at summer (i.e. around Fasht Mu'tarid) or winter (i.e. around Fasht Buthur) feeding grounds, except for two occasions in September when two LDGs were observed concurrently at both feeding grounds.

3.3 | Dugong baseline occupancy and changes in spatial distribution

Structured interviews showed that dugongs were unevenly distributed across the waters of Bahrain with dugong sightings (marked as polygons on maps by respondents) highly clustered around Hawar. Two other dugong core areas were recognized around Fasht Jarim and off the south-western coast. Additionally, the respondents reported a number of dugong sightings beyond the 10 m isobath across all time intervals apart from >30 years. Historical dugong sighting records ($N = 89$) reported from the 1986 and 2006 standardized aerial surveys ($N = 3$) confirmed these spatial trends with 59% of all encounters around Hawar; Fasht Jarim and the south-western coast accounted for 13% and 9% of encounters

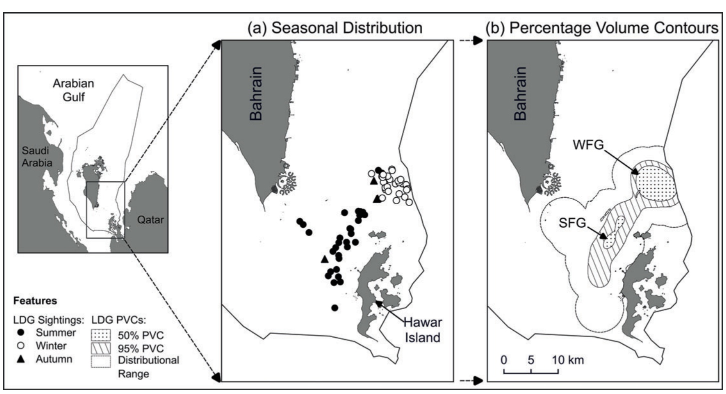

FIGURE 2 Spatio-temporal patterns of large dugong groups (LDGs; >50 dugongs) recorded during 2019–2022 through boat-based surveys and citizen science network: (a) large dugong group sightings classified by season, and (b) spatial extent of the overall distributional range as well as 50 and 95 percentage volume contours (50% and 95% PVC respectively) of large dugong groups. SFG: summer feeding ground; WFG: winter feeding ground.

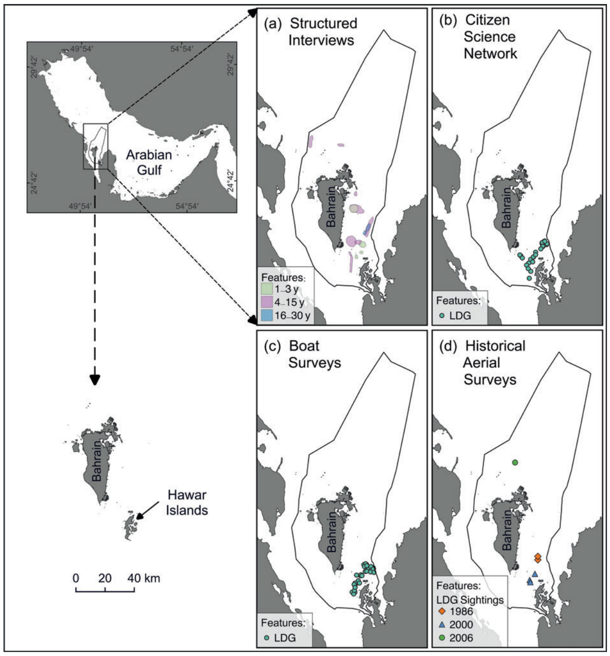

FIGURE 3 Large dugong group (>50 dugongs) sightings recorded by multiple methods: (a) memory recalls obtained through structured interviews (classified according to time intervals: 1–3, 4–15, and 16–30 years), (b) 2019–2022 citizen science network reports, (c) 2019–2022 boat-based surveys, and (d) historical records from 1986 (Preen, 1989; Preen, 2004), 2000 (Bell, 2001), and 2006 (Hodgson, 2009) aerial surveys. LDG: large dugong group; y: years.

FIGURE 4 An aerial photograph of a large dugong group (>50 dugongs) encountered in summer (October 4, 2021) to the north of Hawar Island, Bahrain, indicating the difficulty associated with accurately estimating the group size of large dugong groups. (Photograph courtesy of Janez Lotric, Diplomatic Protocol Communications).

respectively. Confirming the general agreement between the two methods, the memory recall polygons of the corresponding time intervals overlapped with the 1986, 2000, and 2006 aerial survey sightings by 46%, 75%, and 73% respectively (Figure 5).

The occupancy model indicated baseline occupancy (>30 years) of the dugong population around Bahrain at 32% of the total 151 grid cells. In addition, high persistence probability (∼95%) of dugongs was detected across the four time intervals. Colonization probability increased over time, with 35% of unoccupied sites recently occupied by dugongs. This increased overall dugong occupancy in 2021 to 55% (i.e. by nearly 23% from the baseline). Detection probability was estimated at 63% based on the memory recalls of interviewed respondents. Table 1 presents the parameter estimates and Bayesian credible intervals from the final selected model.

3.4 | Additional observations on LDG dynamics and habitat

Of all boat surveys with successful LDG sightings ($n = 54$), a single group was most frequently encountered during the survey (83%). On occasions, however, two (15%) and rarely three (2%) groups were observed. When two or more groups were found, the inter-group distance ranged between 0.2 and 2 km, with a single instance of 17.2 km between sightings. As confirmed by in-water observations, LDGs were found in extensive seagrass areas. These include the three groups surveyed by UAVs on February 14, 15, and 16, 2021, that were located at 3–4.5 m deep seagrass meadows in the winter feeding ground. Independent counts of the UAV footage estimated the average size of these LDGs as 181 (±4 *SD*), 696 (±5 *SD*), and 648 (±8 *SD*)

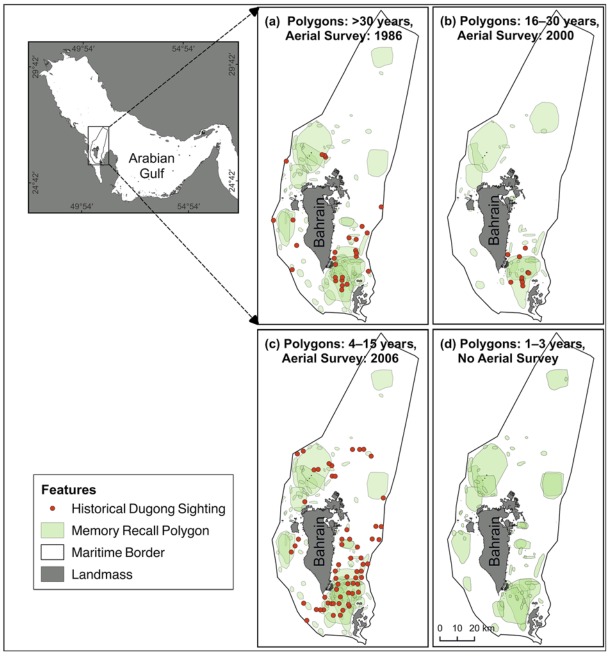

FIGURE 5 Historical dugong occurrence records presented as memory recall polygons (delineated by informants interviewed in 2020–2021), classified according to time intervals: (a) >30 years, (b) 16–30 years, (c) 4–15 years, and (d) 1–3 years. The maps are overlaid with dugong sightings recorded during the 1986 (Preen, 1989; Preen, 2004), 2000 (Bell, 2001), and 2006 (Hodgson, 2009) aerial surveys. There was no aerial survey conducted during the 1–3 years interval. Unlike the 1986 and 2006 surveys, the 2000 aerial survey covered only the south-east of Bahrain.

TABLE 1 Estimates of occupancy model parameters, with standard deviation and Bayesian credible intervals (95% of posterior distribution of probabilities) from one of the best models explaining dugong occurrence around Bahrain across four time intervals (1–3, 4–15, 16–30, and >30 years) based on memory recall data obtained through structured interviews undertaken in 2020–2021. The credible intervals or posterior distributions of effect sizes do not include zero, indicating a significant effect.

State parameters	Notation	Parameter mean (±*SD*)	Credible interval (2.5%)	Credible interval (97.5%)
Pr(occupancy)	ψ	0.315 (±0.063)	0.20	0.44
Pr(persistence)	ϕ	0.96 (±0.013)	0.94	0.99
Pr(colonization)	γ	0.36 (±0.04)	0.30	0.44
Pr(detection)	p	0.63 (±0.02)	0.58	0.66

dugongs respectively. In addition to their exceptional sizes, LDGs appeared in the aerial footage densely clumped particularly when the groups were grazing or fleeing from approaching boats. For instance, ~91% of dugongs in the group sighted on February 15, 2021, were less than two body lengths from their nearest neighbour. The aerial footage further revealed that dugongs often arranged themselves in multiple layers in the water column despite the limited depth. In most cases, the clumped groups occupied an area <0.5 km^2. The sea floor was visible in the captured aerial footage in only parts of the surveyed area, but it was mostly not visible at the spots occupied by the groups possibly due to the sediment clouds generated by their mass grazing (Figure 4). Hence, the size of these LDGs may be larger than estimated, particularly when surveyed from a boat. In essence, comparing boat and UAV counts estimated on February 14, 15, and 16, 2021, indicated that boat counts were found to underestimate those of the UAV flights by 2.66, 5.15, and 4.47 times respectively. A total of 11 (±1 *SD*; 6.1%), 45 (±2 *SD*; 6.4%), and 39 (±1 *SD*; 6.0%) calves were counted within the LDGs surveyed on February 14, 15, and 16, 2021, respectively. Further examination of the UAV footage showed that mother–calf pairs were occasionally difficult to recognize in extracted still images due to the murky waters and the elusive behaviour of calves, suggesting that the calf proportions could be underestimated. Given that clumped LDGs typically occupied an area of <0.5 km^2, the density of dugong calves (i.e. number of calves per unit area) within the foraging area of the LDG was approximately 11–45 calves per 0.5 km^2.

Structured interviews and boat-based surveys showed that many LDGs encountered in cold winter months were in close proximity to the Bahrain–Qatar border and <2 km from the large groups sighted in Qatar by Marshall et al. (2018). Similarly, interviewees marked LDG sightings off Fasht Jarim, <1 km from the Bahrain–Saudi border (Figure 3). At a larger scale, Hawar's LDGs were ~430 km from the dugong core area around Murawah Island in the United Arab Emirates (Figure 6).

4 | DISCUSSION

Hawar Island is a globally significant hotspot for dugong conservation, with some of the largest, most persistent and actively reproducing groups of dugongs recorded across its Indo-Pacific range. Combining data from historical and current distributional studies using a mix of approaches, this study confirms that LDGs, measuring in the hundreds, have used Hawar's shallow seagrass meadows for at least the last four decades. The models suggest that the occupancy range of the dugong population around Bahrain may be expanding in recent years, although LDGs are still mostly restricted to the relatively small core occupancy area around Hawar.

In the field, the groups encountered on February 15 and 16, 2021, outnumber all earlier reports from this region (Preen, 1989; Preen, 2004; Marshall et al., 2018) as well as from Australia

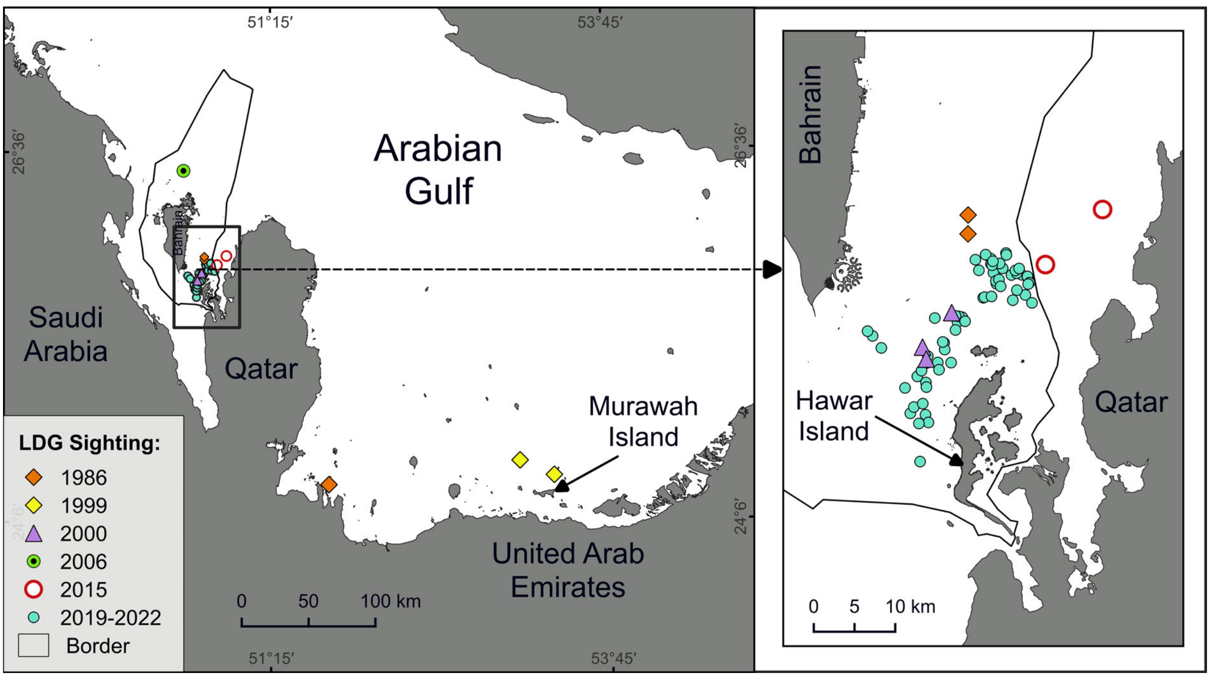

FIGURE 6 Historical and recent large dugong group (>50 dugongs) sightings in the Arabian Gulf, recorded by aerial and boat surveys and citizen science network in 1986 (Preen, 1989; Preen, 2004), 1999 (Preen, 2004), 2000 (Bell, 2001), 2006 (Hodgson, 2009), 2015 (Marshall et al., 2018), and 2019–2022 (this study), indicating their likely transboundary movements. The inset map shows the proximity of the large dugong groups reported in both Bahrain and Qatar to the Bahrain–Qatar border. Arrows indicate the location of Murawah Island (United Arab Emirates) and Hawar Island (Bahrain), the most important core dugong areas in the Arabian Gulf.

(Preen, 1992; Lanyon, 2003), making them the largest ever documented in recent times. These findings, however, should be interpreted with caution considering the difficulties associated with accurately estimating the group size of LDGs (see later). As with the LDGs reported in Australia, these groups tended to be highly clumped and group size extremely fluid, often breaking up into subgroups several kilometres apart that occasionally joined again (Anderson, 1981; Preen, 1989; Preen, 1992; Preen, 2004; Hodgson & Marsh, 2007; Marsh, O'Shea & Reynolds, 2011; Marshall et al., 2018). This characteristic fission and fusion behaviour is common across aggregating species from birds to baboons, and it is also seen in many marine mammal groups (Marsh, f & Reynolds, 2011; Tsai & Mann, 2013; Zuluaga, 2013; Díaz López et al., 2018; O'Shea et al., 2022). It is likely that when dugongs were much more abundant in other parts of the Indo-Pacific, large groups were more common and that the LDGs of the Arabian Gulf and Australia, measuring in the hundreds, may be relicts of a once widespread grouping strategy (see Preen, 1992; Hodgson, 2004). Why dugongs still gather in such large numbers at only certain localities remains a matter of some conjecture (Preen, 1992; Marsh et al., 2002; Marshall et al., 2018; O'Shea et al., 2022). Several factors have been examined to explain dugong grouping behaviour, including population density thresholds, thermoregulation, calf nursing, predatory defence, grazing efficiency, extreme weather conditions, and social interactions (Anderson, 1981; Preen, 1992; Anderson, 1998; Hodgson, 2004; Holley, 2006; Cleguer, 2015). Which of these factors play a role in Hawar's LDGs would require detailed, context-specific studies on environmental, population, and behavioural triggers. Whatever factors determine this grouping behaviour, it likely plays important social functions, including cultural transmission and information sharing about resource distributions and reproduction.

The calf proportions of the studied LDGs are lower than earlier LDG reports from this region (15.7%; Preen, 2004) but comparable to proportions reported in the LDGs of Qatar (5.4–9.9%; Marshall et al., 2018). For most reported LDGs, calf proportions tend to fall within average values reported across dugong populations (Preen, 1992; Hodgson, 2004): United Arab Emirates (7.46–8.4%; Das, 2007), Red Sea (1.4–14.9%; Preen, 1989; Preen, 1992), Hervey Bay (1.5–22.1%; Sobtzick et al., 2017), and New Caledonia (4.7–18.0%; Cleguer et al., 2017). In terms of calf density, however, it was remarkably high in Hawar's LDGs (45 calves occupying <0.5 km^2), conforming with earlier reports from nearby Qatar (51 calves in <1 km^2; Marshall et al., 2018). These results suggest that persistent aggregation sites of LDGs across their range possibly represent important calf birthing and/or rearing grounds. This is further supported by the multi-decadal persistence of mother–calf pairs around Hawar, which is a positive sign that the population is likely reproductively healthy given their slow rate of reproduction and the vulnerability of orphaned calves (Anderson, 1981; Preen, 1992; Marsh et al., 1999; Marsh & Kwan, 2008).

Another remarkable feature of Hawar's LDGs is their persistence in space and time. The core area of dugong occupancy around Hawar has had consistent reports of LDGs for >35 years, indicating that these shallow waters are a traditional grouping location for the population. Considering the difficulties inherent in estimating the group size of LDGs (see later), the persistence of sizeable LDGs of almost the same number (~700 dugongs; Preen, 2004; this study) around Hawar for over three decades further underscores the significance of this area for dugong conservation. The multidecadal persistence of LDGs also lends support to the global importance of the Gulf of Salwa IMMA for dugongs (Knight, Seddon & Al-Midfa, 2011; IUCN–Marine Mammal Protected Areas Task Force, 2021).

Of all historical LDG records in Bahrain (Bell, 2001; Preen, 2004; Hodgson, 2009), 67% were in summer, supporting our findings that dugongs aggregate around Hawar not just in winter, as was previously thought (Preen, 1989; Preen, 2004; Preen et al., 2012; Marshall et al., 2018). To our knowledge, Hawar is second only to Moreton Bay in harbouring groups of >100 dugongs year round (Preen, 1992; Hodgson, 2004; Chilvers et al., 2005; O'Shea et al., 2022). That said, these fluid groups do show distinctive seasonal movements, but at a highly reduced scale, shifting between distinct but slightly overlapping summer and winter feeding grounds. Highlighting the importance of socially transmitted information (Anderson, 1981; O'Shea et al., 2022), these results add to the evidence from Moreton Bay where large groups repeatedly use the same feeding grounds (Anderson, 1981; Lanyon, 2003) in a systematic manner following predictable seasonal movement routes (Hodgson, 2004). Without more detailed studies on seagrass nutrient contents and temporal patterns of seagrass availability, it is difficult to speculate on the reasons for this seasonal movement. However, these small-scale migrations have important consequences for managing these LDGs. The encounter of LDGs at winter feeding grounds during November–March conforms with the results of Marshall et al. (2018), who reported that LDGs start arriving in the nearby Qatari waters in November and persist until February. These consistent reports highlight the transboundary nature of LDGs and underscore the role of seasonality in shaping their spatial distribution and, hence, the larger Arabian Gulf's population (Preen, 2004; Marshall et al., 2018).

The year-round persistence of LDGs around Hawar enabled the mapping of a well-delineated hotspot where hundreds of dugongs spend their summers and winters in large groups. While this allows managers to focus management efforts on a relatively small and well-defined hotspot for conservation, it also increases the vulnerability of the dugong population to site-level threats. Owing to their exceptionally large size, clumped distribution, and high calf density, any significant human-induced stressors to LDGs and/or their primary aggregation sites will have disproportionate impacts on the entire dugong population. Given the global significance of this population, there is a need to urgently put in place a series of management actions with a focus on restricting the use of gillnets and imposing boat speed limits across the LDG occupancy area, since bycatch has been identified as a major source of dugong mortality in the Arabian Gulf (Hodgson, 2009; Knight, Seddon & Al-Midfa, 2011; Environment Agency-Abu Dhabi, 2014; Abdulqader et al., 2017). Also, it is crucial to safeguard the extensive seagrass beds around Hawar from the impacts of accelerating coastal development in the south of Bahrain.

Establishing and maintaining a continuous monitoring programme is a priority to identify any decline in dugong populations or degradation in seagrass habitats at early stages, allowing timely conservation interventions. In all this, it is vital that local communities are made partners in dugong conservation, to ensure that small-scale fishing can sustainably thrive alongside LDGs. There is little doubt that these LDGs cross international jurisdictional boundaries, and hence establishing a regional network of marine protected areas spanning all the Arabian Gulf's range states is crucial to achieving the effective protection of these groups and the larger dugong population. This network should encompass confirmed and potential core dugong aggregation sites, including Murawah Island and Al Yasat Island in the United Arab Emirates, Hawar Island, Fasht Buthur, and Fasht Jarim in Bahrain, the north-western waters of Qatar in addition to the shallow waters between Saudi Arabia, Qatar, and United Arab Emirates. Of these, only the first three have been officially designated as marine protected areas. The network could be established progressively with the first series of core zones encompassing the designated protected areas (42%), followed by Fasht Buthur and the north-western waters of Qatar (29%). The addition of Fasht Jarim and the shallow waters between Saudi Arabia, Qatar, and United Arab Emirates would expand the network by a further 29%. In addition to these core zones, the regional network should promote ecological connectivity by imposing a similar array of interventions on LDG migration corridors and key habitats interconnected with seagrass, particularly coral reefs and islands.

This multidisciplinary study has confirmed the persistence of LDGs around Hawar and defined their core occupancy area using cost-effective methods supported by UAV surveys. In interpreting these results, it is important to consider a few important caveats. Given the chosen boat speed, it is possible that some dugong groups may have been missed. In addition, an important source of information was the structured interviews with key informants, and the possibility of inaccurate recollections of encounters due to failing memories cannot be discounted. Despite their large numbers, clumped dugong groups are often difficult to observe from the air (Preen, 1989; Pollock et al., 2006; Cleguer, 2015; Cleguer et al., 2021; Trotzuk et al., 2022). This is even more complex for boat-based surveys that depend on surfacing individuals; dugongs resting or feeding underwater make accurately estimating group size a real challenge. Given this difficulty it is possible that LDGs could be more common across the dugong global range than currently reported. Despite these caveats, by using multiple approaches, these results are considered to be robust and signify the high conservation importance of this region. It is hoped that the enhanced knowledge on the Arabian Gulf's LDGs from ongoing research in Bahrain, Qatar, and United Arab Emirates will inform evidence-based conservation management.

What is remarkable about dugong groups is just how variable they are in size, from solitary or paired individuals to mega-aggregations of hundreds of dugongs. A complex set of trade-offs and life-history characters underlie this variability (Anderson, 1981; Preen, 1995; Hodgson, 2004; Zeh et al., 2018). This variable grouping behaviour may possibly contract across the dugong's range as accidental bycatch, hunting, seagrass meadow loss, and boat strikes combine to see fragmentation and decline of local populations. What makes the Hawar's LDGs so vital is that they represent an important part of the suite of dugong behaviours across its range. Conserving the LDGs around Hawar should be a global priority to preserve the population of the Arabian Gulf and maintain the remarkable behavioural flexibility this species can show across its range.

Given the LDGs encountered during this study, and assuming that the population sizes reported by Hodgson (2009) and Preen (2004) have not changed substantially over time, it is estimated that ~12% of all dugongs in the Arabian Gulf (equating to ~60% in Bahrain) may aggregate, forming large groups around Hawar. As speculated earlier by Preen (2004), the interval distance between Hawar and Murawah islands is within the large-scale dugong movement range (Sheppard et al., 2006; Deutsch et al., 2022), suggesting possible contributions of regional migration to the formation of Hawar's LDGs. The extension of the LDG occupancy area beyond the Bahrain–Qatar border further highlights the transboundary nature of the LDGs around Hawar. These reports underscore the significance of LDGs in maintaining sizeable dugong populations, a primary consideration for any dugong conservation or management strategies in the Arabian Gulf (Knight, Seddon & Al-Midfa, 2011; Preen et al., 2012). For this globally important population to persist, therefore, the LDGs and their core aggregation sites and migration corridors should be effectively conserved through an evidence-based regional conservation plan. Establishing a regional network of marine protected areas and effectively engaging local communities are critical steps in maintaining the LDGs in their northern distributional limits.

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CONFLICT OF INTEREST STATEMENT

The authors have declared no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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