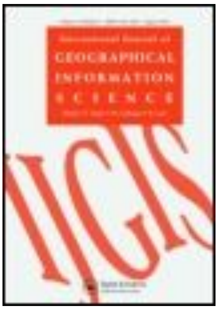

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Sarah M. Hamylton [a] , Annelise B. Hagan [a] & Naomi Doak [b]

[a] Cambridge Coastal Research Unit, University of Cambridge, Cambridge, UK

[b] Seychelles Islands Foundation, Victoria, Seychelles

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Observations of dugongs at Aldabra Atoll, western Indian Ocean: lagoon habitat mapping and spatial analysis of sighting records

Sarah M. Hamylton[a]*, Annelise B. Hagan[a] and Naomi Doak[b]

[a]*Cambridge Coastal Research Unit, University of Cambridge, Cambridge, UK;* [b]*Seychelles Islands Foundation, Victoria, Seychelles*

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Until recently, it was thought that dugongs (*Dugong dugon*) were extinct in the Seychelles. However, a collection of sightings at Aldabra Atoll, a World Heritage Site in the Seychelles, has renewed interest in dugong distribution in the western Indian Ocean. This article consolidates the records of dugong sightings held in the Aldabra Research Station library and explores their spatial patterning. The locations of sightings (2001–2009) are plotted onto a high-resolution benthic habitat map of the Aldabra lagoon created by classifying a QuickBird satellite remote-sensing image in January 2009. A spatial cluster detection procedure is applied to point records of sightings to reveal a statistically significant cluster of sightings in the north-west of the lagoon, at Bras Monsieur Clairemont, suggesting a mutual co-existence of dugongs and seagrass beds. A habitat suitability model combines the point data set of dugong sightings within the continuous benthic habitat map and identifies the central western area as containing the most suitable habitat for dugong inside the Aldabra lagoon.

Keywords: Seychelles; benthic habitat map; remote sensing; cluster analysis; dugong; habitat suitability

1. Introduction

Dugongs are herbivorous mammals that frequent coastal waters and typically occur in wide shallow protected bays, mangrove channels, in the lee of large inshore islands and along continental shelves (Heinsohn *et al*. 1979, Marsh *et al*. 2002). The distribution of many dugong populations is driven by the presence of seagrass beds, in particular *Halodule* sp. and *Halophila* sp., which are low in fibre and high in starch, nitrogen and digestibility (Lanyon 1991, Aragones 1996, Sheppard *et al*. 2007). Dugongs have a low reproductive rate and a longevity upward of 70 years and demonstrate high investment in offspring (Bryden *et al*. 1998). Due to this life history strategy and dugongs' dependence on seagrasses, which in turn are restricted to shallow platforms, which are often sites of substantial coastal development, dugongs are extremely vulnerable to anthropogenic influence. Worldwide dugong populations have been listed in Appendix 1 of the Convention on International Trade in Endangered Species (CITES), which prohibits trade in species that are vulnerable to extinction. The western Indian Ocean marks the western boundary of the dugong's geographical range where small numbers occur off the coasts of Somalia, Kenya,

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*Corresponding author. Email: shamylto@uow.edu.au

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Tanzania and Mozambique and around the islands of Seychelles, Comoros, Madagascar and Mayotte (Marsh *et al*. 2002, Muir *et al*. 2004). Dugongs appear to be rapidly declining in the waters of east Africa due to increases in the human population and associated coastal development causing environmental degradation and significant loss of seagrass. It has been suggested that they are likely to become extinct in this region (Dutton 1998). Until recently, it was thought that dugongs in the Seychelles had gone extinct, but since 2001 a collection of sightings at Aldabra Atoll, the most southern of the Seychelles islands, has renewed conservation interest in their status in these waters (Muir *et al*. 2004).

1.1. Spatial analysis of dugong populations and their associated habitats

Remote-sensing capability for shallow water habitat mapping has been well established since the launch of the first Earth observation satellites that host water-penetrating sensors operating in the visible section of the electromagnetic spectrum (Mumby *et al*. 2004). By sampling multiple wavelengths and adjusting for the confounding influence of the atmosphere, water surface and water column on remote-sensing data (Green *et al*. 2000), links can be drawn between *in situ* observations of ground cover and remote-sensing data that allow shallow marine habitat types to be classified at the landscape scale. Such habitat maps provide exciting opportunities for spatial analysis of tropical shallow water communities.

Cluster detection enables geographical patterning in a series of point records to be evaluated. Detecting spatial clusters of dugong sightings enables the focus to be placed on locations where particular attributes might determine the underlying processes governing dugong distribution, for example, the presence of feeding sites. The statistical significance of pattern descriptors can be tested, along with hypotheses that are used to generate insight into causal factors underlying observed geographical distributions. Techniques of point pattern analysis for the exploration of spatial clusters have largely advanced through the geographical study of disease events (Openshaw *et al*. 1988, Haining and Cliff 2003), crime (Ratcliffe 1999, Turton and Openshaw 2001) and vegetation ecology (Ripley 1987, Andersson 1988).

Spatially explicit population models that interpolate aerial point data sets of dugong sightings provide a synoptic measure of population density that enables the prioritisation of conservation management across large, complex areas such as the Great Barrier Reef World Heritage Area (Grech and Marsh 2007). Evaluating habitat at the landscape scale allows the biomass of seagrass meadows to be estimated, along with the associated dugong carrying capacity (Sheppard *et al*. 2007). Habitat suitability models provide an alternative approach for predicting the spatial distribution of a given species by linking sighting records to available information on its resource utilisation (e.g. a habitat map) (Hirzel *et al*. 2001).

The aims of the study were (1) to present a habitat map of the benthic character of Aldabra lagoon and (2) to investigate patterns of dugong distribution at the sub-lagoon scale by conducting a spatial cluster analysis and developing a habitat suitability model. In achieving these aims, evidence of the continued presence of dugong populations inside the Aldabra lagoon was consolidated and their distribution was empirically investigated using spatial statistical techniques that drew on the location of sighting records to link dugongs to their surrounding habitat.

1.2. Study location: Aldabra Atoll

Aldabra, in the southern Seychelles, western Indian Ocean (9°24′S; 46°20′E), is one of the world's largest raised coral atolls (land area = 115 km^2; 34 km long by 14.5 km wide).

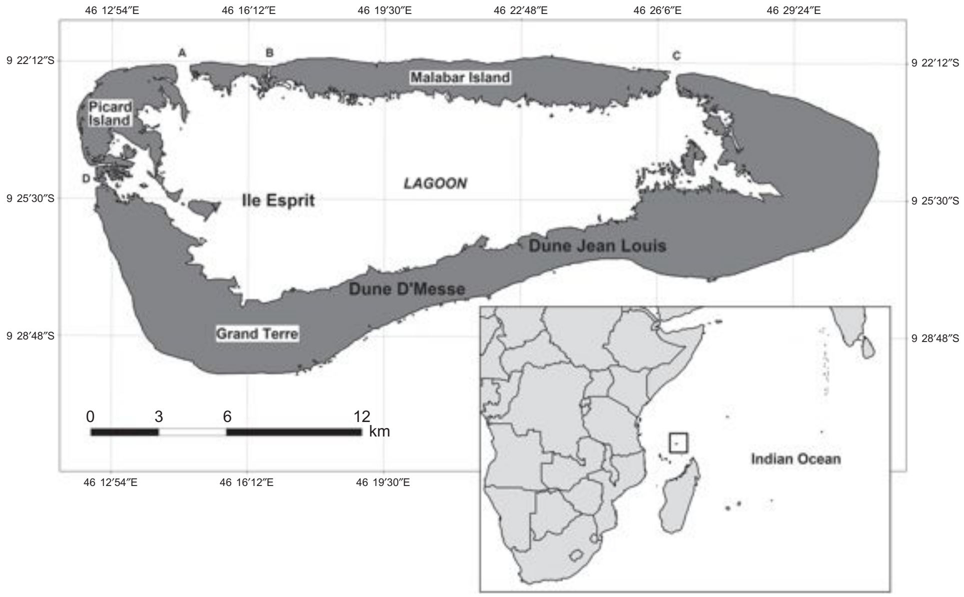


Figure 1. Aldabra Atoll, World Heritage Site. Inset: The location of Aldabra Atoll in the western Indian Ocean. A = Grande Passe, B = Passe Gionnet, C = Passe Houareau and D = West Channels.

Located over 1000 km south-west of Mahé, the principal granitic island of the Seychelles, and several hundred kilometres from east Africa, Madagascar and Comoros, Aldabra is extremely isolated (Figure 1) and is internationally renowned for its wealth of biodiversity and relatively undisturbed ecological state (Stoddart 1968).

The Royal Society established a research station on the north-western island of Picard at Aldabra in 1971, enabling extensive research to be conducted into both the terrestrial and marine ecology of the atoll. Since 1979, the atoll has been managed and protected by the Seychelles Islands Foundation (SIF) and in 1982 Aldabra was designated a UNESCO World Heritage Site, as a unique example of a raised coral atoll, being significantly less disturbed than most other atolls in the Indian Ocean and elsewhere. Its geographical isolation, rough terrain and limited freshwater supply have, in part, aided the preservation of Aldabra's flora and fauna (Hermans and Pistorius 2008). Anthropogenic impacts at Aldabra are minimal, with only a small number of residents (typically around 10 people at one time) living on Picard Island. Marine life in the waters surrounding Aldabra has therefore been relatively undisturbed by humans.

2. Methods

2.1. Consolidation of dugong sighting records

Dugong sightings at Aldabra have been largely opportunistic, typically occurring when site rangers have been moving around the atoll by boat during routine monitoring activities. Some dedicated searches have been conducted around and above the Aldabra lagoon by boat and flying inflatable boat (FIB) (Hermans and Pistorius 2008). Since the establishment of the research station, all dugong sightings have been recorded on event record cards and filed in the station's library. The event card system records the date, location and staff involved for each sighting, in addition to any other relevant information. More recently, event card data have been digitised into a database. Sightings that included Geographical Positioning System (GPS) positions, along with previous records with map grid references, have been plotted onto a topographic map of the atoll and maintained at the research station. To present a consolidated record of all dugong sightings at Aldabra since 1970 (see Appendix 1), extensive searches of the event card system and any other published references or reports containing details of dugong sightings at Aldabra were conducted and all spatially referenced sightings were entered into a Geographical Information System (GIS) database.

2.2. Development of a lagoon habitat map from remotely sensed data

2.2.1. Ground-referencing of lagoon floor habitats

An intensive lagoon mapping project was undertaken at Aldabra Atoll by Cambridge Coastal Research Unit (CCRU) in conjunction with SIF during a 5-week period in January–February 2009. High-resolution benthic habitat mapping was undertaken using three QuickBird satellite images in conjunction with an intensive ground-based survey to produce the first ever high-resolution map (2.4 m spatial resolution) of the 226 km^2 Aldabra lagoon.

To ground-reference the satellite imagery, benthic characteristics of the lagoon floor were recorded from a boat for a total of 487 datapoints distributed widely across the lagoon area. Data records were composed of underwater video footage (278 points) and photographs (209 points) of the lagoon floor and above-water photographs of the lagoon.

Benthic cover type was determined from a snapshot (typically around 30 sec) of oblique underwater video footage taken from video camera tethered to a laptop computer on board a boat. At each video referencing point, the video camera was lowered over the side of the boat into the water and held so that it drifted approximately 10 cm above the lagoon floor. Depth was measured using a HawkEye (Norcross Marine Products Inc., Orlando, Florida) bathymetric sonar sounder and the geographical position of each footage sample was recorded using a differential GPS (horizontal accuracy ±2 m). The rapid video camera deployment permitted efficient ground-referencing over an extensive area of the lagoon in a relatively short time period.

The underwater video footage datapoints were individually examined and the relative proportional cover, totalling 100%, of one or more of the following 21 benthic classes was visually estimated: bare carbonate sand; bedrock; coral rubble; coral rubble with turf; sponges; live coral; dead coral; coralline algae; *Thalassodendron ciliatum*; *Thalassia hemprichii*; *Halodule* sp.; *Halophila ovalis*; *Enteromorpha* sp.; green algal turf; *Hypnea esperi*; *Caulerpa* spp.; *Halimeda* spp.; *Hydroclathrus clathrus*; algal mat; red fleshy algae; and *Sargassum binderi*. These assemblages were selected because they were distinctive and easily identifiable in the field. Percentage cover was chosen in order to standardise between differing areas covered during the period of video camera operation due to variations in boat speed and water current (approximate range of areas covered was 2–6 m^2).

The data set generated from analysis of the video footage was subsequently used to develop a classification scheme for the lagoon habitat map. By calculating pairwise Bray–Curtis similarity for all records, a multivariate analysis was conducted on the coverage statistics derived from the video footage (Bray and Curtis 1957). This formed the basis of a (non-spatial) hierarchical cluster analysis which identified natural groupings in the samples. This approach was selected as it has been found to be appropriate for delineating groups of sites that display distinct community structure (Clarke and Warwick 2001).

2.2.2. *Image processing of remotely sensed data*

Three QuickBird images acquired between February 2004 and March 2006 provided synoptic coverage of the Aldabra lagoon. Each of these images comprised four wavebands: one in each of the red, green and blue sections of the visible electromagnetic spectrum (2.4 m spatial resolution) and one panchromatic band, spanning the red and near-infrared wavelengths (0.6 m resolution). Preprocessing procedures including atmospheric correction, image masking and water-column correction were applied to the three satellite images to yield radiance data across the lagoon that could be used as input data for a classification algorithm.

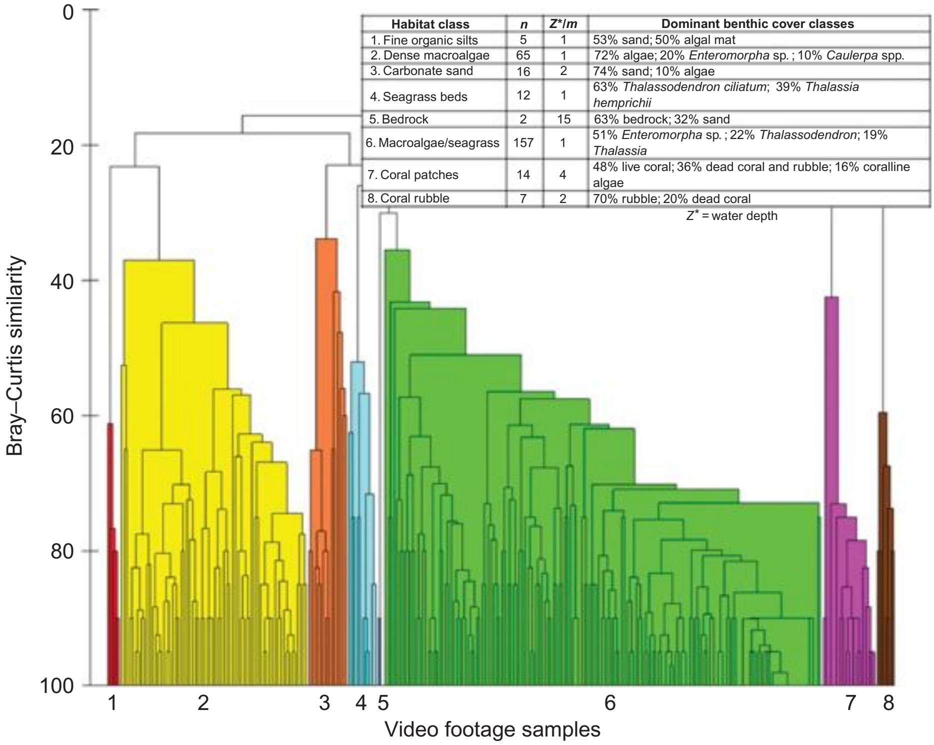
For the atmospheric correction, the empirical line method was applied, which has been shown to be effective in tropical marine settings (Karpouzli and Malthus 2003). Two field spectra of dark (deep water) and light (shallow sand) targets were collected *in situ* using a GER1500 (Spectra Vista Corporation, New York) spectroradiometer (300–1100 nm). These were then plotted against image pixel values at corresponding wavelengths to generate correction factors for converting image data to surface radiance. Land and deep water were masked by extracting the panchromatic band (which does not provide a return signal above water or cloud) and recoding areas with no signal to 1 and the remaining areas (i.e. those above land and/or cloud) to 0. This was then multiplied by the image to yield imagery of subsurface features. The method devised by Lyzenga (1981) was used for band-wise correction of the effects of absorption and scattering in the water column. This technique assumed that the vertical radiative transfer through the water column could be approximated to a logarithmic decrease in radiation with increasing depth and generated depth-invariant indices composed of band ratio pairs. An unsupervised classification was performed using a maximum likelihood parametric rule on the depth-invariant bands of each of the three satellite images of the Aldabra lagoon. The classified output was a single thematic layer composed of 30 classes, which were subsequently interpreted with respect to the ground-referencing data set from the video footage records. Zones of similar benthic habitat type with respect to the scheme outlined in Figure 2 were delineated.

The output habitat map was validated using an independent set of 209 underwater photographs that covered a range of benthic habitat types within the lagoon. Validation was undertaken by overlaying each photograph onto the habitat map and recording the class identified on the map. As a separate exercise, all photographs were independently viewed and assigned a class with respect to the eight classes of the classification scheme (Figure 2). The classes assigned to the map and the photographs were compared and the overall accuracy was defined as the proportion of samples that were assigned the same class as the map layer (Congleton 1991).

2.3. *Spatial analysis: cluster detection of dugong sightings*

Cluster detection was conducted to explore spatial groupings in the lagoon where the number of dugong sightings exceeded that which would be expected on the basis of randomness alone. Two sets of ground reference point records were combined for the analysis: one of positive dugong sightings and a second control set of 648 points visited over a period of 6 years where dugongs were not sighted during ongoing monitoring activities carried out in the lagoon by research station staff.

A Kulldorff scan test was employed to detect clusters by determining whether or not areas of higher incidences of dugong sightings were statistically significant. Kulldorff's scan test was selected for this particular analysis of dugong sighting records because it overcomes the problems of selection bias, multiple testing in which there is a non-zero



Habitat class	*n*	*Z*/m*	Dominant benthic cover classes
1. Fine organic silts	5	1	53% sand; 50% algal mat
2. Dense macroalgae	65	1	72% algae; 20% *Enteromorpha* sp. ; 10% *Caulerpa* spp.
3. Carbonate sand	16	2	74% sand; 10% algae
4. Seagrass beds	12	1	63% *Thalassodendron ciliatum*; 39% *Thalassia hemprichii*
5. Bedrock	2	15	63% bedrock; 32% sand
6. Macroalgae/seagrass	157	1	51% *Enteromorpha* sp. ; 22% *Thalassodendron*; 19% *Thalassia*
7. Coral patches	14	4	48% live coral; 36% dead coral and rubble; 16% coralline algae
8. Coral rubble	7	2	70% rubble; 20% dead coral

Z^* = water depth

Figure 2. Habitat classification scheme developed for the Aldabra lagoon; coverage statistics have been averaged for all video footage samples within each group.

probability that an observed count will occur within the significance level due to chance (Haining 2003) and the modifiable areal unit problem (Openshaw 1984). A regular grid of points spaced 100 m apart was overlain onto the lagoon and a test window was placed iteratively with its centre over each point to cover the entire map. The probability of being a ‘case’ (i.e. a positive dugong sighting) was computed for points with their centroids inside the test window and the likelihood function was expressed as the product of the individual Bernoulli probabilities within that window (Kulldorff 1997). A likelihood ratio statistic (Equation (1)) was calculated as the maximum function under the null hypothesis (that there is an equal probability of a positive dugong sighting at every location in the lagoon and therefore no significant spatial cluster of sightings) divided by its maximum value under the null hypothesis. For each location window, the alternative hypothesis was that there would be an elevated chance of a dugong being observed within the window as compared to outside. Under the Bernoulli assumption, the likelihood function for a specific window is proportional to the following function (Equation (1)):

$$\left(\frac{c}{n}\right)^{c}\left(\frac{n-c}{n}\right)^{n-c}\left(\frac{C-c}{N-n}\right)^{C-c}\left(\frac{(N-n)(C-c)}{N-n}\right)^{(N-n)-(C-c)} I(\;) \tag{1}$$

where C is the total number of cases, c the observed number of cases within the window, n the total number of cases and controls within the window and N the combined total number of cases and controls in the data set. $I(\ )$ is equal to 1 when the window has more cases than expected under the null hypothesis, and 0 otherwise.

Conventionally, the most likely cluster is the zone that maximises the likelihood ratio statistic (Kulldorff and Nagarwalla 1995). The distribution of the likelihood function depends on the underlying population distribution, which cannot be determined. A Monte Carlo simulation was therefore used to test the significance against a null distribution. This simulation consisted of 999 replicates, each of which involved identifying 31 cases at random from the population of 512 cases. For each replicate, the value of the Bernoulli likelihood function was calculated. Simulated likelihood functions were then ordered and ranked, with the highest value being assigned 1. A significant result would therefore be obtained at the 5% probability level if the observed value for the data fell among the highest 50 of these values.

2.4. Dugong lagoon habitat suitability model

A multivariate habitat suitability model that combined the point data set of dugong sightings and the benthic habitat map was used to create a potential dugong distribution map across the 226 km^2 lagoon area. Habitat data (composed of the area occupied by the 8 habitat types as depicted by the map) were exported from the neighbourhood of the 31 point locations where dugongs were sighted between 1970 and 2009.

To calibrate the habitat suitability model, an average neighbourhood habitat was calculated across the 31 records of dugong sightings to yield a global weighting factor (w_i) for each of the habitat coverages in relation to the dugong observation records. Habitat suitability was then modelled across the lagoon using a niche coefficient ($H \in [0, 1]$, Equation (2)), which can be viewed as the probability of each model point belonging to the niche (a *de facto* habitat suitability index) (Hirzel *et al*. 2001):

$$H = \frac{1}{\sum w_i} \sum w_i H_i \tag{2}$$

where H is the habitat suitability at the point location modelled, H_i the area of the ith benthic habitat cover inside the neighbourhood of the model point and w_i the weight assigned to the benthic habitat cover. This value was calculated for a set of point locations across the Aldabra lagoon as a representation of the spatial variability of the preference for dugong habitat.

3. Results

3.1. Dugong sightings 1970–2009

A total of 31 separate dugong sighting locations (total number of dugongs observed = 39) were recorded at Aldabra between February 1970 and December 2009 in group sizes ranging between 1 and 4 individuals with the majority of sightings (88%) involving just 1 individual (mean group size 1.2) (Appendix 1). The first observation of a dugong at Aldabra was made by IR Swingland in February 1970; a pair was observed feeding on *T. ciliatum* seagrass on the reef flat off the north coast of Picard Island. Sightings between 2001 and 2009 averaged 3.11 individuals per year. The highest numbers of sightings were in 2003 ($n = 7$) and 2005 ($n = 6$), but between these peaks, zero sightings were recorded in 2004 despite ongoing research activities in the lagoon. Some individuals in 2003 were recorded as 'sub-adults', while one in 2005 was recorded as a 'juvenile'.

3.2. Benthic habitats of the Aldabra Lagoon

The hierarchical cluster analysis of ground-referencing points over the lagoon floor revealed eight groupings at the 40% level of Bray–Curtis similarity, and these were subsequently used to interpret the classes produced by the image classification. A habitat scheme was developed on the basis of these clusters, which became the key for the habitat map (Figure 2).

The lagoon map generated by the January–February 2009 expedition is the first ever high-resolution benthic habitat map created for the Aldabra lagoon. The dominant benthic cover of the lagoon floor was algae of varying density: the ‘dense macroalgal mat on sand’ and ‘sparse macroalgal and seagrass assemblage on sand’ classes covered 68% of the overall lagoon area (comprising 33% and 35%, respectively). These formed extensive patches across the centre of the lagoon. The next most dominant cover was bare carbonate sand, which accounted for 17% of the overall area mapped. This took the form of an expansive linear sand tongue extending across the lagoon centre at the end of the Grande Passe. Fine organic silts comprised 6% of the benthic cover, which formed a concentric band around the outer edge of the lagoon in association with mangroves. Finally, coral patches, coral rubble, seagrass beds and bedrock were all present in comparatively low proportions concentrated in a patchy manner around the major channels of the lagoon, that is, around the West Channels, Grande Passe and Passe Houareau.

The benthic character of the lagoon can broadly be split into the following zones: the extensive central zone of homogenous sand and algal cover and the more varied habitats exhibited in the extreme east and west zones. Variation occurs around Passe Houareau, to a lesser extent in Bras Takamaka in the east and around the Grande Passe and West Channels. Small localised areas of seagrass (including *H. ovalis*, *Halodule* sp., *T. hemprichii* and *T. ciliatum*) can be seen around the four channels that permit fluxes between the lagoon and the surrounding oceanic water ($\sim$5 km^2 in total) (Figure 3). Comparison of the interpreted output classification with the field validation points revealed the overall accuracy of the map to be 85%.

3.3. Spatial analysis: cluster detection of dugong sightings

The Kulldorff’s scan test detected one primary cluster of 14 cases with a log likelihood ratio of 24.18 (P value $= 0.001$; Table 1). This was located near Bras Monsieur Clairemont and is depicted as a circle of radius 2 km (defined by the test statistic) in Figure 3.

3.4. Dugong lagoon habitat suitability model

The most common habitat types found in the vicinity of dugong observations were dense and sparse macroalgal assemblages on sand. This is largely because of the dominance of these benthic cover types inside the lagoon. Accounting for the relative proportions of cover across the entire lagoon benthic habitat map, both seagrass beds and fine silts with sand were present in a comparatively large area of dugong observation neighbourhoods (with average coverages of 2.09 and 1.14 km^2, respectively). These associations are likely underpinned by the fact that the former is an important food source for dugongs inside the Aldabra lagoon and the latter is found in close association with mangroves, which provide structural complexity that dugongs utilise as sheltered habitat.

Values for the habitat suitability index, H, ranged from 0.08 to 0.88 with the higher values appearing towards the centre of the lagoon on the western side (Figure 4).

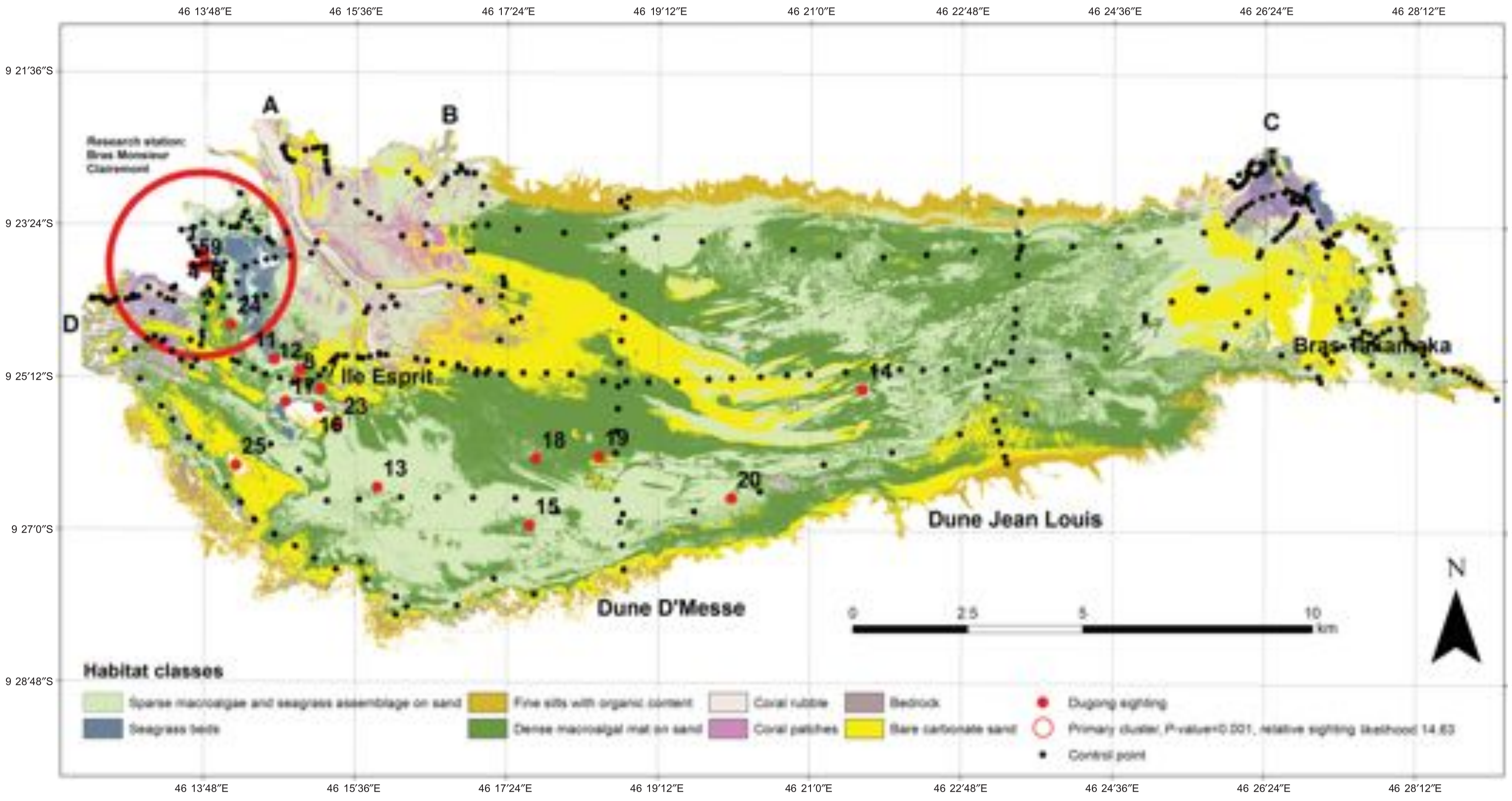


Figure 3. Habitat map of Aldabra lagoon with locations of all dugong sightings and site of primary cluster of dugong sightings 2001–2009 using Kulldorff's scan test. A = Grande Passe, B = Passe Gionnet, C = Passe Houareau and D = West Channels.

Table 1. Details of the most likely cluster detected.

Number of cases	10
Population	14
Number of expected cases	0.68
Case membership	6, 3, 2, 9, 4, 22, 21, 5, 10, 1 (plus 4 control points)
Coordinates/radius	(9.397930°S, 46.229230°E)/2 km
Observed/expected	14.63
Log likelihood ratio	24.18
Monte Carlo rank	1/1000
P-value	0.001

Note: See Figure 3 for geographical location of the cluster.

4. Discussion

Although few dedicated searches for dugongs have been undertaken at Aldabra, routine monitoring activities have ensured regular boat movements across the atoll lagoon since the establishment of the research station in 1971. Despite marine research activities becoming more extensive since 2001, with three operational research vessels regularly crossing the lagoon to satellite research camps in the east, overall numbers of observations remain low. This is typical of the wider western Indian Ocean region (Hermans and Pistorius 2008). There have been no reports of dugongs off Mauritius in recent years and very few remaining individuals along the coasts of Somalia, Kenya, Tanzania and Mayotte (Comoros Archipelago). There is evidence that the catch of dugong for meat has progressed to a directed fishery in the Maputo and Bazaruto Bay areas of Mozambique (Guissamulo and Cockcroft 1997, Cockcroft and Young 1998), but this is not common in the region. Due to the minimal anthropogenic disturbance at Aldabra and its high level of environmental protection, the atoll provides desirable habitat to support undisturbed dugong population growth. Optimal dugong habitat is characterised by saline water 3–15 m deep, shelter from rough winds and heavy waves, an abundant food source and water temperatures of 21–38°C (Sheppard *et al*. 2007). The shallow platform within Aldabra lagoon supports seagrass beds surrounded by an exposed limestone rim that affords shelter from incident waves and represents an island of habitat that largely meets dugong requirements surrounded by deep water across the wider western Indian Ocean region.

Satellite Platform Terminal Transmitter (PTT) and GPS transmitter studies have shown that dugongs travel as far as 560 km, with statistically discernable patterns of movement relating to ranging, dispersal and local movements between seagrass beds (Sheppard *et al*. 2006). Dugongs occur in small numbers at nearby sites such as Mayotte (380 km away), Comoros (390 km), Madagascar (430 km) and east Africa (630 km) (Muir *et al*. 2004). It is therefore possible that the dugongs observed at Aldabra are semi-resident with seasonal movements dictated by changing monsoons, rough weather or variable food sources (Husar 1978). Aldabra falls within the influence of the South Equatorial Current which flows during the northern hemisphere summer (July/August) from the central Indian Ocean in a westerly direction past northern Madagascar to Aldabra and continues west to Africa where it meets the northward-flowing East African Coastal Current (Schott and McCreary 2001). Based on prevailing current directions and the relative ease with which passage could be made given the surface ocean currents during the south-east monsoon (May–August), it is

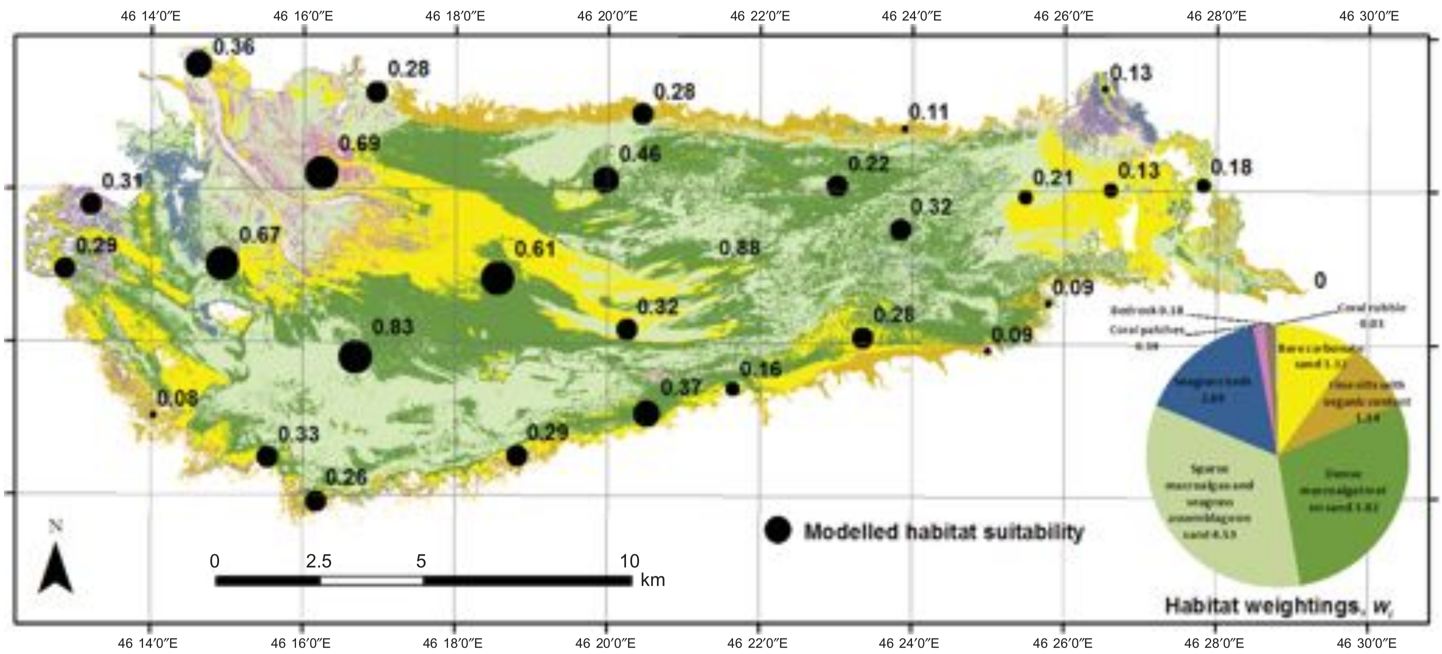


Figure 4. Habitat map of Aldabra lagoon with model point locations of dugong habitat suitability. Inset pie chart showing the areas of habitat in the neighbourhood of dugong sighting records used as a habitat weighting, w_i, for calculating the suitability index.

likely that the source of the Aldabra dugong population is northern Madagascar (Hermans and Pistorius 2008) as opposed to Mozambique or the east African coast. The temporal distribution of sightings supports such a suggestion as there seemed to be a pattern across the 9-year period for which records are available in which elevated dugong sightings occurred between July and October (with an average of 5 sighting events occurring in these months in comparison to 2 for the other months).

The statistically significant cluster of dugong sightings in the west of the lagoon near Picard Island (Figure 3) can be attributed to two factors. First, proximity of the Grande Passe and West Channels allows for regular water exchange with the surrounding ocean creating a diverse array of benthic habitats, including dense seagrass beds and coral patches, which are not observed in the central areas of the lagoon. Seagrass within the lagoon is largely restricted to the vicinity of the channels, where lagoon flushing and water residence times play an important role in controlling seagrass abundance through nutrient recycling and removal of metabolic waste from the system. The upper limit of the meadows is controlled by wave energy, with high-energy environments displaying deeper limits compared to their sheltered counterparts (Hemminga and Duarte 2001). On the western side of the Grande Passe is the largest seagrass meadow in the lagoon (4.2 km^2), which provides an extensive feeding ground for dugongs at Aldabra. It is in this area (near the expansive mangrove system of Bras Monsieur Clairemont which provides relative seclusion from the wider atoll environment) that most of the dugongs have been sighted since 2001 (Figure 3). Second, it should be noted that this area is easily accessible from the research station and a substantial amount of boat travel is undertaken here by researchers. Regular terrestrial monitoring is undertaken by the SIF rangers around the atoll, and dugong sightings appear to coincide with routes taken by boats across the lagoon when travelling to terrestrial camp sites. Nonetheless, the area of elevated observations was found to be significant when compared with a control set of lagoon points (648 points over a period of 6 years). Added to this, the spatial distribution of the habitat suitability index was in broad agreement with the location of the cluster sighting records insofar as both analyses indicated elevated dugong numbers at the western extremity of the lagoon. The habitat suitability model goes some way towards alleviating this sampling bias by applying information on what is known about dugong habitat preferences across the whole lagoon area. Agreement of both the cluster analysis and the habitat suitability model provides compelling evidence for focusing future dugong research effort in this geographical area.

Dugong sightings at Aldabra (1970–2009) can largely be characterised as opportunistic observations made during routine boat movements across the extensive lagoon. This raises the possibility that larger numbers of dugongs are present but remain unobserved. A dedicated aerial survey campaign conducted over substantial temporal and spatial scales would help to identify distribution patterns over the whole lagoon. This would also assist with the extension of future surveys across the reef flats and on the outer fore-reef slope to observe dugong movements and map the benthic habitat across the entire atoll.

Populations of dugongs in the western Indian Ocean appear to be extremely small and fragmented (Marsh *et al*. 2002). This highlights the need for collaborative initiatives across east Africa/western Indian Ocean to investigate long-range movements and the viability of the species in the region. The sighting records presented in this article provide compelling evidence of the continued presence of dugongs at Aldabra. Locally, this presence appears to be linked to the distribution of seagrass inside the lagoon. Collectively, these findings highlight the value of Aldabra Atoll as a unique and important site for dugongs in the western Indian Ocean, adding to the need for its comprehensive protection.

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Appendix 1. Dugong sightings in Aldabra lagoon, 2001–2009

# on Figure 3	Date	Site of observation	# of individuals	Comments
1	02/08/01	Bras Monsieur Clairemont	1	Observed in shallow water, near mangroves; individual 2.5– 3 m in length
2	03/08/01	Bras Monsieur Clairemont	1	Observed near mangroves; individual 1 m in length
3	01/10/01	Bras Monsieur Clairemont	2	2 adults observed in shallow water, near mangroves; individuals 2 m in length
4	12/10/01	Bras Monsieur Clairemont	1	Observed in shallow water, near mangroves; individual 2.5–3 m in length
5	11/11/01	Bras Monsieur Clairemont	1	None
	March 2002	Bras Monsieur Clairemont	2	Seen from FIB, swimming near mangroves in shallow water; during falling spring tide
	April 2002	Bras Monsieur Clairemont	1	Adult with distinctive white spot on dorsum
6	20/05/03	Bras Monsieur Clairemont	1	Adult
	October 2003	Unrecorded	1	Adult sighted from FIB. Location unrecorded
7	24/10/03	North of Ile Esprit	1	Sub-adult
8	25/10/03	North of Ile Esprit	1	Sub-adult

(*Continued*)

Appendix 1. (Continued)

# on Figure 3	Date	Site of observation	# of individuals	Comments
9	25/10/03	Bras Monsieur Clairemont	1	Adult
10	14/12/03	Bras Monsieur Clairemont	1	Sub-adult
11	16/12/03	North of Ile Esprit	1	Adult
12	16/04/05	North of Ile Esprit	1	Adult sighted from FIB, 2.3 m long
13	11/05/05	Dune D'Messe/Ile Esprit	1	Adult between Dune D'Messe and Ile Esprit. Tide ~2.8 m
14	23/07/05	Lagoon centre	4	1 adult, 2 sub-adults, 1 juvenile
15	27/07/05	Dune D'Messe	1	Medium-sized adult moving in the direction of Ile Esprit feeding on seagrass (high tide)
16	27/07/05	North of Ile Esprit	1	Adult
17	25/08/05	200 m north of Ile Esprit	1	Adult, very evasive. Water murky, about 2 m deep
18	15/06/06	Dune D'Messe area	1	Individual sighted at surface moving east between research station and Dune D'Messe
19	28/07/06	Dune D'Messe area	1	One adult appeared to be feeding on seagrass bed and surfaced for air
20	10/01/07	Close to Dune D'Messe	1	One individual surfaced very briefly in murky water
21	04/02/07	Bras Monsieur Clairemont	1	One large individual observed very briefly
22	02/08/08	Bras Monsieur Clairemont	1	One individual sighted in vicinity of Bras Monsieur Clairemont
23	30/01/09	Near Ile Esprit	1	One adult observed swimming north-west close to Ile Esprit
24	15/02/09	Ile Esprit/research station	2	First individual approx. 2 m in length. Second approx. 1.5 m in length
25	10/06/09	Close to Ile Moustique	1	Adult

Note: First column refers to labels on lagoon map, Figure 3, if coordinates known.