Spatial prioritization of dugong habitats in India can contribute towards achieving the 30 x 30 global biodiversity target

Sohom Seal
Wildlife Institute of India
Sharad Bayyana
Wildlife Institute of India
Anant Pande
Wildlife Institute of India
Chinmaya Ghanekar
Wildlife Institute of India
Prachi Sachchidanand Hatkar
Wildlife Institute of India
Sameeha Pathan
Wildlife Institute of India
Shivani Patel
Wildlife Institute of India
Sagar Rajpurkar
Wildlife Institute of India
Sumit Prajapati
Wildlife Institute of India
Swapnali Gole
Wildlife Institute of India
Sweta Iyer
Wildlife Institute of India
Aditi Nair
Wildlife Institute of India
Nehru Prabakaran
Wildlife Institute of India
Kuppusamy Sivakumar
Wildlife Institute of India
Jeyaraj Antony Johnson (jaj@wii.gov.in)
Wildlife Institute of India

Article

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Abstract

Indian coastal waters are critical for dugong populations, the largest in south Asia, in the western Indian Ocean. Spatial planning of these waters can help to achieve biodiversity conservation and area-based protection targets in the region. In this study, we employed environmental niche modelling to predict suitable dugong habitats and identify influencing factors along its entire distribution range in Indian waters. We examined data on fishing pressures collected through systematic interview surveys, citizen-science data, and field surveys to demarcate dugong habitats with varying risk. Seagrass presence was the major contributing factor in determining dugong habitat suitability across the study sites, though variables like depth, bathymetric slope, Euclidean distance from the shore were significant factors, particularly in the context of seasonal suitability. Predicted suitable habitats showed a remarkable shift from pre-monsoon in Palk Bay to post-monsoon in the Gulf of Mannar indicating seasonal movement. The entire coastline along the Palk Bay- Gulf of Mannar (PB-GoM) region were observed to be high to moderate risk, including the Gulf of Mannar Marine National Park as one of the high-risk areas. The Andaman Islands exhibited high suitability during pre and post monsoon, whereas the Nicobar Islands were highly suitable in the monsoon. Risk assessment of modelled suitable areas revealed that < 15% of high-risk areas across Andaman and Nicobar Islands (ANI) and Palk Bay and Gulf of Mannar, Tamil Nadu falls within the existing protected areas. At Gulf of Kutch (GoK), Gujarat few offshore reef islands are identified under high-risk zone. The study highlighted the utility of citizen science and secondary data, in performing large-scale spatial ecological analysis. The study identifies synoptic-scale 'Critical Dugong Habitats' with implications in achieving global 30x30 target through systematic conservation planning.

1. Introduction

Marine mammals are known to benefit from effective area-based conservation measures such as Marine Protected Areas [1]. Given the migratory nature of these species, delineating MPAs through effective spatial planning in an ecosystem context is strongly advised [2]. In south Asia, globally vulnerable but regionally endangered populations of dugongs occur in disjunct pockets [3] declining rapidly from most of their range [4][5]. Reasons for their decline are attributed to degradation of seagrass habitats, loss of reproductive potential and increasing anthropic pressures across their distribution [6][7][8]. With large populations thriving only at the extreme ends of their geographical distribution (Australia and the Red Sea), Indian populations are the only hope for the species' persistence in the western Indian ocean [9].

Understanding species distribution is crucial to identify critical habitats and formulate effective conservation strategies for long-term preservation [10]. Dugong distribution and occupancy is dependent upon various biological (such as seagrass availability - [11];[6]), environmental (sea surface temperature - [12]; turbidity, sea state - [13]) and topographic (depth - [14] parameters. In India, dugong occupancy has declined substantially from Indian territorial waters (over 85% in some parts;[15]). In some isolated regions such as tropical oceanic islands of Andaman & Nicobar Islands, 60% reduction in occupancy was observed in the last few decades [16]. With increasing human footprint in the ocean, rise in activities such as vessel traffic and overfishing in seagrass habitats [17] are presumed to have deleterious impacts on dugong distribution. Currently, the extent of these impacts on dugongs in India is poorly known but is apparently deduced through high incidences of strandings [18][19].

Researchers often rely upon presence-only data when systematic occurrence data on certain species is unavailable (i.e., when species absence is not verified). These uncertainties in species occurrence data stem from opportunistic and sometimes unstructured sampling [20]. Recent advances in species distribution modelling (SDM) or ecological niche modelling (ENM) methods such as MaxEnt [21], are significant due to their utility in the analysis of presence-only data through user-friendly algorithms [22]. These methods reduce effort and cost for large spatial scale species monitoring programmes [23][24]. In the past few years, SDM is increasingly favoured by numerous research groups engaged in wildlife monitoring [24]. This approach has also been influential in developing conservation strategies for marine mammals [25][26] [27].

In the case of dugongs, for seascape-level planning and optimal usage of management resources, identifying critical habitats is enormously significant [15][28]. In the present study, we utilised a comprehensive dataset generated through multiple approaches (semi-structured questionnaire, citizen science, volunteer networks, primary field surveys) to identify suitable habitats for dugong populations in Indian coastal waters. We classify distribution hotspots and high-risk areas for dugongs to support their conservation management with site-specific interventions. In the wake of adoption of the Kunming-Montreal Biodiversity Framework, and to achieve National Biodiversity Targets [29], this assessment was undertaken to spatially delineate potential areas to add to the country's Marine Protected Area cover. We highlight the conservation importance of these high-risk areas as critical dugong habitats to help save the remnant populations from further decline.

2. Results

2.1. Seagrass distribution

Seagrass distribution was predicted along the entire Andaman Islands group with specific patches around central Nicobar (Camorta and Trinket) and Great Nicobar with AUC ± SD = 0.924 ± 0.002 indicating the accuracy of the model (Fig. 1).

The bathymetric depth and wave height had maximum contribution (84.3%) toward seagrass prediction in this region (Table 1).

Table 1
List of variables finalised for modelling seagrass and dugong distribution in pre-monsoon (PreM), monsoon (M) and post-monsoon (PostM) for Andaman and Nicobar Islands, Palk Bay & Gulf of Mannar of Tamil Nadu, and Gulf of Kutch of Gujarat along with their contribution percentages. ['-' not used; Sources: * Global Marine Environmental Datasets (GMED) [30]; # NASA Ocean Colour; $ Modelled data (MaxEnt)]

Layers	Resolution	Seagrass			Dugong						
		ANI	PB-GoM	GoK	ANI			PB-GoM			GoK
					PreM	M	PostM	PreM	M	PostM	
Depth (m) *	30 arc sec	71.8	8.9	0.6	13.2	20.6	17.5	7.5	1.5	4.5	5.3
Slope (°) *	5 arc min (~ 9.2 km)	0.9	0	2.3	2.1	1.6	3.2	52.2	3	4.7	0
Distance from the shore (km) *	5 arc min (~ 9.2 km)	1.7	1.5	73.4	6.6	8.1	4.2	1.4	9.1	2.4	0.1
Salinity (PSS) *	1°	0.9	0	0.7	-	-	-	-	-	-	-
Diffuse Attenuation Coefficient (Kd) *	5 arc min (~ 9.2 km)	0	2.4	2.6	-	-	-	-	-	-	-
Sea Surface Temperature (°C) *	5 arc min (~ 9.2 km)	0.5	26.2	1.7	-	-	-	-	-	-	-
pH*	1°	0.2	0	0	-	-	-	-	-	-	-
Photosynthetically Active Radiation (PAR) (Einstein/m2/day) *	5 arc min (~ 9.2 km)	0.6	7.8	0	-	-	-	-	-	-	-
Sea Surface Wave Height (m) *	5°	12.5	0	0	-	-	-	-	-	-	-
Surface current (m/s) *	0.25°	1.1	0.5	3.5	-	-	-	-	-	-	-
Phosphate (ml/l) *	1°	2.9	40.8	1.1	-	-	-	-	-	-	-
Nitrate (μmol/l) *	1°	0	0	1.1	-	-	-	-	-	-	-
Monthly Diffuse Attenuation Coefficient (Kd) #	4km (monthly climatology)	-	-	-	0.7	3.4	0.1	5.4	5.6	4.8	0.1
Monthly Sea Surface Temperature (°C) #	4km (monthly climatology)	-	-	-	0.3	0.8	0	0.5	19.1	2.5	0.6
Monthly Sea Surface Temperature-max (°C) #	4km (monthly climatology)	1.7	0.1	10.5	-	-	-	-	-	-	0.5
Monthly Sea Surface Temperature-min (°C) #	4km (monthly climatology)	-	-	-	-	-	-	-	-	-	5.7
Chlorophyll-a Conc.#	4km (monthly climatology)	-	-	-	0.1	4	1.1	0.1	4.3	13.9	0.2
Chlorophyll-a Min Conc.#	4km (monthly climatology)	-	-	-	-	-	-	-	-	-	19
Chlorophyll-a Max Conc.#	4km (monthly climatology)	-	-	-	-	-	-	-	-	-	9
Seagrass Presence$	1km	-	-	-	77	61.5	73.7	32.8	57.6	67.2	60

Slope, salinity, photosynthetically active radiation (PAR), pH and sea surface temperature (SST) were the least contributing factors in the ANI region. In the PB-GoM region, availability of phosphate and mean sea surface temperature were key contributing factors (67%). The entire PB- GoM coast was predicted for seagrass presence, with north Palk Bay and the north GoM showing maximum probability (AUC ± SD = 0.850 ± 0.004). Whereas, in the case of GoK, seagrass was strongly predicted in the southern part of the gulf around the islands situated in the region (AUC ± SD = 0.952 ± 0.058) (Fig. 1). Maximum sea surface temperature and distance from the shore showed 83.9% contribution (Table 1).

2.2. Seasonal dugong distribution

Andaman and Nicobar Islands

Ritchie's archipelago, Little Andaman, and the region around Trinket-Camorta islands in central Nicobar were identified as highly suitable regions for all the seasons. Aerial Bay, Diglipur, Mayabunder in the north, Interview Island in the west and Rutland & Chidiya Tapu regions of south Andaman were recorded as moderately suitable regions in the pre- and post-monsoon season (Fig. 2).

During the monsoon season, Great Nicobar Island was observed to be more suitable in comparison to the other two seasons. High suitable areas across Andaman have spread out during the monsoon season, whereas it is restricted to Little Andaman and Ritchie's Archipelago during pre- and post-monsoon seasons. The model performances were noted across seasons for the ANI region with AUC ± SD = 0.987 ± 0.003 (pre-monsoon), AUC ± SD = 0.986 ± 0.005 (monsoon), AUC ± SD = 0.984 ± 0.008 (post-monsoon). The statistical correlation matrix performed amongst the seasons showed high correlation, indicating that habitat suitability was similar (Supplementary Table T1).

Palk Bay and Gulf of Mannar

In the PB-GoM region, there were visible changes in the suitable habitats between the seasons. During the pre-monsoon season, high habitat suitability was observed in the north Palk Bay region, whereas the rest of the region was categorized as low to unsuitable habitats (Fig. 2). This eventually diffused along the entire stretch with the onset of retreating monsoon, predicting moderate to low suitable habitats which further concentrated high suitable regions in the GoM region, post-monsoon. The predictive power of the seasonal MaxEnt models for this region were assessed with AUC ± SD = 0.955 ± 0.011 (pre-monsoon), AUC ± SD = 0.927 ± 0.020 (monsoon), AUC ± SD = 0.835 ± 0.045 (post-monsoon). Though the extent of highly suitable habitats is significantly lower in comparison to moderate and low suitable regions, there is a noticeable trend in the shift of suitable habitats from north to south from pre-monsoon to post-monsoon seasons. This was further supported with I-statistics correlation analysis (Supplementary Table T1) where there is a significant difference between pre-monsoon and post-monsoon site suitability estimates.

Gulf of Kutch

Annual habitat suitability output of the GoK region showed high habitat suitability near Paga, Bhaidar islands and Chushna Pir (Fig. 2). Further moderately suitable habitat region extending from Nor to Beyt Dwarka island. Subtidal regions southwards to Chushna Pir including Ajad Island were identified as low suitable habitats for dugongs throughout the year in this region. The averaged AUC value obtained from MaxEnt models was 0.988 (± 0.004).

Variable contributions

We found seagrass presence as the major factor determining suitable dugong habitats along the study areas. In the ANI region, seagrass contribution was more than 60% for all three seasons. Followed by seagrass, the contribution of depth as a variable for site suitability was approximately 1/5th in all three seasons. Further, distance from shore, slope and diffused attenuation coefficient significantly contributed to suitability prediction in the ANI region (Supplementary Fig. F1). Whereas in PB-GoM, we observed that the seagrass contribution has doubled (32.8 to 67.2) from pre-monsoon to post-monsoon season (Table 1). Slope as a variable had more than 50% contribution in the pre-monsoon season followed by seagrass presence with 32.8%. Sea surface temperature proved significant in the monsoon season, whereas chlorophyll-a contribution was next to seagrass for the post-monsoon season in the PB-GoM region. Depth, distance from the shore and diffuse attenuation coefficient (DAC) had a noticeable impact for all three seasons for the PB-GoM region. In this study site, Chlorophyll-a (minimum) variable showed around 1/5th of variable contribution after seagrass presence. Depth and sea surface temperature (minimum) had a visible contribution with 5.3% and 5.7% respectively. For GoK, with approximately 60% variable contribution of seagrass presence, Chlorophyll-a (minimum) followed with nearly 20% contribution. Lastly both depth and minimum SST contributed little more that 5%.

2.3. Risk assessment

A singular consolidated risk assessment was conducted for all three regions, by averaging the seasonal habitat suitability predictions for all seasons. Highly suitable habitats were also at a higher risk due to anthropogenic influences at all three regions (Fig. 3).

In the ANI region, the risk is high in specific locations along the Andaman group of islands; Ritchie's archipelago, Aerial Bay, and Mayabunder region show high risk, with almost the entire coast susceptible to moderate risk due to human activities, except the west coast in the Middle Andaman region. Risk assessment using boat-based surveys confirmed the high-risk region in Aerial Bay-Diglipur and in Mayabunder region (Fig. 4).

The Rani Jhansi Marine National Park region falls under the high-risk zone in the risk assessment analysis that extends up to middle Andaman to Long Island (Fig. 4). Similarly, the entire coast of Little Andaman is predicted for a moderate amount of risk for the dugong population. In the Nicobar region, a moderate level of threat is available, mainly concentrated around Trinket and Camorta Islands in the Middle Nicobar region and the southern coast of Great Nicobar Island.

Particularly, in the GoM and the north PB region, the extent of high-risk zones is more than 50% of the entire region under prediction. Boat-based risk assessment provided similar observations with a precise prediction for the east and northeast region in North Palk Bay (Fig. 5).

Further, the entire coast in the study area is under moderate to high risk indicating severe anthropogenic pressure on the dugong population present in this region. We observed that the existing Gulf of Mannar Marine National Park entirely falls under high risk for the existing dugong population.

In the GoK study site, the region of high and moderately suitable habitat for dugongs is entirely threatened by a high risk of anthropogenic activities. This was confirmed with a boat-based risk assessment which showed an almost exact prediction for the GoK (Fig. 5). Whereas the low-suitability regions are threatened with a moderate amount of risk in the GoK.

We also estimated the overlap of high-risk regions identified through the study with the existing protected area cover. Only 5.5% (452.42 sq. km out of 478.59 sq. km) of the high-risk region is protected in the ANI. About 13% of the high-risk region is protected in PB -GoM region, where 1754.34 sq km is outside the current protected areas. In Gujarat, the existing Gulf of Kutch Marine National Park and other marine and coastal protected areas cover around 52 percent of the estimated high-risk area in this study (Fig. 3).

3. Discussion

Identifying suitable habitats and mapping risk is crucial to prioritize conservation actions [26]. In this study, we identified intensive-use areas by dugongs in highly restricted areas of their distribution along the Indian coast and pin-pointed high-risk zones to help inform conservation management. Through interview surveys of fisherfolk, we obtained information on a large temporal and spatial scale covering the entire extent of dugong distribution in India. A majority of data used in this study was from opportunistic sightings or secondary sources (fisher interviews, dugong volunteer network), SDM with presence-only data was employed, along with a combination of habitat suitability analysis and risk assessment to highlight areas of high risk for dugongs in its entire distribution range along the Indian coastline.

Seagrass habitats are declining worldwide [31], necessitating country-wide assessments [32] to facilitate conservation action. Availability of healthy seagrass meadows is considered one of the most important determinants of dugong occurrence and habitat-use [33]. Dugongs in turn replenish seagrass meadows through constant grazing, helping nutrient cycling from sediments [6][34]. Through seagrass suitability analysis, we identified suitable seagrass habitats along most of the Andaman Islands (except parts of the northern coast), the whole PB-GoM region and south-western coast of GoK. These areas, presumably the last remaining dugong habitats along most of the Indian subcontinent [35][36] [15][37][38][19], thus assume critical importance. An understanding of the potential expanse of the seagrass habitats would also ignite efforts for assessment of nutrient profiling, carbon sequestration and seagrass-associated micro/macrofauna across spatial scales [33].

Seasonal habitat suitability assessment paves way for ecological interpretation in terms of migration, foraging, and reproduction [39] and developing conservation strategies [40]. We found highly suitable areas for dugong distribution to be restricted in pockets along the ANI coast even though the seagrass presence is predicted along the entire coastline of the region. The patches identified as high/moderate suitable and high-risk regions for dugong distribution show concurrence with the occupancy probability derived during previous studies [16]. Seagrass presence, depth and distance from shore explained habitat suitability for dugongs in ANI region with negligible difference between seasons. This suggests the need to assess seasonal distribution of dugongs [17] and fine-scale mapping [28] in highly suitable but less surveyed areas (such as Little Andaman and central Nicobar). In the PB-GoM region, we observed stark seasonal differences in highly suitable areas for dugongs. During pre-monsoon, north Palk Bay, a gradually sloping sheltered embayment, appears as a conducive habitat for dugongs. Monsoon prediction shows moderate suitability for the entire coastline, whereas highly suitable areas shift to GoM during post-monsoon. Seasonal changes in habitat suitability, attributed to biotic (seagrass presence, chlorophyll-a), topographic (slope) and environmental (sea surface temperature) factors, needs further investigation. In the GoK region, seagrass presence and low organic turbidity (lower values of chlorophyll-a) provide support to clear shallow waters as preferred regions by dugongs [41]. With a relict dugong population in the GoK [19], fine-scale mapping of seasonal dugong occurrence and seagrass distribution is required to address data deficiency in the entire region.

Dugongs are vulnerable to accidental entanglement in fishing nets and boat strikes as they surface regularly to breathe and due to their slow movement respectively, causing mortalities or life-threatening injuries [42]. Bycatch in fishing nets is a major threat to dugongs whereas hunting for meat is also reported from some areas [43]. Our analysis shows that highly suitable dugong habitats are also subjected to high fishing pressure. This includes the eastern coast of the Andaman Islands, north Palk Bay, entire GoM including the GoM Marine National Park and south-western GoK as high-risk areas. At ANI, despite many protected areas (nine National Parks, including two Marine National Parks and 94 Wildlife Sanctuaries) with part coastal cover, most areas identified as suitable for dugong distribution remain unprotected. Critical dugong habitats extend beyond these protected areas, particularly in Aerial Bay, Diglipur, Little Andaman and Central Nicobar. Ground validation of risks in the north Andaman region suggests intensive monitoring in areas outside active protection.

Dugongs display both short-range (< 15km) and long-range (> 15km, up to 560km) movement [7]. Our results indicate a high possibility of seasonal migration of dugongs in PB-GoM, given a considerable shift in suitability between seasons. It also points towards a potential movement across transboundary seagrass habitats along Sri Lankan coasts particularly in the post-monsoon season. Longer migrations have been documented in areas of seagrass habitat loss with implications on genetic diversity and dietary preferences in dugongs [43][26]. However, to validate long distance movements, real-time tracking or photographic capture-based studies (for example using drones - [45]) along with fine-scale environmental data collection is strongly recommended [46].

With influx of large, mechanised vessels, and use of destructive fishing practices (such as bottom trawling), increased loss of seagrass habitats will have a dual negative impact i.e., on fisheries of the region and on the forage-dependent dugong populations. Area estimated outside of the existing protected area cover was about 95% for ANI, 87% for PB-GoM and ~50% for the GoK region. Most of these areas are also critical fishing grounds supporting millions of livelihoods. Effective management of these high-risk-high-priority areas are recommended with a participatory approach taking care of the fishing communities' needs through sustainable practices. Incorporating participatory management approaches (for example, community supported space-time closures for high suitability habitats in particular seasons) would require upscaling of community-led initiatives (such as Friends of Dugong Network [47]) and government supported incentivization programs to reduce pressure on dugong habitats. Most importantly, it will contribute to India's efforts towards the global 30 x 30 biodiversity target while simultaneously achieving species conservation goals. Overall, identification of such synoptic-scale 'Critical Dugong Habitats' with a model-based approach provides significant information for a large mammalian grazer underlining the utility of citizen science and secondary data in performing large-scale spatial ecological analysis. We strongly advocate for the enhanced management of the spatially identified high-risk region for dugongs to ensure their persistence in the south Asia region.

Materials and methods

a. Study sites

In India, dugongs have restricted distribution in isolated pockets in Andaman & Nicobar Islands, Palk Bay- Gulf of Mannar, Tamil Nadu, and the Gulf of Kutch, Gujarat [35][48] (Fig. 6).

These three regions are geographically disjunct (ANI are tropical oceanic islands, PB-GoM are enclosed bays on the south-east Indian coast and GoK is a gulf located on the north-west Indian coast), with unique habitat structure, seagrass availability and extent, climatic patterns, and varying degree of anthropogenic threats.

The oceanic islands of Andaman and Nicobar (6°N to 14°N and 92°E to 94°E) hold high endemic biodiversity [49]. Over 80% of its land area (~8249 sq. km) is covered with tropical rainforests, with a long coastline (~1962 km) indented with several penetrating creeks [50]. Nine national parks (including two Marine

National Parks), 96 wildlife sanctuaries, and one biosphere reserve cover about 20% of the total geographical area of the islands (EIACP Programme Centre "Wildlife & Protected Areas Management", 2021 [51]. ANI consists of two major Island groups, the Andaman to the north and Nicobar groups of islands to the south, separated by the ten-degree channel. The islands receive rainfall mainly from May to September with warm annual weather (mean annual temperature ~ 26.6°C). ANI experiences high rainfall (1133-1725 mm) during south-west monsoon (May-September), followed by ~ post-monsoon (640-849 mm from October–December) and pre-monsoon showers (~ 443-527 mm from January-April) [52][53]. ANI host 12 seagrass species (dominated by *Halophila* sp., *Halodule* sp. [37]) with a coverage of 12.239 km^2 in Andaman group and 17.194 km^2 Nicobar group respectively [54], providing forage to a large number of dugongs (rough estimates suggest 44 – 81 dugongs[35]), with severe decline in dugong occupancy by ~ 60% over the last two decades [16].

The PB-GoM region is part of the coastal waters of the south-eastern state of Tamil Nadu. PB extends from Point Calimere in the north to Rameswaram in the south. GoM is designated from south of Dhanushkodi and extends till Kanyakumari at the tip of Indian peninsula. PB is comparatively calmer than GoM due to obstructed wave action by the Sri Lankan coast, Rameswaram Island, and Indian mainland, whereas GoM is exposed to swells from south to southwest [55]. Hence, PB provides a sheltered habitat, which is ideal for good growth of seagrass meadows, tidal flats, and mangroves [56]. GoM, on the other hand, is embedded with a string of island complexes (21 islands with 2 submerged), macroalgal beds (*Sargassum* spp., *Halimeda* spp., *Caulerpa* spp. and *Ulva reticulata*), seagrass meadows and patches of coral reefs. Gulf of Mannar Biosphere Reserve, the first biosphere reserve in south-east Asia, is known for its rich marine biodiversity (> 3,600 documented species of flora and fauna) [57]. PB-GoM are economically important areas for demersal and pelagic fisheries [58]. The PB-GoM study sites host 14 seagrass species (*Cymodocea serrulata*, *Halophila ovalis*, *Halodule uninervis* etc.) [59] spread over an area of ~ 398 km^2 [60]. PB-GoM also holds the largest dugong population along the Indian coast and in entire south Asia. Rough estimates peg the population to be ~ 150 individuals but with declining occupancy (Sivakumar & Nair, 2013) [15]. Recently, the Tamil Nadu state government notified about 448 sq. km area in the PB region adjoining Thanjavur and Pudukkottai districts as a Marine Protected Area (named Dugong Conservation Reserve [61]).

The GoK, the largest gulf on the western Indian coast along the Arabian sea, covers an area of 7350 km^2 (457.92 km^2 as Marine National Park and Sanctuary) with a cluster of 42 small coastal islands [62]. GoK encompasses the only marine national park along the west coast of India and the only marine sanctuary in the state of Gujarat. Located in the sub-tropical climatic zone, the region faces very high geo-morphological and climatic variation. It hosts 8 seagrass species [59] (*Halophila ovalis*, *Halodule uninervis* etc.), covering ~ 23 km^2 (Anand, 2021) [63] and a relict dugong population of less than 10-15 individuals [35] [19].

b. Habitat suitability

i) Data collection

We conducted intertidal and subtidal surveys using the line-intercept transect method [64] to record seagrass presence at all three regions. We laid 50 metres long transects perpendicular to the shoreline, where a 50 x 50 cm quadrat was placed after an interval of 5 m on the transect line. We also conducted boat-based surveys for subtidal seagrass meadows where diving was not possible, with appropriate visibility (~3-5 m) measured with a Secchi disk. We used drop-down quadrate method, with a GoPro Hero 6 camera attached at the top of the quadrat frame [65] to record seagrass presence. In areas with low water transparency (visibility < depth), we used Van-Veen grabs (such as in near-shore areas of PB-GoM and GoK). All locations were recorded using a Garmin etrex 30x handheld GPS unit.

We also extracted available seagrass polygons for our study areas from [66]. A multi-point file was generated using the ‘polygon to point’ conversion tool in ArcMap v.10.8. The seagrass locations obtained from the model were supplemented with the data from subtidal and intertidal surveys.

Historical information on dugong occurrences were curated from the questionnaire surveys of fisherfolk conducted between 2012- 2013 ([15]; GoK=8, ANI=336 and PB-GoM=263) and between 2018-2021 ([67]; GoK=8, ANI=226), following a standardized CMS-UNEP Dugong questionnaire.

Occurrence record of 45 locations by GEER foundation in the GoK region were also utilized [35]. We obtained dugong sighting locations from a volunteer network, comprising representatives from the fisher community, the Indian Navy, the Indian Coast Guard, and State Forest Departments at ANI (n = 63) and PB-GoM (n = 245). A few direct sighting records were added from primary field data obtained from boat-based surveys (n=6 at ANI), drone-based surveys (n=3 at ANI) and indirect presence from feeding trails (n=3 at GoK). Eventually, after screening the metadata of occurrence information for locations, dates and positional inaccuracies, composite occurrence records (n=64 at GoK, n=634 at ANI and n=508 at PB-GoM) were curated. Site-wise dugong sightings were further segregated for monthly occurrences, which were eventually categorized into seasonal data sets (Supplementary Fig. F2).

ii) Developing a prediction-based model for dugong distribution

We ran three prediction models for pre-monsoon, monsoon, and post-monsoon seasons, respectively. All point locations were spatially rarefied using SDMtoolbox v.2.4 (available from www.sdmtoolbox.org) [68] on ArcMap v.10.8 to reduce the negative influence of spatial autocorrelation on the models [69]. Seasonal segregation of sighting data was not appropriate for the GoK due to low data availability after bias correction. After data cleaning, dugong presence locations of ANI (pre-monsoon =54, monsoon =60 and post-monsoon =56 points), PB-GoM (pre-monsoon =99, monsoon =18 and post-monsoon=107 points) and GoK (n=13 points) were retrieved. Monsoon in ANI is determined by southwest monsoon (SWM) winds, whereas Tamil Nadu experiences retreating monsoon by northeast monsoon (NEM) winds.

The seasons were site-specific, based on the monsoon report published by the India Meteorological Department (Supplementary Table T2).

iii) Selection of environmental variables

To model the suitability of seagrasses, we selected 12 abiotic layers to determine the seagrass distribution [30][66] and six abiotic and one biotic layer for predicting dugong suitability (Table 1) as per data available at different sites. Given the data limitation from the GoK, annual habitat suitability was carried out with additional variable layers to compensate for seasonal variations (Table 1).

We first checked the predictors for data availability, and then multicollinearity was reviewed using ENMTools v.1.0.5 [70] and reshape2 v.1.4.4 packages in R [71]. We used six abiotic layers (Table 1) and the modelled seagrass suitability layer as predictors to determine the dugong habitat suitability. All predictor variables for seagrass and dugong suitability modelling were pre-processed and interpolated at a spatial resolution of 1 km using ArcMap v.10.8. We further resampled the layers to a similar extent using 'ENMTools v.1.0.6' and 'raster v.3.5-21' packages in RStudio v.2021.09.1.

iv) Suitability modelling

We used MaxEnt v.3.4.4 software for seagrass and dugong modelling due to its utility in limited presence-only data [26] [46] [72]. For modelling seagrasses, we used the MaxEnt settings from [66].

In the case of dugong suitability, the best possible MaxEnt settings combination was assessed using the ENMeval v2.0.1 package in R-Software [73]. We ran ENMeval for each season for ANI and PB-GoM, and once for GoK using random k-fold data partitioning technique (for >50 occurrence points) and by jack-knifing (for <50 data points) [74]. We selected the MaxEnt settings with the least Akaike information criterion (AIC) value for final runs (Supplementary Table T3).

To avoid sampling biases, all runs were performed using a bias file with the sighting data [75] [76]. The site and season-specific bias files were created using the kernel density function in R [77].

In the case of both seagrass and dugong MaxEnt outputs, we selected 'logistic' as the output format and the model accuracy was determined by area under curve (AUC) value. Final output maps were prepared using ArcMap 10.8. Response curves of different variables for ANI and PB-GoM, Tamil Nadu are provided as supplementary fig. F3 and F4, respectively. For GoK-Gujarat, variable response curves are presented as supplementary fig. F5.

Final outputs were divided into four quarters of prediction probability of values 0-0.25 (unsuitable), 0.25-0.5 (low suitability), 0.5-0.75 (moderately suitable) and 0.75-1 (highly suitable) region respectively. We also carried out a Niche Similarity Analysis to understand if the season-wise suitability of two sites (i.e., PB-GoM and ANI) are significantly different from each other, using I-statistics [78] in ENM tools v.1.3 [79].

v) Classifying fishing pressure

We used the fishing pressure layer from [15]. This layer was created as grid-based polygons (n=894) at a spatial resolution of 10 Km. Covariates used in creating the layer were fishing months, motor type and power and gear type. The layer was interpolated to 1 km spatial resolution using ArcMap v.10.8.

vi) Risk Assessment

Seasonal suitability layers were combined into one layer for each site, using the raster calculator function in ArcMap v.10.8. We multiplied the combined suitability layer with the fishing pressure layer to identify high risk areas. The risk assessment layers were categorised by manually segregating the raster classification from 0-100% with 100-51 classified as high risk, 50-26 as moderate risk and 25-0 as low risk on ArcMap v.10.8. A flowchart of the detailed methodology has been given in Fig. 7.

Further, we conducted boat survey-based threat mapping (fishing gear, vessel number and types) in representative high-risk areas from the three identified sites. This included Aerial Bay-Diglipur and Mayabunder area from North Andaman, Rani Jhansi Marine National Park (RJMNP, Ritchies' Archipelago) from South Andaman; Bhaidar, Ajad, Chushna Pir, Nor, Beyt Dwarka islands and Paga reef from GoK, Gujarat and coastal waters from Rajamadam to Ammapattinam in north Palk Bay region of PB-GoM. We scanned for boats and fishing gears for 10 minutes at the centroids of randomly selected 2x2 km grids at these sites. These surveys were conducted between 2019-21 in ANI, between 2020-21 in Tamil Nadu and between 2020-22 in Gujarat. We ran Inverted Distance Weightage (IDW) analysis at 1 km spatial resolution (powers 0.001 to 10; interval - 0.01) to classify high, moderate, and low threat areas. This layer was overlaid on the dugong habitat suitability layer to cross-verify the risk assessment conducted using secondary data. Areas of high risk outside the existing MPAs along the Indian coast were quantified to estimate proportional area without legal protection at all the study sites.

Ethics approval and consent to participate

All required permissions to carry out this study were obtained from the Ministry of Environment, Forest and Climate Change, Government of India (CAMPA Authority letter number: 13-28(01)/2015-CAMPA). The study was in accordance with the relevant guidelines and regulations. The interview surveys were conducted using standardised dugong catch/bycatch questionnaire (CMS-UNEP Dugong MoU [80]). These interview surveys were based on the revised and ethical protocols developed by the Project GLoBAL Rapid Bycatch Assessment (http://bycatch.env.duke.edu/) but also drew on protocols developed at the Phuket Marine Biological Center (Thailand), at San Francisco State University (USA) and at James Cook University (Australia). This was translated into local languages, and interpreters conversant with regional languages assisted with data collection. Free, prior and informed verbal consent was taken from every interviewee during the surveys. Personal information of the interviewee is not published or shared as part of this manuscript. Only secondary information on dugong occurrences across spatial and temporal scale was extracted from the interview surveys. Further, we declare that no invasive and/or biological data collection from humans or animals was conducted as part of this study.

Declarations

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Authors contributions

S.S. and S.B. compiled and analysed the data, prepared the output maps, and wrote the entire manuscript. A.P. and K.S. conceived the study, reviewed, and supervised in manuscript writing. C.G., P.S.H., Sa.P., Sh.P., S.R., Su.P., S.G., S.I. and A.N. helped in situ data collection and conducted interview surveys. C.G., P.S.H., Sa.P., Sh.P. and S.G. reviewed the drafts. N.P., J.A.J., and K.S. supervised the entire project and reviewed the entire manuscript. J.A.J. acquired the funds for the work. S.S. and S.B. share equal contribution in authorship.

Competing Interests

The authors declare no competing interests.

Data availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

References

1. Gormley, A. M. *et al.* First evidence that marine protected areas can work for marine mammals. *Journal of Applied Ecology*, **49(2)**, 474-480 (2012).
2. Hoyt, E. Sustainable ecotourism on Atlantic islands, with special reference to whale watching, marine protected areas and sanctuaries for cetaceans. *Biology and environment: proceedings of the Royal Irish Academy*, **105,** no. 3, pp. 141-154 (2005).
3. Marsh, H. & Sobtzick, S. *Dugong dugon* (amended version of 2015 assessment). *The IUCN Red List of Threatened Species 2019*: e.T6909A160756767; https://dx.doi.org/10.2305/IUCN.UK.2015-4.RLTS.T6909A160756767.en (2019).
4. Lin, M. *et al*. Functional extinction of dugongs in China. *Royal Society open science*, **9(8),** 211994 (2022).
5. Kayanne, H., Hara, T., Arai, N., Yamano, H., & Matsuda, H. Trajectory to local extinction of an isolated dugong population near Okinawa Island, Japan. *Scientific Reports,* **12(1),** 1-8 (2022).
6. Preen, A., & Marsh, H. Response of dugongs to large-scale loss of seagrass from Hervey Bay, Queensland Australia. *Wildlife Research*, **22(4),** 507-519 (1995).
7. Marsh, H., & Kwan, D. Temporal variability in the life history and reproductive biology of female dugongs in Torres Strait: The likely role of sea grass dieback. *Continental Shelf Research*, **28(16),** 2152-2159 (2008).
8. Brodie, J., & Waterhouse, J. A critical review of environmental management of the 'not so Great'Barrier Reef. *Estuarine, Coastal and Shelf Science*, **104,** 1-22 (2012).
9. Srinivas, Y. *et al*. Mitochondrial phylogeography reveals high haplotype diversity and unique genetic lineage in Indian dugongs (Dugong dugon). *Aquatic Conservation: Marine and Freshwater Ecosystems*, **31(4),** 818-829 (2021).
10. Pompa, S., Ehrlich, P. R., & Ceballos, G. Global distribution and conservation of marine mammals. *Proceedings of the National Academy of Sciences,* **108(33),** 13600-13605 (2011).
11. Preen, A. R. Interactions between dugongs and seagrasses in a subtropical environment *Doctoral dissertation, James Cook University* (1992).
12. Fuentes, M. M., Delean, S., Grayson, J., Lavender, S., Logan, M., & Marsh, H. Spatial and temporal variation in the effects of climatic variables on dugong calf production. *PloS one*, **11(6),** 0155675; https://doi.org/10.1371/journal.pone.0155675 (2016).
13. Pollock, K. H., Marsh, H. D., Lawler, I. R., & Alldredge, M. W. Estimating animal abundance in heterogeneous environments: an application to aerial surveys for dugongs. *The Journal of Wildlife Management*, **70(1),** 255-262 (2006).
14. Marsh, H., Prince, R. I. T., Saafeld, W. K., & Shepherd, R. The distribution and abundance of the dugong in Shark Bay, Western Australia. *Wildlife Research*, **21(2),** 149-161 (1994).

15. Sivakumar, K., & Nair, A. Assessment of Dugong distribution, habitat and risks due to fisheries and other anthropogenic activities in India. *Wildlife Institute of India–Technical Report*. 74 pp; https://wii.gov.in/images/images/documents/rr_ass_dugong_dist_2013.pdf. (2013).
16. D'Souza, E., Patankar, V., Arthur, R., Alcoverro, T., & Kelkar, N. Long-term occupancy trends in a data-poor dugong population in the Andaman and Nicobar archipelago. *PLoS One*, **8(10),** 76181; 10.1371/journal.pone.0076181 (2013).
17. Ng, S. Z., Ow, Y. X., & Jaafar, Z. Dugongs (Dugong dugon) along hyper-urbanized coastlines. *Frontiers in Marine Science*, **9,** 947700; fmars.2022.947700 (2022).
18. Dudhat, S. *et al.* Spatio-temporal analysis identifies marine mammal stranding hotspots along the Indian coastline. Sci Rep **12**, 4128 https://doi.org/10.1038/s41598-022-06156-0 (2022).
19. Pathan, S., Pande, A., Sivakumar, K., & Johnson, J. A. Scars of hope and forewarn of a bleak future: Post-mortem findings of dugongs (Dugong dugon). *Current Science*, **123(7)**, 919-924 (2022).
20. Royle, J. A., Chandler, R. B., Yackulic, C., & Nichols, J. D. Likelihood analysis of species occurrence probability from presence-only data for modelling species distributions. *Methods in Ecology and Evolution*, **3(3),** 545-554 (2012).
21. Kass, J. M. *et al.* ENMeval 2.0: Redesigned for customizable and reproducible modeling of species' niches and distributions. *Methods in Ecology and Evolution*, **12(9),** 1602-1608 (2021).
22. Smith, J. N., Kelly, N., & Renner, I. W. Validation of presence-only models for conservation planning and the application to whales in a multiple-use marine park. *Ecological Applications*, **31(1),** 2214;10.1002/eap.2214 (2021).
23. Pinto-Ledezma, J. N., & Cavender-Bares, J. Using remote sensing for modeling and monitoring species distributions. *Remote Sensing of Plant Biodiversity*, 199-223. (Springer Open, 2020).
24. Randin, C. F. *et al*. Monitoring biodiversity in the Anthropocene using remote sensing in species distribution models. *Remote Sensing of Environment*, **239,** 111626; 10.1016/j.rse.2019.111626 (2020).
25. Bonizzoni, S. *et al.* Modelling dolphin distribution within an Important Marine Mammal Area in Greece to support spatial management planning. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **29(10),** 1665-1680 (2019).
26. Hashim, M. *et al.* Using fisher knowledge, mapping population, habitat suitability and risk for the conservation of dugongs in Johor Straits of Malaysia. Marine Policy, **78,** 18-25 (2017).
27. Hunt, T. N., Allen, S. J., Bejder, L., & Parra, G. J. Identifying priority habitat for conservation and management of Australian humpback dolphins within a marine protected area. *Scientific Reports*, **10(1),** 14366 (2020).
28. Derville, S., Cleguer, C., & Garrigue, C. Ecoregional and temporal dynamics of dugong habitat use in a complex coral reef lagoon ecosystem. *Scientific Reports*, **12(1),** 552 (2022).
29. Onial, M., Jasmine, B., Singh, Y., Pande, A., Ramesh, C., Sivakumar, K., & Mathur, V. B. Updating India's National Biodiversity Action Plan. *Current Science*, **115(3)**, 422-427; https://www.researchgate.net/profile/Yashaswi-Singh-2/publication/325060192_Updating_India's_National_Biodiversity_Action_PlanThe_Process_and_Way_Forward/links/5b69d968a6fdcc87df6d84d6/Updat Indias-National-Biodiversity-Action-PlanThe-Process-and-Way-Forward.pdf (2018).
30. Basher, Z., Bowden, D. A. & Costello, M. J. Global Marine Environment Datasets (GMED). *World Wide Web electronic publication.* Version **2.0** (Rev.02.2018). http://gmed.auckland.ac.nz on <15.06.2021> (2018).
31. Dunic, J. C., Brown, C. J., Connolly, R. M., Turschwell, M. P., & Côté, I. M. Long-term declines and recovery of meadow area across the world's seagrass bioregions. *Global Change Biology*, **27(17),** 4096-4109 (2021).
32. Hernawan, U. E. *et al*. The first nation-wide assessment identifies valuable blue-carbon seagrass habitat in Indonesia is in moderate condition. *Science of The Total Environment*, **782,** 146818 (2021).
33. Sheppard, J. K. *et al*. Movement heterogeneity of dugongs, Dugong dugon (Müller), over large spatial scales. *Journal of Experimental Marine Biology and Ecology*, **334(1),** 64-83 (2006).
34. Aragones, L. V., Lawler, I. R., Foley, W. J., & Marsh, H. Dugong grazing and turtle cropping: grazing optimization in tropical seagrass systems?. *Oecologia*, **149,** 635-647 (2006).
35. Frazier, J. G., & Mundkur, T. Dugong dugon Muller in the Gulf of Kutch, Gujarat. *Journal of the Bombay Natural History Society*, **87(3),** 368-379 (1990).
36. Pandey, N., Tatu, K. & Anand, Y. Status of Dugong (*Dugong dugon*) in India report, *Geer Foundation Report* (2010).
37. D'Souza, E., Patankar, V., Arthur, R., Marbà, N., & Alcoverro, T. Seagrass herbivory levels sustain site-fidelity in a remnant dugong population. *Plos One*, **10(10),** 0141224; 10.1371/journal.pone.0141224 (2015).
38. Rajpurkar, S. *et al.* Lightweight unmanned arial vehicle surveys detect dugongs and other globally threatened marine species from the Andaman and Nicobar Islands, India. *Current Science*, **121(2),** 195 (2021).
39. Putra, M. I. H., & Mustika, P. L. K. Incorporating in situ prey distribution into foraging habitat modelling for marine megafauna in the Solor waters of the Savu Sea, Indonesia. *Aquatic Conservation: marine and freshwater ecosystems*, **30(12),** 2384-2401 (2020).
40. Boitani, L. *et al.* What spatial data do we need to develop global mammal conservation strategies?. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **366(1578),** 2623-2632 (2011).
41. Cleguer, C., Garrigue, C., & Marsh, H. Dugong (Dugong dugon) movements and habitat use in a coral reef lagoonal ecosystem. *Endangered Species Research,* **43,** 167-181 (2022).
42. Verutes, G. M. *et al.* Using GIS and stakeholder involvement to innovate marine mammal bycatch risk assessment in data-limited fisheries. *PLoS One*, **15(8),** 0237835; 10.1371/journal.pone.0237835. (2020).

43. Ilangakoon, A. D., Sutaria, D., Hines, E., & Raghavan, R. Community interviews on the status of the dugong (Dugong dugon) in the Gulf of Mannar (India and Sri Lanka). *Marine mammal science*, **24(3),** 704-710 (2008).
44. Poommouang, A. *et al*. Genetic diversity in a unique population of dugong (Dugong dugon) along the seacoasts of Thailand. *Scientific Reports*, **11(1),** 11624 (2021).
45. Raoult, V. *et al.* Operational protocols for the use of drones in marine animal research. *Drones*, **4(4),** 64 (2020).
46. Noviello, N. *et al.* Modelling Critically Endangered marine species: Bias-corrected citizen science data inform habitat suitability for the angelshark (Squatina squatina). *Aquatic Conservation: Marine and Freshwater Ecosystems*, **31(12),** 3451-3465 (2021).
47. Hatkar, P. *et al*. Review of stranding records of megaherbivore the Dugong (*Dugong dugon*, Müller, 1776) in the Gulf of Kutch, India-an implication to the conservation of marine mammals in Gujarat. *Journal of Survey in Fisheries Sciences*, **10,** 62-77 (2023).
48. Sivakumar, K. Status and conservation of Dugong dugon in India: strategies for species recovery. *Ecology and conservation of tropical marine faunal communities*, 419-432 (2013).
49. Reddy, C. S., Joseph, A., Abraham, G. A., & Sabu, M. M. Patterns of animal and plant discoveries, distribution and endemism in India - implications on the effectiveness of the protected area network. *Environmental Monitoring and Assessment*, **193(2),** 1-16 (2021).
50. Thangaradjou, T., Sivakumar, K., Nobi, E. P., &Dilipan, E. Distribution of seagrasses along the Andaman and Nicobar Islands: a post tsunami survey. *Recent Trends in Biodiversity of Andaman and Nicobar Islands*, 157-160. (Zoological Survey of India, 2010).
51. EIACP Programme Centre "Wildlife & Protected Areas Management" *Andaman Nicobar Islands Protected Area Gazette Notification Database (Andaman Nicobar Islands).* https://wiienvis.nic.in/Database/Andaman_Nicobar_Islands_7843.aspx (2021).
52. Bera, S., Majumdar, D. D., & Paul, A. K. Estimation of tourism carrying capacity for Neil Island, South Andaman, India. *Journal of Coastal Sciences*, ***2*(2),** 46-53 (2015).
53. Velmurugan, A. *et al*. Climate of Andaman and Nicobar Islands: Long-term pattern analysis. *Journal of the Andaman Science Association*, **23(1),** 1-7 (2018).
54. Paulose, N. E., Dilipan, E., & Thangaradjou, T. Integrating Indian remote sensing multi-spectral satellite and field data to estimate seagrass cover change in the Andaman and Nicobar Islands, India. *Ocean Science Journal*, **48,** 173-181 (2013).
55. Gowthaman, R. *et al.* Waves in Gulf of Mannar and Palk Bay around Dhanushkodi, Tamil Nadu, India. *Current Science*, **104,** 1431-1435 (2013).
56. James, K. *et al*. Seasonal variability in the distribution of microplastics in the coastal ecosystems and in some commercially important fishes of the Gulf of Mannar and Palk Bay, Southeast coast of India. *Regional Studies in Marine Science*, **41,** 101558 (2021).
57. Kumaraguru, A. K., Joseph, V. E., Marimuthu, N., & Wilson, J. J. Scientific information on Gulf of Mannar-A bibliography. *Gulf of Mannar Marine Biosphere Reserve Trust.* (2006).
58. Jagadeesan, L. *et al*. Ocean currents structuring the mesozooplankton in the Gulf of Mannar and the Palk Bay, southeast coast of India. *Progress in Oceanography*, **110,** 27-48 (2013).
59. Thangaradjou, T., & Bhatt, J. R. Status of seagrass ecosystems in India. *Ocean & Coastal Management*, **159,** 7-15 (2018).
60. Geevarghese, G. A. *et al.* A comprehensive geospatial assessment of seagrass distribution in India. *Ocean & Coastal Management*, **159,** 16-25 (2018).
61. Special Correspondent. India gets its first Dugong Conservation Reserve in Tamil Nadu. *The Hindu*. https://www.thehindu.com/news/national/tamil-nadu/india-gets-its-first-dugong-conservation-reserve-in-tamil-nadu/article65918239.ece (2022).
62. Sukumaran, S., Vijapure, T., Mulik, J., Rokade, M. A., & Gajbhiye, S. N. Macrobenthos in anthropogenically influenced zones of a coralline marine protected area in the Gulf of Kachchh, India. *Journal of sea research*, **76,** 39-49 (2013).
63. Anand, Y. A. A study on marine mammals of Gulf of Kachchh, Gujarat, India. [Doctoral thesis, Gujarat University] (2021).
64. McKenzie, L. J. *et al.* The global distribution of seagrass meadows. *Environmental Research Letters*, **15(7),** 074041 (2020).
65. Bertelli, C. M., Bull, J. C., Cullen-Unsworth, L. C., & Unsworth, R. K. Unravelling the Spatial and Temporal Plasticity of Eelgrass Meadows. *Frontiers in plant science*, **12,** 939 (2021).
66. Jayathilake, D. R., & Costello, M. J. A modelled global distribution of the seagrass biome. *Biological Conservation*, **226,** 120-126 (2018).
67. Johnson J.A. *et al*. Annual Progress Report VI (2021-23), CAMPA-Recovery of dugongs and their habitats in India: An integrated participatory approach. *Wildlife Institute of India, (Ministry of Environment, Forest & Climate Change), Dehradun*, pp. 234 (2023).
68. Brown, J. L., Bennett, J. R., & French, C. M. SDMtoolbox 2.0: the next generation Python-based GIS toolkit for landscape genetic, biogeographic and species distribution model analyses. *PeerJ*, **5,** e4095; articles/4095 (2017).
69. Galante, P. J. *et al*. The challenge of modeling niches and distributions for data-poor species: a comprehensive approach to model complexity. *Ecography*, **41(5),** 726-736 (2018).
70. Warren, D. L. *et al.* ENMTools 1.0: an R package for comparative ecological biogeography. *Ecography*, **44(4),** 504-511 (2021).
71. Wickham, H. reshape2: Flexibly reshape data: a reboot of the reshape package. *R package version*, **1(2).** (2012).
72. McKenzie, L. J., Campbell, S. J., & Roder, C. A. Seagrass-watch: Manual for Mapping and Monitoring Seagrass Resources. 2nd Edition. 100 pp. QFS, NFC; Cairns. https://www.seagrasswatch.org/wp-content/uploads/Methods/manuals/PDF/Seagrass-Watch%20monitoring%20guidelines%20-%202nd_Ed.pdf. (2003).
73. Muscarella, R. *et al.* ENM eval: An R package for conducting spatially independent evaluations and estimating optimal model complexity for Maxent ecological niche models. *Methods in ecology and evolution*, **5(11),** 1198-1205 (2014).

74. Shcheglovitova, M., & Anderson, R. P. Estimating optimal complexity for ecological niche models: a jackknife approach for species with small sample sizes. *Ecological Modelling*, **269,** 9-17 (2013).

75. Vollering, J., Halvorsen, R., Auestad, I., & Rydgren, K. Bunching up the background betters bias in species distribution models. *Ecography*, **42(10),** 1717-1727 (2019).

76. Dorji, T., Linke, S., & Sheldon, F. Optimal model selection for Maxent: a case of freshwater species distribution modelling in Bhutan, a data poor country. *Authorea,* 93380163;10.22541/au.160551779.93380163/v1 (2020).

77. Fourcade, Y., Engler, J. O., Rödder, D., & Secondi, J. Mapping species distributions with MAXENT using a geographically biased sample of presence data: a performance assessment of methods for correcting sampling bias. *PloS one*, **9(5),** 97122; 10.1371/journal.pone.0097122 (2014).

78. Warren, D. L., Glor, R. E., & Turelli, M. Environmental niche equivalency versus conservatism: quantitative approaches to niche evolution. *Evolution*, **62(11),** 2868-2883 (2008).

79. Warren, D. L., Glor, R. E., & Turelli, M. ENMTools: a toolbox for comparative studies of environmental niche models. *Ecography*, **33(3),** 607-611 (2010).

80. Pilcher, N. J., & Kwan, D. Dugong questionnaire survey project manual. *CMS-UNEP Abu Dhabi Office.* Available online at: http://www.cms.int/dugong/en/document/standardised-dugong-questionnaire-project-manual (2012).

Figures

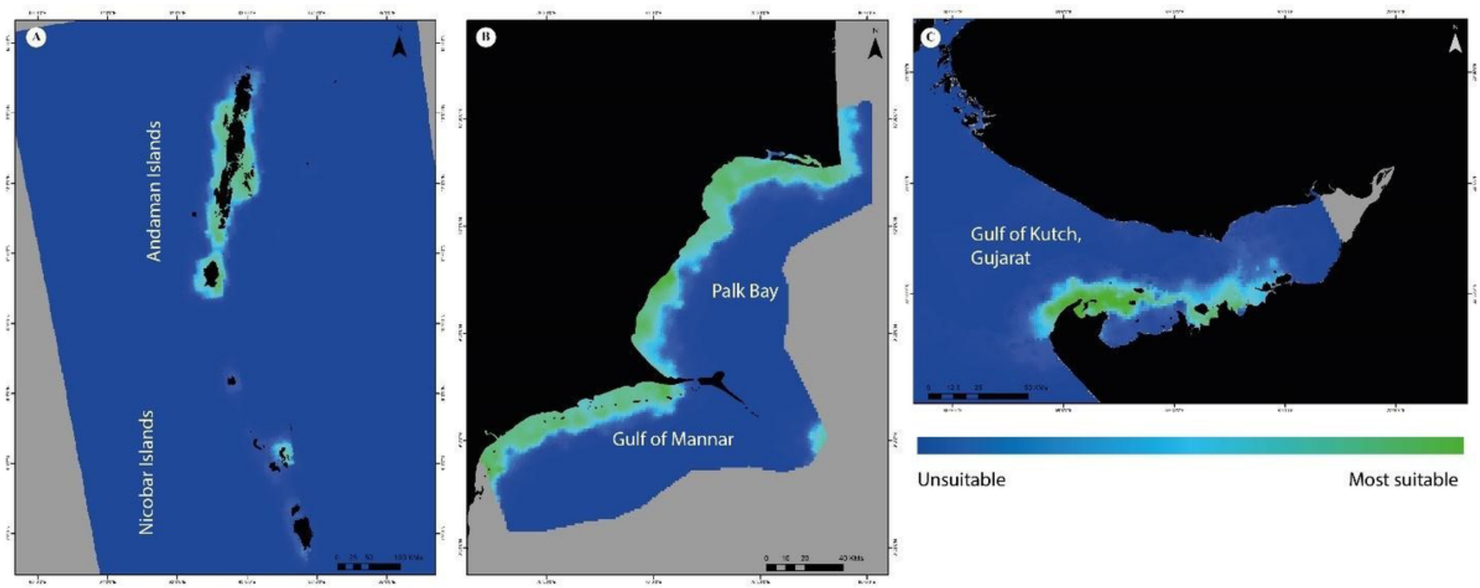

Figure 1

Habitat suitability for seagrass meadows in A. Andaman and Nicobar Islands B. Palk Bay and Gulf of Mannar, Tamil Nadu and C. Gulf of Kutch, Gujarat. Here 'unsuitable' corresponds to 0 and 'most suitable' corresponds to 1.

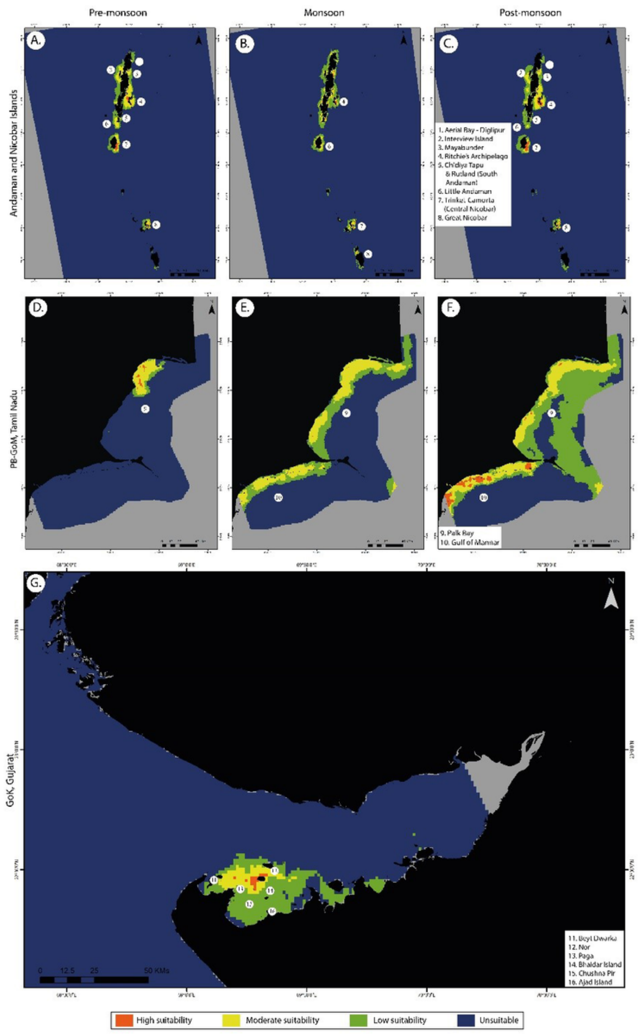

Figure 2

Habitat suitability predictions for dugongs in A) pre-monsoon, B) monsoon, C) post-monsoon at Andaman & Nicobar Islands; D) pre-monsoon, E) monsoon, F) post-monsoon at Palk Bay and Gulf of Mannar, Tamil Nadu; and G) Gulf of Kutch region, Gujarat. Here, each class corresponds to values 0-0.25 (unsuitable), 0.25-0.5 (low suitability), 0.5-0.75 (moderately suitable) and 0.75-1 (highly suitable) regions respectively.

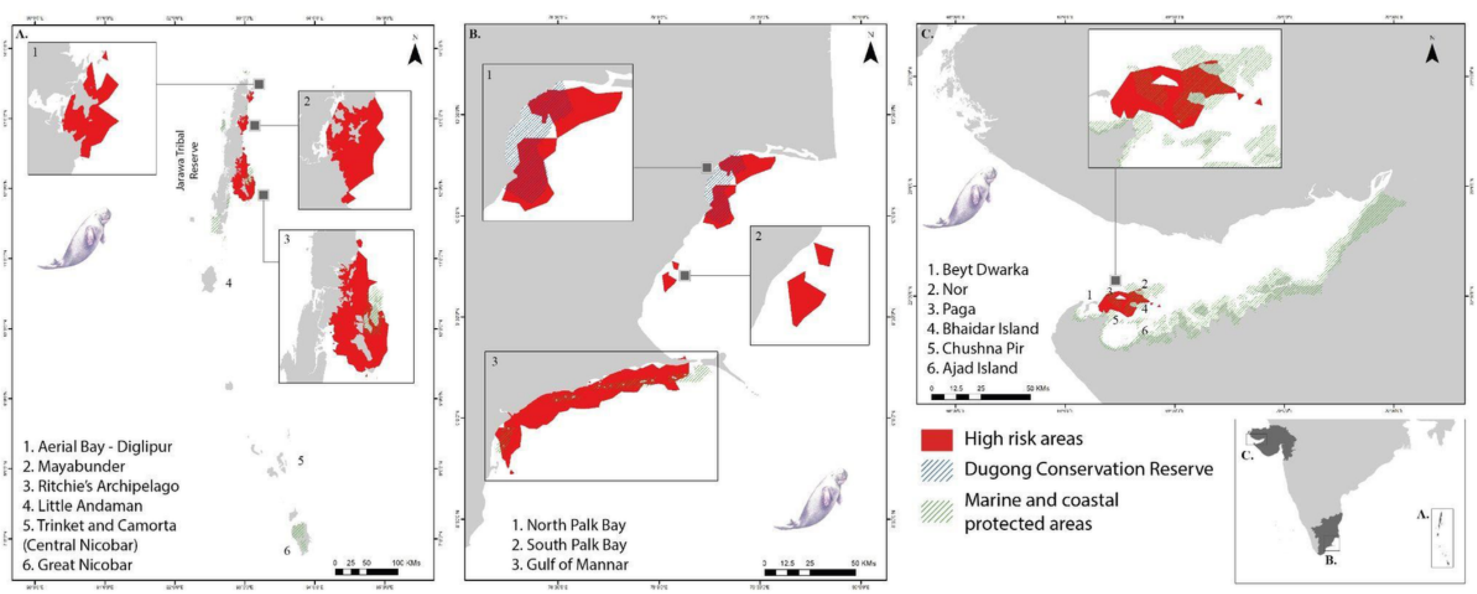

Figure 3

Risk predictions due to fishing pressure in A. Andaman and Nicobar Islands; B. Palk Bay and Gulf of Mannar, Tamil Nadu and C. Gulf of Kutch, Gujarat. Here, each class corresponds to 0-0.25 (low risk), 0.25-0.5 (moderate risk), 0.5 and above (high risk) percentage values of total range.

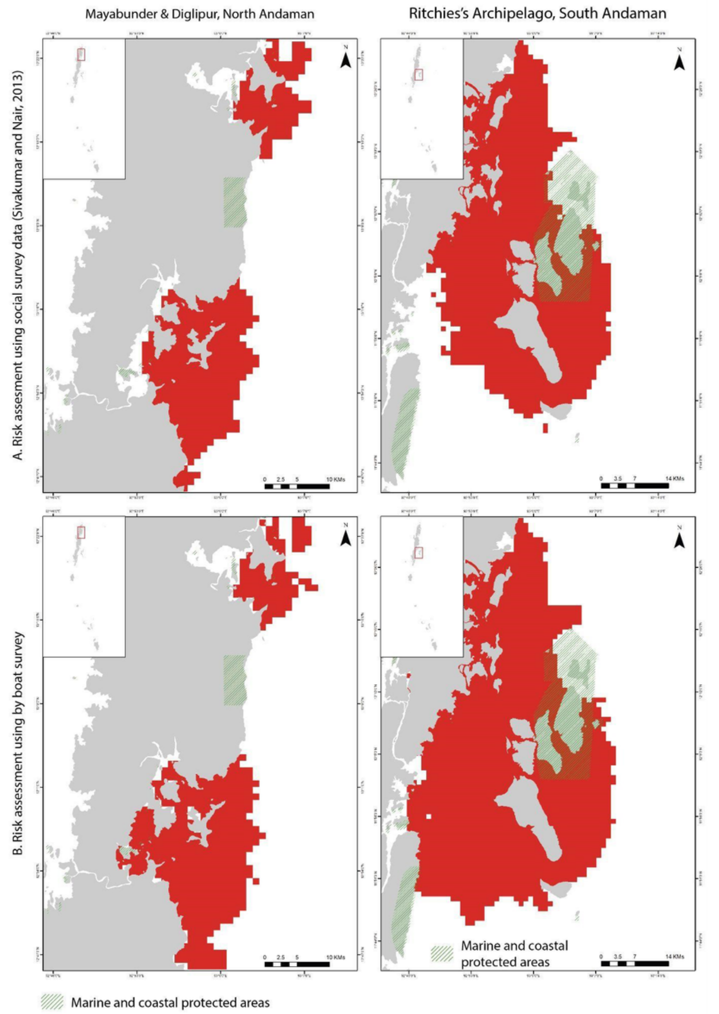

Figure 4

Comparison of selected high-risk habitats. Top row shows the risk based on suitability models derived from social surveys and bottom row shows the result from the boat-based surveys [Mayabunder and Diglipur, North Andaman (left) and Ritchie's Archipelago, South Andaman (right)].

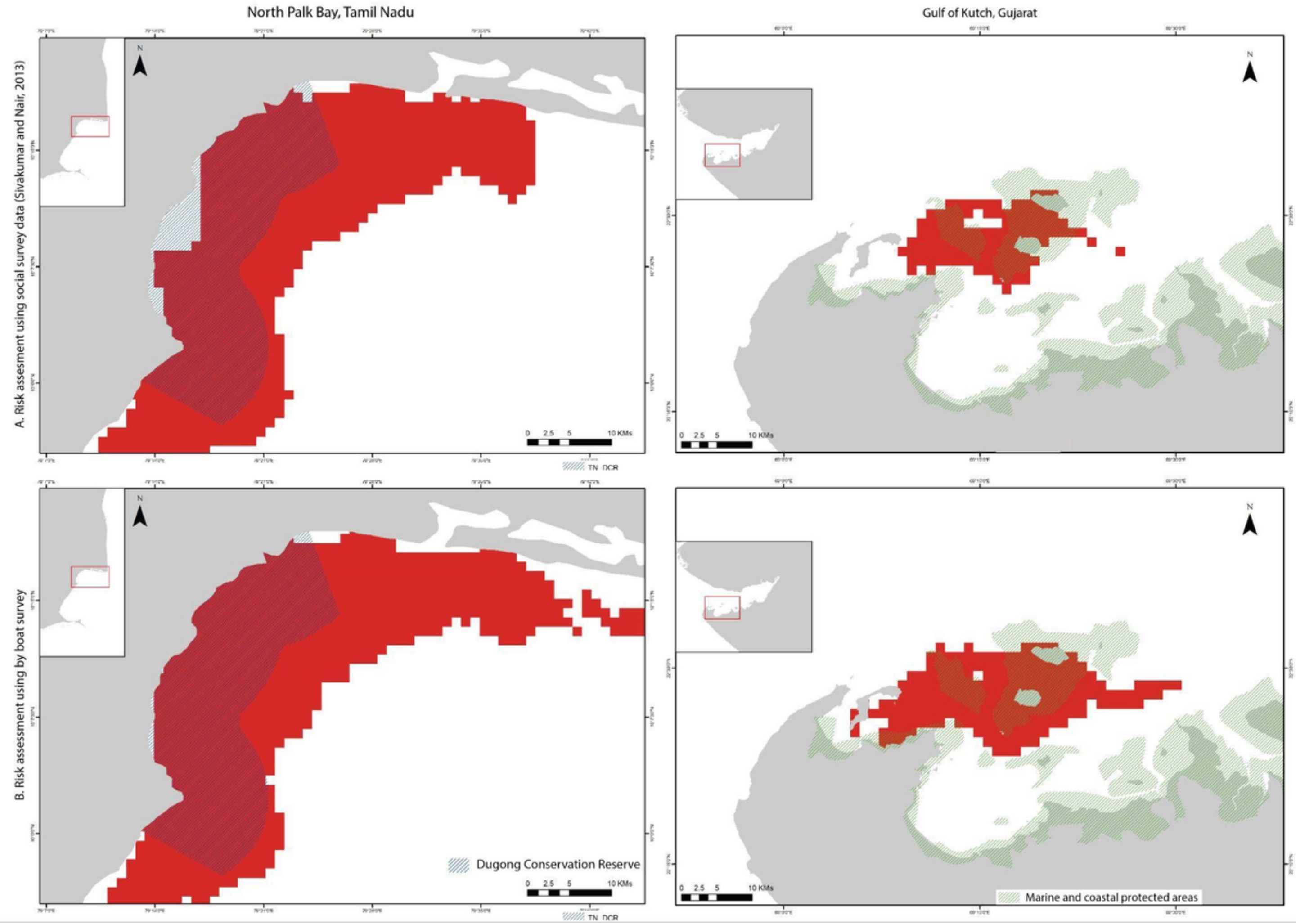

Figure 5

Comparison of selected high-risk habitats. Top row shows the risk based on suitability models derived from social surveys and the bottomrow shows the result from the boat-based surveys [North Palk Bay, Tamil Nadu (left) and Gulf of Kutch, Gujarat (right)].

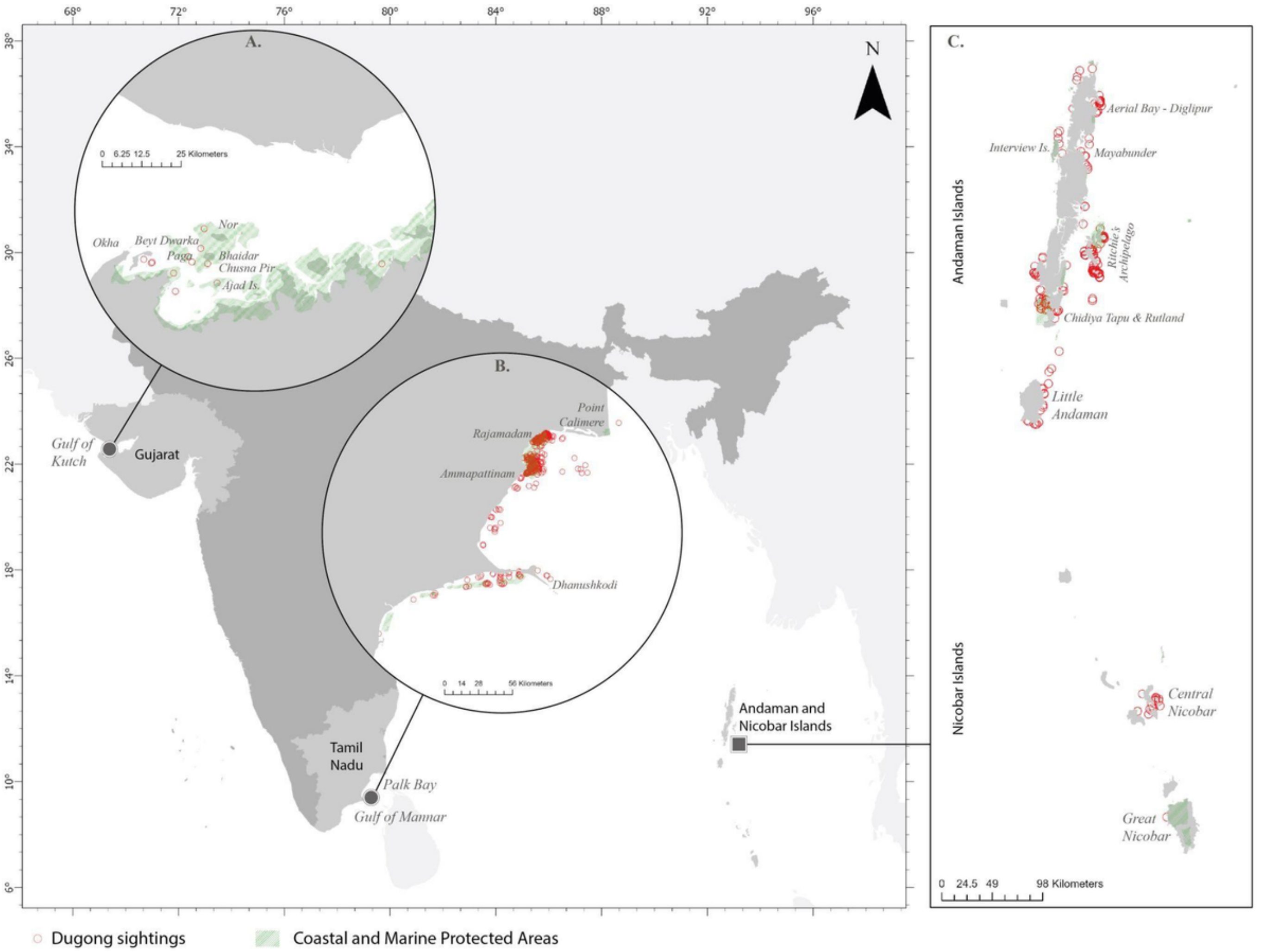

Figure 6

Study sites along the Indian coastline A) Gulf of Kutch (GoK), Gujarat in the northwest coast in the Arabian sea; (B) Andaman & Nicobar Islands (ANI) - offshore islands located in the Bay of Bengal to the southeast of peninsular India (C) Palk Bay and Gulf of Mannar (PB-GoM), Tamil Nadu to the southeast coast in the Bay of Bengal. The red circles represent dugong sighting locations between 2008 and 2021.

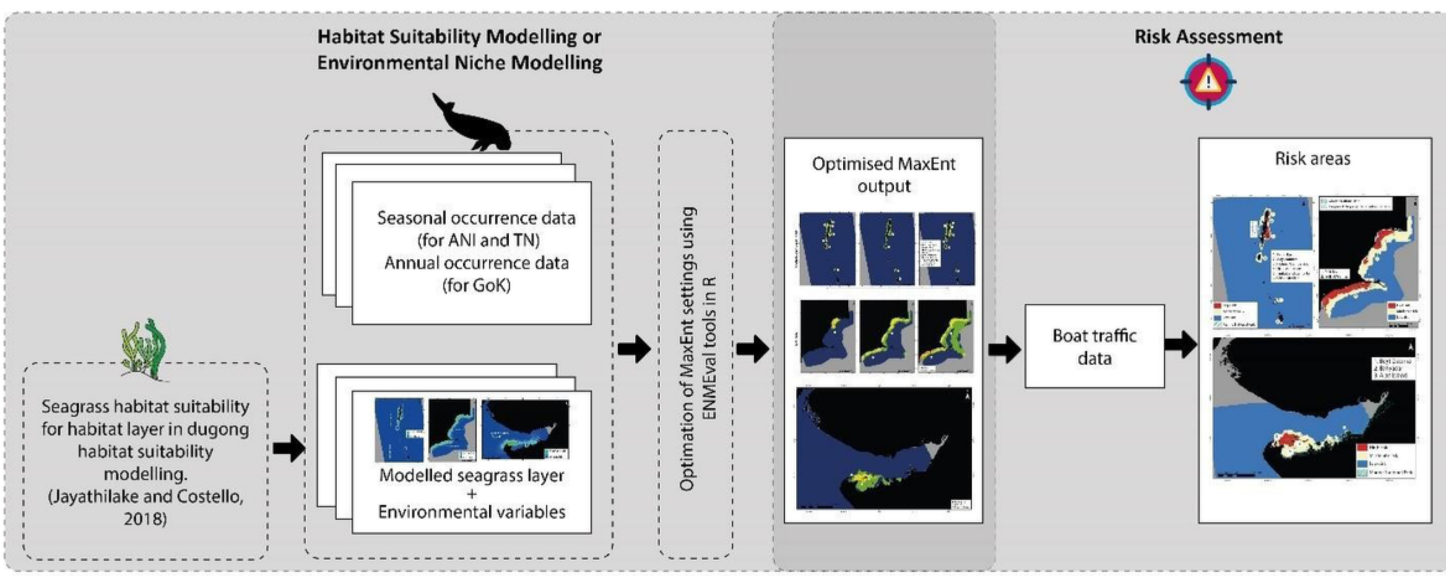

Figure 7

A flowchart to show the methodology in detail.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Supplementarymaterial.docx