

**Spatial modelling of Critical Dugong Habitats
(CDHs) in India**

Thesis submitted to the

**Forest Research Institute (deemed to be) University
Indian Council of Forestry Research and Education,
Dehradun, Uttarakhand**



**for the award of the degree of
DOCTOR OF PHILOSOPHY
IN
FORESTRY (FOREST GEOINFORMATICS)**

By

SOHOM SEAL



**भारतीय वन्यजीव संस्थान
Wildlife Institute of India**

2024

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Wildlife Institute of India

Declaration

I hereby declare that the thesis titled “Spatial modelling of Critical Dugong Habitats (CDHs) in India”, submitted by myself, Mr. Sohom Seal (Registration No. 19PHD572) to Forest Research Institute deemed to be University, Dehradun for the award of Doctor of Philosophy in Forestry (Forest Geo-informatics) is a record of original research work carried out by me under the supervision of Dr. K Sivakumar (Professor, Pondicherry University) and co-supervision of Dr. Mini Raman (Retd. Scientist-G and Head, Space Applications Centre, Ahmedabad). The doctoral research has not formed the basis for an award of any other degree or diploma in other university or organisation. I also declare that the thesis embodies my own work, observations, and analysis, and in that respect, the investigation appears to advance knowledge in the subject. The materials obtained from different sources has been duly acknowledged in the thesis. The thesis has been duly checked through DrillBit, a plagiarism detection tool approved by FRI deemed to be University, and has a plagiarism to acceptable limits.

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Date: 25/08/2024

Sohom Seal

Countersigned:

Dr. K Sivakumar (Supervisor)

Dr. Mini Raman (Co-supervisor)

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Place: Puducherry

Date: 14-08-2024

Dr. K Sivakumar

(Supervisor)

Ex-Scientist G, WII



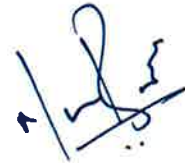
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Place: AHMEDABAD

Date: 20.8.2024



Dr. Mini Raman
(Co-supervisor)



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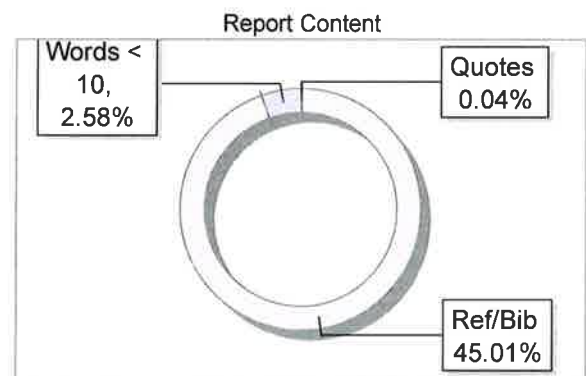
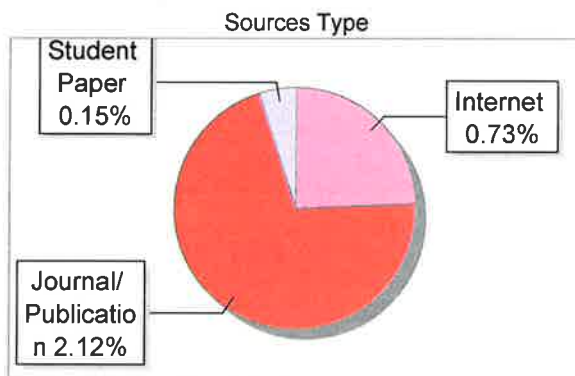
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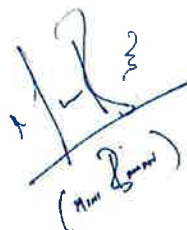
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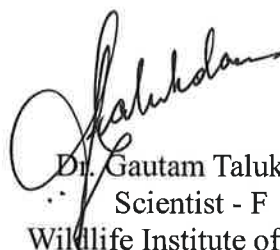
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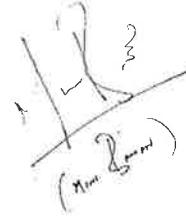
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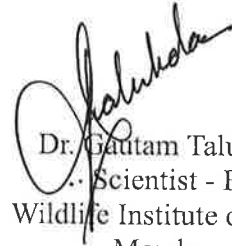
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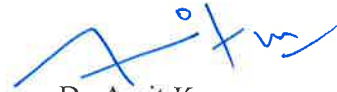
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विषय: वानिकी में डॉक्टर ऑफ फिलॉसफी डिग्री के लिए पंजीकरण।

प्रिय महोदय,

आपको अवगत करना है कि इस संस्थान में वानिकी में डॉक्टर ऑफ फिलॉसफी की डिग्री के लिए शोध छात्र (रिसर्च स्कॉलर) के रूप में आपके नामांकन हेतु निम्नलिखित निर्णय लिए गए हैं:

1. आपको डॉक्टर ऑफ फिलॉसफी के लिए दिनांक 01.03.2020 से 31.08.2025 तक पीएचडी शोध छात्र के रूप में पंजीकृत किया गया है।
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9. The research scholar shall appear before the Research Advisory Committee to make presentation of the progress of his/her work for evaluation and further guidance.
10. Ph.D. Scholar shall be required to be present in the research center concerned for a minimum period two years from the date of registration. Their presence shall be duly recorded and maintained in the research center concerned.
11. **Registration of a Ph.D. Scholar is liable to be cancelled by the Director at any time if:-**
 - i. Two consecutive six monthly progress reports are not submitted at all or are not satisfactory as per recommendations/comments of RAC.
However, the research scholar is required to submit the 1st six monthly progress report through his/his Supervisor & Chairman of RAC and 2nd and 3rd six monthly progress reports duly reviewed by RAC. The candidate will make six monthly presentation of 2nd & 3rd six monthly Progress Report before RAC. After that all the 6 monthly Progress Reports shall be submitted through supervisor/Chairman, RAC while annual presentation would be held before RAC.
The six monthly progress reports are to be submitted till pre-thesis submission seminar.
 - ii. The attendance of Research Scholar is less than 75% in any term.
 - iii. The scholar violates the clause 5.1.4 of the PhD ordinance regarding compulsion of 2 years Study leave for pursuing PhD in case of In-service candidates (except the employees of ICFRE and Research Centers of FRI Deemed to be University).
12. No Ph.D. Scholar (except in-service candidates availing study leave) shall accept during the period of research any paid assignment apart from Research Fellowships, Research Assistantship etc. (in the same institute) unless in the opinion of the RAC such an assignment will not interfere with his/his research work.
13. A Ph.D. Scholar shall not be permitted to take any other degree course, but may be permitted by the RAC to take part-time Diploma or Certificate course(s) not affecting the scholar's research work adversely.
14. **A Research Scholar is required to pursue research in the Institute/Research Centre under the supervision of his/his Supervisor on the approved subject for not less than twenty-four months commencing from the date of his/her registration.**
15. **The Research Scholar may not later than three months from the date of issue of registration letter, modify the scheme of the research work or nature or scope of the subject, on the recommendation of the Supervisor and RAC, with the approval of Director.**
16. In case a Research Scholar does not submit his/her thesis within a period of 6 years from the date of his/her admission unless the term is extended by the Research Degree Committee on the specific recommendation of the Research Advisory Committee for a period of upto 1 calendar year, his/her registration shall lapse.

The recommendations of the R.A.C.s for extension of term of registration must reach this office before expiry of the term of registration.

The women candidates and Persons with Disability (more than 40% disability) may be allowed relaxation of two years in the maximum duration of registration i.e. 5 years and six months. In addition, during the entire period of registration the women candidates may be provided Maternity Leave/Child Care Leave once in the entire duration of Ph.D. for up to 240 days with the approval of Vice Chancellor on the recommendation of Supervisor/Head of Division/Nodal Officer of the Research Centre concerned.

17. Prior to the submission of the thesis but at least 3 months before the expiry of term of registration, the scholar shall make a presentation in the Department before the Research Advisory Committee of the Institution concerned in Pre-thesis Submission Seminar. The minutes of RAC meeting for pre-thesis submission seminars to be sent to the Registrar, FRI Deemed University with full comment along with a panel of examiners duly signed by R.A.C.
18. Ph.D. scholars must publish at least one (1) research paper in refereed journal and make two paper presentations in conferences/seminars before the submission of the thesis for adjudication, and produce evidence for the same in the form of presentation certificates and/or reprints. While submitting for evaluation, the thesis shall have an undertaking from the research scholar and a certificate from the Research Supervisor attesting to the originality of the work, vouching that there is no plagiarism and that the work has not been submitted for the award of any other degree/diploma of the same Institution where the work was carried out, or to any other Institution..
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20. Please note that your Registration as Research Scholar is to be governed as per rules, regulations and ordinances of FRI Deemed to be University, with applicable amendments made by the University from time to time. For all further correspondence, please quote your enrolment number.

(ए.के. त्रिपाठी)

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कुलसचिव

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EXECUTIVE SUMMARY

The conservation of dugongs, a vital species for marine ecosystem health, is crucial due to their role in maintaining seagrass meadows through their grazing activities. Dugongs help in nutrient cycling and provide essential ecosystem services. However, they are increasingly threatened by habitat loss, fishing activities, and other anthropogenic pressures. Therefore, the identification of important dugong habitats for focused conservation measures is necessary in the country where their population occur in a wider seascape in three different regions. In this context, this study was conducted aimed to address the pressing need for effective conservation strategies by identifying suitable habitats, assessing risks, and identifying Critical Dugong Habitats (CDHs) for data-driven and targeted management efforts along the Indian coast.

In India, there is a scarcity of comprehensive data on dugong distribution and their habitat suitability, complicating the development of effective conservation strategies. Baseline data on priority areas for dugong conservation was provided by the Wildlife Institute of India back in 2012. Therefore, a temporal data gap exists for a re-evaluation study of CDHs through collating recent dugong occurrences and fishing pressure collected through primary surveys. Further, this study could fill the data gaps by employing advanced spatial modelling techniques and integrating primary and secondary data collected through multi-stakeholder involvement, thereby providing a robust understanding of recent and more accurate CDHs.

The study focused on four key dugong ranges along the Indian coast: the Andaman and Nicobar Islands (ANI), Palk Bay and the Gulf of Mannar (PB-GoM) in Tamil Nadu, and the Gulf of Kutch (GoK) in Gujarat. These regions are recognised for their rich marine biodiversity and extensive seagrass meadows, which are critical for dugong survival. The ANI features relatively pristine marine environments, while PB-GoM and GoK are heavily impacted by fishing activities and coastal development, making them significant areas for conservation focus.

The primary objectives of this study are: 1) To understand the distribution status of seagrass meadows in selected dugong habitats using in situ and remote sensing data, 2) Mapping the interface between dugong distribution and fisheries in selected dugong habitats, 3) Mapping the environmental governing factors that determine dugong distribution, and 4) Integrating environmental and habitat parameters in GIS platform to classify Critical Dugong Habitats (CDHs).

The study employed a combination of *in-situ* surveys and remote sensing techniques to map seagrass meadows. Intertidal and subtidal surveys were conducted using the line-intercept transect method, and satellite imagery from Sentinel-2A and 2B was utilised for classification in the Google Earth Engine platform. The study highlights the challenges of mapping in turbid waters and identifies suitable classification algorithms curated for different water conditions for better mapping accuracy. I found the Classification and Regression Tree as the best-fit algorithm in more transparent waters, as in Andaman (Overall accuracy: 96%) and Gulf of Mannar (Overall accuracy: 79%) regions, whereas the Random Forest is the preferred algorithm in turbid waters, as in case of Palk Bay (Overall accuracy: 71%). Random Forest has also been found to be the most general supervised classification (Overall accuracy: 71-94%) algorithm to be used in any water conditions. Study findings reveal that previous mapping studies have under-reported the seagrass cover because most of them are localised studies and lacked intensive *in-situ* data collection. Also, a range of satellite imageries were used for classification, making the output maps non-uniform in terms of spatial resolution. Of the three regions, Palk Bay has the most extensive seagrass meadows because of its sheltered bathymetric profile and nutrient-rich water, followed by the Gulf of Mannar and South Andaman. Seagrass mapping exercise was not conducted for the Gulf of Kutch region because of high turbidity levels.

Seagrass distribution modelling was performed using MaxEnt software to generate a continuous layer for dugong distribution modelling. Thirteen environmental variables were used to predict the seagrass distribution. The model's performance was evaluated using the Area Under Curve (AUC) ($AUC \pm SD$ of 0.76 ± 0.004), which is higher than the global average.

In the case of the entire Andaman Islands, seagrass distribution was predicted along the entire island group with specific patches around central Nicobar (Camorta and Trinket) and Great Nicobar. The bathymetric depth and wave height had a maximum contribution (84.3%) toward seagrass prediction in islands. 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, similar to the global prediction of ~75% contribution, maximum sea surface temperature and distance from the shore in combination showed a maximum contribution of 83.9%. The entire PB-GoM coast was predicted for seagrass presence, with north Palk Bay and the north GoM showing maximum probability. In the case of GoK, seagrass was strongly predicted to be in the southern part of the gulf around the

islands situated in the region. The phosphate availability and mean sea surface temperature were key contributing factors (67%) in identifying seagrass habitats in GoK.

The research highlights the increasing economic and volume output trends from marine fisheries in regions such as Tamil Nadu and the Andaman and Nicobar Islands, notwithstanding the impact of regulatory measures during the COVID-19 lockdowns. Seagrass ecosystems, crucial for dugongs and various marine species, face significant threats from anthropogenic activities, including trawling, dredging, and boat anchoring, which lead to extensive habitat degradation and species loss. Of the total mapped seagrass area of 250 km² in the Gulf of Mannar region, 32 km² are subjected to moderate to high fishing pressure. In South Andaman, seagrass meadows are sparse, leading to minimal overlap with fishing areas near Wandoor and Burmanallah, mostly due to transit activities. However, the seagrass meadows in the southern part of South Cinque Island, which are protected under the Cinque Island Sanctuary by the Wildlife Protection Act of 1972, still experience moderate to high fishing pressure as this area serves as a significant fishing ground for the local community.

The study juxtaposes past mapping efforts based on interview surveys with current, more precise methodologies utilising GPS data loggers. This technological shift has markedly improved the resolution and accuracy of spatial data, providing a granular representation of fishing activities and their impact on dugong habitats especially the critical dugong habitats, offering detailed insights for effective conservation and management strategies.

I used the Species Distribution Modelling (SDM) techniques, such as MaxEnt, to predict suitable habitats over large spatial scales. The study could incorporate a comprehensive dataset from various sources, including semi-structured questionnaires, citizen science initiatives, volunteer networks, and primary field surveys, to identify critical dugong habitats and develop informed conservation strategies.

The methodology includes intertidal and subtidal surveys using the line-intercept transect method and boat-based surveys with visibility measurements. Historical (2012-13) and present (2018-21) dugong occurrence data were gathered using interview surveys and primary surveys (boat and drone). The study also utilised occurrence records from previous literature and a volunteer network, which included members of the fisher community, the Indian Navy, the Indian Coast Guard, and State Forest Departments. In conclusion, the research emphasises that effective conservation of seagrass meadows requires precise and consistent mapping

efforts. It provides valuable insights into a standard nationwide seagrass mapping exercise protocol, contributing to global conservation goals.

In Ritchie's Archipelago, the Hut Bay region of Little Andaman and the Trinket-Camorta islands in central Nicobar have been identified as highly suitable habitats for dugongs throughout all seasons. In contrast, areas such as Aerial Bay, Diglipur, Mayabunder in northern Andaman, Interview Island in the west, and Rutland & Chidiya Tapu in southern Andaman were classified as moderately suitable during the pre- and post-monsoon periods.

In the Palk Bay –Gulf of Mannar regions, dugong's habitat suitability exhibited clear seasonal variations. High suitability was observed primarily in northern Palk Bay during the pre-monsoon period, while the rest of the region was mostly deemed low or unsuitable. As the retreating monsoon progressed, these areas of high suitability expanded throughout the region, forming patches of high suitability amidst areas of moderate to low suitability. By the post-monsoon season, the most suitable habitats became more concentrated in the Gulf of Mannar (GoM).

The effectiveness of the seasonal MaxEnt models for RB-GoM region was measured with AUC \pm SD values of 0.96 ± 0.029 for pre-monsoon, 0.911 ± 0.022 for monsoon, and 0.825 ± 0.031 for post-monsoon. Although the extent of highly suitable habitats was notably smaller compared to moderate and low-suitability areas, there was a distinct trend of shifting suitability from north to south from the pre-monsoon to the post-monsoon seasons. This shift was further supported by the I-statistics correlation analysis (Table 4.4), which revealed significant differences in habitat suitability between the pre-monsoon and post-monsoon periods.

The annual habitat suitability assessment for the GoK region revealed high suitability zones near Paga, Bhaidar, and Chushna Pir, extending up to Beyt Dwaraka island. A moderately suitable area for dugongs was also identified, stretching from Beyt Dwarka island to the east, reaching beyond Nor Island. Conversely, the subtidal regions south of Chushna Pir, including Ajad Island, were consistently classified as having low suitability for dugongs year-round. The average AUC value from the MaxEnt models was $0.983 (\pm 0.005)$.

This study highlights the significance of seagrass ecosystems and underscores the need for improved mapping strategies. The research concludes that addressing the dynamic nature of seagrass habitats through advanced mapping and monitoring techniques at a higher temporal

scale is essential for their effective conservation, aligning with global efforts to preserve marine biodiversity and ecosystem health.

The research developed prediction models for dugong distribution during pre-monsoon, monsoon, and post-monsoon seasons. The predictors were checked for data availability and multicollinearity, and suitability modelling was conducted using MaxEnt software. The final output maps were categorised into prediction probability classes to identify highly suitable dugong areas.

The study combined seasonal suitability layers with fishing pressure data to assess risks and pinpoint high-risk areas. Areas identified as high risk and with high habitat suitability were designated as CDHs. In high-risk areas, boat surveys were conducted to map threats, including fishing gear and vessel numbers and types. The threat layer was overlaid on the dugong habitat suitability layer to cross-check the risk assessment obtained from secondary data. The study quantified high-risk areas outside existing Marine Protected Areas (MPAs) to estimate the proportion of unprotected areas at all study sites.

The overlap between high-risk areas (i.e., CDHs) and existing protected zones varied across regions. In the ANI region, only 5.5% (26.16 sq. km out of 478.59 sq. km) of high-risk areas fall within protected zones. In the PB-GoM region, approximately 28% of high-risk areas are protected, leaving 1708.97 sq. km unprotected. In Gujarat, around 37% of the high-risk areas are covered by the Gulf of Kutch Marine National Park and other marine and coastal protected areas (Figure 4.8). All identified high-risk areas, both within and outside existing protected zones, are considered Critical Dugong Habitats (CDHs). In Tamil Nadu, there is a noticeable shift in critical CDHs from Palk Bay during the pre-monsoon season to the Gulf of Mannar in the post-monsoon season, indicating a probable short-range migration among the local dugong population.

Despite efforts, the existing Marine Protected Area currently cover only 0.26% of India's geographical area, significantly below the Aichi Biodiversity Target 11 goal of 10% protection for coastal and marine areas. The recently adopted Kunming-Montreal Global Biodiversity Framework sets an even more ambitious target of conserving at least 30% of terrestrial, inland water, coastal, and marine areas by 2030 (30x30 target). The findings highlight that the majority of the identified CDHs are yet to have any protection, underlining the importance of expanding and effectively managing MPAs to halt the population decline of dugongs, preserve seagrass habitats, and thereby achieve the 30x30 target. The study emphasises the

need for data-driven modelling research and risk assessment to effectively delineate Marine Protected Areas and enhance conservation strategies for dugongs in India.

In conclusion, this research underscores the importance of precise and consistent mapping efforts for the effective conservation of seagrass meadows. It provides valuable insights into developing a standardised protocol for nationwide seagrass mapping exercises, thereby contributing to global conservation goals. The study highlights the critical role of seagrass ecosystems and the necessity for improved mapping strategies. It concludes that addressing the dynamic nature of seagrass habitats through advanced mapping and monitoring techniques with higher temporal resolution is crucial for their effective conservation, aligning with global initiatives to preserve marine biodiversity and ecosystem health. Additionally, the thesis emphasises the need for geo-tagging dugongs to obtain confirmatory evidence of localised migration patterns. The significant spatial gaps in safeguarding Critical Dugong Habitats (CDHs) highlight the urgency of expanding the Marine Protected Area network through coordinated multi-stakeholder engagement.

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LIST OF ABBREVIATIONS

AIC	Akaike Information Criterion
ANI	Andaman and Nicobar Islands
AUC	Area Under Curve
CAMPA	Compensatory Afforestation Fund Management & Planning Authority
CART	Classification and Regression Tree
CBD	Convention on Biological Diversity
CCA	Community Conserved Areas
CDH	Critical Dugong Habitat
CoP	Conference of Parties
DAC	Diffuse Attenuation Coefficient
DCR	Dugong Conservation Reserve
DII	Depth Invariant Index
DNA	Deoxyribonucleic Acid
ENM	Environmental Niche Model
ETM+	Enhanced Thematic Mapper Plus
GEE	Google Earth Engine
GIS	Geographic Information System
GMED	Global Marine Environment Dataset
GoK	Gulf of Kutch
GoM	Gulf of Mannar
GPS	Global Positioning System
IMD	India Meteorological Department
IRS	Indian Remote Sensing Satellite
IUCN	International Union for Conservation of Nature
KM	K-Means
LISS	Linear Imaging Self Scanning Sensor
MaxEnt	Maximum Entropy
MD	Maximum Distance
MGMNP	Mahatma Gandhi Marine National Park
MPA	Marine Protected Area
NCP	Net Community Production
NDC	National Determined Contributions
NPB	North Palk Bay

NWM	North-west Monsoon
OECM	Other Effective Conservation Measures
OLI	Operational Land Imager
PA	Protected Area
PAR	Photosynthetically Active Radiation
PB	Palk Bay
PB-GoM	Palk Bay and Gulf of Mannar
RF	Random Forest
RJMNP	Rani Jhansi Marine National Park
ROC	Receiver Operating Characteristic
SA	South Andaman
SD	Standard deviation
SDG	Sustainable Development Goals
SDM	Species Distribution Model
SST	Sea Surface Temperature
SVM	Support Vector Machine
SWM	South-west Monsoon
TN	Tamil Nadu
UPES	University of Petroleum and Energy Studies
WII	Wildlife Institute of India

CHAPTER 1:
INTRODUCTION

CHAPTER 1: INTRODUCTION

1.1. The dugong

The dugong (*Dugong dugon*) is one of the four surviving species in the Order Sirenia and the only extant species of the exclusive herbivorous marine mammal. Historically, dugongs were distributed across the tropical and subtropical regions of the Indo-Pacific Ocean, inhabiting shallow coastal waters ranging from the east coast of Africa to the western Pacific Ocean (Marsh et al., 2002). Currently classified as ‘vulnerable’ by the IUCN Red List, their distribution is restricted to Australia, parts of southeast Asia, the Indian subcontinent, the Arabian Gulf, and the eastern coast of Africa (Marsh & Sobotzick, 2015). India retains the largest dugong population in the South Asia sub-region and thus plays a significant role in dugong conservation at a regional and global scale (Sivakumar, 2013). In a landmark decision, the Government of Tamil Nadu declared India's first-ever Dugong Conservation Reserve in the Palk Bay region in 2022. Spanning an area of approximately 450 km², this reserve aims to protect the critical seagrass habitats essential for dugongs while promoting sustainable fishing practices in the region. This initiative underscores the growing recognition of dugong conservation at both regional and national levels (Government of Tamil Nadu, 2022).

1.2. “Dugongs: Seagrass Community Specialists”

As the subheading suggested by Marsh et al. (2018), dugongs are specialised in exploiting seagrass herbivory in terms of biomass, food quality (nitrogen, starch, and water-soluble carbohydrates, structural carbohydrate and fibre, secondary metabolites, etc.). They are primary consumers, feeding almost exclusively on marine phanerogams (flowering plants) of the family Potamogetonaceae and Hydrocharitaceae (Heisohn & Birch, 1972; Prater, 1928). Marine algae are occasionally eaten when seagrasses are not in adequate quantity (Spain & Heisohn, 1973). Intake of invertebrates has also been recorded but may be consumed incidentally with seagrasses (Spain & Heisohn, 1973). Therefore, they can be characterised as the specialists of the seagrass herbivory.

1.3. Seagrass meadows as significant habitat for dugongs and other associated fauna

As an essential ecological niche, supporting very specific and ecologically important organisms in the marine food chain and regulating the health of the ocean as well as the coast, they have been considered under goal no. 14, ‘Life under water’, under the United Nations Sustainable Development Goals (SDGs). Seagrass meadows are associated with high net community production (NCP), with the global mean estimated at around 6.70 t C ha⁻¹ year⁻¹ (Duarte et al., 2013). With such high productivity, seagrasses play an important role in

harbouring a variety of marine life, ranging from microbes to bigger mammals like dugongs (D'Souza & Patankar, 2009; Umamaheswari et al., 2009). Cullen-Unsworth & Unsworth, (2016) noted 697 species of fish from seagrass meadows of the Indo-Pacific and Hughes et al., (2009) highlighted that there is, more than one threatened associated species for every seagrass species globally. Such interdependencies and linkages at various levels illustrate the importance of an ecosystem-based management approach for their conservation.

1.4. Distribution of dugongs and seagrasses in Indian waters

Once spread out throughout the Indian coast, dugongs are currently restricted to pockets of the Gulf of Kutch, Gulf of Mannar, Palk Bay, and Andaman & Nicobar Islands, with only 200 individuals (approx.) left in the wild (Sivakumar, 2013). Numerous factors can be attributed as detrimental to their existence, such as., seagrass habitat loss, gill netting (Heinsohn and Spain, 1974), disease, water pollutants, indigenous use, and poaching. Of all the aforementioned threats, habitat destruction is one of the most imminent ones. Many studies show that the dugongs are heavily dependent on seagrass beds, and significant crashes in the dugong population have been observed because of the extensive decimation of seagrass beds (Preen & Marsh, 1995), also adversely affecting their reproductive ability (Marsh & Kwan, 2008).

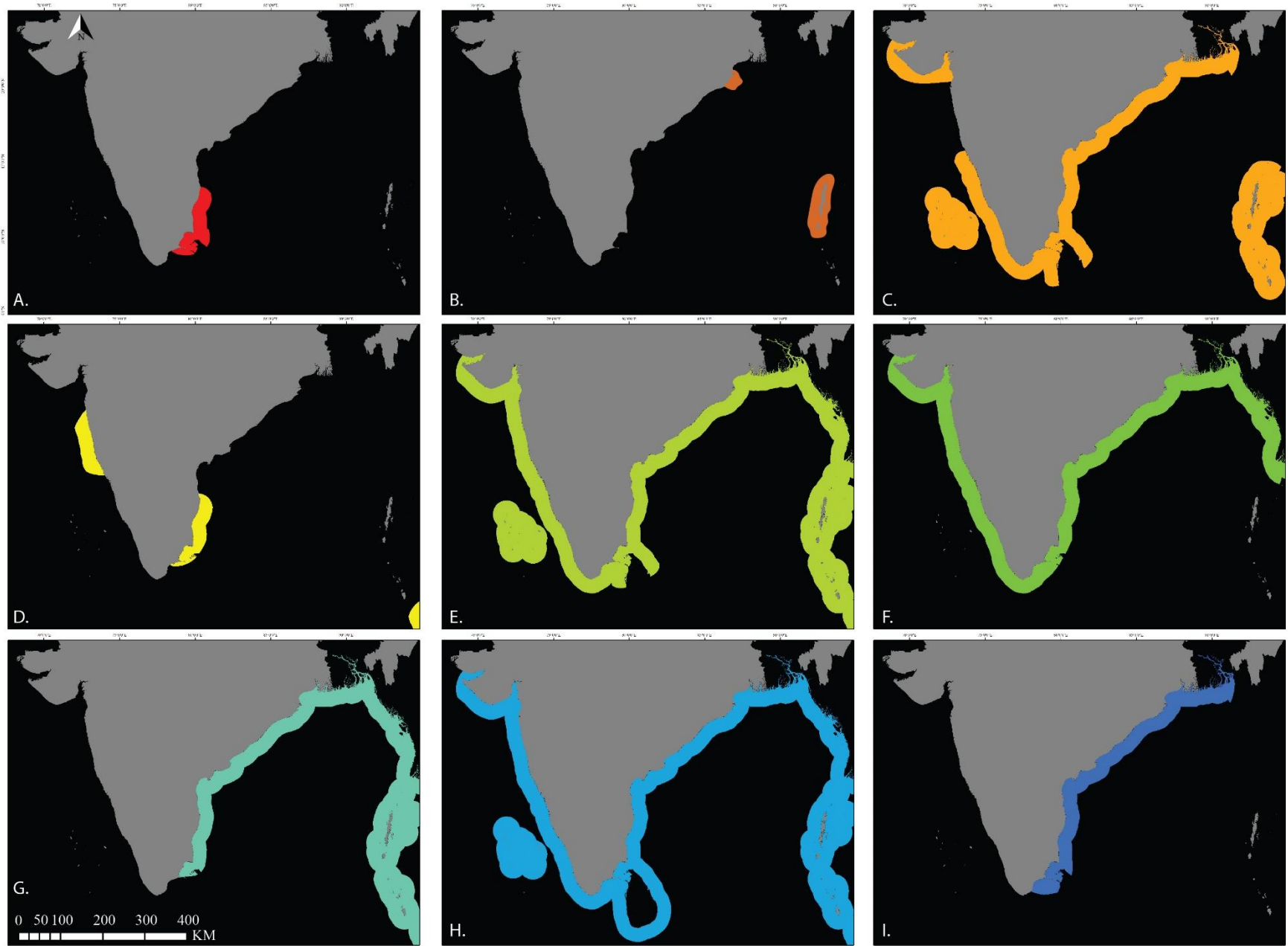
Though the IUCN website (IUCN, 2024) exhibits that seagrasses are distributed along the entire 8000 km coastline of India, the literature suggests that the distribution is restricted in isolated locations, including bays, open seas, estuaries, lagoons, and backwaters (Thangaradjou & Bhatt, 2018). The occurrence of seagrasses in the country has been recorded since the 1880s (Hooker, 1888a, 1893a), yet the exact number of species present in Indian waters is still under question (Thangaradjou & Bhatt, 2018). The most recent review removed discrepancies and shortlisted 15 seagrass species (15 species +1 sub-species) from a list of 22 species, as provided by various sources (Thangaradjou & Bhatt, 2018). The earlier count was 14 species (**Figure 1.1**), as reported by Dilipan et al., (2018) and Lucas et al., (2012).

The major coastal areas along the Indian coast that are rich in seagrass meadows are Palk Bay and Gulf of Mannar (14 species), Andaman and Nicobar Islands (12 species), Lakshadweep Islands (10 species), Odisha (8 species) and Gujarat (8 species) (**Table 1.1**). Comprehensive mapping of seagrasses has been done by Nobi et al., (2012); Nobi & Thangaradjou, (2012) and Umamaheswari et al., (2009), using geospatial technology in parts of the aforementioned hotspots of seagrasses. Using remote sensing techniques, seagrass patches to 5 m depth have been mapped, which reveals a country-level extent of 250 km². This excludes major seagrass meadows in backwaters, lagoons, and areas beyond 5 m depth since various studies show that

the seagrasses (namely, *Enhalus acoroides*) can be found to 25 m depth. Combining both zones, the national seagrass extent has been estimated as 500 km² (Geevarghese et al., 2018; Thangaradjou & Bhatt, 2018).

Table 1.1.: Distribution of seagrass species in different coastal states in India, where 'Green' indicates 'presence' and 'red' indicates 'absence'. (Thangaradjou & Bhatt, 2018)

S. No.	Species	Gujarat	Mahara shtra	Goa	Karnat aka	Kerala	Tamil Nadu			Andhra Pradesh	Orissa	West Bengal	Laksha dweep	Andaman Islands	Nicobar Islands
							Gulf of Mannar	Palk Bay	Other sites						
1	<i>Enhalus acoroides</i>	Red	Red	Red	Red	Green	Green	Green	Red	Red	Red	Green	Green	Green	
2(i)	<i>Halophila ovalis</i>	Green	Red	Green	Red	Green	Green	Green	Green	Green	Green	Green	Green	Green	
2(ii)	<i>H. ovalis ramamurthiana</i>	Red	Red	Red	Red	Red	Red	Green	Green	Green	Red	Red	Red	Red	
3	<i>H. ovata</i>	Green	Red	Red	Red	Red	Green	Green	Red	Green	Green	Green	Green	Green	
4	<i>H. decipiens</i>	Red	Green	Red	Red	Red	Green	Green	Red	Red	Red	Green	Green	Red	
5	<i>H. stipulacea</i>	Red	Red	Red	Red	Red	Green	Green	Red	Red	Red	Red	Green	Red	
6	<i>H. beccarii</i>	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Red	Red	Red	
7	<i>H. minor</i>	Red	Red	Red	Red	Red	Red	Red	Red	Green	Red	Red	Green	Red	
8	<i>Thalassia hemprichii</i>	Green	Red	Red	Red	Red	Green	Green	Red	Red	Red	Green	Green	Green	
9	<i>Syringodium isoetifolium</i>	Red	Red	Red	Red	Red	Green	Green	Red	Red	Red	Green	Green	Green	
10	<i>Cymodocea serrulata</i>	Green	Red	Red	Red	Red	Green	Green	Red	Red	Red	Green	Green	Green	
11	<i>C. rotundata</i>	Red	Red	Red	Red	Red	Green	Green	Red	Red	Red	Green	Green	Green	
12	<i>Halodule pinifolia</i>	Green	Red	Red	Red	Red	Green	Green	Green	Green	Green	Green	Green	Green	
13	<i>H. uninervis</i>	Green	Red	Red	Red	Red	Green	Green	Green	Green	Green	Green	Green	Green	
14	<i>H. wrightii</i>	Red	Red	Red	Red	Red	Green	Green	Green	Red	Green	Red	Red	Red	
15	<i>Ruppia maritima</i>	Green	Red	Red	Red	Red	Green	Red	Red	Red	Green	Red	Red	Red	



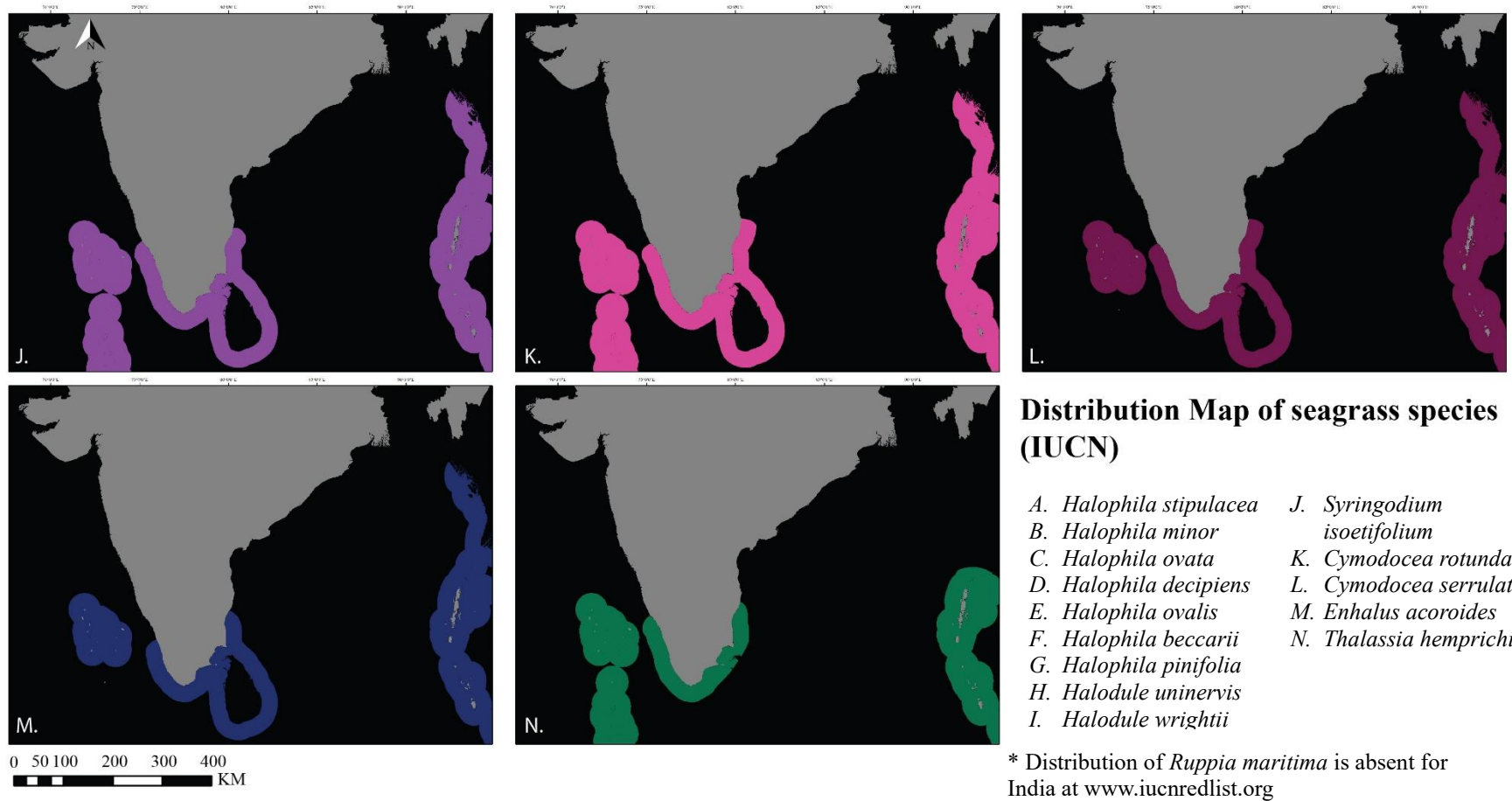


Figure 1.1.: Distribution maps of different seagrass species found in Indian waters. Seagrass species *Ruppia maritima* was not reported in IUCN Red List. Data source: IUCN

1.5. Study area

The Indian seascape is a part of the Indian Ocean, divided into the Arabian Sea and the Bay of Bengal. 75% of India's land area is bordered by seas with a vast coastline of 7517 km, of which 5423 km belongs to peninsular India and 2904 km belongs to Andaman, Nicobar and Lakshadweep Islands. With a 2.4% share of the global landmass, India harbours the highest human population of more than 1.43 billion. Therefore, a huge population is dependent on the rich coastal and marine resources of this coastline.

The state of Tamil Nadu shares the second largest coastline of 1076 km along the Bay of Bengal, bordering Sri Lanka by Palk Bay (Henceforth PB) and the Gulf of Mannar (henceforth GoM). The PB is a semi-enclosed shallow water body between the southeast coast of India and Sri Lanka, with a water depth maximum of 13 m. Palk Bay is located between 8° 50' and 10° North latitudes and 78° 50' and 80° 30' East longitudes, comprising three districts, namely, Thanjavur, Pudukottai and partly Ramanathapuram (from north to south). The width of PB ranges from 57 to 107 km, and the length is around 150 km, harbouring the recently declared Dugong Conservation Reserve in the north (Government of Tamil Nadu, 2022). The GoM is 160 km long and 130–275 km wide. It is a large, shallow bay that's part of the Laccadive Sea in the Indian Ocean. It also harbours South and Southeast Asia's first marine biosphere reserve, named the Gulf Mannar Biosphere Reserve. It runs from Rameswaram Island to Thoothukkudi for 140 km, with the Gulf of Mannar Marine National Park at its core. The primary surveys were focussed on the Gulf of Mannar Marine National Park region, which contains 21 islands that run parallel to the gulf's coastline, along with 37 small towns and villages from two districts, namely, part of Ramanathapuram district and Thoothukkudi with a population of 4,60,004 (**Figure 1.2-B**).

On the other hand, the South Andaman (henceforth the South Andaman or SA) district belongs to the union territory of the Andaman and Nicobar Islands (ANI). It harbours two Marine National Parks, namely Mahatma Gandhi Marine National Park (MGMNP) and Rani Jhansi Marine National Park (RJMNP). The Andaman group of islands is nestled in the Bay of Bengal with comparatively deeper and clearer waters than PB. Here, the primary surveys were targeted at the MGMNP region in the South Andaman district, which harbours two tehsils, namely Ferrarganj and Port Blair, with a combined population of 2,08,471 (**Figure 1.2-C**).

For a holistic criticality analysis of dugong habitats in India, the Gulf of Kutch (henceforth GoK) in the state of Gujarat was also considered in the later part of the thesis. The GoK, the largest gulf along the Arabian Sea on India's western coast, spans an area of 7,350 km²,

including 457.92 km² designated as the Marine National Park and Sanctuary. This region, comprising a cluster of 42 small coastal islands, is home to the only marine national park on India's west coast and the sole marine sanctuary in Gujarat (Sukumaran et al., 2013). Situated in the subtropical climatic zone, GoK experiences significant geomorphological and climatic variability. It supports eight species of seagrass (e.g., *Halophila ovalis*, *Halodule uninervis* etc.), covering approximately 23 km² (Pandey et al., 2010; Pathan et al., 2022), and harbors a small relict population of dugongs, estimated at fewer than 10–15 individuals (Anand, 2021) (Figure 1.2-A).

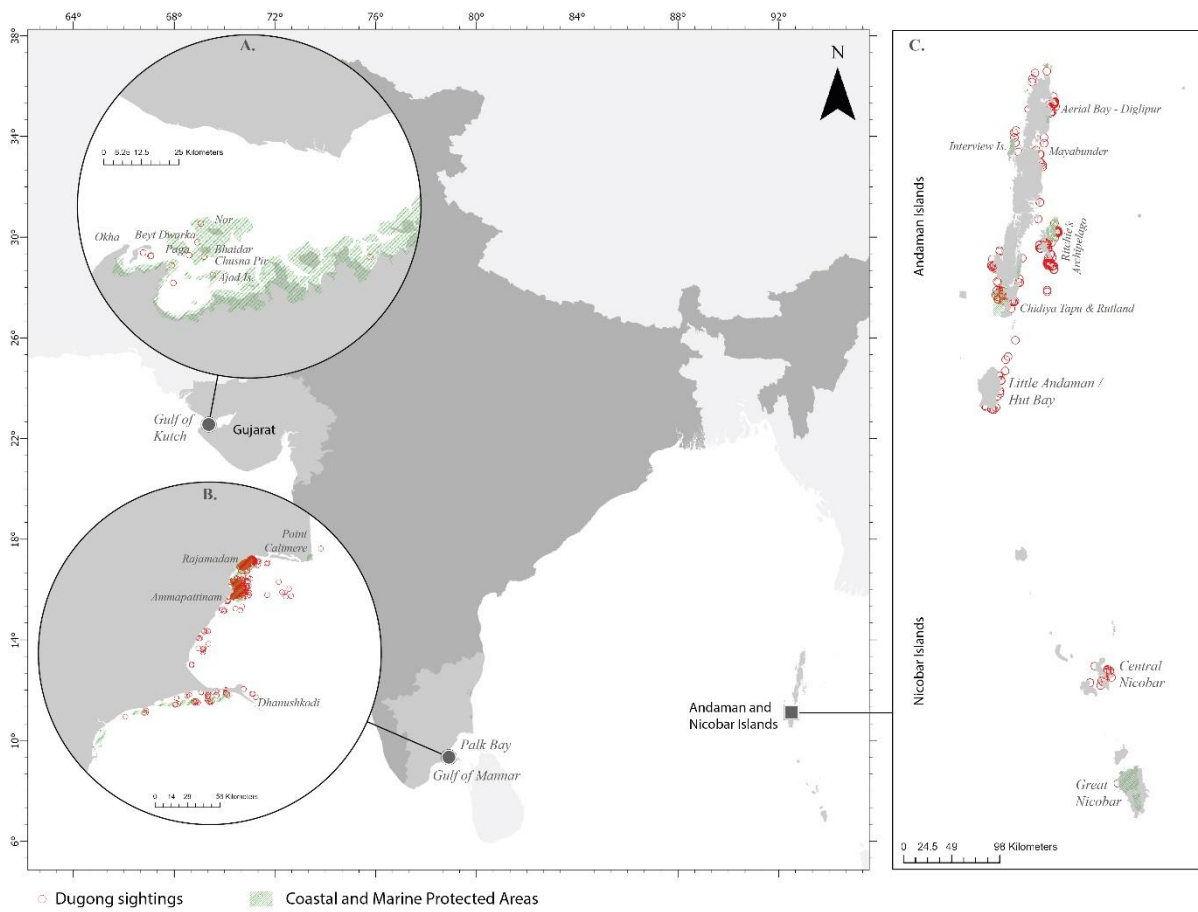


Figure 1.2: Study sites along the Indian coastline (A) Gulf of Kutch (GoK), Gujarat on the northwest coast in the Arabian Sea; (B) Palk Bay and Gulf of Mannar (PB-GoM), Tamil Nadu to the south–east coast in the Bay of Bengal and (C) Andaman & Nicobar Islands (ANI)—offshore islands located in the Bay of Bengal to the south–east of peninsular India. The red circles represent dugong sighting locations between 2008 and 2021. The output maps were generated using ArcGIS Pro 3.2.1 software.

1.6. Scope of the current study

The IUCN overestimated the dugong distribution in almost the entire west coast of India and in the Tamil Nadu region of the east coast. The distribution has been declining over the years and is currently restricted to some pockets of the Indian coastline, namely, the Gulf of Kutch in Gujarat, Palk Bay and Gulf of Mannar in Tamil Nadu and Andaman and Nicobar Islands (Sivakumar & Nair, 2013). Also, after the recent functional extinction of the species from China (Lin et al., 2022), India harbours the only dugong population in South Asia. Therefore, it is important to remap the distribution of the Indian population of dugongs to optimise conservation efforts.

Secondly, seagrasses are the major habitat for dugongs and provide various ecosystem services; unlike mangroves, they do not have any regular mapping exercises in India (Thangaradjou & Bhatt, 2018). Some efforts have been made at a regional scale with coarser resolution or paid satellite imageries (Geevarghese et al., 2018; Gunasekara & Mishra, 2014; Nobi & Thangaradjou, 2012; Paulose et al., 2013; Umamaheswari et al., 2009).

Thirdly, in the report by Sivakumar & Nair (2013), the fishing pressure was quantified on the basis of a social survey. The precision to identify the highly fished areas could be better.

The current study addresses these gaps by mapping the seagrass distribution in the study area by using the freely available sentinel 2A and 2B satellite imageries at a resolution of 10m and further modelling the dugong distribution with collected sighting locations between 2012-13 and between 2018-21. The fishing tracks were collected by using GPS loggers to quantify the fishing pressure with higher precision. Finally, all the layers were collated to identify the critical dugong habitats (CDHs) to optimise conservation and management efforts.

1.7. Objectives of the study

The principal aim of the study is to classify and further identify the Critical Dugong Habitats (CDHs) in the study area. To attain the principal objective, we mapped the seagrass distribution using satellite imageries as their major habitat. We also collated other environmental governing factors that determine dugong distribution to model the dugong distribution in the study area. Simply distribution modelling of dugongs may not give a holistic picture to identify the CDHs. Therefore, we mapped the fishing pressure in the area by GPS, tracking the fishing routes of identified fisherfolk and overlaying them with the distribution layer to identify the CDHs.

To summarise the objectives of the study:

1. To understand the distribution status of seagrass meadows in selected dugong habitats using in situ and remote sensing data.
2. Mapping the interface between dugong distribution and fisheries in selected dugong habitats.
3. Mapping the environmental governing factors that determine dugong distribution.
4. Integrating environmental and habitat parameters in GIS platform to classify Critical Dugong Habitats (CDHs).

1.8. Chapter organisation

Chapter One introduces the target animal (i.e., dugong) and its major habitat (i.e., seagrass). It also talks about their distribution in Indian waters. It also describes the study area, scope and objectives of the study.

Chapter Two talks about the mapping of seagrasses using in situ location data and remote sensing satellite imageries. It also explains how turbidity can affect the classification process and how to select the best-fit classification algorithm for better overall accuracy. It also identifies the novelty of this mapping technique in comparison to previous mapping attempts.

Chapter Three explains the second objective of the study, which is how fishing pressure can be mapped using GPS data loggers.

Chapter Four integrates the third and fourth objectives of the study that what are the environmental governing factors that influence the dugong distribution, and identifies the CDHs in the study area.

Chapter Five concludes the study by summarising the key findings, policy implications and shading light towards the scope of future studies.

CHAPTER 2:
SEAGRASSES

CHAPTER 2: SEAGRASSES

2.1. Introduction

Seagrasses are marine flowering plants that inhabit all coastal zones of 191 countries, irrespective of any continent except Antarctica (Duarte et al., 2013; McKenzie et al., 2020). Around 60 species belonging to 11 genera and four families are found worldwide (Green & Short, 2003; Horton et al., 2017) along tropical and temperate shallow coastal waters (Larkum et al., 2006). The global extent of seagrasses is estimated to be between 1,77,000 km² and 6,00,000 km² (Duarte et al., 2010; Green & Short, 2003). A recent study estimated a cover of 1,60,387 km² with moderate to high confidence from 103 countries, with the tropical Indo-Pacific bio-region having the most extensive cover of 87,789 km² (~44% of the global cover).

Seagrass meadows are vital for maintaining marine biodiversity and ecosystem health, providing habitat and sustenance for a wide range of life, from microbes to dugongs, while also supporting high net community production (D'Souza & Patankar, 2009; Umamaheswari et al., 2009). Hughes et al. (2009) highlighted a global average of associating more than one threatened species with every seagrass species. Considering the species richness in seagrass meadows, their importance aligns well with UN Sustainable Development Goal 14 (Life under water) (Duarte et al., 2013) They aid in nutrient recycling, maintaining water quality (Umamaheswari et al., 2009) and light availability (Björk et al., 2008), which is crucial for the proper functioning of coastal ecosystems. Additionally, they stabilise coastlines and provide food and livelihoods to the coastal populations, like India's (Authority, 2016). They can hold twice the amount of carbon compared to terrestrial ecosystems. Recognising this ecosystem service as a significant climate change mitigator globally, conserving these ecosystems is imperative, especially in countries with extensive seagrass beds like India (Koshy et al., 2018; Rudd, 2014). The mandates of the Paris Climate Agreement, which delineate National Determined Contributions (NDCs) aimed at emission reduction, amplify international attention towards the spatial coverage, decline, and rehabilitation of seagrass ecosystems (McKenzie et al., 2020).

As a tropical country, India also houses diverse species of seagrasses, covering approximately 500 km² (Geevarghese et al., 2018; Thangaradjou & Bhatt, 2018). The occurrence of seagrasses in the country has been recorded since the 1880s (Hooker, 1888b, 1893b). Though the exact number of species present in Indian waters is still under question, a recent comprehensive study reported 15 seagrass species (15 species +1 sub-species) from a list of 22 species, as provided by various sources (Thangaradjou & Bhatt, 2018). The earlier count

was 14 species, as reported by Dilipan et al., (2018); Kannan et al., (1999) and Lucas et al., (2012).

The mapping of seagrass distribution started long back in 1871 (Ascherson & Beccari, 1871). Since then, various studies attempted to map seagrass meadows at national and global levels. Conventional survey methods are very labour-intensive and time-consuming due to the constraints of working in the marine environment. Hence, remote sensing provides a handy tool to map seagrass distribution and assess change detection with Geographic Information System (GIS) techniques (Kendrick et al., 2002). In India, the use of satellite imaging for seagrass detection and mapping studies has been minimal (**Table: 2.1**).

Table 2.1.: Details of previous studies from India to map seagrasses using different satellite imageries and their respective accuracies.

Sl. No.	Imageries Used	Spatial Resolution	Study area	Accuracy (%)	Citation
1	IRS LISS III	23.5 m	Lakshadweep	67.5	(Nobi & Thangaradjou, 2012)
2	Landsat 8 OLI.	30 m	(i) Palk Bay (ii) Gulf of Mannar (Tamil Nadu) (iii) Gulf of Kachchh (Gujarat) (iv) Chilika Lake (Odisha) (v) Islands of Andaman & Nicobar and (vi) lagoons of Lakshadweep Islands	64 to 83.5	(Geevarghese et al., 2018)
3	IRS-1D, LISS III	23.5 m	Gulf of Mannar		(Umamaheswari et al., 2009)
4	IRS P6 LISS IV	5.8 m	Lakshadweep Islands	73.16	(Nobi et al., 2012)
5	Landsat ETM+	30 m	i. Gulf of Mannar ii. Palk Bay	85.19 92.59	(Gunasekara & Mishra, 2014)
6	IRS P6 LISS III	23.5 m	Andaman and Nicobar Islands	40	(Paulose et al., 2013)

Umamaheswari et al. (2009) started the comprehensive mapping of seagrasses using geospatial technology in the Gulf of Mannar region. (Nobi et al., 2012, 2013; Nobi & Thangaradjou, 2012; Paulose et al., 2013) succeeded in mapping seagrass patches to 5 m depth in Lakshadweep and Andaman Islands, which reveals a country-level extent of 250 km² seagrass cover. Bayyana et al., 2020 reported successful mapping of seagrass meadows to 21 m of depth. Hence, the previous studies lack mapping of major seagrass meadows in backwaters, lagoons, and areas beyond 5 m depth.

However, in India, unlike mangroves (mapped at every two-year interval) and corals (mapped at decadal intervals), there is no such regular mapping scheme available for seagrasses (Thangaradjou & Bhatt, 2018). Also, India stands 16th in the number of publications on seagrasses (York et al., 2017), whereas countries with a much lesser coastal extent and EEZ are in the lead. Therefore, in India, seagrass ecosystems have yet to gain attention from the scientific fraternity regarding management and conservation. With a commitment to creating an additional carbon sink of 2.5–3 billion tonnes of carbon dioxide in its 2015 climate plan (Ministry of Environment, 2015), India has an excellent opportunity to develop a detailed plan to prepare a holistic policy towards long-term monitoring and conservation of such essential but fragile habitats.

Consequently, there is also an urgent necessity for enhancing the precision and consistency in assessing the worldwide spatial dispersion of seagrass. Limited mapping efforts and dynamicity in their extent (naturally changing in expanse, without anthropogenic interference) underscore the disparity in their global seagrass extent. Also, the mapping exercise sometimes gets complex because of varying turbidity and depth profiles (McKenzie et al., 2020) (**Plate 2.1**). Therefore, a combination of remote sensing techniques and validation using conventional methods is suggested for more precise results.

Hence, this chapter discusses the effective mapping technique of seagrasses at a finer spatial scale by addressing the limiting factors like turbidity and variation in depth. It also explores the possibility of habitat modelling techniques to predict seagrass distribution at a larger spatial scale. It outlines the various datasets used in mapping and modelling methodologies, output maps, and habitat suitability models of seagrass distribution and their comparison with previous studies. Finally, it concludes with effective mapping algorithms on a case-to-case basis, with some management recommendations.

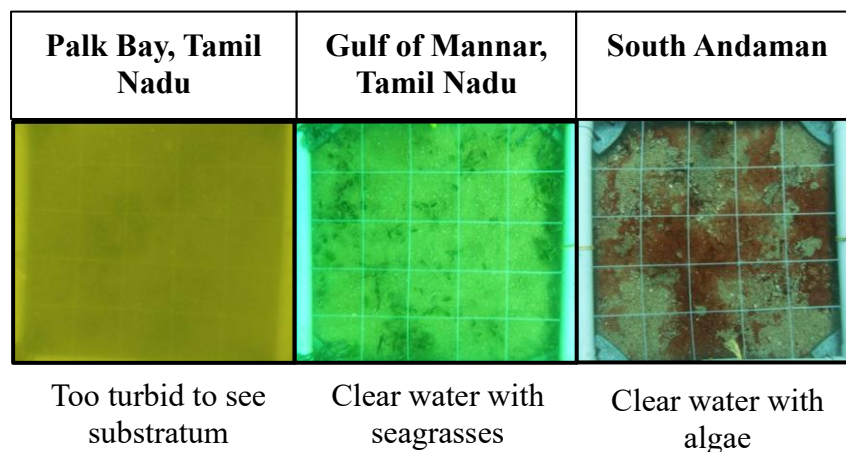


Plate 2.1: Turbidity at different study sites at Palk Bay and Gulf of Mannar in Tamil Nadu and Andaman and Nicobar Islands, as recorded in GoPro videos.

2.2. Methods and materials

In situ presence locations, in combination with remotely sensed satellite data, were used to map the seagrasses in the study area. Moreover, a set of eco-geographical variables was used to derive a Maximum Entropy (MaxEnt) model for a greater spatial extent and to generate a raster layer with continuous pixel values.

2.2.1. Seagrass survey

2.2.1.1. For mapping of seagrasses

We conducted intertidal and subtidal surveys between 2020 and 2023 using the line-intercept transect method (McKenzie et al., 2020) to record seagrass presence/absence in PB, GoM and SA. For intertidal surveys (**Plate 2.2**), 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 the depth (measured with HawkEye DT1H Handheld Depth Finder) is greater than the water turbidity (measured with a Secchi disk), we used the drop-down quadrat method with a GoPro Hero 6

camera attached at the top of the quadrat frame (Bertelli et al., 2021) to record seagrass presence. All locations were recorded using a Garmin eTrex 30x handheld GPS unit.

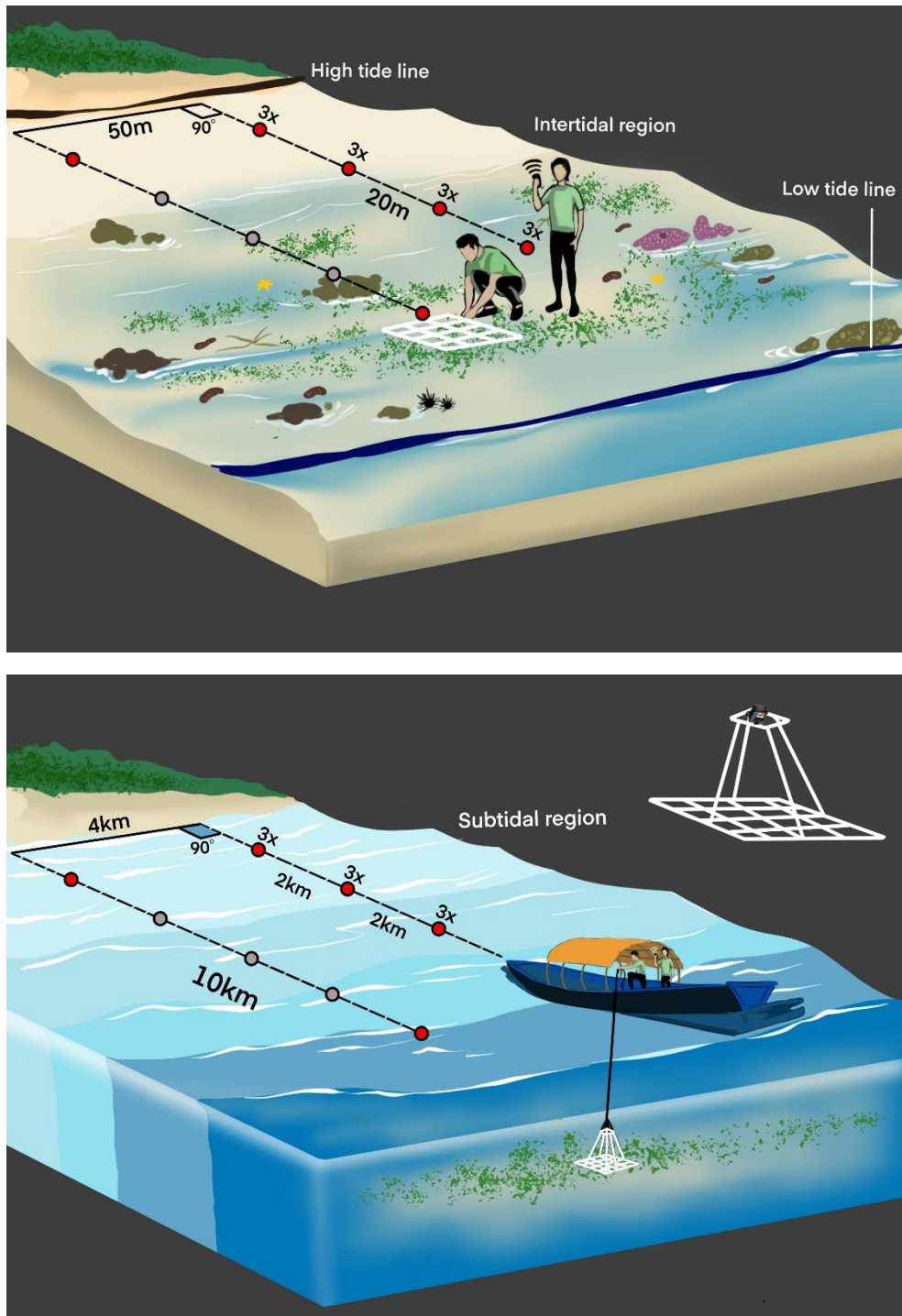


Plate 2.2: Illustrations of the methodology used in intertidal (top) and subtidal (bottom) surveys to record seagrass presence/absence data (Illustrations credit: Vabesh Tripura).

The videos were further analysed in the lab to calculate the percentage cover of seagrasses and the substrate present (Plate 2.2). Also, depth was recorded at every sampling station (Plate 2.3). Feature classes were drawn as small object-based polygons for signature classes, and the total data points were segregated into 70:30 for training and validation.



Plate 2.3.: A. Structure for drop-down quadrat with a GoPro fixed over it. B. Assessing the transparency using a Secchi Disk. C. Dropping off the quadrat and recording the observation. Photos credits: Sweta Iyer, Sohom Seal, Ajith Kumar.

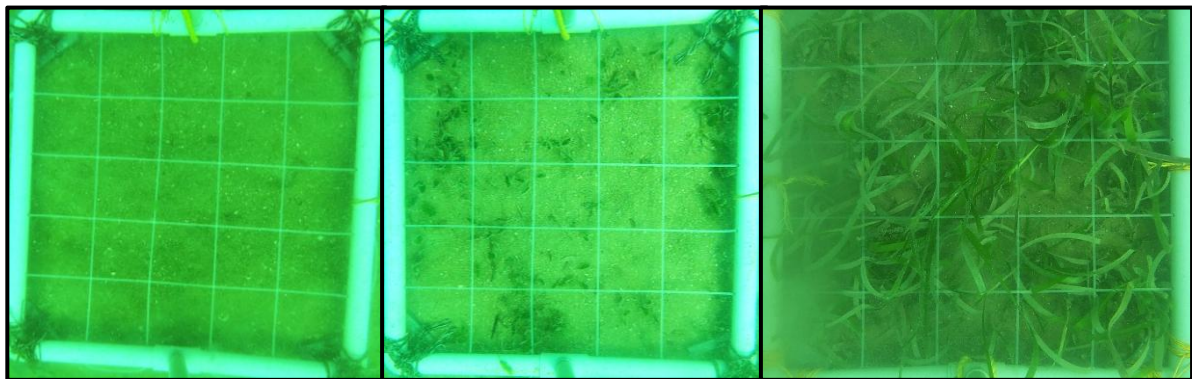


Plate 2.4.: Representative photos to assess seagrass cover (a) 0% (b) 40% and (c) 100%.

2.2.1.2. Seagrass distribution modelling

Seagrass mapping is almost impossible in the GoK region because of high turbidity. Therefore, the seagrass distribution modelling was also tried out in this region and in the other two sites as well. We conducted intertidal and subtidal surveys between 2018 and 2021 using the line-intercept transect method (McKenzie et al., 2020) to record seagrass presence across three regions. Fifty-meter transects were laid perpendicular to the shoreline, with 50 x 50 cm quadrats placed at 5-meter intervals along the transect line. For subtidal seagrass meadows where diving was not feasible, we performed boat-based surveys with visibility of approximately 3-5 meters measured by a Secchi disk. We used the drop-down quadrat method, equipped with a GoPro Hero 6 camera mounted on the quadrat frame, to document seagrass presence (Bertelli et al., 2021). In areas with low water transparency (visibility less than depth), such as near-shore areas of PB-GoM and GoK, we employed Van-Veen grabs. All locations were recorded using a Garmin eTrex 30x handheld GPS unit.

Seagrass polygons, given by Jayathilake & Costello, (2018), were also extracted for the study areas. 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.

2.2.2. Remotely sensed and environmental variables

2.2.2.1. For mapping of seagrasses

To maintain uniformity in classification methodology and compare the results at different sites, a cloud-based Google Earth Engine (GEE) platform was used to extract, process, and classify satellite imagery (Traganos et al., 2018). Sentinel 2A and 2B data (**Table 2.2**) at a spatial resolution of 10m was used to map the seagrass distribution of SA and GoM.

Table 2.2: Details of the satellite imagery used for mapping seagrasses along with bands used.

<i>Metadata of the imagery used</i>	
<i>Satellite</i>	Sentinel-2A and 2B
<i>Processing level</i>	Level-2A
<i>Product Type</i>	S2MSI2A
<i>Instrument</i>	Multispectral Instrument (MSI)
<i>Bands used</i>	Band 2 Blue (496.6 nm-S2A/492.1 nm-S2B)-depth-invariant
	Band 3 Green (560 nm-S2A/559 nm-S2B)-depth-invariant
	Band 4 Red (664.5 nm-S2A/665 nm-S2B)-depth-invariant
	Band 8 NIR (835.1 nm-S2A/833 nm-S2B)-depth-invariant
	Depth
	Normalised Differential Seagrass Index (NDSgI)
<i>Spatial Resolution</i>	10 m
<i>Sensing date</i>	01-12-2020 to 31-03-2021 (ANI)
	01-10-2021 to 15-02-2022 (GoM)
	01-12-2021 to 31-03-2023 (PB.)
<i>Cloud cover</i>	1%

Land masking was done using B3 (Green) and B8 (NIR) bands by eqn (i) (McFeeters, 1996).

$$B' = \frac{B3 - B8}{B3 + B8} \dots \dots \dots eqn (i)$$

To nullify the effect of depth, sand locations at different depths were extracted to compute the Depth Invariant Index (DII) (Lyzenga, 1981). Regression lines with the natural logarithmic values of respective band combinations (B2~3, B3~4, B4~2) were plotted for randomly selected points with varying depths. The R2 values were calculated to assess the fitness of the regression lines. Furthermore, the DII was calculated by the eqn (ii) (Lyzenga, 1981).

$$DII \text{ at individual points} = \ln(B_i) - \left(\frac{K_i}{K_j}\right) * \ln(B_j) \dots \dots \dots eqn. (ii)$$

$$\frac{K_i}{K_j} = a + \{\sqrt{(a^2 + 1)}\}$$

$$a = \frac{\{var(B_i) - var(B_j)\}}{\{2 * CoV(B_{ij})\}}$$

where, $B_i = \text{Band 1}$, $B_j = \text{Band 2}$

$var(B_i) = \text{variance of band 1}$, $var(B_j) = \text{variance of band 2}$

$CoV(B_{ij}) = \text{Covariance of band 1 and 2}$

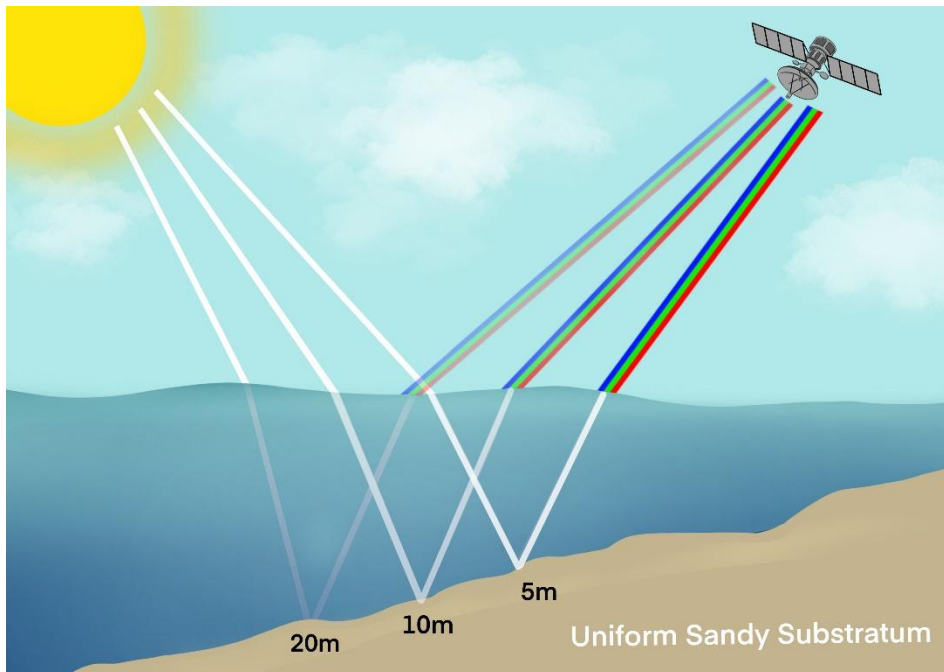


Plate 2.5.: Illustration to show the change in reflectance with depth (Illustration credit: Vabesh Tripura).

Since seagrasses were reported up to 23 m of depth in India, depths beyond 30 m in SA were masked using bathymetric charts collected from the National Hydrographic Office, Dehradun, to increase the accuracy of the classification.

Finally, unsupervised and supervised classification algorithms were tested at SA and GoM for optimum overall accuracy and to understand the effect of turbidity and depth on mapping accuracy. The output maps for the respective study areas were generated in ArcMap v.10.8 (www.esri.com) software, and area calculation was done by down-sampling the raster layer to 100 m for faster computation.

2.2.2.2. For seagrass distribution modelling

Seagrass distribution modelling was carried out for the entire regions of GoK, PB-GoM and ANI in MaxEnt v.3.4.4 (https://biodiversityinformatics.amnh.org/open_source/maxent) software and a combination of 13 abiotic variables (Table 2.3) (Jayatilake & Costello, 2018). The variables were downloaded from the Global Marine Environment Dataset (GMED) (<https://gmed.auckland.ac.nz/>) and were checked for their variability in the concerned study

sites. Further, all the variables were resampled at 1km spatial resolution. Multi-collinearity among the variables was tested for each site, by which one variable from Jayathilake & Costello (2018), namely dissolved oxygen, was dropped. Further, two additional variables, euphotic depth and surface current, were considered per ecological knowledge. All the layers were standardised to a spatial resolution of 1km. The MaxEnt model was run through 10 cross-validated replications, incorporating specific parameters: a convergence threshold of 10^{-5} , a regularisation multiplier of 1, a maximum of 10,000 background points, and a maximum of 1000 iterations. The cross-validation process involved partitioning the sample into folds, with each fold serving as test data (Jayathilake & Costello, 2018; Phillips & Dudík, 2008). The model's performance was evaluated using the Receiver Operating Characteristic (ROC) method (Phillips et al., 2006). We selected 'logistic' as the output format and assessed model accuracy with Area Under Curve (AUC) value. The AUC within the ROC, ranging from 0 to 0.5, signifies predictions equivalent to random chance, while a value of 1 represents optimal prediction quality (Elith et al., 2011; Phillips et al., 2006).

Table 2.3: List of environmental variables used in this study from Global Environment Dataset (GMED) (Basher et al., 2018)

Layers	Original resolution
Depth (m)	30 arc sec
Slope (°)	5 arc min (~9.2 km)
Euphotic depth (m)	2.5 arc min (~4 km)
Distance from the shore (km)	5 arc min (~9.2 km)
Salinity (PSS.)	1°
pH	1°
Photosynthetically Active Radiation (P.A.R.) (Einstein/m ² /day)	5 arc min (~9.2 km)
Sea Surface Wave Height (m)	5°
Surface current (m/s)	0.25°
Phosphate (ml/l)	1°
Nitrate (µmol/l)	1°
Diffuse Attenuation Coefficient (Kd) (m ⁻¹)	5 arc min (~9.2 km)
Sea Surface Temperature-mean (°C)	5 arc min (~9.2 km)
Sea Surface Temperature-max (°C)	5 arc min (~9.2 km)

2.3. Results and discussion

2.3.1. Outputs of seagrass mapping

The study highlights the attempt to map seagrass distribution with freely available high-resolution satellite imagery at a spatial resolution of 10 m. Previous studies entrusted on either coarser resolution satellite imageries (Geevarghese et al., 2018; Gunasekara & Mishra, 2014; Nobi et al., 2013; Nobi & Thangaradjou, 2012; Paulose et al., 2013; Umamaheswari et al., 2009) or commercially available products (Nobi et al., 2012), with varying degrees of

accuracy ranging from 40-92%. In the case of ANI, the highest mapping accuracy of 99% could be recorded from Richies' Archipelago (Bayyana et al., 2020). We could successfully map seagrass meadows at varying site parameters with acceptable and consistent accuracy (**Table 2.5**).

Conversely to the previous study by Geevarghese et al. (2018), which found better mapping accuracy in PB (73%) and GoM (83%) than ANI (64-67%), our study highlights seagrasses from transparent waters (as in GoM and SA) can be more accurately mapped in comparison to that of turbid waters (as in PB).

The seagrass meadows in PB are somewhat continuous and extend well beyond the coastline to 9 km (Mathews et al., 2010), whereas GoM and ANI harbour seagrass only at the edges of the coastline because of their abrupt change in depth profile. PB's topography and sediment texture favours luxuriant seagrass growth (Mathews et al., 2010) with a coverage area of 384 km² and Ramanathapuram district in the southern part having the largest share. GoM and ANI, on the other hand, though having more transparent waters with good light penetration, have sparse meadows (**Figure 2.2**). The latter two sites are also subjected to higher wave action because of the openness of the seascape, which may hinder seagrass growth. Moreover, we suspect the previous studies in the PB-GoM region to be under-reported in terms of seagrass cover. The intensive survey in the current study enabled us to estimate a seagrass cover of 634 km² from the region (**Table 2.4**).

Table 2.4: Cover of seagrass in different study sites (*from Thondi to Pamban).

Regions	Districts / Protected areas	Area (km ²)	Previous studies		Reference
			Area (km ²)	Year	
Palk Bay	Thanjavur	33.54	26.58	2004	(Sridhar et al., 2010)
	Pudukottai	82.132			
	Ramanathapuram	268.464	175*	2008	(Mathews et al., 2010)
Gulf of Mannar		201.785	76	2008	(Mathews et al., 2010)
	Thoothukkudi	48.27			
South Andaman	MGMNP, South Andaman	25.033			

In comparison to 3 classification algorithms [Random Forest (RF), Support Vector Machine (SVM) and K-nearest neighbour] as tested in previous studies (Bayyana et al., 2020), a total of 6 algorithms as available on GEE platform [one unsupervised, namely K-Means and five supervised, namely, Maximum Distance, SVM, Classification and Regression Tree (CART),

Naïve Bayes and RF] were tested based on overall accuracy and kappa value. To test these algorithms, classification was run in three sites with different site parameters: north PB (NPB), GoM and South Andaman (SA). CART was found to be better suitable in simpler systems, as in clearer waters of GoM and SA. Interestingly, as suggested by Bakirman & Gumusay (2020) and Bayyana et al. (2020), SVM performed well in terms of overall accuracy but was not supported by accepted kappa value; hence, it was not prepared as a classifier algorithm (**Figure 2.1**).

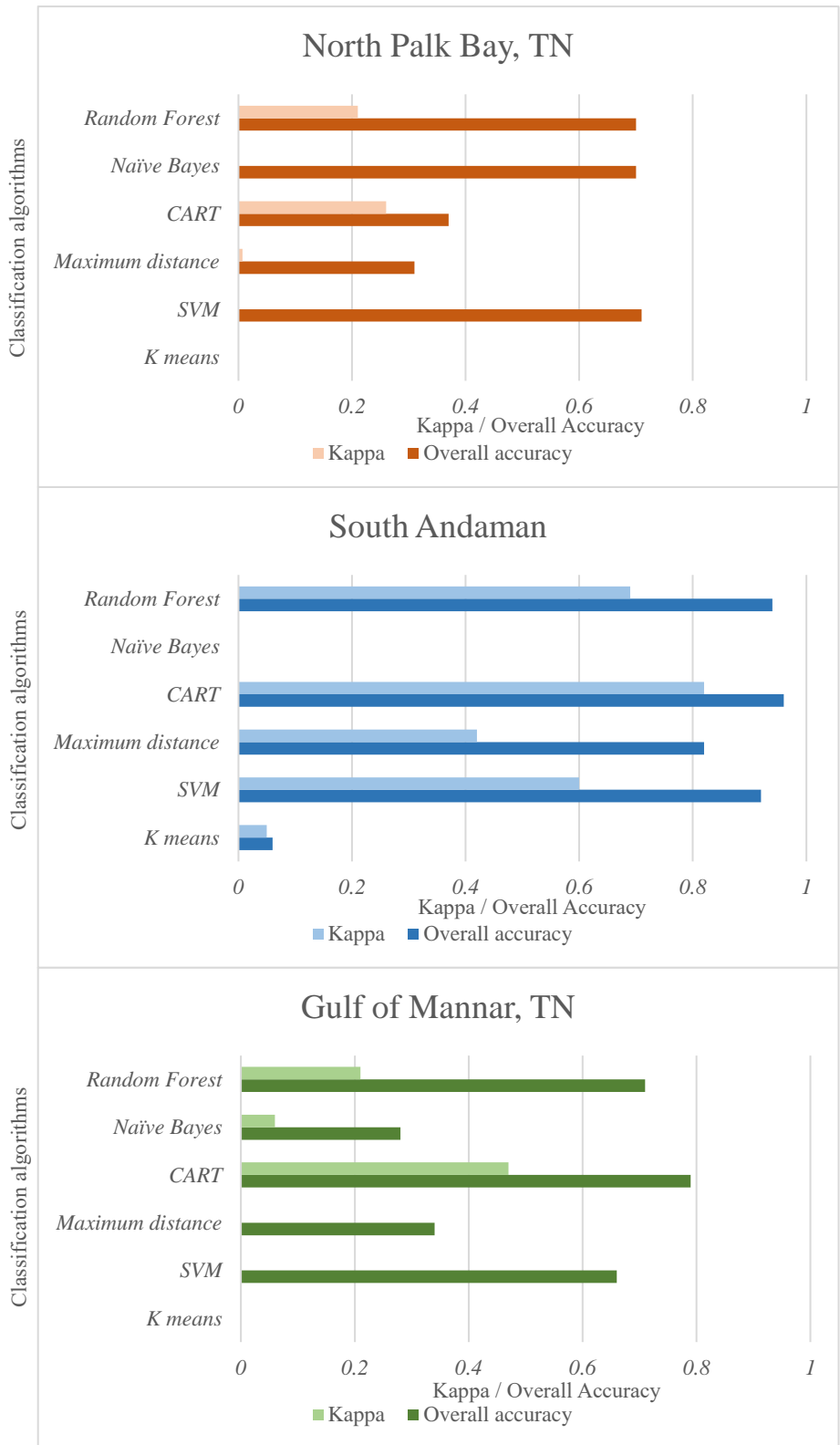


Figure 2.1.: Performance charts of different classification algorithms used for seagrass mapping. (CART = Classification and Regression Tree, SVM = Support Vector Machine, TN = Tamil Nadu).

Random Forest, as it addresses more complex systems more accurately, was found to be the best-fit algorithm in turbid waters, as in NPB. However, CART and RF gave almost similar results when the classification was run for the entire PB region. In this context, it is also to be noted that RF gave decent accuracy in more transparent waters of GoM and SA. Hence, RF

has proved to be the consistent performer (Wicaksono & Lazuardi, 2019) with an accuracy difference of 0-0.08% from the respective best-fit algorithms in three sites (**Table 2.5**). Hence, RF could be used as the preferred classifier algorithm irrespective of any bathymetry and/or turbidity profile, and for mapping larger areas, any of the two algorithms can be chosen to classify seagrasses.

Table 2.5: Best-fit classifier algorithm (RF-Random Forest, CART-Correlation and Regression Tree) for each site (NPB-North Palk Bay, SA-South Andaman, GoM-Gulf of Mannar) along with respective overall accuracy and Cohen's Kappa values.

Study sites	NPB	GoM	SA
Preferred classifier algorithm	RF	CART	CART
Overall accuracy	0.71	0.79	0.96
Cohen's Kappa coefficient	0.22	0.47	0.82
Performance RF as classifier algorithm			
Overall accuracy	0.71	0.71	0.94
Cohen's Kappa coefficient	0.22	0.21	0.69

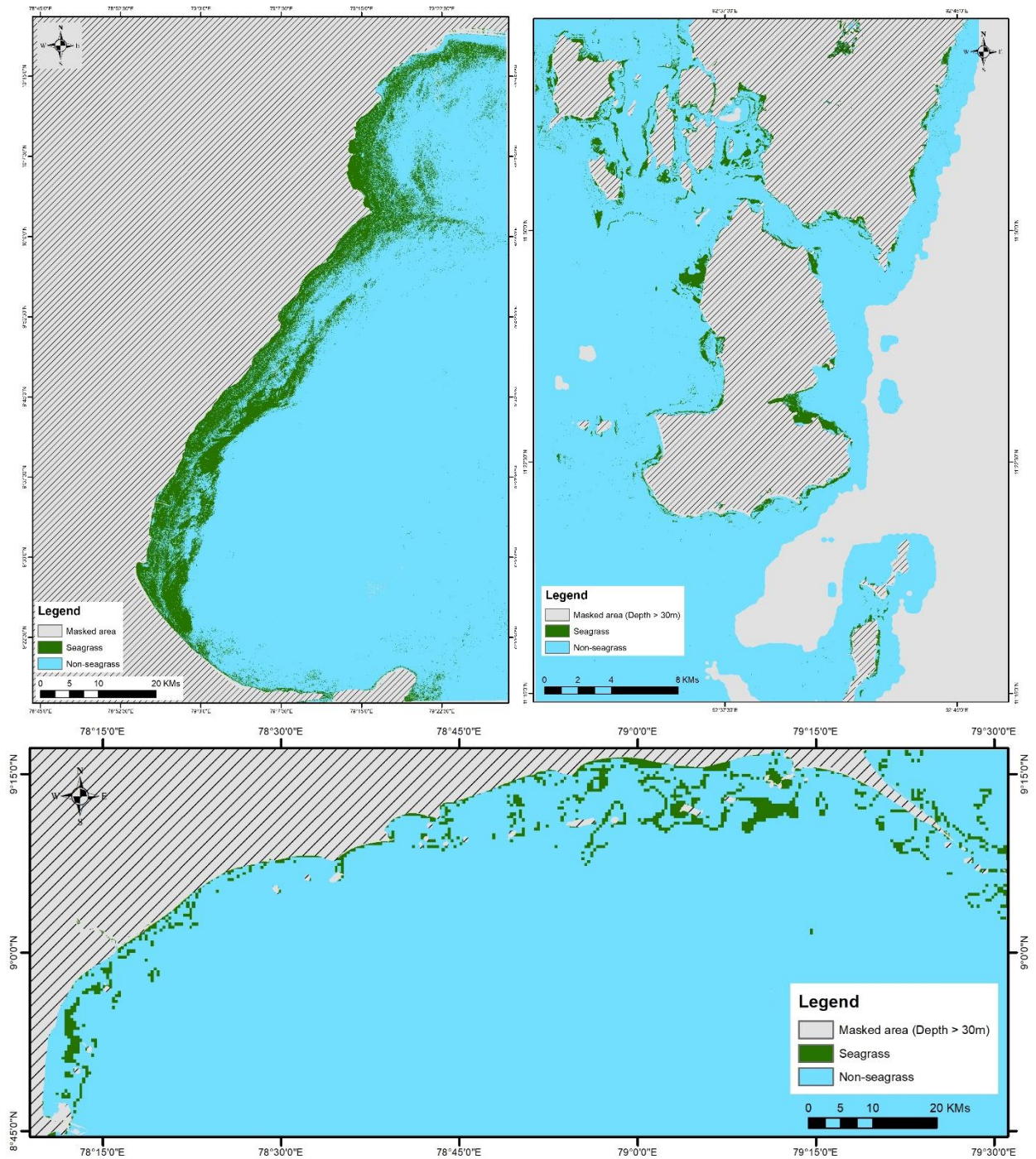


Figure 2.2.: Output map of seagrass distribution in South Andaman, Palk Bay and Gulf of Mannar, as prepared in ArcMAP v.10.8.

2.3.2. Outputs of seagrass modelling

The predictive power of the individual models was higher than the global average, with an AUC \pm SD of 0.76 ± 0.004 (Jayathilake & Costello, 2018) (Table 2.6). In the case of the entire Andaman Islands, seagrass distribution was predicted along the entire island group with specific patches around central Nicobar (Camorta and Trinket) and Great Nicobar.

The bathymetric depth and wave height had a maximum contribution (84.3%) toward seagrass prediction in this region (**Table 2.6**). 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, similar to the global prediction of ~75% contribution (Jayathilake & Costello, 2018), maximum sea surface temperature and distance from the shore in combination showed a maximum contribution of 83.9% (**Table 2.6**). The entire PB-GoM coast was predicted for seagrass presence, with north Palk Bay and the north GoM showing maximum probability (Fig). In the case of GoK, seagrass was strongly predicted to be in the southern part of the gulf around the islands situated in the region (**Figure 2.3**). The phosphate availability and mean sea surface temperature were key contributing factors (67%) (**Table 2.6**).

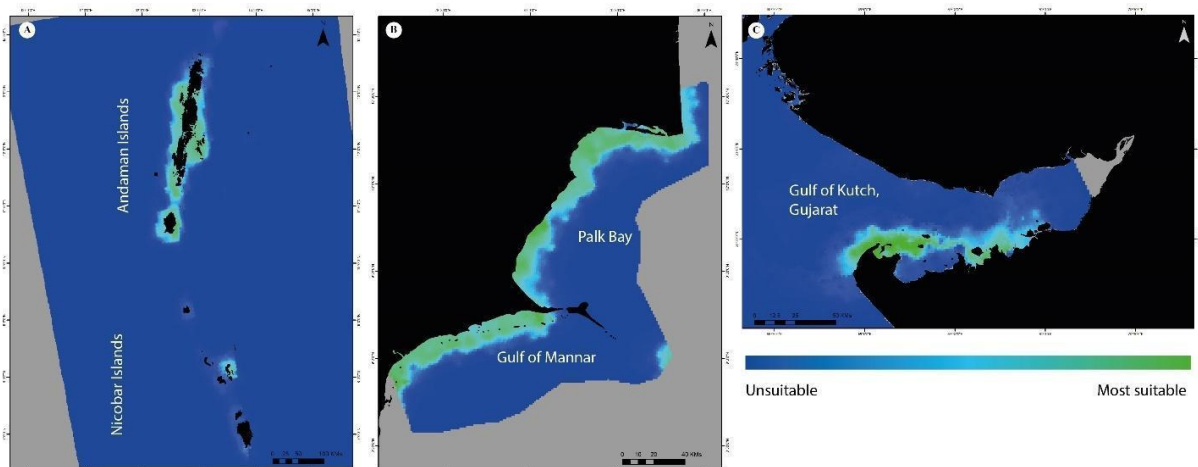


Figure 2.3.: Habitat suitability map for seagrass distribution in three sites, namely, A. Andaman and Nicobar Islands, B. Palk Bay, and Gulf of Mannar, Tamil Nadu and C. Gulf of Kutch, Gujarat.

Table 2.6: List of variables finalised for modelling seagrass distribution for Andaman and Nicobar Islands (ANI), Palk Bay & Gulf of Mannar (PB-GoM) of Tamil Nadu, and Gulf of Kutch (GoK) of Gujarat along with their contribution percentages with the predictive power of individual models depicted by Area Under Curve \pm Standard Deviation ($AUC \pm SD$). [Source of environmental layers: Global Marine Environmental Datasets (GMED) (Basher et al., 2018)].

Layers	ANI	PB-GoM	GoK
Depth (m)	71.8	0.6	8.9
Slope (°)	0.9	2.3	0
Euphotic depth (m)	5.2	2.6	6.2
Distance from the shore (km)	1.7	73.2	1.5
Salinity (PSS.)	0.9	0.7	-
pH	0.2	-	0
Photosynthetically Active Radiation (P.A.R.) (Einstein/m ² /day)	0.6	-	7.8
Sea Surface Wave Height (m)	12.5	-	0
Surface current (m/s)	1.1	3.5	0.5
Phosphate (ml/l)	2.9	1.1	40.8
Nitrate (μ mol/l)	0	1.1	5.7

Diffuse Attenuation Coefficient (Kd) (m ⁻¹)	0	2.6	2.4
Sea Surface Temperature-mean (°C)	0.5	1.7	26.2
Sea Surface Temperature-max (°C)	1.7	10.5	0.1
AUC ±	0.924 ±	0.851 ±	0.952 ±
SD	0.002	0.007	0.058

2.4. Conclusion

In conclusion, integrating remote sensing and GIS technologies using best-fit classifier algorithms represents a robust methodology for mapping seagrass at a finer spatial scale by addressing the challenges posed by depth and turbidity variations. By incorporating machine learning algorithms, such as Random Forest or Correlation and Regression Tree, into the mapping process, fine-scale mapping of seagrass habitats becomes feasible even in areas with high turbidity or varying depths.

The findings presented in this chapter underscore the significance of employing advanced analytical techniques to overcome the complexities inherent in seagrass mapping. By harnessing the power of machine learning, future studies can be conducted to effectively extract meaningful patterns from remote sensing data, enabling more accurate delineation of seagrass extents and a better understanding of their spatial distribution dynamics.

However, it is essential to recognise the ongoing challenges associated with large-scale seagrass mapping, including the need for high-quality input data, model validation, and accounting for temporal variability. In such cases, distribution modelling approaches supported by ecologically rational variables can predict the distribution at larger scales with significant accuracy.

Future research efforts should focus on refining modelling approaches, incorporating additional environmental variables, and integrating ground-truth data to improve model accuracy and reliability.

Overall, the combined use of remote sensing, GIS technologies, and distribution modelling, coupled with machine learning algorithms, holds great promise for advancing our understanding of seagrass ecosystems at different spatial scales. By continuing to innovate and refine these methodologies, regular monitoring exercises can be formulated to conserve and manage these critical marine habitats in the face of ongoing environmental changes.

Highlights for managers:

- Formulating a standard protocol to map seagrass ecosystems in India by addressing various site factors affecting mapping accuracy (like turbidity and depth as used in this study).
- Like mangroves and corals, mapping of seagrasses at regular intervals to understand change dynamics.
- Attempts to use Indian satellite imageries to map seagrasses have been made in previous studies. The recent release of freely available LISS-4 (Linear Imaging Self Scanner) with 5.8 m spatial resolution can be tried for mapping seagrasses.
- Future investigations ought to concentrate on enhancing cost-effective methodologies for gathering image and video data and advancing deep learning techniques for automatic annotation and classification. Additionally, there should be a focus on developing real-time algorithms for calculating percentage coverage.

CHAPTER 3:
DUGONG AND FISHING
INTERFACE

CHAPTER 3: DUGONG AND FISHING INTERFACE

3.1. Introduction

The geographical extent of marine fisheries has expanded from the coastline to the continental shelf and beyond (**Figure 3.1 and 3.2**). According to the recently developed spatial expansion metric, it is proposed that the Indian shelf fisheries expanded to approximately fourfold their coverage area from 1970 to 2000 (Bhathal & Pauly, 2008). Figures 3.1 and 3.2 illustrate the economic and volumetric trends in marine fisheries output for regions inhabited by dugongs, namely the Andaman and Nicobar Islands, Tamil Nadu, and Gujarat. Figure 3.1 highlights a consistent increase in economic output across all regions over the years, with a notable dip during the 2020-21 period, attributable to the COVID-19 pandemic's regulatory impact on fishing activities. Figure 3.2 complements this by showcasing a similar increasing trend in output by volume, albeit with slight regional variations. These trends underscore the growing pressure from fisheries on marine ecosystems, including seagrass meadows, which are critical dugong habitats.

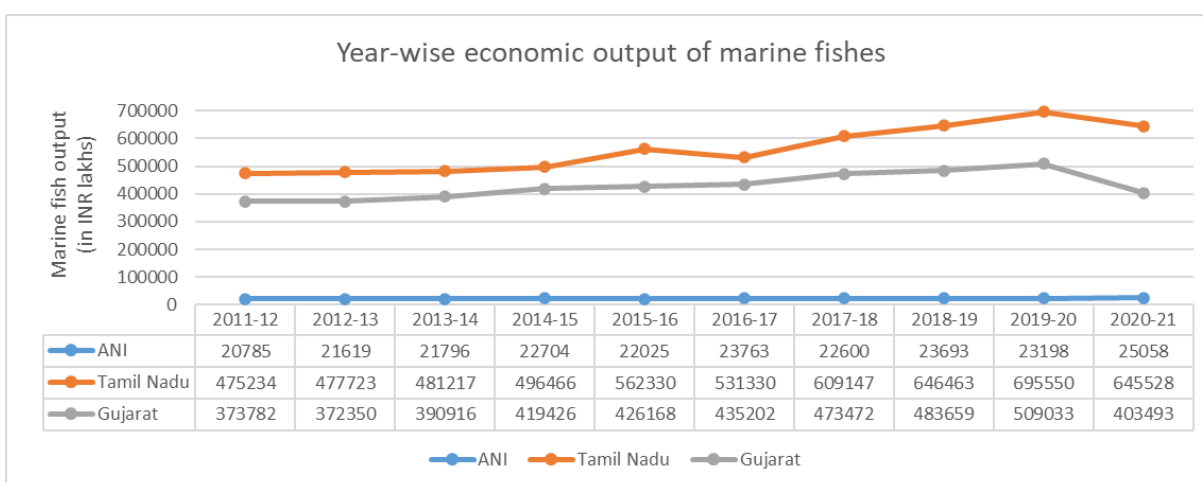


Figure 3.1.: Increasing trend in economic output from marine fishery in ANI, Tamil Nadu and Gujarat for a period of 9 years. The data is collated from State-wise and item-wise value of output from agriculture, forestry, and fishing Year: 2011-12 to 2020-21 with base year: 2011-12 (2023), National Statistical Office, Ministry of Statistics and Programme Implementation, Government of India. A dip in overall output for the year 2020-21 can be attributed to regulated fishing activities during Corona-virus lockdown.

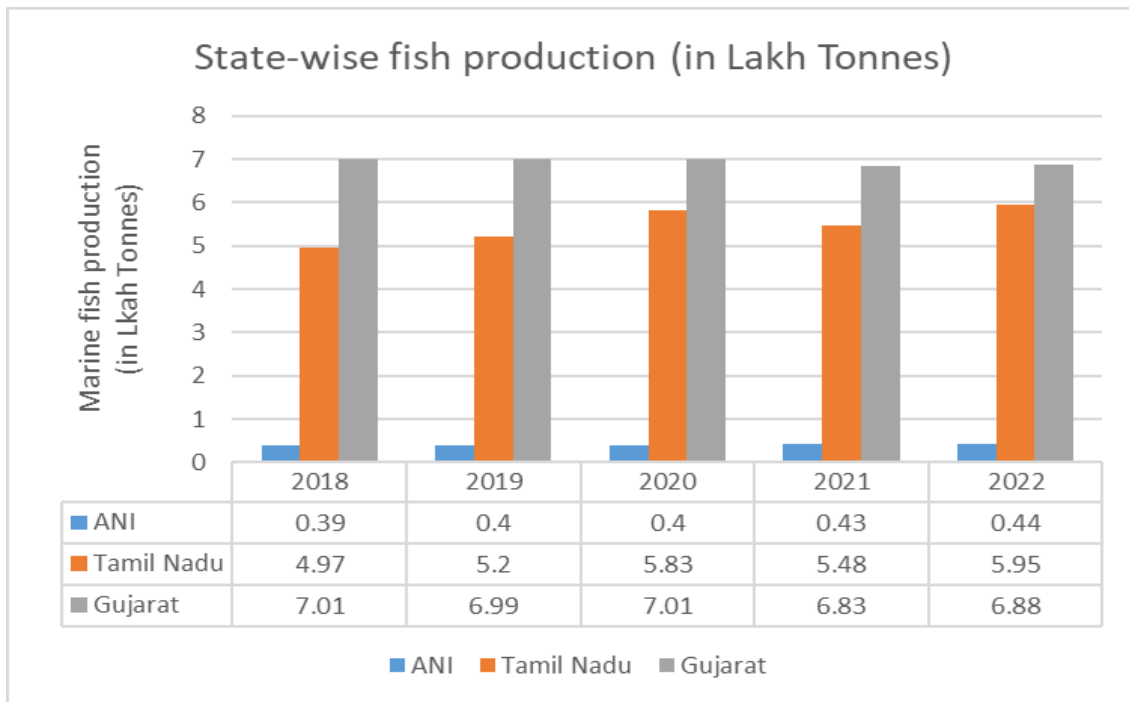


Figure 3.2.: Increasing trend in output by volume from marine fishery in ANI, Tamil Nadu and Gujarat for a period of 5 years. The data is collated from state-wise output from Handbook of Fisheries Statistics-2022 report, Department of Fisheries, Ministry of Fisheries, Ministry of Fisheries, Animal Husbandry & Dairying, Government of India. A dip in overall output for the year 2021 can be attributed to regulated fishing activities during Corona-virus lockdown.

As mentioned earlier, seagrass ecosystems are high in primary production, providing breeding grounds for fish. Hence, the ecosystem is exploited commercially for fishery purposes. Even non-commercial species in seagrasses act as an important food source to commercial species (Gillanders, 2006). Such benefits make them vulnerable to over-exploitation. Duarte (2002) identifies physical damage as the most unambiguous threat to seagrasses, which includes trawling, dredging, push nets, anchoring, and dynamite fishing. Bottom trawling has far-reaching impacts, as it penetrates up to 30mm into the soil depending on the substrate (de Groot, 1984) and draws the entire benthic flora and fauna. A review of 45 case studies worldwide was conducted by Erftemeijer & Robin Lewis (2006), who estimated a total loss of 21023 ha of seagrass vegetation due to dredging. When comparing the undisturbed seagrass sediment with the boat anchoring impacted areas, the sediments of the latter are less cohesive, contain less organic material, and have less species richness as well (Collins et al., 2010). In Indian context, seagrass percent loss from previous studies has been given in (Table 3.1).

Table 3.1: Studies on changes in seagrass cover in India (Thangaradjou & Bhatt, 2018)

Site	Cover (ha)	Change (ha)	Percent loss	Reasons	Reference
Palk Bay (1996–2004)	2922.62–2658.31	(–) 264.31	9.0	Anthropogenic pressure	Sridhar et al. (2010)
Gulf of Mannar (2000–2004)	1856.51–1327.15	(–) 529.6	28.5	Paper shell collection	Thangaradjou et al. (2008)
Gulf of Mannar (1998–2005)	8571.0–5710.66	(–) 2860.3	33.4	Erosion and submergence of islands	ICMAM PD, 2001; Susila et al., 2012
Lakshadweep (2000–2008)	1139.62–1066.59	(–) 73.03	6.5	Anthropogenic pressure	Nobi and Thangaradjou (2012)
Andaman (2004–2007)	1370.4–1223.9	(–)146.5	10.7	Indian ocean tsunami	Nobi and Thangaradjou (2012)
Nicobar (2004–2007)	3192.3–1719.4	(–)1472.9	46.1	Indian ocean tsunami	Nobi & Thangaradjou (2012)

The distribution of dugongs is directly linked with seagrasses, and a high overlap between the dugong habitats and intensively fished areas (Sivakumar & Nair, 2013). Other than the degradation of seagrass habitats, the mortality of dugongs can also be attributed to boat hits, propellor cuts, accidental net entanglement and bycatch (**Plate 3.1**). Except for the Andaman and Nicobar Islands, in the other two states, more than 99% of the vessels are mechanised and motorised (FRAEED & CMFRI, 2023), risking the dugong population to such accidental faceoffs (**Plate 3.2**). Also, the gill net is the preferred gear for fishing, which increases dugong mortality due to bycatch and accidental net entanglement. Currently, the extent of these impacts on dugongs in India is poorly known but is apparently deduced through high incidences of strandings (Dudhat et al., 2022; Pathan et al., 2022).

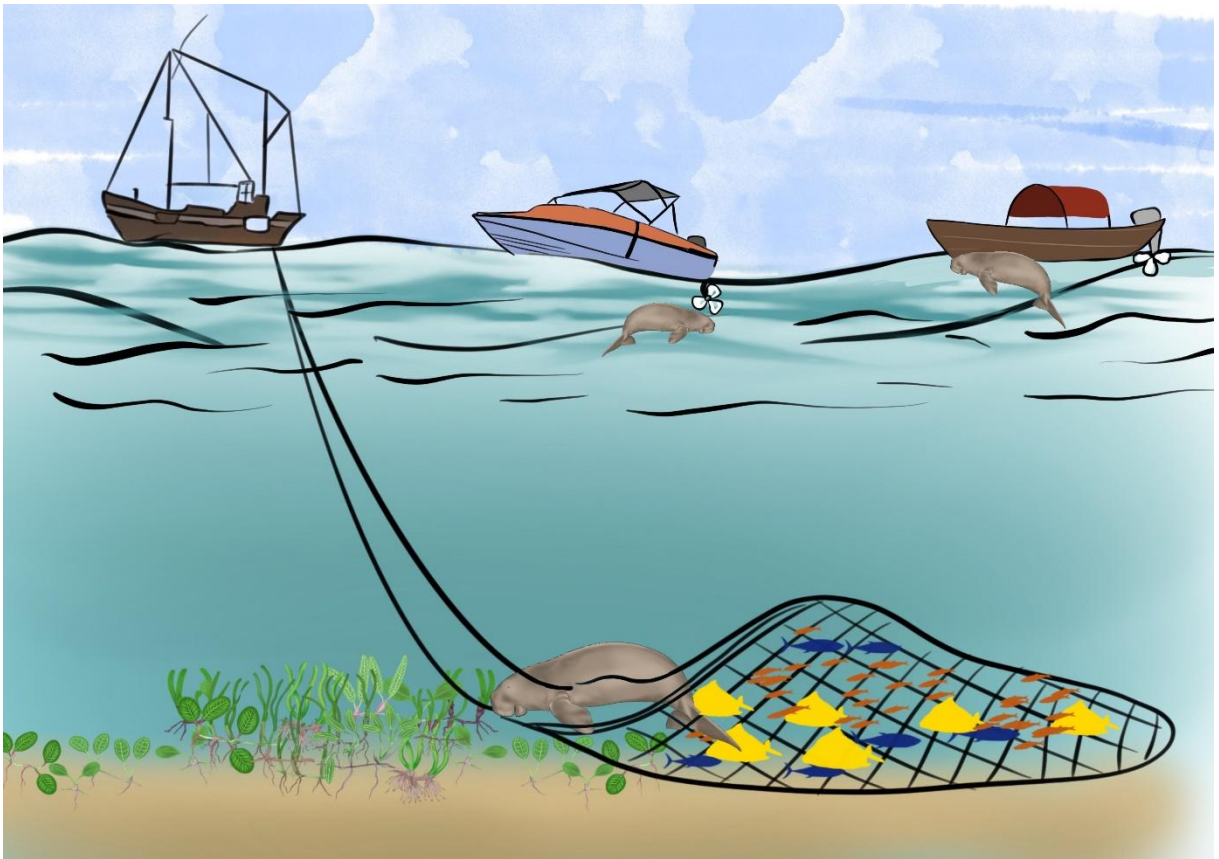


Plate 3.1: Threats to seagrasses and dugongs (Illustration credit: Vabesh Tripura)



Plate 3.2.: On-field photographs from Palk Bay – Gulf of Mannar, Tamil Nadu, showing a number of trawl boats.

3.2. Methods and materials

3.2.1. Fishing pressure in dugong-inhabited Indian states (2012-13)

The fishing pressure layer created by Sivakumar & Nair (2013) was collected for all three states. This layer was created as grid-based polygons (n=894) at a spatial resolution of 10 km. Covariates used in making 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.

3.2.2. Mapping of current fishing pressure in targeted dugong habitats

To investigate the status of current fishing pressure, the fishing tracks were recorded using GPS data loggers in SA and GoM. On interaction with the fishing community, the longest fishing trip extends for around seven days. Hence, the GPS data loggers were customised in

collaboration with the University of Petroleum and Energy Studies (UPES), Dehradun, to enhance the battery life to 7 days.

The respondent fishers were selected in such a way that they covered the entire spatial extent of the respective study areas. Also, the minimum number of tracks to be collected from a particular fishing village was determined to be 10% of its total population.

A total of 10 GPS data loggers were distributed to the selected fishers on a rotation basis to record their fishing tracks. Also, if any marine mammal was sighted, we asked them to note the date, time, numbers and other details of the sightings (**Plate 3.3**).



Plate 3.3.: Distribution and collection of GPS loggers in the field

3.3. Results and discussion

3.3.1. Past (2012-13) and current status (2020-2024) of fishing pressure in selected dugong habitats

The mapping exercise conducted by Sivakumar & Nair (2013) relied heavily on interview surveys to collect data, resulting in a map with relatively coarse resolution. This approach, while providing valuable insights, was limited by the subjective nature of interview responses and the potential inaccuracies in self-reported data. The data collection method inherently needed more precision for detailed spatial analysis.

In contrast, the recent mapping exercise adopted a more robust methodology by deploying GPS data loggers to record actual fishing tracks. This method significantly enhanced the

resolution and accuracy of the mapping process, as it was based on direct, primary data collection rather than inferred or reported information. The use of GPS technology allowed for the capture of precise spatial coordinates and detailed movement patterns, resulting in a finely tuned map that accurately represents fishing activities.

Furthermore, the scope of the mapping exercises differed notably (**Figure 3.3 and 3.4**). The 2012 map (Sivakumar & Nair, 2013) provided a broad overview, covering the entire region of Tamil Nadu and the Andaman and Nicobar Islands. This comprehensive approach, while extensive, may have diluted the focus on specific areas of ecological importance. In contrast, the recent mapping exercise was strategically targeted towards selected dugong habitats. This focused approach enabled a more detailed and relevant analysis of critical habitats, facilitating better conservation and management efforts for the dugong populations in these areas.

By utilising advanced GPS technology and concentrating on key habitats, the recent mapping exercise not only improved the spatial resolution and accuracy of the data but also provided more actionable insights for conservation strategies. This methodological enhancement underscores the importance of employing precise, primary data collection techniques in ecological studies to achieve reliable and high-resolution mapping outcomes.

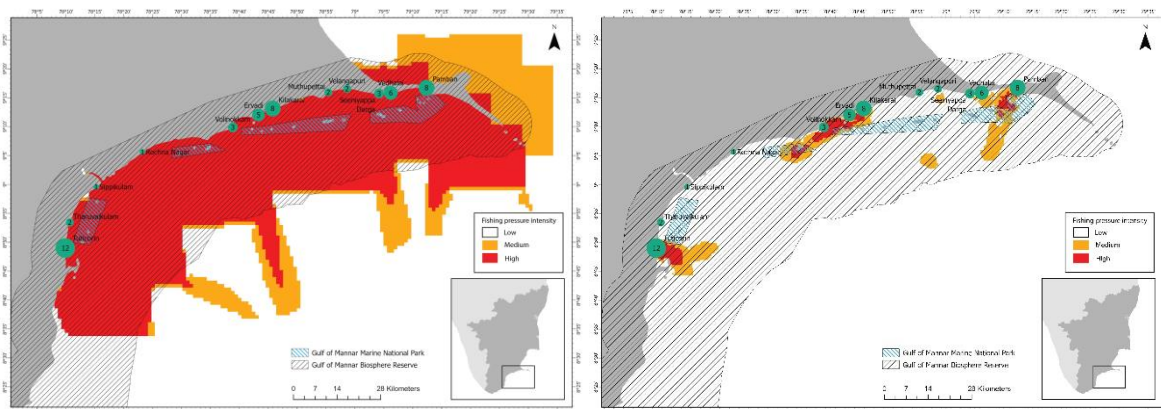


Figure 3.3: (a) Past and (b) current fishing pressure map of Gulf of Mannar, Tamil Nadu.

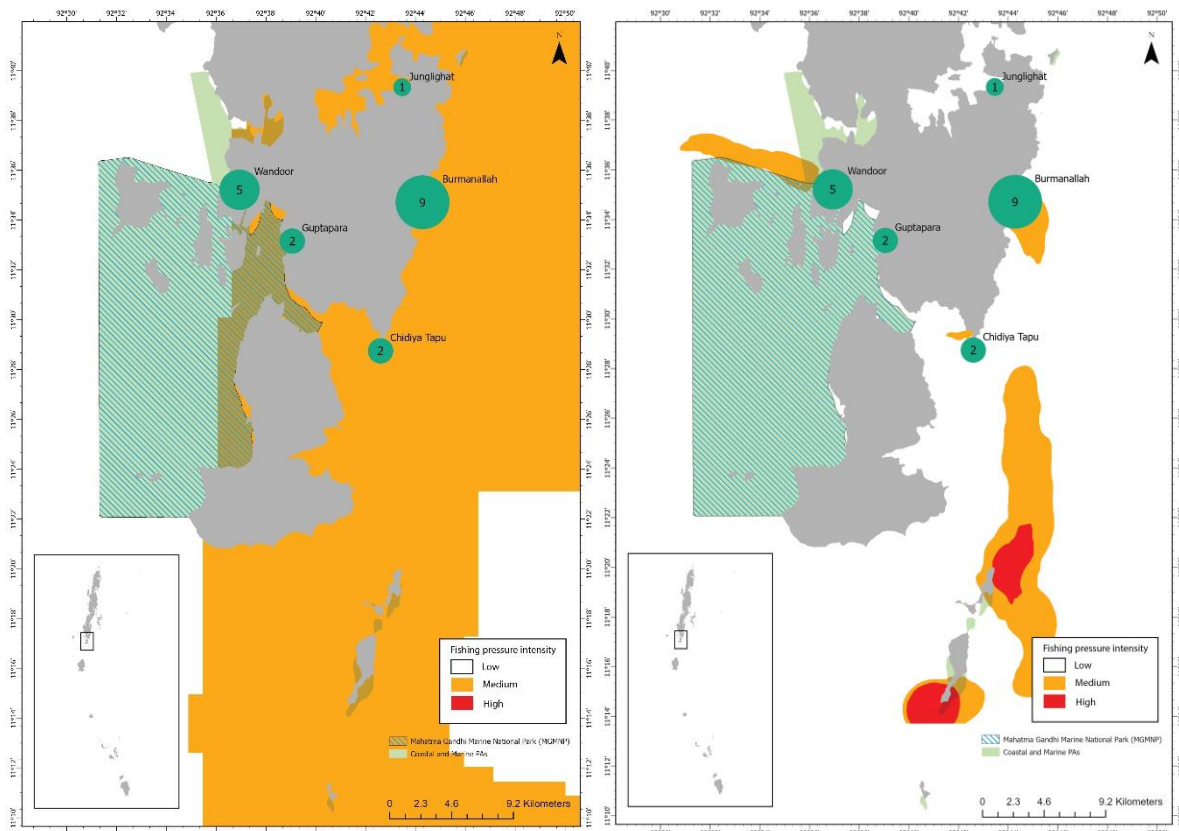


Figure 3.4: (a) Past and (b) current fishing pressure map of South Andaman, Andaman and Nicobar Islands.

3.4. Conclusion

In conclusion, the comparative analysis between the past mapping exercise and the recent survey underscores significant advancements in data collection methodologies and their impact on seascape conservation planning. The shift from interview-based surveys to using GPS data loggers has markedly improved the resolution and accuracy of spatial data, offering a more detailed and reliable representation of fishing activities. Additionally, the focused approach of the recent mapping exercise, concentrating on selected dugong habitats, has provided more specific and actionable insights for conservation efforts.

The findings highlight the critical importance of employing precise, primary data collection techniques in ecological studies to enhance the quality and utility of mapping outputs. The recent mapping exercise sets a new standard for spatial analysis in marine conservation by leveraging advanced technologies and targeting key habitats. These methodological improvements facilitate more effective management and protection strategies for vulnerable species like the dugong, ultimately contributing to the sustainability and preservation of critical marine ecosystems.

Highlights for managers:

- While broad mapping exercises provide valuable overviews, targeted studies on specific habitats or regions of ecological importance yield more actionable insights.
- Managers should prioritise using advanced data collection technologies, such as GPS data loggers. This approach ensures higher accuracy and resolution in spatial data, leading to more reliable mapping and analysis.
- Encourage collaboration between researchers, conservationists, and local communities to enhance data collection efforts. Provide training on using GPS technology and data analysis tools to ensure consistent and accurate data gathering.

CHAPTER 4:
CRITICAL DUGONG
HABITATS (CDHs)
IDENTIFICATION

CHAPTER 4: CRITICAL DUGONG HABITATS (CDHs) IDENTIFICATION

4.1. Introduction

Marine Protected Areas (MPAs) are known to significantly benefit marine mammals by providing secure habitats that reduce human pressures and preserve essential ecosystems (Gormley et al., 2012). Given the migratory nature of these species, delineating MPAs through effective spatial planning in an ecosystem context is strongly advised (Hoyt, 2005). This chapter focuses on how area-based conservation measures such as MPAs can be demarcated through data-driven modelling research and risk assessment.

Dugongs have experienced a rapid decline due to various factors, including habitat degradation, loss of reproductive potential, and increasing anthropogenic pressures. The largest populations are found at the geographical extremes of their range, such as the east coast of Australia extending to New Caledonia and the east coast of Africa, with India's dugong populations representing a significant hope for the species' persistence in South Asia (Srinivas et al., 2021).

In India, dugongs inhabit several large MPAs, including the Gulf of Kutch Marine National Park, Gulf of Mannar Marine National Park, Rani Jhansi Marine National Park, and Mahatma Gandhi Marine National Park, as well as areas beyond these protected boundaries (Sivakumar & Nair, 2013). Expanding and effectively managing these MPAs is crucial for halting the population decline, preserving seagrass habitats, and ensuring the long-term survival of dugongs.

Despite these efforts, MPAs currently cover only 0.26% of India's geographical area, which is significantly below the Aichi Biodiversity Target 11 goal of 10% protection for coastal and marine areas (Wildlife Institute of India, 2023). The recently adopted Kunming-Montreal Global Biodiversity Framework (GBF) sets an even more ambitious target of conserving at least 30% of terrestrial, inland water, coastal, and marine areas by 2030 (Carroll & Noss, 2022; CBD, 2022).

Advances in species distribution modelling (SDM), such as MaxEnt (Kass et al., 2021), are instrumental for analysing presence-only data, making it feasible and cost-effective to monitor species over large spatial scales (Pinto-Ledezma & Cavender-Bares, 2020; Randin et al., 2020). These techniques are essential for identifying critical habitats and informing effective conservation strategies for marine mammals like dugongs (Bonizzoni et al., 2019; Hashim et al., 2017; Hunt et al., 2020).

The increasing human footprint in marine environments, including vessel traffic and overfishing, significantly impacts dugong habitats. The prevalence of mechanised and motorised vessels further exacerbates risks to dugong populations. The extent of these impacts in India is not fully understood, but high incidences of strandings suggest severe consequences (Dudhat et al., 2022; Gopalakrishnan, 2023; Ng et al., 2022).

This study utilises a comprehensive dataset from various sources, including semi-structured questionnaires, citizen science initiatives, volunteer networks, and primary field surveys. By leveraging this data, the research aims to identify critical dugong habitats and develop informed conservation strategies to enhance the effectiveness of MPAs and ensure the long-term preservation of this endangered species.

4.2. Methods and materials

A flowchart outlining this methodology is shown in **Figure 4.1**.

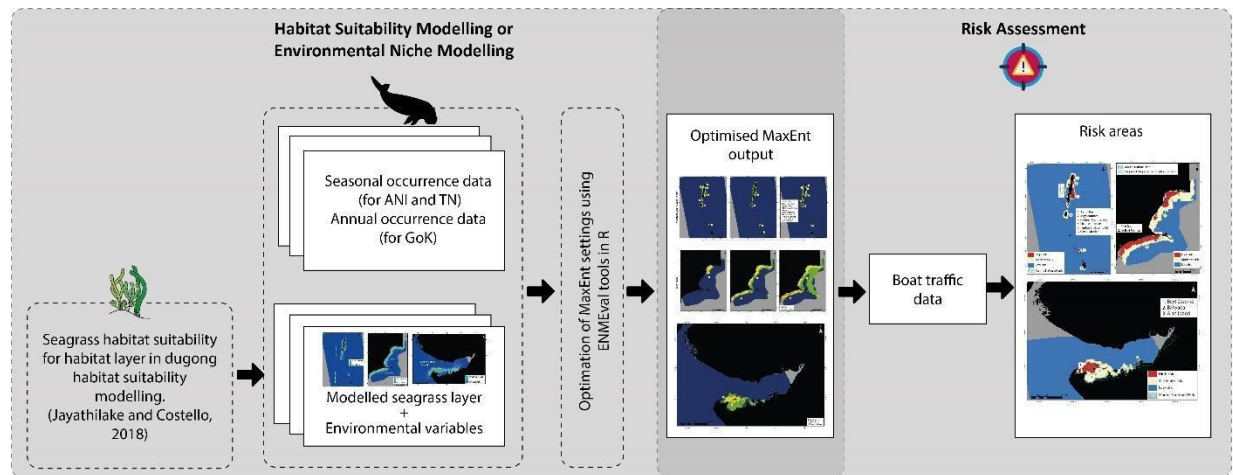


Figure 4.1: Graphical flowchart to show the methods used in detail to elucidate Critical Dugong Habitats in India.

4.2.1. Habitat suitability

4.2.1.1. Data collection

Historical dugong occurrence data were gathered from questionnaire surveys conducted among fisherfolk between 2012-2013 (Sivakumar & Nair, 2013) (GoK=8, ANI=336, PB-GoM=263) and 2018-2021 (Johnson et al., 2023) (GoK=8, ANI=226), following the standardised CMS-UNEP Dugong questionnaire. The survey protocols were based on the revised guidelines developed by the Project GLoBAL Rapid Bycatch Assessment (<http://bycatch.env.duke.edu/>) and incorporated protocols from the Phuket Marine Biological Centre, San Francisco State University, and James Cook University (Pilcher & Kwan, 2012).

Verbal consent was obtained from all interviewees after explaining the purpose of data collection.

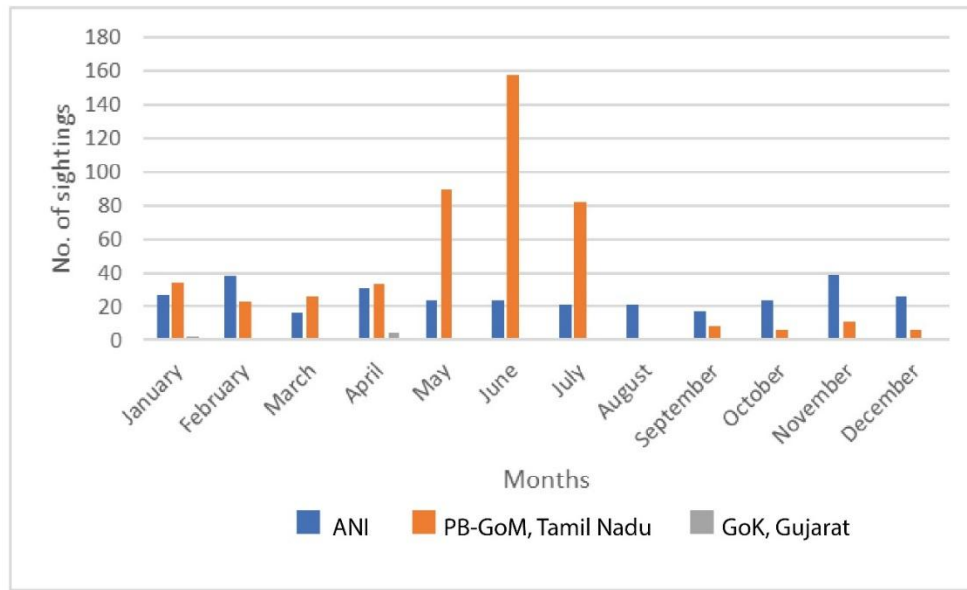


Figure 4.2: Monthly occurrence of dugongs from all three study sites recorded between 2008-2021.

Additionally, we utilised occurrence records from the GEER Foundation (Pandey et al., 2010), which included 45 locations in the GoK region. Dugong sighting locations were also collected from a volunteer network, including members of the fisher community, the Indian Navy, the Indian Coast Guard, and State Forest Departments, reporting 63 sightings in ANI and 245 in PB-GoM. Further direct sighting records were gathered from boat-based surveys (6 sightings in ANI), drone-based surveys (3 sightings in ANI), and indirect presence from feeding trails (3 sightings in GoK). After screening the metadata for locations, dates, and positional inaccuracies, we curated composite occurrence records (64 in GoK, 634 in ANI, and 508 in PB-GoM). These records were then organised into monthly occurrences and categorised into seasonal datasets (Figure 4.2).

4.2.1.2. Developing a prediction-based model for dugong distribution

We developed three prediction models for the pre-monsoon, monsoon, and post-monsoon seasons. To minimise the impact of spatial autocorrelation on the models, we spatially rarefied all point locations using SDMtoolbox v.2.4 (available from www.sdmtoolbox.org) (Brown et al., 2017) on ArcMap v.10.8 and the spatial auto-correlation was checked (Galante et al., 2018). Due to limited data availability after bias correction, we could not segregate sighting data seasonally for the GoK. After data cleaning, we retrieved dugong presence locations for ANI (pre-monsoon = 54, monsoon = 60, post-monsoon = 56 points), PB-GoM (pre-monsoon = 99, monsoon = 18, post-monsoon = 107 points), and GoK (n = 13 points). The monsoon seasons were determined by the southwest monsoon (SWM) winds in ANI and the northeast

monsoon (NEM) winds in Tamil Nadu. Seasonal definitions were site-specific, based on the monsoon report published by the India Meteorological Department (IMD) (**Table 4.1**).

Table 4.1: Classification of seasons with respect to monsoon in Andaman & Nicobar Islands, Palk Bay and Gulf of Mannar, Tamil Nadu.

Sites	Pre-monsoon	Monsoon	Post Monsoon	Reference
ANI (South-west Monsoon)	Jan-Apr	May-Sep	Oct-Dec	(Bera et al., 2015; Sahu et al., 2013)
Tamil Nadu (North-east Monsoon)	Jun-Sep	Oct-Dec	Jan-May	(IMD, 2021)

4.2.1.3. Selection of environmental variables

The detailed methodology used for seagrass distribution modelling and the results have been discussed in Chapter 2 (subsection 2.2. and 2.3.). The same output has been further used as an environmental layer for habitat suitability modelling of dugongs.

Five abiotic layers, namely depth (m), slope ($^{\circ}$), distance from the shore (km), monthly diffuse attenuation coefficient (Kd), monthly sea-surface temperature-mean ($^{\circ}$ C) (**Table 4.2**) were incorporated along with the seagrass modelled layer for dugong suitability modelling. The reasons for selecting these variables are detailed in **Table 4.2**, based on the availability of data at different sites. Due to data constraints from the GoK, we conducted annual habitat suitability modelling with two extra variable layers (i.e., monthly sea-surface temperature-minimum and maximum) to account for seasonal differences, using seven abiotic and one biotic variable (**Table 4.2**).

Table 4.2: Assumptions and relevance of explanatory variables used in this study with specific references.

Sl. No.	Layers	References
1	Depth (m)	(Hashim et al., 2017)
2	Slope ($^{\circ}$)	As per ecological knowledge.

		TN has undulating slopes favouring SG growth and hence dugongs whereas ANI has rugged bathymetry harbouring less number of dugongs. Further, all three geographical regions included in our study are of different coastal topography.
3	Distance from the shore (km)	(Hashim et al., 2017)
4	Monthly Diffuse Attenuation Coefficient (Kd)	Turbidity as a predictor variable was suggested by Briscoe et al., (2014). Therefore, Monthly Diffuse Attenuation Coefficient was used as proxy to turbidity.
5	Monthly Sea Surface Temperature-mean (°C)	(Astudillo-Scalia & de Albuquerque, 2020)
6	Monthly Sea Surface Temperature-max (°C)	(Astudillo-Scalia & de Albuquerque, 2020)
7	Monthly Sea Surface Temperature-min (°C)	(Astudillo-Scalia & de Albuquerque, 2020)
11	Seagrass Presence	Seagrass being the major feed for dugongs, the modelled habitat suitability layer for seagrasses was used.

Initially, we checked the predictors for data availability and assessed multicollinearity using ENMTools v.1.0.5 (Warren et al., 2021) and the reshape2 v.1.4.4 package in R (Wickham, 2012). All predictor variables for seagrass and dugong suitability modelling were pre-processed and interpolated to a spatial resolution of 1 km using ArcMap v.10.8. Subsequently, the layers were resampled to ensure consistent extent using ENMTools v.1.0.6 and the raster v.3.5-21 package in RStudio v.2021.09.1.

4.2.1.4. Suitability modelling

We employed MaxEnt v.3.4.4 software for modelling both seagrass and dugong habitats due to its effectiveness with presence-only data (Hashim et al., 2017; Noviello et al., 2021). For dugong habitat suitability, we identified the best MaxEnt settings using the ENMeval v2.0.1 package in R (Muscarella et al., 2014). We ran ENMeval for each season for ANI and PB-GoM, and once for GoK, using random k-fold data partitioning for datasets with more than 50

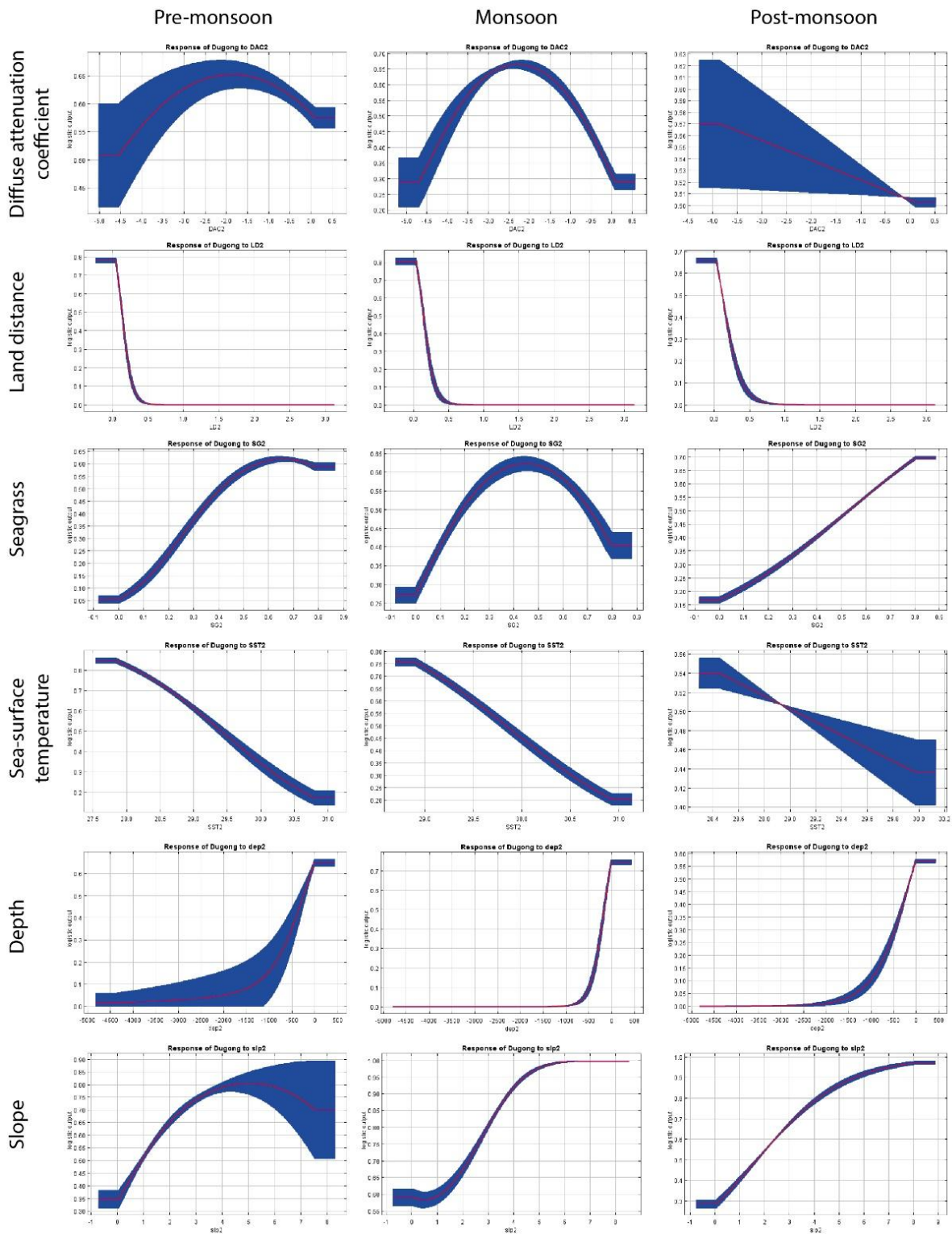
occurrence points and jack-knifing for those with fewer. The settings with the lowest Akaike Information Criterion (AIC) value were chosen for the final models (**Table 4.3**).

Table 4.3: Best fit maxent settings with least AIC values for modelling dugong distribution in the study sites of Andaman & Nicobar Islands, Palk Bay & Gulf of Mannar, Tamil Nadu and Gulf of Kutch, Gujarat (L = Linear, Q = Quadratic, H = Hinge, P = Product, T = Threshold, CV = Crossvalidate, BS = Bootstrap).

MaxEnt Settings	Andaman & Nicobar Islands			Palk Bay- Gulf of Mannar			Gulf of Kutch(n =13)
	Pre-monsoon (n=54)	Monsoon (n=60)	Post-monsoon (n=56)	Pre-monsoon (n=99)	Monsoon (n=18)	Post-monsoon (n=107)	
Data partitioning	Random k-fold	Random k-fold	Random k-fold	Random k-fold	Jackknife	Random k-fold	Jackknife
Feature class	LQ	LQ	L	LQHPT	L	LQHPT	L
Output format	Logistic	Logistic	Logistic	Logistic	Logistic	Logistic	Logistic
Replicate run type	CV	CV	CV	CV	BS	CV	BS
No. of replicates	10	10	10	10	18	10	13
Regularisation Multiplier	0.5	0.5	0.5	2	1.5	3	0.5
Max. no. of background points	10000	10000	10000	10000	10000	10000	5000
Max. iterations	1000	1000	1000	1000	1000	1000	1000
Convergence threshold	10 ⁻⁵	10 ⁻⁵	10 ⁻⁵	10 ⁻⁵	10 ⁻⁵	10 ⁻⁵	10 ⁻⁵

To mitigate sampling biases, we used a bias file for all runs created using sighting data (Dorji et al., 2020; Vollering et al., 2019). Site- and season-specific bias files were generated with the kernel density function in R (Fourcade et al., 2014). For dugong MaxEnt outputs, we selected

'logistic' as the output format and assessed model accuracy with the Area Under Curve (AUC) value. We prepared the final output maps using ArcMap v.10.8. The response curves for



different variables for ANI and PB-GoM, Tamil Nadu, are available in **Figures 4.3 and 4.4**, respectively, and those for GoK-Gujarat in **Figure 4.5**.

Figure 4.3.: Response curves of different variables for habitat suitability modelling for dugongs during pre-monsoon, monsoon and post-monsoon seasons in Andaman and Nicobar Islands.

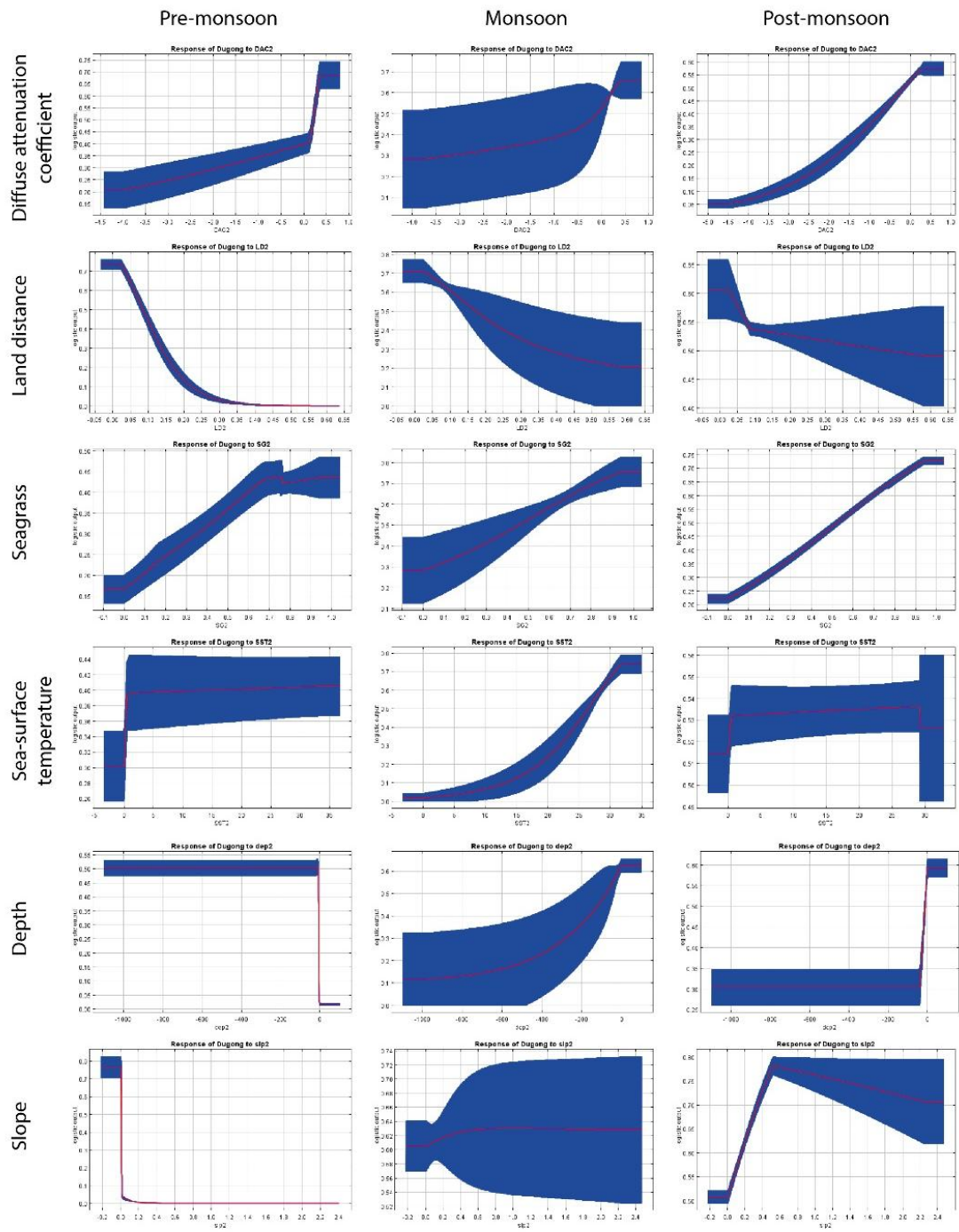


Figure 4.4.: Response curves of different variables for habitat suitability modelling for dugongs during pre-monsoon, monsoon and post-monsoon seasons in Palk Bay & Gulf of Mannar, Tamil Nadu.

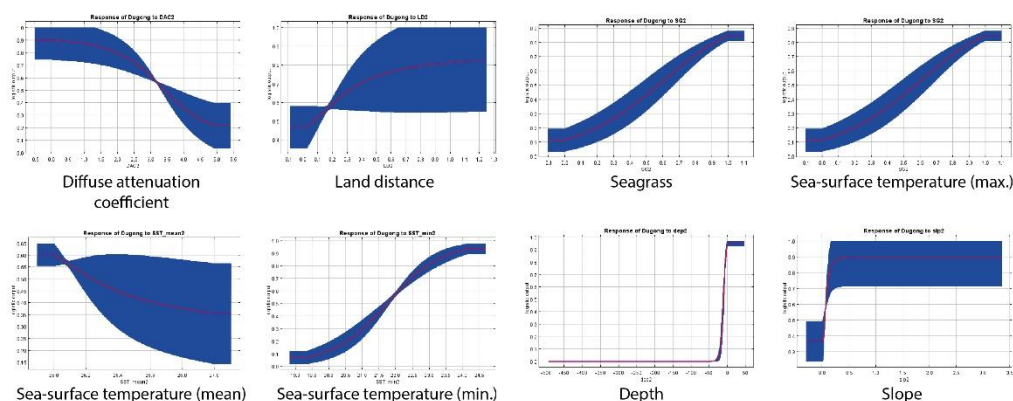


Figure 4.5.: Response curves of different variables for habitat suitability modelling for dugongs in Gulf of Kutch, Gujarat.

The final output maps were categorised into four prediction probability classes: 0-0.25 (unsuitable), 0.25-0.5 (low suitability), 0.5-0.75 (moderately suitable), and 0.75-1 (highly suitable). Additionally, we performed a Niche Similarity Analysis to examine if the seasonal suitability of PB-GoM and ANI differed significantly, using I-statistics in ENMTools v.1.3 (Warren et al., 2008, 2010).

4.2.1.5. Classifying fishing pressure

We incorporated the fishing pressure layer from a previous study, which was initially created as grid-based polygons (n=894) with a spatial resolution of 10 km. The covariates for this layer included fishing months, motor type and power, and gear type. We then interpolated this layer to a finer spatial resolution of 1 km using ArcMap v.10.8.

4.2.1.6. Risk assessment

We combined seasonal suitability layers into a single layer for each site using the raster calculator function in ArcMap v.10.8. This combined suitability layer was then multiplied by the fishing pressure layer to pinpoint high-risk areas. We categorised the risk assessment layers manually, with classifications ranging from 0-100%: areas with 100-51% risk were labelled as high risk, 50-26% as moderate risk, and 25-0% as low risk, all using ArcMap v.10.8. Areas identified as high risk (greater than 50%) and with high habitat suitability (greater than 0.75 prediction probability) were designated as Critical Dugong Habitats (CDHs).

Furthermore, we performed boat surveys to map threats, including fishing gear, vessel numbers, and types, in high-risk areas from the three identified sites. This included Aerial Bay-Diglipur and Mayabunder in North Andaman; Rani Jhansi Marine National Park (RJMNP, Ritchies' Archipelago) in South Andaman; Bhaidar, Ajad, Chushna Pir, Nor, Beyt Dwarka islands, and Paga reef in GoK, Gujarat; and coastal waters from Rajamadam to

Ammappattinam in the northern Palk Bay region of PB-GoM. Surveys involved examining boats and fishing gear for 10 minutes at the centres of randomly selected 2x2 km grids at these locations. These surveys were conducted between 2019-21 in ANI, 2020-21 in Tamil Nadu, and 2020-22 in Gujarat. We conducted an Inverted Distance Weighting (IDW) analysis at a 1 km spatial resolution (with powers ranging from 0.001 to 10 and intervals of 0.01) to categorise areas as high, moderate, or low threat. This threat layer was then overlaid on the dugong habitat suitability layer to cross-check the risk assessment obtained from secondary data. Additionally, we quantified high-risk areas outside existing MPAs along the Indian coast to estimate the proportion of unprotected regions at all study sites.

4.3. Results

4.3.1. Seasonal dugong distribution

4.3.1.1. Andaman and Nicobar Islands (ANI)

Ritchie's Archipelago, the Hut Bay region of Little Andaman, and the Trinket-Camorta islands in central Nicobar have been identified as highly suitable habitats for dugongs throughout all seasons. In contrast, areas such as Aerial Bay, Diglipur, Mayabunder in northern Andaman, Interview Island in the west, and Rutland & Chidiya Tapu in southern Andaman were classified as moderately suitable during the pre and post-monsoon periods (**Figure 4.6**).

During the monsoon season, areas with high suitability are more pronounced in Central and Great Nicobar Islands compared to other seasons. In Andaman, high suitability areas are more widespread during the monsoon, while they are more confined to Little Andaman and Ritchie's Archipelago during the pre and post-monsoon seasons. The model's performance for the Andaman & Nicobar Islands was recorded with AUC \pm SD values of 0.987 ± 0.003 for pre-monsoon, 0.987 ± 0.005 for monsoon, and 0.982 ± 0.008 for post-monsoon. Analysis of the correlation matrix across different seasons indicated a high degree of consistency in habitat suitability (**Table 4.4**).

4.3.1.2. Palk Bay and Gulf of Mannar, Tamil Nadu (PB-GoM)

In the PB-GoM region, habitat suitability exhibited clear seasonal changes. High suitability was observed primarily in northern Palk Bay during the pre-monsoon period, while the rest of the region was mostly deemed low or unsuitable (**Figure 4.6**). As the retreating monsoon progressed, these areas of high suitability expanded throughout the region, forming patches of high suitability amidst areas of moderate to low suitability. By the post-monsoon season, the most suitable habitats became more concentrated in the Gulf of Mannar (GoM). The effectiveness of the seasonal MaxEnt models for this region was measured with AUC \pm SD

values of 0.96 ± 0.029 for pre-monsoon, 0.911 ± 0.022 for monsoon, and 0.825 ± 0.031 for post-monsoon. Although the extent of highly suitable habitats was notably smaller compared to moderate and low-suitability areas, there was a distinct trend of shifting suitability from north to south from the pre-monsoon to the post-monsoon seasons. This shift was further supported by the I-statistics correlation analysis (**Table 4.4**), which revealed significant differences in habitat suitability between the pre-monsoon and post-monsoon periods.

Table 4.4: Information on the I-statistics correlation matrix for niche similarity of different seasons in the Andaman and Nicobar Islands and Palk Bay & Gulf of Mannar, Tamil Nadu.

ANI			
Seasons	Pre-monsoon	Monsoon	Post-monsoon
Pre-monsoon	1	0.9735568	0.9569629
Monsoon	x	1	0.9342551
Post-monsoon	x	x	1
PB-GoM, Tamil Nadu			
Seasons	Pre-monsoon	Monsoon	Post-monsoon
Pre-monsoon	1	0.7205054	0.7207523
Monsoon	x	1	0.937226
Post-monsoon	x	x	1

4.3.1.3. Gulf of Kutch, Gujarat (GoK)

The annual habitat suitability assessment for the GoK region revealed high suitability zones near Paga, Bhaidar, and Chushna Pir, extending up to Beyt Dwaraka island (**Figure 4.6**). A moderately suitable area was also identified, stretching from Beyt Dwaraka island to the east, reaching beyond Nor Island. Conversely, the subtidal regions south of Chushna Pir, including Ajad Island, were consistently classified as having low suitability for dugongs year-round. The average AUC value from the MaxEnt models was $0.983 (\pm 0.005)$.

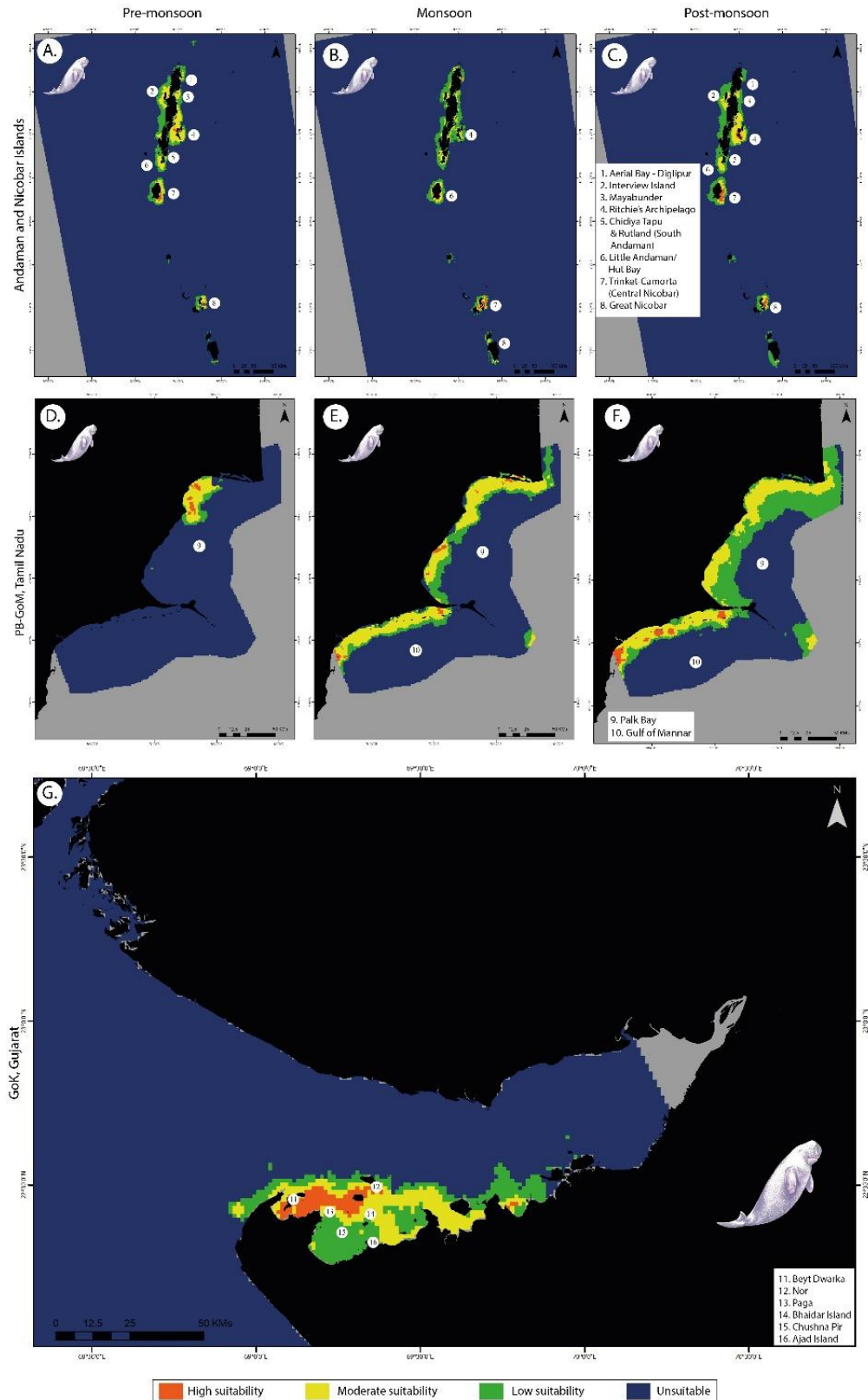


Figure 4.6.: Predictions of dugong habitat suitability: A) pre-monsoon, B) monsoon, C) post-monsoon for the Andaman & Nicobar Islands; D) pre-monsoon, E) monsoon, F) post-monsoon for Palk Bay and Gulf of Mannar in Tamil Nadu; and G) Gulf of Kutch in Gujarat. The suitability categories are 0-0.25 (unsuitable), 0.25-0.5 (low suitability), 0.5-0.75 (moderately suitable), and 0.75-1 (highly suitable). The suitability layers were developed using MaxEnt v.3.4.4 software, with the final maps produced using ArcGIS Pro v.3.2.1..

4.3.1.4. Variable contributions

In our study, seagrass presence emerged as the primary determinant of suitable dugong habitats across the regions investigated. In the Andaman and Nicobar Islands (ANI), seagrass accounted for more than 50% of the suitability factor throughout all seasons, ranging from over 70% in the pre-monsoon and post-monsoon to 58% during the monsoon. Depth was the next most significant factor, contributing about 20% in each season. Other influential variables in the ANI region included distance from shore, slope, and the diffuse attenuation coefficient (**Table 4.5 and Figure 4.7**).

*Table 4.5: Variables used to model dugong distribution across pre-monsoon, monsoon, and post-monsoon periods in the Andaman and Nicobar Islands (ANI), Palk Bay & Gulf of Mannar (PB-GoM) in Tamil Nadu, and Gulf of Kutch (GoK) in Gujarat, with their respective contribution percentages. ['- ' indicates not used; Sources: * Global Marine Environmental Datasets (GMED) (Basher et al., 2018); # NASA Ocean Colour; \$ Modelled data (MaxEnt)]*

Layers	ANI			PB-GoM			GoK
	Pre Monsoon	Monsoon	Post Monsoon	Pre Monsoon	Monsoon	Post Monsoon	
Seagrass Presence ^{\$}	76.2	58.3	73.6	33.5	66	70.8	70.5
Depth (m) *	14.8	18.9	18.2	8.8	2.2	5.7	20.3
Slope (°) *	2.1	1.9	3.8	51.4	0.3	5	0.6
Distance from the shore (km) *	5.3	12.5	4.2	0.9	5.3	1.8	2.8
Monthly Diffuse Attenuation Coefficient (Kd) #	0.2	7.2	0	5	3.3	11	2.4
Monthly Sea Surface Temperature-mean (°C) #	1.4	1.2	0.1	0.5	23	5.6	0.8
Monthly Sea Surface Temperature-max (°C) #	-	-	-	-	-	-	0.4
Monthly Sea Surface	-	-	-	-	-	-	2.2

Temperature-min (°C) #							
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In the Palk Bay and Gulf of Mannar (PB-GoM) region, the role of seagrass increased substantially from 33.5% in the pre-monsoon to 70.8% in the post-monsoon season (Table 4.5). During the pre-monsoon season, slope was the most influential factor, contributing over 50%, while seagrass presence was at 33.5%. Sea surface temperature (SST) was particularly significant during the monsoon season, while in the post-monsoon period, slope, depth, and mean SST had equal contributions. Depth, distance from shore, and the diffuse attenuation coefficient (DAC) consistently affected habitat suitability across all seasons in PB-GoM.

For the Gulf of Kutch (GoK), seagrass presence was the most important variable, contributing 70% to the suitability assessment, followed by depth at nearly 20%. The diffuse attenuation coefficient, distance from shore, and minimum SST each contributed approximately 2.5% (Table 4.5).

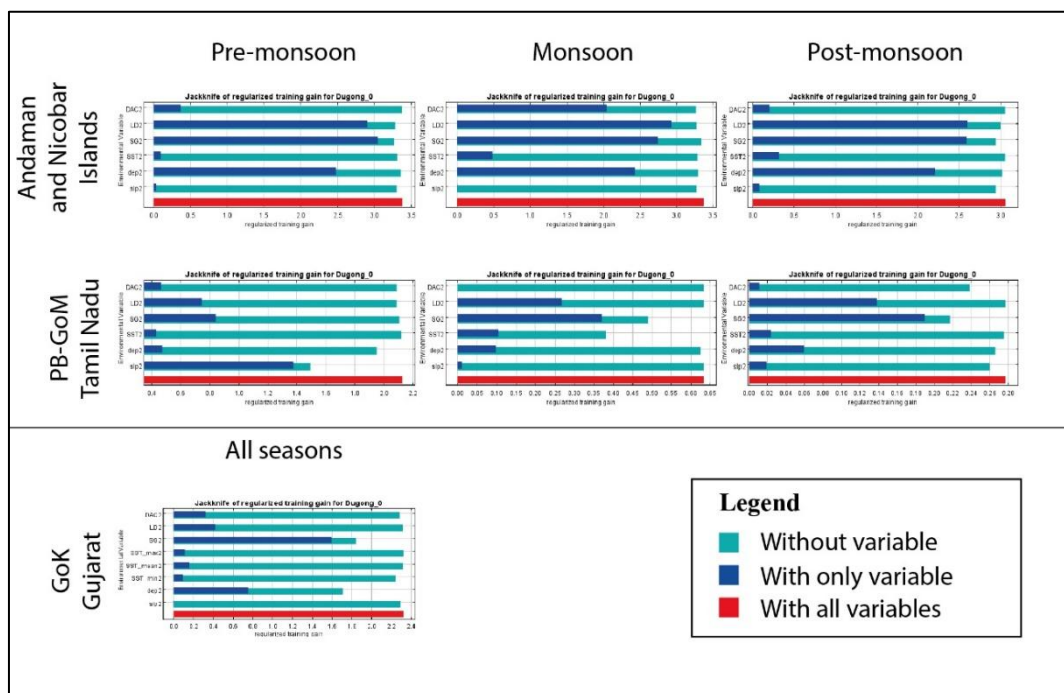


Figure 4.7.: Jackknife test results of variable importance using AUC on test data in predicting habitat suitability of dugongs in Andaman and Nicobar Islands, Palk Bay and Gulf of Mannar, Tamil Nadu and Gulf of Kutch, Gujarat.

4.3.2. Risk assessment

A unified risk assessment across all three regions was conducted by averaging habitat suitability predictions from different seasons. This analysis revealed that highly suitable habitats also face elevated risks due to human activities in all regions.

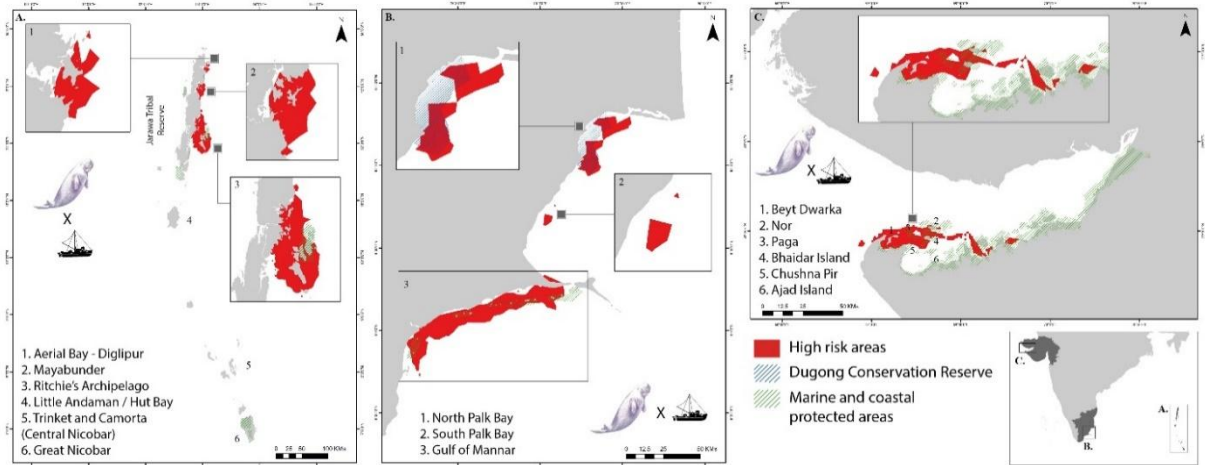


Figure 4.8.: Critical Dugong Habitats (CDHs) mapped through risk predictions due to fishing pressure in A. Andaman and Nicobar Islands; B. Palk Bay and Gulf of Mannar, Tamil Nadu; and C. Gulf of Kutch, Gujarat. High-risk areas are those with risk levels of 50% or more, overlaid with existing marine protected areas. The maps were generated using ArcGIS Pro 3.2.1.

In the Andaman and Nicobar Islands (ANI), high-risk zones were identified along specific areas such as Ritchie's Archipelago, Aerial Bay, and Mayabunder. Almost the entire coast faces moderate risk due to human activities, except for the west coast of Middle Andaman (**Figure 4.10**). These findings were supported by boat-based surveys, which highlighted high-risk zones in Aerial Bay-Diglipur and Mayabunder (**Figure 4.8**).

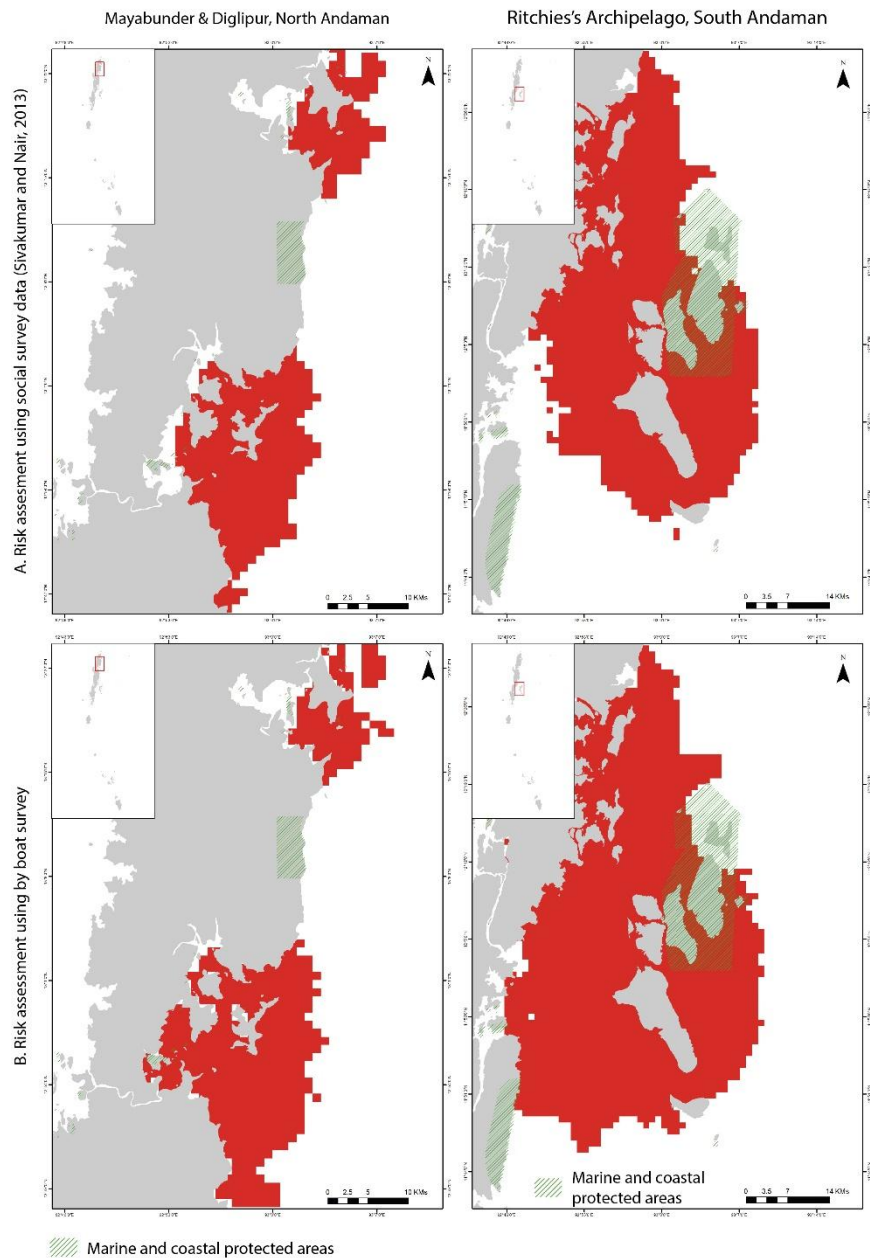


Figure 4.9.: Comparison of selected high-risk habitats. The top row shows risk based on suitability models from social surveys, and the bottom row shows results from boat-based surveys [Mayabunder and Diglipur, North Andaman (left) and Ritchie's Archipelago, South Andaman (right)]. The maps were produced using ArcGIS Pro 3.2.1.

Rani Jhansi Marine National Park was found to be part of a high-risk zone extending from Middle Andaman to Long Island (**Figure 4.9**). The coast of Little Andaman also exhibited moderate risk for dugongs, while the Nicobar region showed moderate threat levels, particularly around Trinket and Camorta Islands and the southern coast of Great Nicobar Island (**Figure 4.10**).

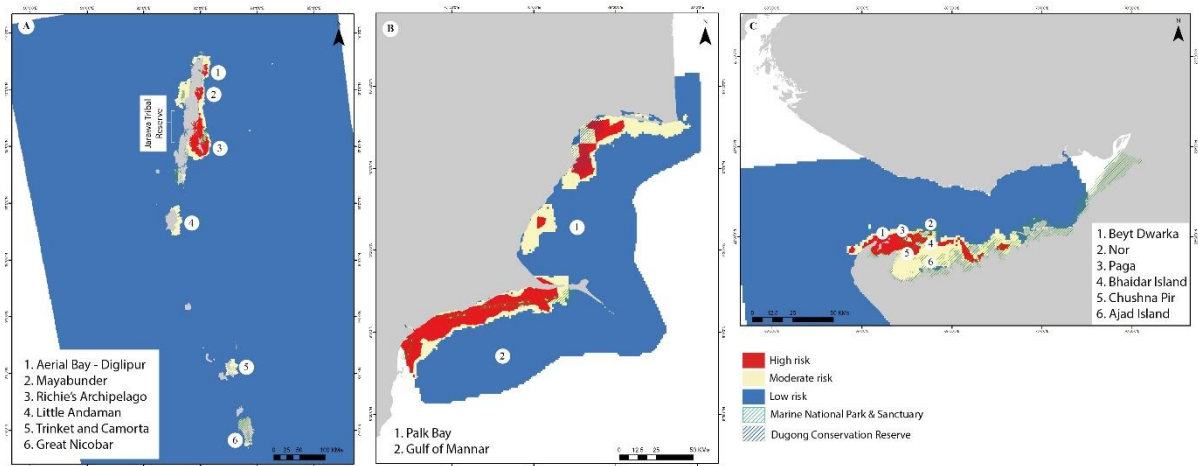


Figure 4.10.: Risk predictions due to fishing pressure in A. Andaman and Nicobar Islands; B. Palk Bay and Gulf of Mannar, Tamil Nadu and C. Gulf of Kutch, Gujarat. The output maps were generated using ArcGIS Pro 3.2.1.

In the Palk Bay and Gulf of Mannar (PB-GoM) region, over 50% of the area was classified as high-risk. Boat-based risk assessments confirmed this, with precise identification of high-risk areas in the east and northeast regions of North Palk Bay (Figure 4.11).

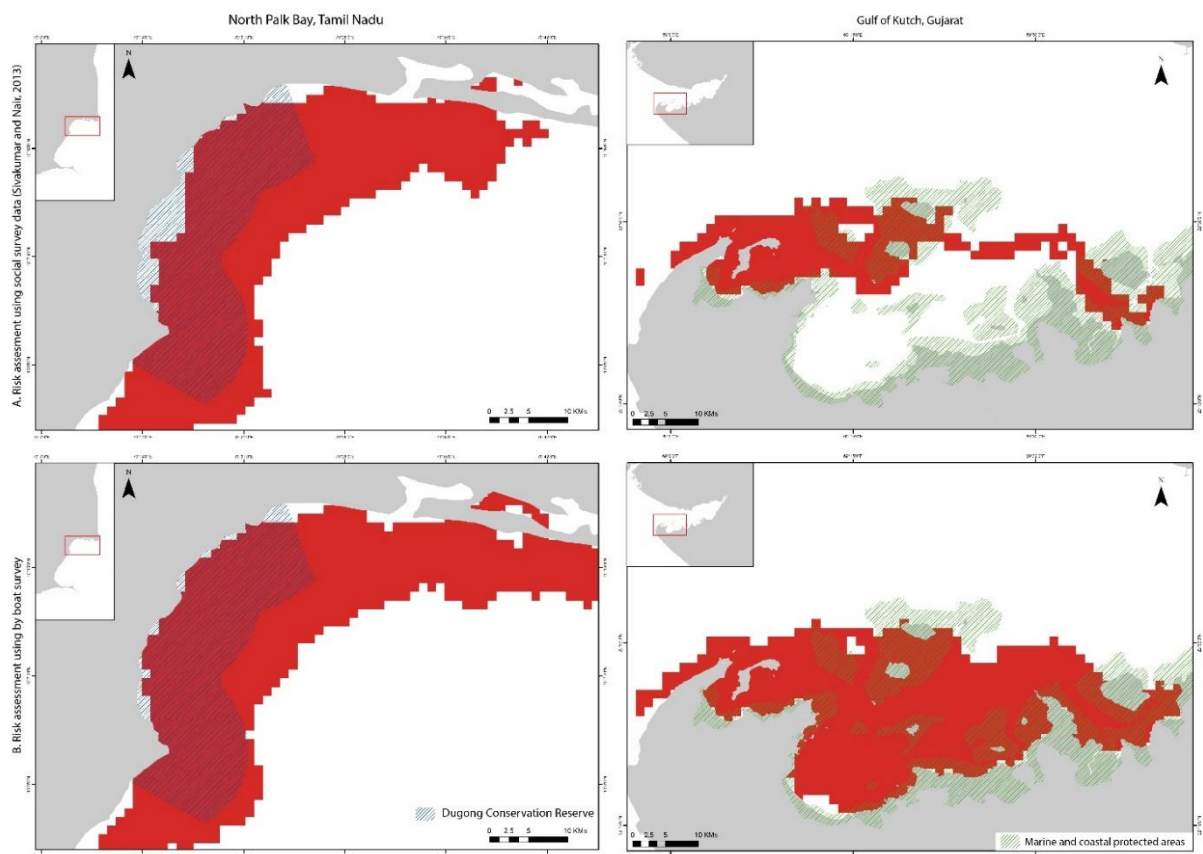


Figure 4.11.: Comparison of selected high-risk habitats. The top row shows risk based on suitability models from social surveys, and the bottom row shows results from boat-based surveys [North Palk Bay, Tamil Nadu (left) and Gulf of Kutch, Gujarat (right)]. The maps were created using ArcGIS Pro 3.2.1.

In the Gulf of Kutch (GoK), all highly suitable habitats were categorised as high-risk zones. Although experiencing moderate risk along its southern coast, the Gulf of Kutch Marine

National Park was identified as being at high risk across most of its area according to boat-based surveys (**Figure 4.11**). Low-suitability regions also faced moderate risk.

The overlap between high-risk areas and existing protected zones varied across regions. In the ANI region, only 5.5% (26.16 sq. km out of 478.59 sq. km) of high-risk areas fall within protected zones. In the PB-GoM region, approximately 28% of high-risk areas are protected, leaving 1708.97 sq. km unprotected. In Gujarat, around 37% of the high-risk areas are covered by the Gulf of Kutch Marine National Park and other marine and coastal protected areas (**Figure 4.8**). All identified high-risk areas, both within and outside existing protected zones, are considered Critical Dugong Habitats (CDHs).

4.4. Discussion

Determining suitable habitats and assessing risks are essential for prioritising conservation efforts (Hashim et al., 2017). This study identified areas of intensive dugong use within their restricted distribution along the Indian coast and highlighted high-risk zones to guide conservation strategies. By conducting interviews with local fisherfolk, we collected extensive temporal and spatial data across the dugong's range in India. Much of the data came from opportunistic sightings and secondary sources, such as fisher interviews and a dugong volunteer network. The monthly occurrence patterns of dugongs across the three study sites have been presented in Figure 4.2, derived from interview surveys spanning 2008 to 2021. The data indicate a consistent presence of dugongs in certain key habitats, with notable peaks during specific months, suggesting potential seasonal preferences or migration patterns. These findings align with the environmental and ecological dynamics of the study regions, such as seagrass availability and fishing activity. Understanding these temporal patterns is crucial for effective conservation planning and for identifying periods of heightened vulnerability for dugong populations. We utilised Species Distribution Modelling (SDM) with presence-only data, combining habitat suitability analysis with risk assessment to identify high-risk areas for dugongs along the Indian coastline.

Globally, seagrass habitats are in decline (Dunic et al., 2021), making comprehensive assessments crucial for effective conservation actions (Hernawan et al., 2021). Healthy seagrass meadows are a primary factor influencing dugong occurrence and habitat use (Sheppard et al., 2006). Dugongs contribute to the health of seagrass meadows through grazing, which supports nutrient cycling (Aragones et al., 2006; Preen & Marsh, 1995). Our analysis identified suitable seagrass habitats along most of the Andaman Islands (except parts of the northern coast), throughout the PB-GoM region, and the southwestern coast of the Gulf of Kutch (GoK). These areas represent some of the last remaining dugong habitats on the

Indian subcontinent (D'Souza et al., 2015; Frazier & Mundkur, 1990; Pandey et al., 2010; Pathan et al., 2022; Rajpurkar Sagar et al., 2021; Sivakumar & Nair, 2013). We used a single annual seagrass distribution layer for our dugong suitability analysis, but seasonal changes in seagrass contribution suggest that other factors influence dugong populations throughout the year (**Table 4.5**). This underscores the importance of studying seasonal variations in seagrass availability (density, composition, biomass, etc.) at Critical Dugong Habitats (CDHs) and understanding nutrient profiles, seasonal biomass, carbon sequestration, and associated micro/macrofauna (Sheppard et al., 2006).

Seasonal habitat suitability assessments provide insights into migration, foraging, and reproduction (Putra & Mustika, 2020) and help develop conservation strategies (Boitani et al., 2011). Our findings show that highly suitable dugong habitats are confined to specific areas along the ANI coast despite widespread seagrass presence. The identified high/moderate suitability and high-risk regions align with previous studies on dugong occupancy probability (Marsh et al., 1994). In the ANI region, seagrass presence, depth, and distance from shore are key factors in habitat suitability. Although the similarity correlation matrix (**Table 4.4**) suggests minimal seasonal differences in suitable sites, notable variations in variable contributions highlight the need for seasonal assessments (Ng et al., 2022) and fine-scale mapping (Derville et al., 2022) in less studied areas like Little Andaman and central Nicobar. In PB-GoM, we observed significant seasonal variations in suitable areas for dugongs. During the pre-monsoon season, north Palk Bay, a sheltered embayment with a gradual slope, appears to be favourable for dugongs. The monsoon season shows moderate suitability along the entire coastline, with highly suitable areas shifting to GoM during the post-monsoon. Seasonal changes in habitat suitability, influenced by biotic (seagrass presence), topographic (slope), and environmental (sea surface temperature) factors, require further research. In GoK, seagrass presence and low organic turbidity support clear shallow waters preferred by dugongs (Cleguer et al., 2020). Given the relict dugong population in GoK (Pathan et al., 2022), detailed mapping of seasonal dugong occurrence and seagrass distribution is needed.

Dugongs are at risk from accidental entanglement in fishing nets and boat strikes due to their regular surfacing and slow movement, which can lead to injuries or fatalities (Verutes et al., 2020). Bycatch and hunting are significant threats (Ilangakoon et al., 2008). Our analysis indicates that highly suitable dugong habitats are also subject to high fishing pressure, including the eastern coast of the Andaman Islands, north Palk Bay, and the entire GoM, including the GoM Marine National Park and southwestern GoK. Despite numerous protected areas in ANI (nine National Parks, including two Marine National Parks and 94 Wildlife

Sanctuaries), many suitable dugong habitats remain unprotected. CDHs extend beyond these protected zones, particularly in Aerial Bay, Diglipur, Little Andaman, and Central Nicobar. Ground validation in north Andaman suggests the need for intensive monitoring outside protected areas.

Dugongs exhibit both short-range (<15 km) and long-range (>15 km, up to 560 km) movements (Marsh & Kwan, 2008). Our findings suggest significant seasonal migration in PB-GoM, potentially involving transboundary seagrass habitats along Sri Lankan coasts, particularly during the post-monsoon season. Seasonal variations in seagrass extent and density, influenced by human activities (Geevarghese et al., 2018), may facilitate dugong movements. Long migrations, driven by seagrass habitat loss, can impact dugong genetic diversity and dietary preferences (Hashim et al., 2017; Poommouang et al., 2021; Raoult et al., 2020). Real-time tracking or photographic studies [e.g., using drones (Raoult et al., 2020)] and fine-scale environmental data collection are recommended to validate long-distance movements (Noviello et al., 2021).

The rise of large mechanised vessels and destructive fishing practices (e.g., bottom trawling) is leading to the loss of seagrass habitats, adversely affecting both fisheries and dugong populations. Areas outside the current protected area network include approximately 95% for ANI, 72% for PB-GoM, and 63% for GoK. Many of these regions are critical fishing grounds supporting millions of livelihoods. Effective management of these high-risk, high-priority areas is essential, incorporating participatory approaches to balance community needs with sustainable practices. Engaging in community-supported space-time closures and government-supported incentives could help reduce pressure on dugong habitats.

Implementing participatory regulatory mechanisms, such as Community Conserved Areas (CCAs) or Other Effective Conservation Measures (OECMs), could enhance biodiversity protection, maintain critical ecosystems, and support global conservation goals, including the Convention on Biological Diversity's (CBD) '30 x 30' target and efforts to reverse biodiversity loss (CBD, 2022).

Overall, identifying Critical Dugong Habitats (CDHs) using a model-based approach provides valuable insights for conserving this large mammalian grazer, highlighting the importance of citizen science and secondary data in large-scale spatial ecological analysis. This study emphasises the need to expand India's Marine Protected Area (MPA) network in dugong habitats to support the '30 x 30' global biodiversity target and achieve effective and equitable conservation outcomes.

4.5. Conclusion

The research presented in this chapter emphasises the crucial role of spatial prioritisation for dugong habitat conservation in India, highlighting its potential contribution to global biodiversity targets. Utilising environmental niche modelling, the study identified key factors influencing dugong habitat suitability, such as seagrass presence, depth, bathymetric slope, and distance from the shore. The research revealed significant seasonal shifts in suitable habitats, particularly between pre-monsoon and post-monsoon seasons in the Palk Bay and Gulf of Mannar regions. These findings underscore the necessity of considering seasonal dynamics in conservation planning.

Furthermore, the study integrated data on fishing pressures from systematic interview surveys, citizen-science contributions, and field surveys to assess the risk levels in various dugong habitats. The results indicated that the entire coastline along the Palk Bay-Gulf of Mannar region, including the Gulf of Mannar Marine National Park, faces moderate to high risk. In contrast, the Andaman Islands exhibited high suitability during both pre- and post-monsoon seasons, suggesting these areas as critical refuges for dugongs.

This research contributes valuable insights for conservation managers and policymakers, advocating for targeted protection measures in high-risk areas and highlighting the importance of protecting seagrass meadows to ensure dugong survival. By prioritising these habitats, India can make significant strides towards achieving the 30×30 global biodiversity target, which aims to protect 30% of the world's land and ocean areas by 2030. Integrating habitat suitability modelling and risk assessment provides a robust framework for spatial planning. It can serve as a model for conservation efforts in other regions with similar ecological and socio-economic contexts.

Highlights for managers:

- **Critical Dugong Habitats Identified:** Key areas with high habitat suitability and high risk for dugongs have been identified in the Andaman and Nicobar Islands (ANI), Palk Bay-Gulf of Mannar (PB-GoM), and the Gulf of Kutch (GoK). These regions require focused conservation efforts.
- **Seasonal Habitat Variations:** Significant seasonal shifts in habitat suitability were observed, particularly in the PB-GoM region, where highly suitable areas move from north Palk Bay pre-monsoon to the Gulf of Mannar post-monsoon.
- **Seagrass Presence as a Major Factor:** Seagrass availability is the most critical determinant of suitable dugong habitats across all regions and seasons. Conservation efforts should prioritise protecting and restoring seagrass meadows.
- **Insufficient Protected Area Coverage:** Current Marine Protected Areas (MPAs) do not sufficiently cover the critical areas. For instance, only 5.5% of the high-risk area in ANI is protected, and significant portions of PB-GoM and GoK regions fall outside existing protected areas.
- **Necessity for Seasonal Monitoring:** Due to seasonal changes in habitat suitability and seagrass distribution, regular and fine-scale monitoring is essential to adapt conservation strategies effectively.
- **Community Participation:** Engaging local communities in conservation efforts through participatory approaches and incentivisation programs can help reduce anthropogenic pressure on dugong habitats.
- **Potential for Transboundary Conservation:** The potential for dugong migration across international boundaries, particularly between India and Sri Lanka, suggests a need for collaborative conservation efforts at a regional scale.
- **Research and Data Collection:** There is a critical need for real-time tracking and detailed environmental data collection to better understand dugong movements and habitat use patterns, which can inform more effective conservation strategies.
- **Policy Implications:** Conservation managers should advocate for expanding the MPA network to include high-risk areas identified in this study. This would support India's efforts to meet global biodiversity targets, such as the '30×30' initiative.

CHAPTER 5:
CONCLUSION

CHAPTER 5: CONCLUSION

5.1. Introduction

This chapter concludes the findings of the research on criticality assessment of dugong habitats in India, emphasising the crucial role of spatial prioritisation and the integration of environmental niche modelling and risk assessment. The results of the study provide a framework for targeted conservation efforts and offer valuable insights for conservation managers and policymakers.

5.2. Summary of Key Findings

5.2.1. Spatial Prioritization for Dugong Habitat Conservation

The study highlights the importance of spatial prioritisation in identifying critical dugong habitats. Key factors influencing dugong habitat suitability include the presence of seagrass, depth, bathymetric slope, and distance from the shore. These factors were crucial in determining suitable habitats in the Palk Bay and Gulf of Mannar regions, with significant seasonal shifts observed between pre-monsoon and post-monsoon seasons.

5.2.2. Seasonal Dynamics in Habitat Suitability

The research revealed that dugong habitats in the Palk Bay-Gulf of Mannar region exhibit significant seasonal shifts. Highly suitable areas move from the north Palk Bay during pre-monsoon to the Gulf of Mannar during post-monsoon. This finding underscores the necessity of considering seasonal dynamics in conservation planning to ensure the protection of dugongs throughout the year.

5.2.3. Risk Assessment and Fishing Pressures

By integrating data from systematic interview surveys, citizen-science contributions, and field surveys, the study assessed the risk levels in various dugong habitats. The entire coastline along the Palk Bay-Gulf of Mannar region, including the Gulf of Mannar Marine National Park, faces moderate to high risk. In contrast, the Andaman Islands exhibited high habitat suitability during both pre- and post-monsoon seasons, suggesting these areas as critical refuges for dugongs.

5.2.4. Conservation Implications

The findings advocate for targeted protection measures in high-risk areas and highlight the importance of protecting seagrass meadows to ensure dugong survival. By prioritising these habitats, India can make significant strides towards achieving the 30×30 global biodiversity target, which aims to protect 30% of the world's land and ocean areas by 2030.

5.3. Recommendations for Conservation Managers

5.3.1. Critical Dugong Habitats identified

Key areas with high habitat suitability and high risk for dugongs have been identified in the Andaman and Nicobar Islands, Palk Bay-Gulf of Mannar, and the Gulf of Kutch. These regions require focused conservation efforts to protect and restore critical habitats.

5.3.2. Seagrass presence as a major factor

Seagrass availability is the most critical determinant of suitable dugong habitats across all regions and seasons. Conservation efforts should prioritise protecting and restoring seagrass meadows to maintain dugong populations.

5.3.3. Insufficient protected area coverage

Current Marine Protected Areas (MPAs) do not sufficiently cover critical dugong habitats. Only 5.5% of the high-risk area in the Andaman and Nicobar Islands is protected, and 72% of the Palk Bay-Gulf of Mannar and 63% of the Gulf of Kutch regions fall outside existing protected areas. Expanding the MPA network to include high-risk areas is essential.

5.3.4. Necessity for seasonal monitoring

Due to seasonal changes in habitat suitability and seagrass distribution, especially in Tamil Nadu, regular and fine-scale monitoring is essential to adapt conservation strategies effectively. This approach will ensure that protection measures are responsive to seasonal dynamics.

5.3.5. Community participation

Engaging local communities in conservation efforts through participatory approaches and incentivisation programs can help reduce anthropogenic pressure on dugong habitats. In this study, building a good rapport with the fishing community enables us to collect important data on fishing ranges, dugongs, and other marine megafauna sighting locations. Therefore, community involvement is crucial for the success of conservation initiatives.

5.3.6. Potential for transboundary conservation

The potential for dugong migration across international boundaries, particularly between India and Sri Lanka, suggests a need for collaborative conservation efforts at a regional scale. The signing of the UNEP-CMS Dugong MoU paved the way for addressing the issue. Strengthening such policies through expanding transboundary conservation initiatives can enhance the effectiveness of protection measures.

5.4. Policy Implications

5.4.1. Expanding the Marine Protected Area (MPA) network

Conservation managers should advocate for expanding the MPA network to include high-risk areas identified in this study. This expansion is vital for meeting global biodiversity targets, such as the '30×30' initiative, and ensuring the long-term survival of dugongs and other seagrass-associated fauna.

5.4.2. Integrating Habitat Suitability Modelling and Risk Assessment

Integrating habitat suitability modelling and risk assessment provides a robust framework for spatial planning. This approach can serve as a model for conservation efforts in other regions with similar ecological and socio-economic contexts.

5.4.3. Enhancing Data Collection Methods

The shift from interview-based surveys to the utilisation of advanced technologies, such as GPS data loggers, has markedly improved the resolution, precision and accuracy of spatial data related to fishing pressure. This methodological improvement facilitates more effective management and protection strategies for vulnerable species like the dugong.

There is a critical need for real-time tracking and detailed environmental data collection to better understand dugong movements and habitat use patterns. This information can inform more effective conservation strategies and management plans.

5.5. Future Research Directions

5.5.1. Long-distance migration and genetic diversity

Further research is needed to validate the long-distance migration of dugongs and understand their impact on genetic diversity and dietary preferences. GPS tagging of the animals and behavioural studies using drones are recommended. e-DNA studies can play a pivotal role in ascertaining migration patterns.

5.5.2. Impact of Climate Change on Seagrass Habitats

Investigating the impact of climate change on seagrass habitats and dugong populations is crucial for developing adaptive conservation strategies. Understanding how climate change influences seagrass distribution and health will help plan for future conservation needs. Also, the concept of dynamic protected areas can be leveraged for long-term conservation planning.

5.5.3. Socio-Economic Impact of Conservation Measures

Assessing the socio-economic impact of conservation measures on local communities is essential. This research will help in designing participatory regulatory mechanisms, such as

Community Conserved Areas (CCAs) or Other Effective Conservation Measures (OECMs), that balance community needs with biodiversity protection.

5.5. Limitations

The primary limitations of seagrass mapping in this study include inaccessibility to certain areas in the Andaman and Gulf of Mannar regions due to high wave action and bathymetry, which constrained data collection. Additionally, the study was conducted within a specific time frame, and given the dynamic nature of seagrass meadows, the maps produced are representative of that period only. Incorporating temporal replicates in future studies would enable a more comprehensive understanding and provide more robust inferences about seagrass dynamics.

Our study draws its findings and inferences from the CMS-UNEP Dugong Questionnaire, which relies on opportunistic sightings and secondary information gathered through interview surveys with fisherfolk, a dugong volunteer network, and other stakeholders. While this approach demonstrates the value of citizen science in mapping the spatial distribution of marine mammals, the dataset is subject to certain uncertainties. One key limitation is the reliance on opportunistic occurrence data from an extensive informant network, which may introduce spatial and temporal biases related to the range and timing of fishing activities across seasons. For the PB-GoM region, pre-monsoon data predominantly originated from Palk Bay. **Figure 4.2** highlights the occurrence frequency throughout the year, with higher values observed during the pre-monsoon season. To mitigate these biases, we applied bias correction techniques and rarefied the data to one observation per grid for analysis.

5.6. Conclusion

The research underscores the importance of integrating spatial prioritisation, seasonal dynamics, and risk assessment in dugong habitat conservation. By focusing on critical habitats, protecting seagrass meadows, and engaging local communities, India can contribute significantly to global biodiversity targets and ensure the survival of dugongs. The findings provide a framework for conservation managers and policymakers to develop effective and equitable conservation strategies, setting a precedent for other regions with similar ecological and socio-economic contexts.

REFERENCES

REFERENCES

- Anand, Y. A. (2021). *A study on marine mammals of Gulf of Kachchh, Gujarat, India*. University School of Sciences, Gujarat University.
- Aragones, L. V., Lawler, I. R., Foley, W. J., & Marsh, H. (2006). Dugong grazing and turtle cropping: grazing optimization in tropical seagrass systems? *Oecologia*, *149*(4), 635–647. <https://doi.org/10.1007/s00442-006-0477-1>
- Ascherson, P., & Beccari, O. (1871). *Plantae phanerogamae marinae, quas cl. Eduardus Beccari in Archipelago Indico annis 1866 et 1867, et in Mari Rubro anno 1870 collegit, enumeratae*. G. Pellas.
- Astudillo-Scalia, Y., & de Albuquerque, F. S. (2020). The geography of high-priority conservation areas for marine mammals. *Global Ecology and Biogeography*, *29*(12), 2097–2106. <https://doi.org/10.1111/geb.13175>
- Authority, N. D. (2016). National Disaster Management Plan. Retrieved from National Disaster Management Authority: [https://ndma.gov.in/Images/Policyplan/Dmplan/National% 20Disaster% 20Management% 20Plan% 20May, 2, 02016](https://ndma.gov.in/Images/Policyplan/Dmplan/National%20Disaster%20Management%20Plan%20May,2,2016).
- Bakirman, T., & Gumusay, M. U. (2020). Assessment of machine learning methods for seagrass classification in the mediterranean. *Baltic Journal of Modern Computing*, *8*(2). <https://doi.org/10.22364/BJMC.2020.8.2.07>
- Basher, Z., Bowden, D. A., & Costello, M. J. (2018). GMED: Global Marine Environment Datasets for environment visualisation and species distribution modelling. *Earth System Science Data Discussions*.
- Bayyana, S., Pawar, S., Gole, S., Dudhat, S., Pande, A., Mitra, D., Johnson, J. A., & Sivakumar, K. (2020). Detection and mapping of seagrass meadows at Ritchie’s archipelago using Sentinel 2A satellite imagery. *Current Science*, *118*(8). <https://doi.org/10.18520/cs/v118/i8/1275-1282>
- Bera, S., Das Majumdar, D., & Paul, A. K. (2015). Estimation of Tourism Carrying Capacity for Neil Island, South Andaman, India. *Journal of Coastal Sciences*, *2*(2), 46–53.
- Bertelli, C. M., Bull, J. C., Cullen-Unsworth, L. C., & Unsworth, R. K. F. (2021). Unravelling the Spatial and Temporal Plasticity of Eelgrass Meadows. *Frontiers in Plant Science*, *12*. <https://doi.org/10.3389/fpls.2021.664523>

- Bhathal, B., & Pauly, D. (2008). 'Fishing down marine food webs' and spatial expansion of coastal fisheries in India, 1950–2000. *Fisheries Research*, *91*(1), 26–34.
<https://doi.org/10.1016/J.FISHRES.2007.10.022>
- Björk, M., Short, F., Mcleod, E., & Beer, S. (2008). Managing Seagrasses for Resilience to Climate Change IUCN Global Marine Programme. In *IUCN Resilience Science Group Working Paper Series* (Issue 3).
- Boitani, L., Maiorano, L., Baisero, D., Falcucci, A., Visconti, P., & Rondinini, C. (2011). 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. <https://doi.org/10.1098/rstb.2011.0117>
- Bonizzoni, S., Furey, N. B., Santostasi, N. L., Eddy, L., Valavanis, V. D., & Bearzi, G. (2019). 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. <https://doi.org/10.1002/aqc.3148>
- Briscoe, D., Hiatt, S., Lewison, R., & Hines, E. (2014). Modeling habitat and bycatch risk for dugongs in Sabah, Malaysia. *Endangered Species Research*, *24*(3), 237–247.
<https://doi.org/10.3354/esr00600>
- Brown, J. L., Bennett, J. R., & French, C. M. (2017). SDMtoolbox 2.0: the next generation Python-based GIS toolkit for landscape genetic, biogeographic and species distribution model analyses. *PeerJ*, *5*, e4095. <https://doi.org/10.7717/peerj.4095>
- Carroll, C., & Noss, R. F. (2022). How percentage-protected targets can support positive biodiversity outcomes. *Conservation Biology*, *36*(4). <https://doi.org/10.1111/cobi.13869>
- CBD. (2022). *Decision adopted by the Conference of Parties to the Convention on Biological Diversity, Kunming-Montreal Global Biodiversity Framework*.
<https://www.cbd.int/conferences/post20202CBD/WG8J/11/7,CBD/SBSTTA/23/9,CBD/SBSTTA/24/12andCBD/SBI/3/21,respectively>.
- Cleguer, C., Garrigue, C., & Marsh, H. (2020). Dugong (*Dugong dugon*) movements and habitat use in a coral reef lagoonal ecosystem. *Endangered Species Research*, *43*, 167–181. <https://doi.org/10.3354/ESR01061>

- Collins, K. J., Suonpää, A. M., & Mallinson, J. J. (2010). The impacts of anchoring and mooring in seagrass, Studland Bay, Dorset, UK. *Underwater Technology*, 29(3), 117–123. <https://doi.org/10.3723/UT.29.117>
- Cullen-Unsworth, L. C., & Unsworth, R. K. F. (2016). Strategies to enhance the resilience of the world's seagrass meadows. *Journal of Applied Ecology*, 53(4), 967–972.
- de Groot, S. J. (1984). The impact of bottom trawling on benthic fauna of the North Sea. *Ocean Management*, 9(3–4), 177–190. [https://doi.org/10.1016/0302-184X\(84\)90002-7](https://doi.org/10.1016/0302-184X(84)90002-7)
- Derville, S., Cleguer, C., & Garrigue, C. (2022). Ecoregional and temporal dynamics of dugong habitat use in a complex coral reef lagoon ecosystem. *Scientific Reports*, 12(1), 552. <https://doi.org/10.1038/s41598-021-04412-3>
- Dilipan, E., Lucas, C., Papenbrock, J., & Thangaradjou, T. (2018). Tracking the Phylogeny of Seagrasses: Inferred from 18S rRNA Gene and Ancestral State Reconstruction of Morphological Data. *Proceedings of the National Academy of Sciences India Section B - Biological Sciences*, 88(2), 497–504. <https://doi.org/10.1007/S40011-016-0780-5/METRICS>
- Dorji, T., Linke, S., & Sheldon, F. (2020). Optimal model selection for Maxent: a case of freshwater species distribution modelling in Bhutan, a data poor country. *Authorea*.
- D'Souza, E., & Patankar, V. (2009). First underwater sighting and preliminary behavioural observations of Dugongs (Dugong dugon) in the wild from Indian waters, Andaman Islands. *Journal of Threatened Taxa*, 1(1). <https://doi.org/10.11609/jott.o2002.49-53>
- D'Souza, E., Patankar, V., Arthur, R., Marbà, N., & Alcoverro, T. (2015). Seagrass Herbivory Levels Sustain Site-Fidelity in a Remnant Dugong Population. *PLOS ONE*, 10(10), e0141224. <https://doi.org/10.1371/journal.pone.0141224>
- Duarte, C. M. (2002). The future of seagrass meadows. *Environmental Conservation*, 29(2), 192–206. <https://doi.org/10.1017/S0376892902000127>
- Duarte, C. M., Kennedy, H., Marbà, N., & Hendriks, I. (2013). Assessing the capacity of seagrass meadows for carbon burial: Current limitations and future strategies. *Ocean and Coastal Management*, 83. <https://doi.org/10.1016/j.ocecoaman.2011.09.001>
- Duarte, C. M., Marbà, N., Gacia, E., Fourqurean, J. W., Beggins, J., Barrón, C., & Apostolaki, E. T. (2010). Seagrass community metabolism: Assessing the carbon sink capacity of

- seagrass meadows. *Global Biogeochemical Cycles*, 24(4).
<https://doi.org/10.1029/2010GB003793>
- Dudhat, S., Pande, A., Nair, A., Mondal, I., Srinivasan, M., & Sivakumar, K. (2022). Spatio-temporal analysis identifies marine mammal stranding hotspots along the Indian coastline. *Scientific Reports*, 12(1), 4128. <https://doi.org/10.1038/s41598-022-06156-0>
- Dunic, J. C., Brown, C. J., Connolly, R. M., Turschwell, M. P., & Côté, I. M. (2021). Long-term declines and recovery of meadow area across the world's seagrass bioregions. *Global Change Biology*, 27(17), 4096–4109. <https://doi.org/10.1111/gcb.15684>
- Elith, J., Phillips, S. J., Hastie, T., Dudík, M., Chee, Y. E., & Yates, C. J. (2011). A statistical explanation of MaxEnt for ecologists. *Diversity and Distributions*, 17(1).
<https://doi.org/10.1111/j.1472-4642.2010.00725.x>
- Erfteimeijer, P. L. A., & Robin Lewis, R. R. (2006). Environmental impacts of dredging on seagrasses: A review. *Marine Pollution Bulletin*, 52(12), 1553–1572.
<https://doi.org/10.1016/J.MARPOLBUL.2006.09.006>
- Fourcade, Y., Engler, J. O., Rödder, D., & Secondi, J. (2014). 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), e97122.
<https://doi.org/10.1371/journal.pone.0097122>
- FRAEED, & CMFRI. (2023). *Marine Fish Landings in India-2022*.
- Frazier, J. G., & Mundkur, T. (1990). Dugong dugon Muller in the Gulf of Kutch, Gujarat. *J. Bombay Nat. Hist. Soc.*, 87(3), 368–379.
- Galante, P. J., Alade, B., Muscarella, R., Jansa, S. A., Goodman, S. M., & Anderson, R. P. (2018). The challenge of modeling niches and distributions for data-poor species: a comprehensive approach to model complexity. *Ecography*, 41(5), 726–736.
<https://doi.org/10.1111/ecog.02909>
- Geevarghese, G. A., Akhil, B., Magesh, G., Krishnan, P., Purvaja, R., & Ramesh, R. (2018). A comprehensive geospatial assessment of seagrass distribution in India. *Ocean and Coastal Management*, 159, 16–25. <https://doi.org/10.1016/j.ocecoaman.2017.10.032>
- Gillanders, B. (2006). Seagrasses, fish, and fisheries. In *Seagrasses: biology, ecology and conservation* (pp. 503–536).

- Gopalakrishnan, A. (2023). Marine Fish Landings in India-2022. In *CMFRI Booklet Series* (Issue 31). www.cmfri.org.in
- Gormley, A. M., Slooten, E., Dawson, S., Barker, R. J., Rayment, W., Du Fresne, S., & Bräger, S. (2012). First evidence that marine protected areas can work for marine mammals. *Journal of Applied Ecology*, 49(2), 474–480. <https://doi.org/10.1111/J.1365-2664.2012.02121.X>
- Government of Tamil Nadu. (2022). *Tamil Nadu Government Gazette, Declaration of Dugong Conservation Reserve in Palk Bay of Wildlife (Protection) Act, 1972*. <https://www.cms.int/dugong/sites/default/files/2022-09-21%20PalkBay%20Dugong%20Reserve-Gazette%20Notification-FULL.pdf>
- Green, E. P., & Short, F. T. (2003). World atlas of seagrasses. Prepared by the UIMEP world conservation monitoring centre. In *Choice Reviews Online* (Vol. 41, Issue 06).
- Gunasekara, S. S., & Mishra, A. K. (2014). *Mapping the Coverage of Seagrass Meadows of Gulf of Mannar and Palk Bay (India) Using Landsat Etm+ Data*. 18, 2014.
- Hashim, M., Ito, S., Numata, S., Hosaka, T., Hossain, M. S., Misbari, S., Yahya, N. N., & Ahmad, S. (2017). Using fisher knowledge, mapping population, habitat suitability and risk for the conservation of dugongs in Johor Straits of Malaysia. *Marine Policy*, 78, 18–25. <https://doi.org/10.1016/j.marpol.2017.01.002>
- Heisohn, G. E., & Birch, W. R. (1972). FOODS AND FEEDING HABITS OF THE DUGONG, DUGONG DUGONG (ERXLEBEN), IN NORTHERN QUEENSLAND, AUSTRALIA. *Mammalia*, 36(3). <https://doi.org/10.1515/mamm.1972.36.3.414>
- Hernawan, U. E., Rahmawati, S., Ambo-Rappe, R., Sjafrie, N. D. M., Hadiyanto, H., Yusup, D. S., Nugraha, A. H., La Nafie, Y. A., Adi, W., Prayudha, B., Irawan, A., Rahayu, Y. P., Ningsih, E., Riniatsih, I., Supriyadi, I. H., & McMahan, K. (2021). The first nation-wide assessment identifies valuable blue-carbon seagrass habitat in Indonesia is in moderate condition. *Science of The Total Environment*, 782, 146818. <https://doi.org/10.1016/j.scitotenv.2021.146818>
- Hooker, J. D. (1888a). *Hydrocharitaceae: Flora of British India* (Hooker, J.D. (Ed.)). L. Reeve and Co.
- Hooker, J. D. (1888b). *Hydrocharitaceae*. In: *Hooker, J.D. (Ed.), Flora of British India* (Vol. 5). L. Reeve and Co.

- Hooker, J. D. (1893a). *Hydrocharitaceae: Flora of British India* (Hooker, J.D. (Ed.)). L. Reeve and Co.
- Hooker, J. D. (1893b). *Naijadaceae. In: Hooker, J.D. (Ed.), Flora of British India* (Vol. 5). L. Reeve and Co.
- Horton, T., Gofas, S., Kroh, A., Poore, G. C. B., Read, G., Rosenberg, G., Stöhr, S., Bailly, N., Boury-Esnault, N., Brandão, S. N., Costello, M. J., Decock, W., Dekeyzer, S., Hernandez, F., Mees, J., Paulay, G., Vandepitte, L., Vanhoorne, B., & Vranken, S. E. (2017). Improving nomenclatural consistency: A decade of experience in the World Register of Marine Species. *European Journal of Taxonomy*, 2017(389).
<https://doi.org/10.5852/ejt.2017.389>
- Hoyt, E. (2005). 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*, 105B(3), 141–154. <https://doi.org/10.1353/BAE.2005.0005>
- Hughes, A. R., Williams, S. L., Duarte, C. M., Heck, K. L., & Waycott, M. (2009). Associations of concern: Declining seagrasses and threatened dependent species. *Frontiers in Ecology and the Environment*, 7(5). <https://doi.org/10.1890/080041>
- Hunt, T. N., Allen, S. J., Bejder, L., & Parra, G. J. (2020). Identifying priority habitat for conservation and management of Australian humpback dolphins within a marine protected area. *Scientific Reports*, 10(1), 14366. <https://doi.org/10.1038/s41598-020-69863-6>
- Ilangakoon, A. D., Sutaria, D., Hines, E., & Raghavan, R. (2008). 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. <https://doi.org/10.1111/j.1748-7692.2008.00209.x>
- IMD. (2021). *Report on Northeast Monsoon – 2020*.
<https://mausam.imd.gov.in/chennai/monsoon.php>
- IUCN. (2024). *IUCN Red List*. <https://www.iucnredlist.org/search?permalink=7a76187b-ff1f-48d4-b90e-5bfce55bde4e>
- Jayathilake, D. R. M., & Costello, M. J. (2018). A modelled global distribution of the seagrass biome. *Biological Conservation*, 226. <https://doi.org/10.1016/j.biocon.2018.07.009>

- Kannan, L., Thangaradjou, T., & Anantharaman, P. (1999). Status of seagrasses of India. *Namakkal [Seaweed Res. Util.]*, 21(1–2).
- Kass, J. M., Muscarella, R., Galante, P. J., Bohl, C. L., Pinilla-Buitrago, G. E., Boria, R. A., Soley-Guardia, M., & Anderson, R. P. (2021). ENMeval 2.0: Redesigned for customizable and reproducible modeling of species' niches and distributions. *Methods in Ecology and Evolution*, 12(9), 1602–1608. <https://doi.org/10.1111/2041-210X.13628>
- Kendrick, G. A., Aylward, M. J., Hegge, B. J., Cambridge, M. L., Hillman, K., Wyllie, A., & Lord, D. A. (2002). Changes in seagrass coverage in Cockburn Sound, Western Australia between 1967 and 1999. *Aquatic Botany*, 73(1). [https://doi.org/10.1016/S0304-3770\(02\)00005-0](https://doi.org/10.1016/S0304-3770(02)00005-0)
- Koshy, N. E., Bhatt, J. R., & Vakily, J. M. (2018). Synthesis of the Conference on Management and Conservation of Seagrass Ecosystems in India. *Ocean and Coastal Management*, 159(October), 3–6. <https://doi.org/10.1016/j.ocecoaman.2017.11.001>
- Larkum, A. W. D., Orth, R. J. (Robert J., & Duarte, C. M. (2006). *Seagrasses : biology, ecology, and conservation*. Springer.
- Lin, M., Turvey, S. T., Han, C., Huang, X., Mazaris, A. D., Liu, M., Ma, H., Yang, Z., Tang, X., & Li, S. (2022). Functional extinction of dugongs in China. *Royal Society Open Science*, 9(8). <https://doi.org/10.1098/rsos.211994>
- Lucas, C., Thangaradjou, T., & Papenbrock, J. (2012). Development of a DNA barcoding system for seagrasses: Successful but not simple. *PLoS ONE*, 7(1). <https://doi.org/10.1371/journal.pone.0029987>
- Lyzenga, D. R. (1981). Remote sensing of bottom reflectance and water attenuation parameters in shallow water using aircraft and Landsat data. *International Journal of Remote Sensing*, 2(1), 71–82. <https://doi.org/10.1080/01431168108948342>
- Marsh, H., Grech, A., & McMahon, K. (2018). Dugongs: Seagrass Community Specialists. In *Seagrasses of Australia* (pp. 629–661). Springer International Publishing. https://doi.org/10.1007/978-3-319-71354-0_19
- Marsh, H., & Kwan, D. (2008). 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. <https://doi.org/10.1016/j.csr.2008.03.023>

- Marsh, H., Penrose, H., & Eros, C. (2002). *Dugong Status Report and Action Plans for Countries and Territories*.
- Marsh, H., Prince, R., Saafeld, W., & Shepherd, R. (1994). The distribution and abundance of the dugong in Shark Bay, Western Australia. *Wildlife Research*, 21(2), 149. <https://doi.org/10.1071/WR9940149>
- Marsh, H., & Sobtzick, S. (2015, August 5). *Dugong dugon (amended version of 2015 assessment)*. The IUCN Red List of Threatened Species 2019. <https://doi.org/https://dx.doi.org/10.2305/IUCN.UK.2015-4.RLTS.T6909A160756767.en>
- Mathews, G., Raj, K. D., Thinesh, T., Patterson, J., & Edward, J. K. P. (2010). newslettervol.222010. *South Indian Coastal and Marine Bulletin*, 2(2), 1–21.
- McFeeters, S. K. (1996). The use of the Normalized Difference Water Index (NDWI) in the delineation of open water features. *International Journal of Remote Sensing*, 17(7), 1425–1432. <https://doi.org/10.1080/01431169608948714>
- McKenzie, L. J., Nordlund, L. M., Jones, B. L., Cullen-Unsworth, L. C., Roelfsema, C., & Unsworth, R. K. F. (2020). The global distribution of seagrass meadows. *Environmental Research Letters*, 15(7). <https://doi.org/10.1088/1748-9326/ab7d06>
- Ministry of Environment, F. and C. C. (2015). *India: First biennial update report to the United Nations framework convention on climate change*. Ministry of Environment, Forest and Climate Change, Government of India.
- Muscarella, R., Galante, P. J., Soley-Guardia, M., Boria, R. A., Kass, J. M., Uriarte, M., & Anderson, R. P. (2014). ENMeval: An R package for conducting spatially independent evaluations and estimating optimal model complexity for <scp>Maxent</scp> ecological niche models. *Methods in Ecology and Evolution*, 5(11), 1198–1205. <https://doi.org/10.1111/2041-210X.12261>
- Ng, S. Z. H., Ow, Y. X., & Jaafar, Z. (2022). Dugongs (Dugong dugon) along hyper-urbanized coastlines. *Frontiers in Marine Science*, 9. <https://doi.org/10.3389/fmars.2022.947700>
- Nobi, E. P., Dilipan, E., Sivakumar, K., & Thangaradjou, T. (2012). Estimation of the Aerial Cover of Seagrasses of Lakshadweep Islands (India) Using Indian Remote Sensing Satellite (IRS P6 LISS IV). *Journal of the Indian Society of Remote Sensing*, 40(3), 467–481. <https://doi.org/10.1007/s12524-011-0179-y>

- Nobi, E. P., Dilipan, E., Thangaradjou, T., & Dinesh Kumar, P. K. (2013). Restoration scaling of seagrass habitats in the oceanic islands of Lakshadweep, India using geospatial technology. *Applied Geomatics*, 5(2). <https://doi.org/10.1007/s12518-013-0109-5>
- Nobi, E. P., & Thangaradjou, T. (2012). Evaluation of the spatial changes in seagrass cover in the lagoons of Lakshadweep islands, India, using IRS LISS III satellite images. *Geocarto International*, 27(8), 647–660. <https://doi.org/10.1080/10106049.2012.665501>
- Noviello, N., McGonigle, C., Jacoby, D. M. P., Meyers, E. K. M., Jiménez-Alvarado, D., & Barker, J. (2021). 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. <https://doi.org/10.1002/aqc.3711>
- Pandey, N., Tatu, K., & Anand, Y. (2010). *Status of Dugong (Dugong dugon) in India report*.
- Pathan, S., Pande, A., Sivakumar, K., & Johnson, J. A. (2022). Scars of hope and forewarn of a bleak future: Post-mortem findings of dugongs (*Dugong dugon*). *Current Science*, 123(7), 919–924.
- Paulose, N. E., Dilipan, E., & Thangaradjou, T. (2013). 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(2), 173–181. <https://doi.org/10.1007/s12601-013-0014-1>
- Phillips, S. J., Anderson, R. P., & Schapire, R. E. (2006). Maximum entropy modeling of species geographic distributions. *Ecological Modelling*, 190(3–4). <https://doi.org/10.1016/j.ecolmodel.2005.03.026>
- Phillips, S. J., & Dudík, M. (2008). Modeling of species distributions with Maxent: New extensions and a comprehensive evaluation. *Ecography*, 31(2). <https://doi.org/10.1111/j.0906-7590.2008.5203.x>
- Pilcher, N. J., & Kwan, D. (2012). *Dugong Questionnaire Survey Project Manual*.
- Pinto-Ledezma, J. N., & Cavender-Bares, J. (2020). Using Remote Sensing for Modeling and Monitoring Species Distributions. In *Remote Sensing of Plant Biodiversity* (pp. 199–223). Springer International Publishing. https://doi.org/10.1007/978-3-030-33157-3_9
- Poommouang, A., Kriangwanich, W., Buddhachat, K., Brown, J. L., Piboon, P., Chomdej, S., Kampuansai, J., Mekchay, S., Kaewmong, P., Kittiwattanawong, K., & Nganvongpanit,

- K. (2021). Genetic diversity in a unique population of dugong (*Dugong dugon*) along the sea coasts of Thailand. *Scientific Reports*, *11*(1), 11624. <https://doi.org/10.1038/s41598-021-90947-4>
- Prater, S. H. (1928). The dugong or sea cow (*Halicore dugong*). *Journal of the Bombay Natural History Society*, *33*(1), 84–99.
- Preen, A., & Marsh, H. (1995). Response of dugongs to large scale loss. *Wildlife Research*, *22*(4), 507–519.
- Putra, M. I. H., & Mustika, P. L. K. (2020). 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. <https://doi.org/10.1002/aqc.3379>
- Rajpurkar Sagar, Pande, A., Sharma, S., Gole, S., Dudhat, S., Johnson, J. A., & Sivakumar, K. (2021). Lightweight unmanned aerial vehicle surveys detect dugongs and other globally threatened marine species from the Andaman and Nicobar Islands, India. *Current Science*, *121*(2), 195–197.
- Randin, C. F., Ashcroft, M. B., Bolliger, J., Cavender-Bares, J., Coops, N. C., Dullinger, S., Dirnböck, T., Eckert, S., Ellis, E., Fernández, N., Giuliani, G., Guisan, A., Jetz, W., Joost, S., Karger, D., Lembrechts, J., Lenoir, J., Luoto, M., Morin, X., ... Payne, D. (2020). Monitoring biodiversity in the Anthropocene using remote sensing in species distribution models. *Remote Sensing of Environment*, *239*, 111626. <https://doi.org/10.1016/j.rse.2019.111626>
- Raoult, V., Colefax, A. P., Allan, B. M., Cagnazzi, D., Castelblanco-Martínez, N., Ierodiaconou, D., Johnston, D. W., Landeo-Yauri, S., Lyons, M., Pirotta, V., Schofield, G., & Butcher, P. A. (2020). Operational Protocols for the Use of Drones in Marine Animal Research. *Drones*, *4*(4), 64. <https://doi.org/10.3390/drones4040064>
- Rudd, M. A. (2014). Scientists' perspectives on global ocean research priorities. *Frontiers in Marine Science*, *1*(AUG). <https://doi.org/10.3389/fmars.2014.00036>
- Sahu, B. K., Begum, M., Khadanga, M. K., Jha, D. K., Vinithkumar, N. V., & Kirubakaran, R. (2013). Evaluation of significant sources influencing the variation of physico-chemical parameters in Port Blair Bay, South Andaman, India by using multivariate statistics. *Marine Pollution Bulletin*, *66*(1–2), 246–251. <https://doi.org/10.1016/j.marpolbul.2012.09.021>

- Sheppard, J. K., Preen, A. R., Marsh, H., Lawler, I. R., Whiting, S. D., & Jones, R. E. (2006). Movement heterogeneity of dugongs, *Dugong dugon* (Müller), over large spatial scales. *Journal of Experimental Marine Biology and Ecology*, 334(1), 64–83. <https://doi.org/10.1016/j.jembe.2006.01.011>
- Sivakumar, K. (2013). Status and Conservation of *Dugong dugon* in India: Strategies for Species Recovery. In *Ecology and Conservation of Tropical Marine Faunal Communities* (pp. 419–432). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-38200-0_27
- Sivakumar, K., & Nair, A. (2013). *Dugong distribution, habitat and risks due to fisheries and other anthropogenic activities in India Final Report Wildlife Institute of India*.
- Spain, A. V., & Heinsohn, G. E. (1973). Cyclone associated feeding changes in the dugong (Mammalia: Sirenia). *Mammalia*, 37, 678–680. <https://doi.org/10.11238/MAMMALIANSCIENCE.41.23>
- Sridhar, R., Thangaradjou, T., Kannan, L., & Astalakshmi, S. (2010). Assessment of coastal bio-resources of the Palk Bay, India, using IRS-LISS-III data. *Journal of the Indian Society of Remote Sensing*, 38(3). <https://doi.org/10.1007/s12524-010-0040-8>
- Srinivas, Y., Pande, A., Gole, S., Jothi, P. V. R. P., Magesh, K. M., Pathan, S., Dudhat, S., Shekar, R., Ghanekar, C., Kukadia, D., Johnson, J. A., Mondol, S., & Sivakumar, K. (2021). 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. <https://doi.org/10.1002/aqc.3490>
- Sukumaran, S., Vijapure, T., Mulik, J., A.Rokade, M., & Gajbhiye, S. N. (2013). Macrobenthos in anthropogenically influenced zones of a coralline marine protected area in the Gulf of Kachchh, India. *Journal of Sea Research*, 76, 39–49. <https://doi.org/10.1016/j.seares.2012.11.001>
- Thangaradjou, T., & Bhatt, J. R. (2018). Status of seagrass ecosystems in India. In *Ocean and Coastal Management* (Vol. 159, pp. 7–15). Elsevier Ltd. <https://doi.org/10.1016/j.ocecoaman.2017.11.025>
- Traganos, D., Aggarwal, B., Poursanidis, D., Topouzelis, K., Chrysoulakis, N., & Reinartz, P. (2018). Towards global-scale seagrass mapping and monitoring using Sentinel-2 on Google Earth Engine: The case study of the Aegean and Ionian Seas. *Remote Sensing*, 10(8), 1–14. <https://doi.org/10.3390/rs10081227>

- Umamaheswari, R., Ramachandran, S., & Nobi, E. P. (2009). Mapping the extend of seagrass meadows of Gulf of Mannar Biosphere Reserve, India using IRS ID satellite imagery. *International Journal of Biodiversity and Conservation*, *1*(5), 187–193.
- Verutes, G. M., Johnson, A. F., Caillat, M., Ponnampalam, L. S., Peter, C., Vu, L., Junchompoo, C., Lewison, R. L., & Hines, E. M. (2020). Using GIS and stakeholder involvement to innovate marine mammal bycatch risk assessment in data-limited fisheries. *PLOS ONE*, *15*(8), e0237835. <https://doi.org/10.1371/journal.pone.0237835>
- Vollering, J., Halvorsen, R., Auestad, I., & Rydgren, K. (2019). Bunching up the background betters bias in species distribution models. *Ecography*, *42*(10), 1717–1727. <https://doi.org/10.1111/ecog.04503>
- Warren, D. L., Glor, R. E., & Turelli, M. (2008). ENVIRONMENTAL NICHE EQUIVALENCY VERSUS CONSERVATISM: QUANTITATIVE APPROACHES TO NICHE EVOLUTION. *Evolution*, *62*(11), 2868–2883. <https://doi.org/10.1111/j.1558-5646.2008.00482.x>
- Warren, D. L., Glor, R. E., & Turelli, M. (2010). ENMTools: a toolbox for comparative studies of environmental niche models. *Ecography*, *33*(3), 607–611. <https://doi.org/10.1111/j.1600-0587.2009.06142.x>
- Warren, D. L., Matzke, N. J., Cardillo, M., Baumgartner, J. B., Beaumont, L. J., Turelli, M., Glor, R. E., Huron, N. A., Simões, M., Iglesias, T. L., Piquet, J. C., & Dinnage, R. (2021). ENMTools 1.0: an R package for comparative ecological biogeography. *Ecography*, *44*(4), 504–511. <https://doi.org/10.1111/ecog.05485>
- Wicaksono, P., & Lazuardi, W. (2019). Random Forest Classification Scenarios for Benthic Habitat Mapping using Planetscope Image. *International Geoscience and Remote Sensing Symposium (IGARSS)*. <https://doi.org/10.1109/IGARSS.2019.8899825>
- Wickham, H. (2012). reshape2: Flexibly reshape data: a reboot of the reshape package. *R Package Version*, *1*(2).
- Wildlife Institute of India, D. (2023, July). *ELACP Programme Centre “Wildlife & Protected Areas Management.”*
- York, P. H., Smith, T. M., Coles, R. G., McKenna, S. A., Connolly, R. M., Irving, A. D., Jackson, E. L., McMahan, K., Runcie, J. W., Sherman, C. D. H., Sullivan, B. K., Trevathan-Tackett, S. M., Brodersen, K. E., Carter, A. B., Ewers, C. J., Lavery, P. S.,

Roelfsema, C. M., Sinclair, E. A., Strydom, S., ... Whitehead, S. (2017). Identifying knowledge gaps in seagrass research and management: An Australian perspective. *Marine Environmental Research*, 127. <https://doi.org/10.1016/j.marenvres.2016.06.006>

PUBLICATIONS



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

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Indian coastal waters are critical for dugong populations in the western Indian Ocean. Systematic spatial planning of dugong habitats 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 risks. Seagrass presence was the primary factor in determining dugong habitat suitability across the study sites. Other variables such as depth, bathymetric slope, and Euclidean distance from the shore were significant factors, particularly in predicting seasonal suitability. Predicted suitable habitats showed a remarkable shift from pre-monsoon in Palk Bay to post-monsoon in the Gulf of Mannar, indicating the potential of seasonal dugong movement. The entire coastline along the Palk Bay-Gulf of Mannar region was observed to be at high to moderate risk, including the Gulf of Mannar Marine National Park, a high-risk area. The Andaman Islands exhibited high suitability during pre- and post-monsoon season, whereas the Nicobar Islands were highly suitable for monsoon season. Risk assessment of modelled suitable areas revealed that <15% of high-risk areas across Andaman and Nicobar Islands and Palk Bay and Gulf of Mannar, Tamil Nadu, fall within the existing protected areas. A few offshore reef islands are identified under high-risk zones in the Gulf of Kutch, Gujarat. We highlight the utility of citizen science and secondary data in performing large-scale spatial ecological analysis. Overall, identifying synoptic scale 'Critical Dugong Habitats' has positive implications for the country's progress towards achieving the global 30 × 30 target through systematic conservation planning.

Keywords Species distribution modelling, Environmental niche modelling, Marine mammal conservation, Habitat risk assessment, Marine spatial planning

Marine mammals are known to benefit from effective area-based conservation measures such as Marine Protected Areas (MPAs)¹. Given the migratory nature of these species, delineating MPAs through effective spatial planning in an ecosystem context is strongly advised². India recently declared its first marine mammal-focused Marine Protected Area (MPA) in the country³. About 448 sq. km area was notified as Dugong Conservation Reserve, adjoining Thanjavur and Pudukkottai districts of Tamil Nadu state, bordering the south-east coast of India in the Palk Bay region. This newest MPA in the country aims to protect globally vulnerable but regionally endangered populations of primarily herbivorous marine mammals—dugongs, that occur in disjunct pockets⁴ and are declining rapidly from most of their range^{5,6}. Reasons for their decline are attributed to degradation of seagrass habitats, loss of reproductive potential and increasing anthropic pressures across their distribution^{7–9}.

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With large populations reported from the extreme ends of their global geographical distribution (the east coast of Australia extending up to New Caledonia and the east coast of Africa)^{4,10–12}, the dugong population in India are the major hope for the species' persistence in South Asia.

Indian dugong populations exist within large MPAs such as the Gulf of Kutch Marine National Park (MNP), Gulf of Mannar MNP, Rani Jhansi MNP and Mahatma Gandhi MNP as well as in the waters beyond MPA boundaries¹³. Expanding the area coverage with effective management of these MPAs would help in halting the population decline, reducing disturbances, retaining seagrass ecosystems, and ensuring the long-term survival of dugongs. As of now, MPAs recognized through legislation span only 0.26% of India's geographical area, falling drastically short of the 10% area-based protection for coastal and marine areas envisaged in the Aichi Biodiversity Target 11 (Strategic Plan for Biodiversity 2011–2020). Overall, MPA cover (8717 Km²) is less than 5% of the overall Protected Area (PA) cover (178,640 Km²) which includes terrestrial PAs¹⁴. In the wake of the adoption of the Kunming-Montreal Global Biodiversity Framework (henceforth GBF¹⁵), which requires signatory countries to conserve at least 30% of their terrestrial, inland water, coastal, and marine areas by 2030 (Target 3, also known as '30×30'), effective area-based conservation measures for coastal and marine areas in the country is an urgent priority. Action-oriented targets such as '30×30' can be complemented with biodiversity outcome-focused conservation¹⁶, such as protecting and restoring seagrass habitats to facilitate dugong movement, increase the species' genetic diversity, and improve ecosystem functioning.

Understanding species distribution is crucial to identifying important habitats and formulating effective conservation strategies for long-term preservation¹⁷. Dugong distribution and occupancy are dependent upon various biological (such as seagrass availability^{7,18}), environmental (sea surface temperature¹⁹; turbidity, sea state²⁰) and topographic (depth²¹ parameters). In India, dugong occupancy has declined substantially from Indian territorial waters (over 85% in some parts²²). In some isolated regions, such as the tropical oceanic islands of Andaman and Nicobar Islands, a 60% reduction in occupancy was observed in the last few decades¹³. With the increasing human footprint in the ocean, the rise in activities such as vessel traffic and overfishing (Supplementary Figs. S1, S2 online) in seagrass habitats²³ are presumed to have deleterious impacts on dugong distribution. Also, mechanized and motorized vessels comprise > 99% of all the registered vessels in two of the targeted study states²⁴, risking the dugong population to a great extent. Currently, the extent of these impacts on dugongs in India is poorly known but is apparently deduced through high incidences of strandings^{25,26}.

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 sampling²⁷. Recent advances in species distribution modelling (SDM) or ecological niche modelling (ENM) methods, such as MaxEnt²⁸, are significant due to their utility in the analysis of presence-only data through user-friendly algorithms²⁹. These methods reduce effort and cost for large spatial scale species monitoring programmes^{30,31}. In the past few years, SDM has been increasingly favoured by numerous research groups engaged in wildlife monitoring³¹. This approach has also been influential in developing conservation strategies for marine mammals^{32–34}.

In the case of dugongs, identifying critical habitats is enormously significant for seascape-level planning and optimal usage of management resources^{13,35}. In the present study, we utilized a comprehensive dataset generated through multiple approaches (semi-structured questionnaires, citizen science, volunteer networks, and primary field surveys)¹¹. We predict highly suitable dugong habitats within their current area of distribution in Indian coastal waters, identify high-risk areas, and validate them with primary surveys to classify them as Critical Dugong Habitats (CDHs). In the wake of the '30×30' target and National Biodiversity Targets³⁶, we highlight the importance of area-based conservation of CDHs to inform dugong conservation with recommendations for site-specific management interventions.

Results

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 $AUC \pm SD = 0.924 \pm 0.002$, indicating the accuracy of the model (Fig. 1).

The bathymetric depth and wave height had a maximum contribution (84.3%) toward seagrass prediction in this region (Supplementary Table S3 online).

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, maximum sea surface temperature and distance from the shore showed an 83.9% contribution (Supplementary Table S3 online). The entire PB-GoM coast was predicted for seagrass presence, with north Palk Bay and the north GoM showing maximum probability ($AUC \pm SD = 0.850 \pm 0.004$). Whereas, in the case of GoK, seagrass was strongly predicted in the southern part of the gulf around the islands situated in the region ($AUC \pm SD = 0.952 \pm 0.058$) (Fig. 1). The availability of phosphate and mean sea surface temperature were key contributing factors (67%) in this region.

Seasonal dugong distribution

Andaman and Nicobar islands (ANI)

Ritchie's archipelago, the Hut Bay region of Little Andaman, and the region around Trinket-Camorta islands in central Nicobar were identified as highly suitable regions for all 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, highly suitable areas are more prominent in Central and Great Nicobar Island than in the other two seasons. High suitable areas across Andaman have spread out during the monsoon season,

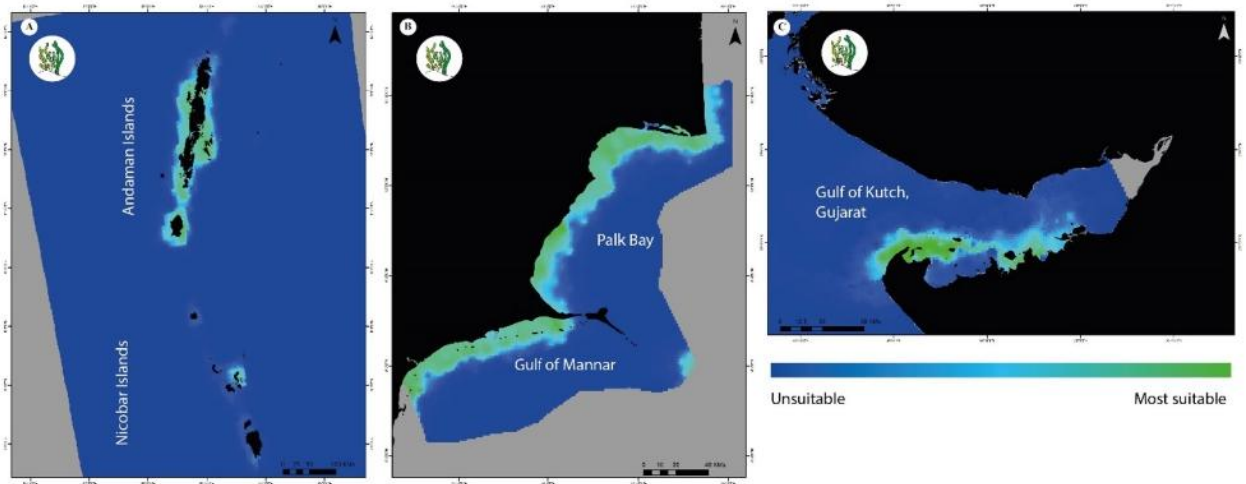


Figure 1. Habitat suitability for seagrass meadows in (A) Andaman and Nicobar Islands (B) Palk Bay and Gulf of Mannar, Tamil Nadu and (C) Gulf of Kutch, Gujarat. Here, ‘unsuitable’ corresponds to 0 and ‘most suitable’ corresponds to 1. The suitability layers were generated using MaxEnt v.3.4.4 software (https://biodiversityinformatics.amnh.org/open_source/maxent), and the final maps were generated using ArcGIS Pro v.3.2.1 software (<https://www.esri.com/en-us/arcgis/products/arcgis-pro/overview>).

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 $AUC \pm SD = 0.987 \pm 0.003$ (pre-monsoon), $AUC \pm SD = 0.987 \pm 0.005$ (monsoon), $AUC \pm SD = 0.982 \pm 0.008$ (post-monsoon). The statistical correlation matrix performed among the seasons showed a high correlation, indicating that habitat suitability was similar (Supplementary Table S4 online).

Palk Bay and Gulf of Mannar (PB-GoM)

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 patches of high suitable region along 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 was assessed with $AUC \pm SD = 0.96 \pm 0.029$ (pre-monsoon), $AUC \pm SD = 0.911 \pm 0.022$ (monsoon), $AUC \pm SD = 0.825 \pm 0.031$ (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 S4 online), where there is a significant difference between pre-monsoon and post-monsoon site suitability estimates.

Gulf of Kutch (GoK)

Annual habitat suitability output of the GoK region showed high suitability near Paga, Bhaidar and Chushna Pir extending up to Beyt Dwaraka island (Fig. 2). Further, a moderately suitable habitat region extending from Beyt Dwaraka island and beyond Nor Island in the East is identified. Subtidal regions southwards to Chushna Pir, including Ajad Island, were identified as having low suitable habitats for dugongs throughout the year in this region. The averaged AUC value obtained from MaxEnt models was $0.983 (\pm 0.005)$.

Variable contributions

We found seagrass presence to be the major factor in determining suitable dugong habitats along the study areas. In the ANI region, seagrass contribution was more than 50% for all three seasons, fluctuating from > 70% in the pre-monsoon and post-monsoon to 58% during the monsoon. 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 diffuse attenuation coefficient significantly contributed to suitability prediction in the ANI region (Table 1, Supplementary Fig. S5 online). In PB-GoM, we observed that the seagrass contribution doubled (33.5–70.8%) from pre-monsoon to post-monsoon season (Table 1). The slope was a variable that contributed more than 50% in the pre-monsoon season, followed by seagrass presence at 33.5%. Sea Surface Temperature (SST) proved significant during the monsoon season, whereas Slope, Depth, and Mean SST contributed equally during the post-monsoon season in the PB-GoM region. Depth, distance from the shore and diffuse attenuation coefficient (DAC) had a noticeable impact on the PB-GoM region for all three seasons. For GoK, with a 70% variable contribution of seagrass presence, the depth variable followed with nearly 20% contribution. Lastly, Diffuse Attenuation Coefficient, Distance from the shore and minimum SST contributed equally ~ 2.5%.

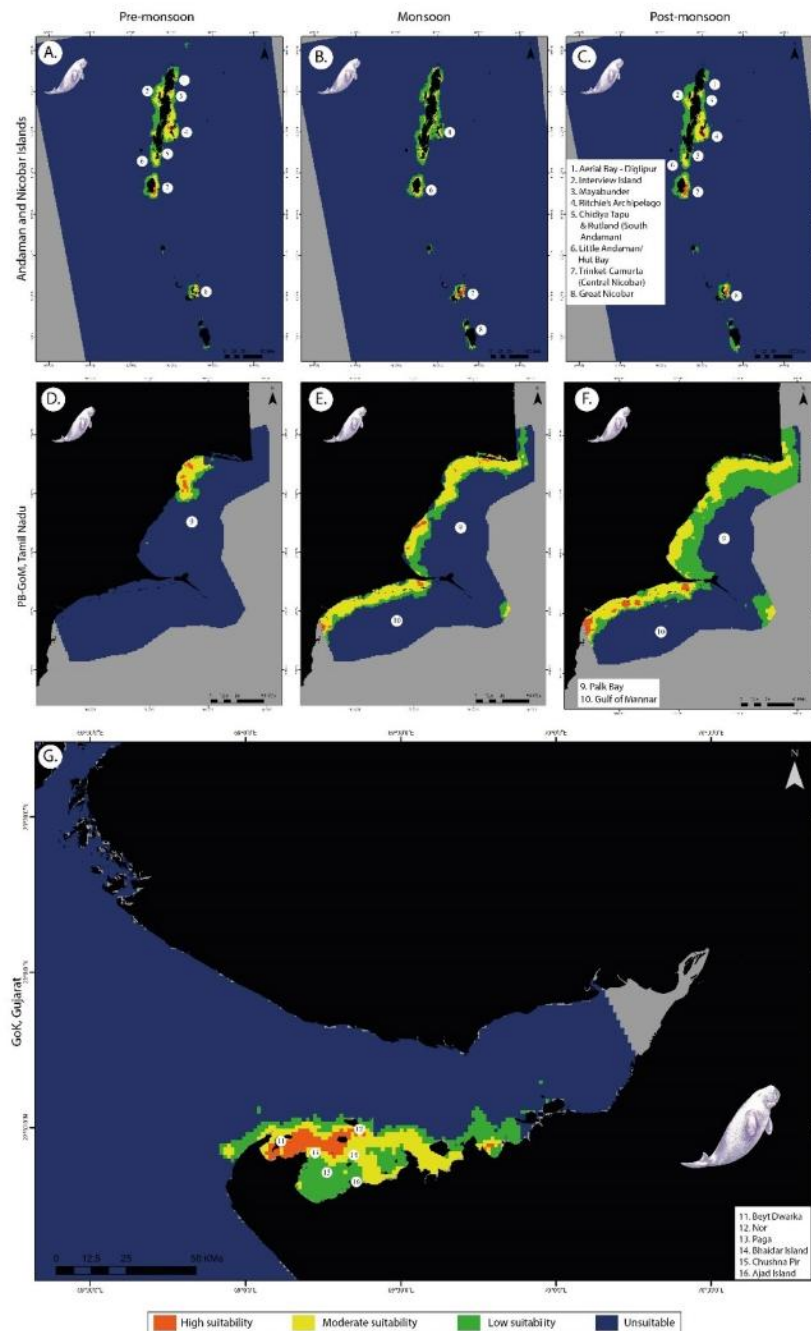


Figure 2. Habitat suitability predictions for dugongs in (A) pre-monsoon, (B) monsoon, (C) post-monsoon at Andaman & Nicobar Islands; (D) pre-monsoon, (E) monsoon, (F) post-monsoon at Palk Bay and Gulf of Mannar, Tamil Nadu; and (G) Gulf of Kutch region, Gujarat. Here, each class corresponds to values 0–0.25 (unsuitable), 0.25–0.5 (low suitability), 0.5–0.75 (moderately suitable) and 0.75–1 (highly suitable) regions, respectively. The suitability layers were generated using MaxEnt v.3.4.4 software (https://biodiversityinformatics.amnh.org/open_source/maxent), and the final maps were generated using ArcGIS Pro v.3.2.1 software (<https://www.esri.com/en-us/arcgis/products/arcgis-pro/overview>).

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 in 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 (Supplementary Fig. S6

Layers	ANI			PB-GoM			GoK
	Pre Monsoon	Monsoon	Post Monsoon	Pre Monsoon	Monsoon	Post Monsoon	
Seagrass presence [‡]	76.2	58.3	73.6	33.5	66	70.8	70.5
Depth (m) [*]	14.8	18.9	18.2	8.8	2.2	5.7	20.3
Slope (°) [*]	2.1	1.9	3.8	51.4	0.3	5	0.6
Distance from the shore (km) [*]	5.3	12.5	4.2	0.9	5.3	1.8	2.8
Monthly diffuse attenuation coefficient (Kd) [‡]	0.2	7.2	0	5	3.3	11	2.4
Monthly sea surface temperature-mean (°C) [*]	1.4	1.2	0.1	0.5	23	5.6	0.8
Monthly sea surface temperature-max (°C) [*]	–	–	–	–	–	–	0.4
Monthly sea surface temperature-min (°C) [*]	–	–	–	–	–	–	2.2

Table 1. List of variables finalized for modelling dugong distribution in pre-monsoon, monsoon and post-monsoon in Andaman and Nicobar Islands (ANI), Palk Bay & Gulf of Mannar (PB-GoM) of Tamil Nadu, and Gulf of Kutch (GoK) of Gujarat along with their contribution percentages. ‘–’ not used; Sources: ^{*}Global Marine Environmental Datasets (GMED)³⁷; [‡]NASA Ocean Colour; [§]Modelled data (MaxEnt).

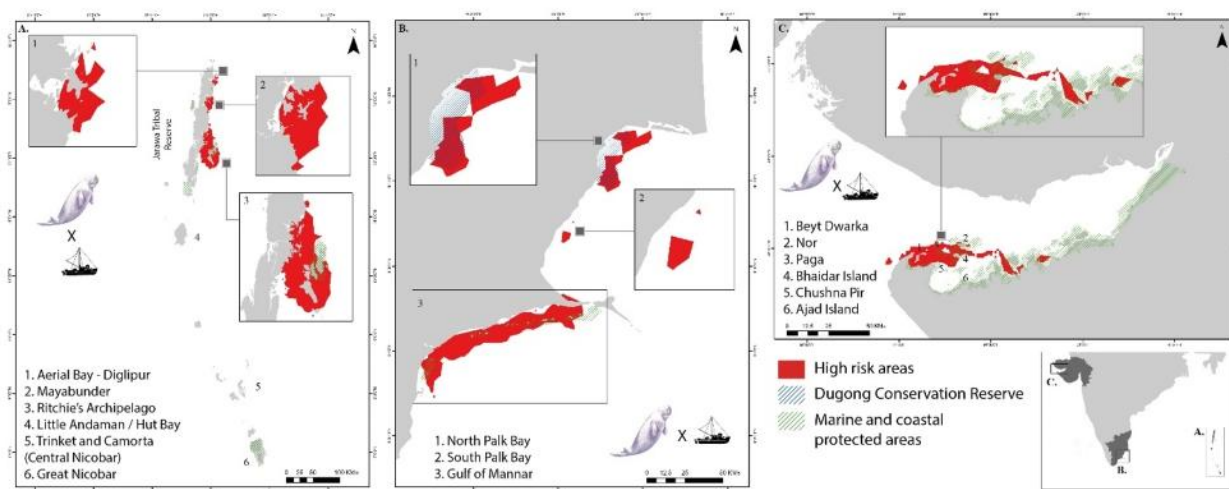


Figure 3. Risk predictions due to fishing pressure in (A) Andaman and Nicobar Islands; (B) Palk Bay and Gulf of Mannar, Tamil Nadu and (C) Gulf of Kutch, Gujarat. Here, the high-risk class corresponds to 50% and above values of the total range, overlaid with current marine protected areas. The output maps were generated using ArcGIS Pro 3.2.1 software (<https://www.esri.com/en-us/arcgis/products/arcgis-pro/overview>).

online). Risk assessment using boat-based surveys confirmed the high-risk region in Aerial Bay-Diglipur and in the Mayabunder region (Fig. 4).

The Rani Jhansi Marine National Park 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 moderate amount of risk for the dugong population. A moderate threat level is available in the Nicobar region, mainly concentrated around Trinket and Camorta Islands in the Middle Nicobar region and the southern coast of Great Nicobar Island (Supplementary Fig. S6 online).

In the PB-GoM, 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 regions in North Palk Bay (Fig. 5).

Further, the entire coast in the study area is under moderate to high risk (Supplementary Fig. S6 online), indicating severe anthropogenic pressure (here, we have considered the fishing-based threats such as boat traffic, fishing gears and intensive fishing practices) 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 highly suitable habitat for dugongs (Fig. 2G) is entirely threatened by high risk. While the Gulf of Kutch Marine National Park is under moderate risk along the southern coast, the boat-based risk assessment highlights that the entire region of high and moderately suitable habitats is under a high-risk zone (Fig. 5). The low-suitability regions are threatened with moderate risk.

The overlap of high-risk regions, identified through this study with the existing protected area cover, varies across the study sites. Only 5.5% (26.16 sq. km out of 478.59 sq. km) of the high-risk region is protected in the ANI. About 28% of the high-risk region is protected in the PB-GoM region, where 1708.97 sq km is outside

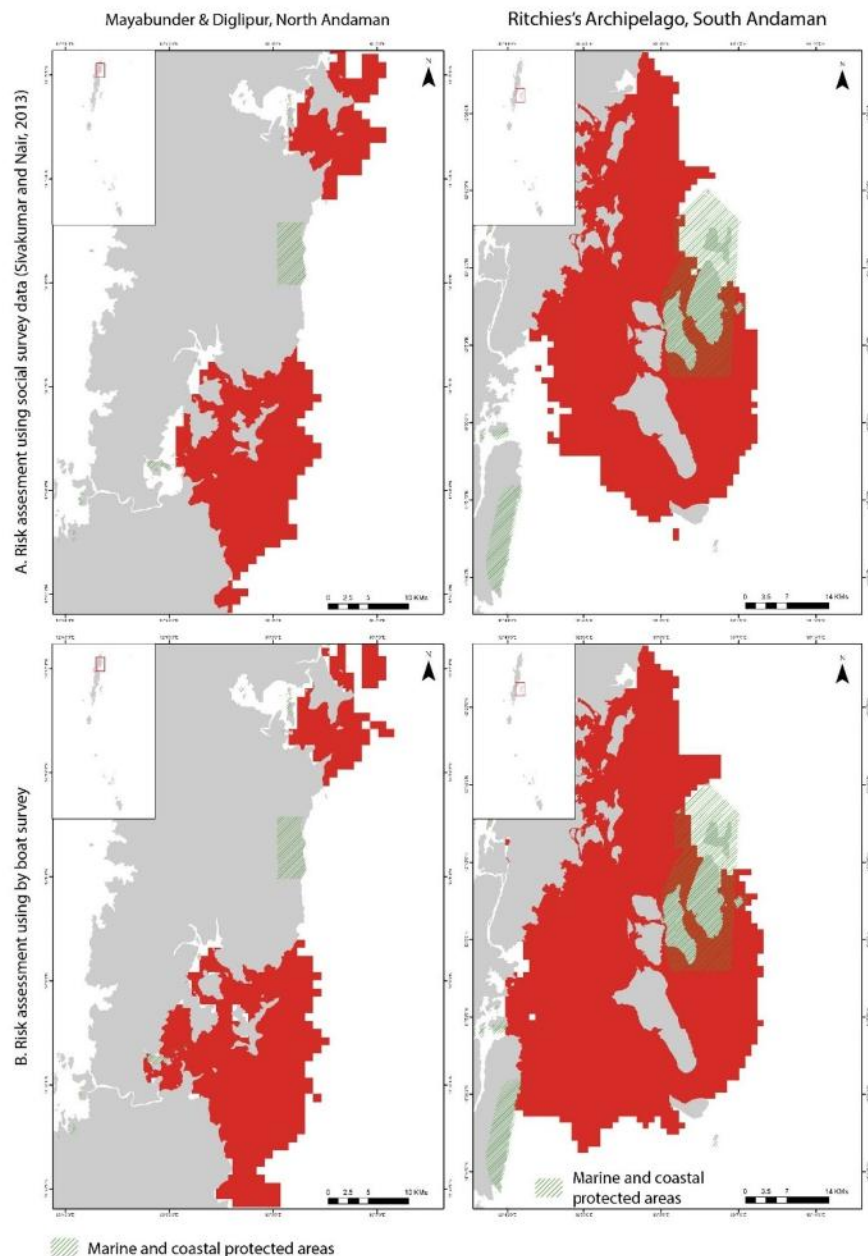


Figure 4. Comparison of selected high-risk habitats. The top row shows the risk based on suitability models derived from social surveys, and the bottom row shows the result from the boat-based surveys [Mayabunder and Diglipur, North Andaman (left) and Ritchie's Archipelago, South Andaman (right)]. The output maps were generated using ArcGIS Pro 3.2.1 software (<https://www.esri.com/en-us/arcgis/products/arcgis-pro/overview>).

the current protected areas. In Gujarat, the existing Gulf of Kutch Marine National Park and other marine and coastal protected areas cover around 37% of the estimated high-risk area in this study (Fig. 3). All these high-risk areas, can be categorized as CDHs, including the area currently under protection and the predicted area beyond the MPA network.

Discussion

Identifying suitable habitats and mapping risk is crucial to prioritize conservation actions³³. 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. The 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

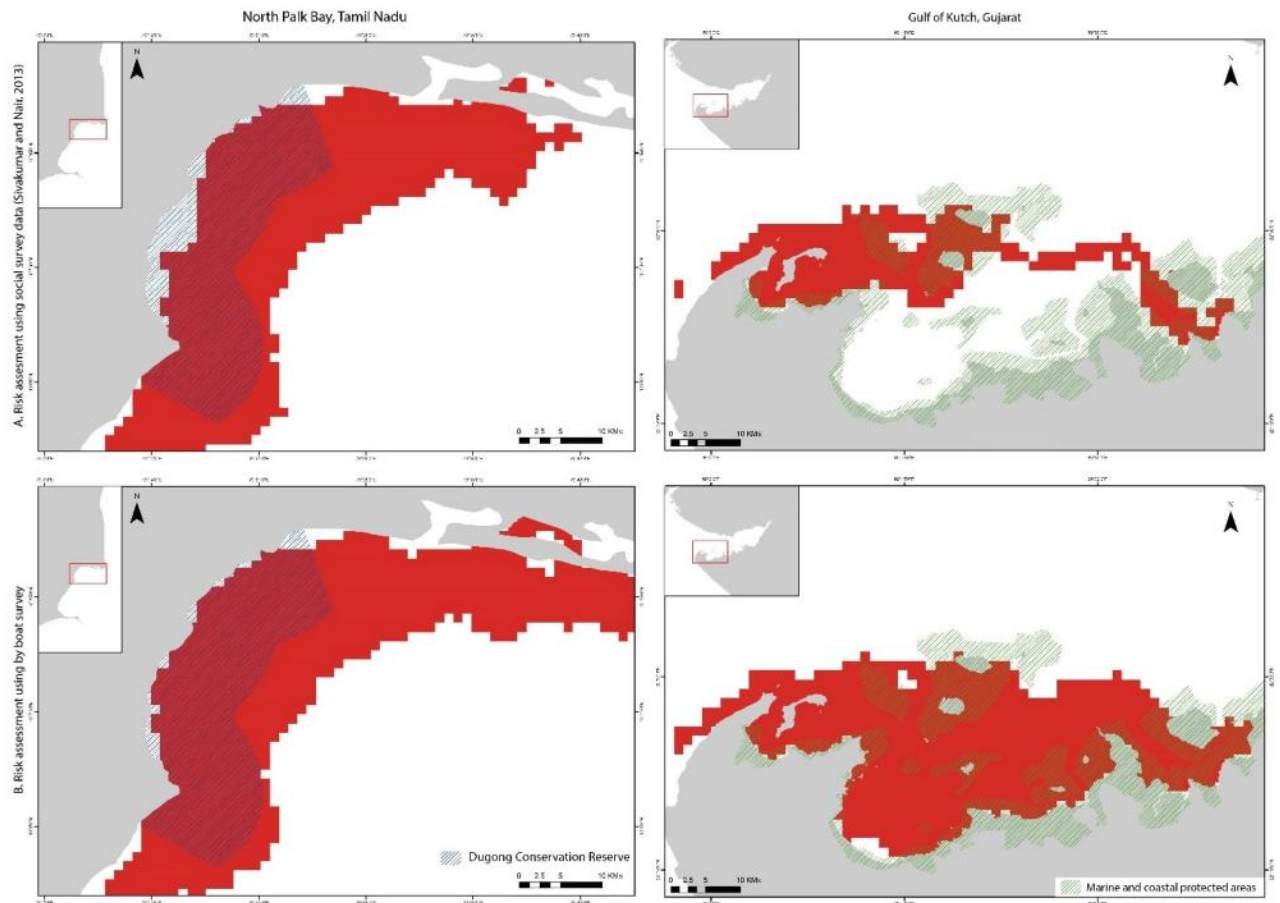


Figure 5. Comparison of selected high-risk habitats. The top row shows the risk based on suitability models derived from social surveys, and the bottom row shows the result from the boat-based surveys [North Palk Bay, Tamil Nadu (left) and Gulf of Kutch, Gujarat (right)]. The output maps were generated using ArcGIS Pro 3.2.1 software (<https://www.esri.com/en-us/arcgis/products/arcgis-pro/overview>).

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 worldwide³⁸, necessitating country-wide assessments³⁹ to facilitate conservation action. The availability of healthy seagrass meadows is considered one of the most important determinants of dugong occurrence and habitat use⁴⁰. Dugongs, in turn, replenish seagrass meadows through constant grazing, helping nutrient cycling from sediments^{7,41}. 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 the south-western coast of GoK. These areas, presumably the last remaining dugong habitats along most of the Indian subcontinent^{13,26,42–45}, thus assume critical importance. Our current study considers only a single annual seagrass distribution layer for the dugong suitability analysis. The change in the contribution of seagrass across seasons indicates that other parameters influence the population over different times of the year (Table 1). However, this change in seagrass contribution across seasons highlights the importance of studying seasonal seagrass availability (density, composition, biomass, etc.) at all CDHs. Understanding the potential expanse of the seasonal seagrass habitats would also ignite efforts to assess nutrient profiling, seasonal seagrass biomass availability, carbon sequestration and seagrass-associated micro/macrofauna across spatial scales⁴⁰.

Seasonal habitat suitability assessment paves the way for ecological interpretation in terms of migration, foraging, and reproduction⁴⁶ and developing conservation strategies⁴⁷. We found high 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 studies²¹. Seagrass presence, depth, and distance from shore explained the habitat suitability of dugongs in the ANI region. Although the similarity correlation matrix (Supplementary Table S4 online) suggests negligible differences in suitable sites between seasons, there are considerable differences in the percentage contribution of variables between the seasons. This suggests the need to assess the seasonal distribution of dugongs²³ and fine-scale mapping³⁵ in high suitable but less surveyed areas (such as Little Andaman and central Nicobar). In the PB-GoM region, we observed stark seasonal differences in high suitable areas for dugongs. During pre-monsoon season, north Palk Bay, a gradually sloping sheltered embayment, appears to be a conducive habitat for dugongs. Monsoon

prediction shows moderate suitability for the entire coastline, whereas high suitable areas shift to GoM during post-monsoon. Seasonal changes in habitat suitability, attributed to biotic (seagrass presence), topographic (slope) and environmental (sea surface temperature) factors, need further investigation. In the GoK region, seagrass presence and low organic turbidity support clear shallow waters as preferred regions by dugongs⁴⁸. With a relict dugong population in the GoK²⁶, 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, cause mortalities or life-threatening injuries⁴⁹. Bycatch in fishing nets is a major threat to dugongs, whereas hunting for meat is also reported in some areas⁵⁰. 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, and the 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. CDHs 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 is required in areas outside active protection.

Dugongs display both short-range (< 15 km) and long-range (> 15 km, up to 560 km) movement⁸. 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 during the post-monsoon season. Additionally, the spatial extent and density of seagrass meadows in Indian waters change with season and anthropogenic activities⁵¹, which may facilitate the seasonal movements of dugongs. Longer migrations have been documented in areas of seagrass habitat loss with implications on dugong genetic diversity and their dietary preferences^{33,52}. However, to validate long-distance movements, real-time tracking, or photographic capture-based studies (for example, using drones⁵³) along with fine-scale environmental data collection is strongly recommended⁵⁴.

With the influx of large, mechanized vessels and use of destructive fishing practices (such as bottom trawling) (Fig. 6), increased loss of seagrass habitats will have a dual negative impact, i.e., on fisheries of the region and on the seagrass-dependent dugong populations. The area estimated outside the existing protected area cover was about 95% for ANI, 72% for PB-GoM and 63% for the GoK region. Most of these areas are also intensive fishing grounds supporting millions of livelihoods. Effective management of these high-risk, high-priority areas is recommended, using a participatory approach to care for 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 Network⁵⁵) and government-supported incentivization programs to reduce pressure on dugong habitats. Even introducing other participatory regulatory mechanisms such as Community Conserved Areas (CCAs) or Other Effective area-based Conservation Measures (OECMs) could be considered given the potential of the region to support high-value biodiversity, maintain the integrity of critical ecosystems (such as seagrass and coral reefs) and help in retention of genetic diversity. It would also support the country's efforts to recover endangered species as well as contribute towards the Convention on Biological Diversity's (CBD) goals to achieve, '30 × 30', reverse biodiversity loss and safeguard the rights of people¹⁵.

Overall, identifying such synoptic-scale 'Critical Dugong Habitats' (CDHs) 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. Most importantly, it suggests an addition to India's current MPA network in dugong inhabited areas to contribute to the country's efforts towards achieving the '30 × 30' global biodiversity target with equitable and effective management to derive positive conservation outcomes.



Figure 6. On-field photographs from Palk Bay to Gulf of Mannar, Tamil Nadu, showing a number of trawling boats.

Materials and methods

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^{43,56} (Fig. 7).

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 northwest 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–14° N and 92° E–94° E) hold high endemic biodiversity⁵⁷. Over 80% of its land area (~8249 sq. km) is covered with tropical rainforests, with a long coastline (~1962 km) indented with several penetrating creeks⁵⁸. 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 islands⁵⁹. 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 southwest monsoon (May–September), followed by ~ post-monsoon (640–849 mm from October to December) and pre-monsoon showers (~443–527 mm from January to April)^{60,61}. ANI host 12 seagrass species (dominated by *Halophila* sp., *Halodule* sp.⁴²) with coverage of 12.239 km² in the Andaman group and 17.194 km² in the Nicobar group, respectively⁶², providing forage to a large number of dugongs (rough estimates suggest 44–81 dugongs⁴³), with severe decline in dugong occupancy by ~60% over the last two decades²².

The PB-GoM region is part of the coastal waters of the southeastern 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 the Indian peninsula. PB is comparatively calmer than GoM due to obstructed wave action by the Sri Lankan coast, Rameswaram Island, and the Indian mainland. In contrast, GoM

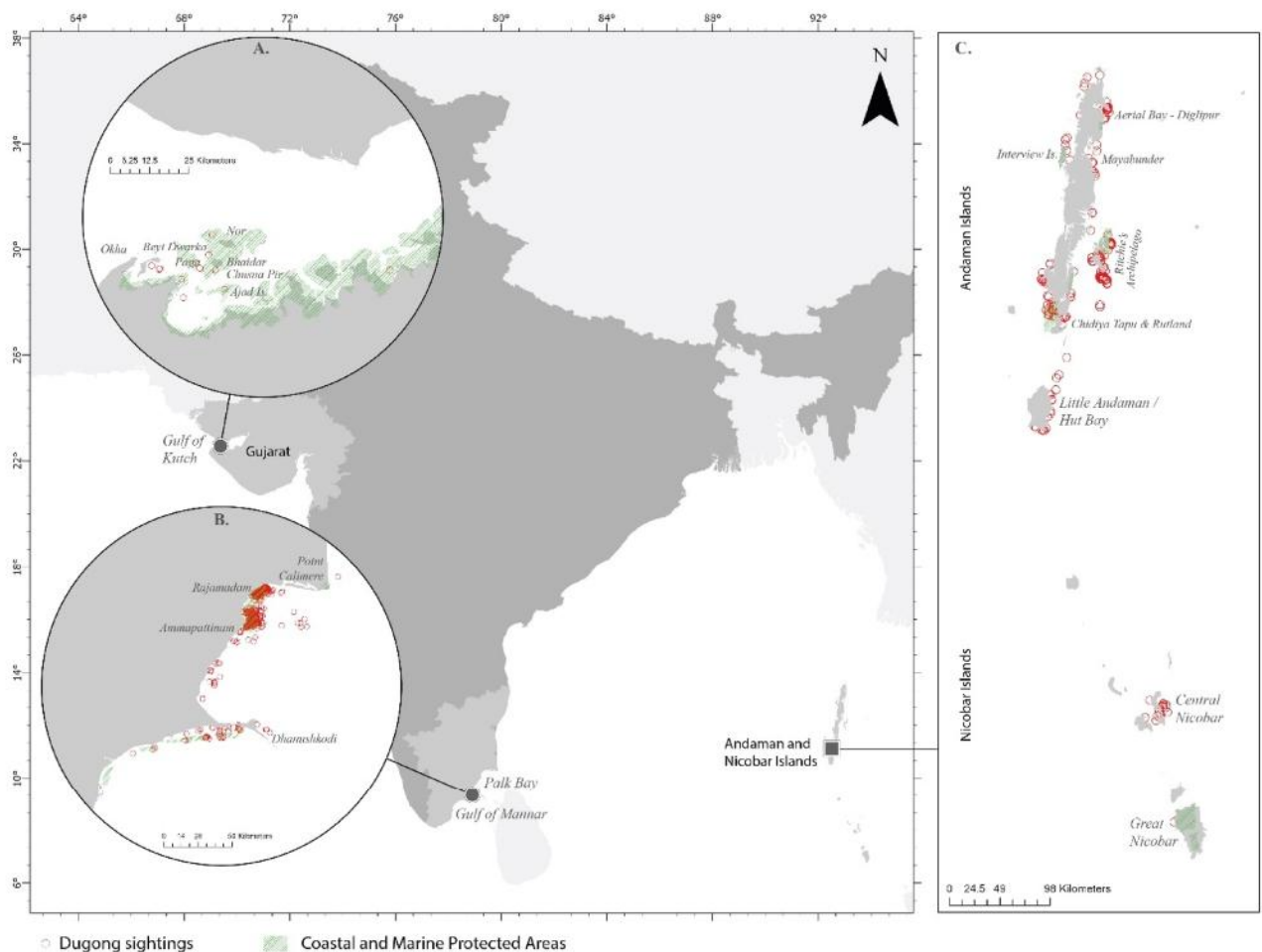


Figure 7. Study sites along the Indian coastline (A) Gulf of Kutch (GoK), Gujarat on the northwest coast in the Arabian Sea; (B) Andaman & Nicobar Islands (ANI)—offshore islands located in the Bay of Bengal to the south-east of peninsular India (C) Palk Bay and Gulf of Mannar (PB-GoM), Tamil Nadu to the south-east coast in the Bay of Bengal. The red circles represent dugong sighting locations between 2008 and 2021. The output maps were generated using ArcGIS Pro 3.2.1 software (<https://www.esri.com/en-us/arcgis/products/arcgis-pro/overview>).

is exposed to swells from south to southwest⁶³. Hence, PB provides a sheltered habitat, ideal for good growth of seagrass meadows, tidal flats, and mangroves⁶⁴. GoM, on the other hand, is embedded with a string of island complexes (21 islands with two 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 (> 3600 documented species of flora and fauna)⁶⁵. PB-GoM are economically important areas for demersal and pelagic fisheries⁶⁶. The PB-GoM study sites host 14 seagrass species (*Cymodocea serrulata*, *Halophila ovalis*, *Halodule uninervis* etc.)⁶⁷ spread over an area of ~ 398 km²⁵¹. PB-GoM also has the largest dugong population along the Indian coast and South Asia. Rough estimates peg the population to be ~ 150 individuals but with declining occupancy¹³.

The GoK, the largest gulf on the western Indian coast along the Arabian Sea, covers an area of 7350 km² (457.92 km² as Marine National Park and Sanctuary) with a cluster of 42 small coastal islands⁶⁸. GoK encompasses the only marine national park along the west coast of India and the only marine sanctuary in the state of Gujarat. The region is located in the sub-tropical climatic zone and faces very high geo-morphological and climatic variation. It hosts eight seagrass species⁶⁵ (*Halophila ovalis*, *Halodule uninervis* etc.), covering ~ 23 km²⁶⁹ and a relict dugong population of less than 10–15 individuals^{26,43}.

Habitat suitability

Data collection

We conducted intertidal and subtidal surveys between 2018 and 2021 using the line-intercept transect method⁷⁰ to record seagrass presence in all three regions. We laid 50 m long transects perpendicular to the shoreline, where a 50 × 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 the drop-down quadrat method, with a GoPro Hero 6 camera attached at the top of the quadrat frame⁷¹ 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 30 × handheld GPS unit.

We also extracted available seagrass polygons for our study areas from⁷². 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 was curated from the questionnaire surveys of fisherfolk conducted between 2012 and 2013 (¹³; GoK = 8, ANI = 336 and PB-GoM = 263) and between 2018 and 2021 (⁷³; GoK = 8, ANI = 226), following a standardized CMS-UNEP Dugong questionnaire. The survey was based on the revised 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)⁷⁴. Verbal consent was obtained from every interviewee upon informing them of the purpose of the data collection.

Occurrence records of 45 locations by the GEER foundation in the GoK region were also utilized⁴³. 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. S7 online).

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.sdmttoolbox.org)⁷⁵ on ArcMap v.10.8 to reduce the negative influence of spatial autocorrelation on the models⁷⁶. 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. Southwest monsoon (SWM) winds determine monsoons in ANI, whereas Tamil Nadu experiences retreating monsoons caused by northeast monsoon (NEM) winds.

The seasons were site-specific, based on the monsoon report published by the India Meteorological Department (Supplementary Table S8 online).

Selection of environmental variables

To model the suitability of seagrasses, we selected fourteen abiotic layers to determine the seagrass distribution^{37,72,77}. The resultant seagrass layer was further used to predict dugong habitat suitability⁷⁸ along with five other abiotic layers (Table 1). Explanations behind choosing the variables are given in supplementary table S9 online 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. In this case, seven abiotic and one biotic variable were considered (Table 1).

We first checked the predictors for data availability, and then multicollinearity was reviewed using ENMTools v.1.0.5⁷⁹ and reshape2 v.1.4.4 packages in R⁸⁰. 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.

Suitability modelling

We used MaxEnt v.3.4.4 software for seagrass and dugong modelling due to its utility in limited presence-only data^{33,54,81}. For modelling seagrasses, we used the MaxEnt settings from⁷².

In the case of dugong suitability, the best possible MaxEnt settings combination was assessed using the ENMeval v2.0.1 package in R-Software⁸². We ran ENMeval for each season for ANI and PB-GoM and once for GoK using a random k-fold data partitioning technique (for > 50 occurrence points) and by jack-knifing (for < 50 data points)⁸³. We selected the MaxEnt settings with the least Akaike Information Criterion (AIC) value for final runs (Supplementary Table S10 online).

All runs were performed using a bias file with the sighting data to avoid sampling biases^{84,85}. The site and season-specific bias files were created using the kernel density function in R⁸⁶.

In the case of both seagrass and dugong MaxEnt outputs, we selected 'logistic' as the output format, and the model accuracy was determined by the 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 Figs. S11, S12 online, respectively. For GoK-Gujarat, variable response curves are presented in the supplementary Fig. S13 online.

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-statistics⁸⁷ in ENM tools v.1.3⁸⁸.

Classifying fishing pressure

We used the fishing pressure layer from¹⁷. 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.

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 categorized by manually segregating the raster classification from 0 to 100%, with 100–51 classified as high risk, 50–26 as moderate risk and 25–0 as low risk on ArcMap v.10.8. These high-risk areas (over 50% risk) with high habitat suitability (over 0.75 prediction probability) were classified as Critical Dugong Habitats. A flowchart of the detailed methodology has been given in Fig. 8.

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 gear for 10 min at the centroids of randomly selected 2 × 2 km grids at these sites. These surveys were conducted between 2019 and 21 in ANI, 2020–21 in Tamil Nadu, and 2020–22 in Gujarat. We ran an Inverted Distance Weightage (IDW) analysis at 1 km spatial resolution (powers 0.001–10; 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

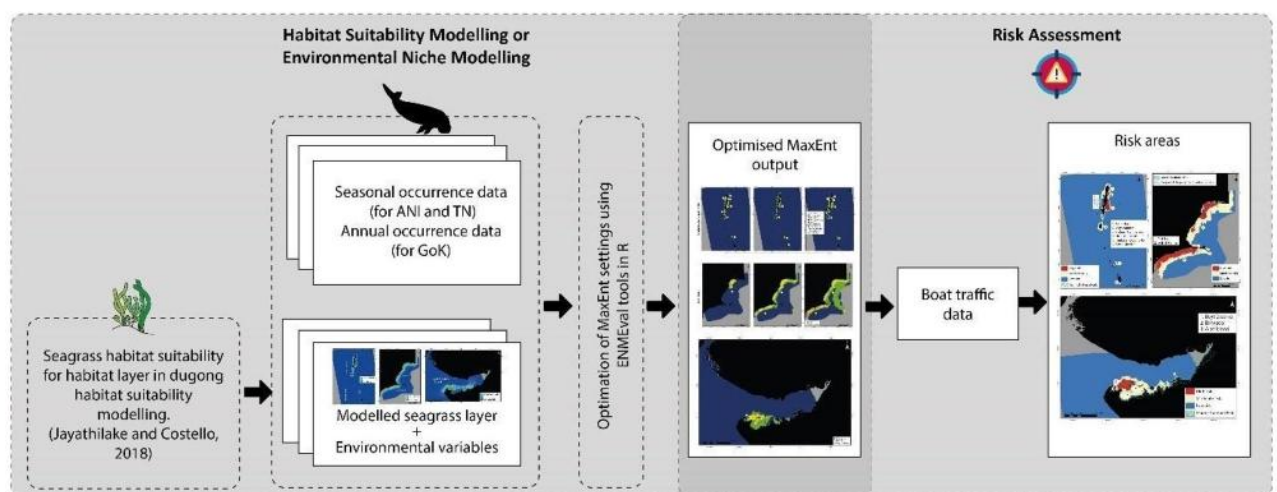


Figure 8. Graphical flowchart to show the methods used in detail to elucidate Critical Dugong Habitats in India.

conducted using secondary data. Areas of high risk outside the existing MPAs along the Indian coast were quantified to estimate proportional areas without legal protection at all the study sites.

Ethics approval and consent to participate

The study was approved by the Research Ethics Review Committee of the Wildlife Institute of India. All procedures performed complied with the relevant guidelines and regulations.

Limitations

Our study derives the results and inferences based on the CMS-UNEP Dugong Questionnaire, which obtained information from opportunistic sightings or secondary sources through interview surveys of fisherfolk, dugong volunteer network and other stakeholders. Although this effort highlights the application of citizen science in understanding spatial distribution patterns of marine mammals, these datasets pose few uncertainties. The first is the opportunistic dugong occurrence data from the extensive informant network. The seasonal occurrence data is potentially limited by the spatial and temporal bias of the range of fishing operations in the categorized seasons. For the PB-GoM region, pre-monsoon occurrence data was majorly available from Palk Bay. Supplementary Figure S6 online emphasizes the occurrence frequency across the year and the high values during the pre-monsoon season. These biases were addressed by implementing bias correction^{84–86} as well as rarefying the occurrences⁷⁵ to one observation per grid for our analysis.

Data availability

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

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References

- Gormley, A. M. *et al.* First evidence that marine protected areas can work for marine mammals. *J. Appl. Ecol.* **49**(2), 474–480. <https://doi.org/10.1111/j.1365-2664.2012.02121.x> (2012).
- Hoyt, E. Sustainable ecotourism on Atlantic islands, with special reference to whale watching, marine protected areas and sanctuaries for cetaceans. *Biol. Environ.: Proc. R. Ir. Acad.* **105**(3), 141–154 (2005).
- 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).
- Marsh, H. & Soltzick, S. *Dugong dugon* (amended version of 2015 assessment). *IUCN Red List Threat. Species* **2019**, eT6909A160756767. <https://doi.org/10.2305/IUCN.UK.2015-4.RLTS.T6909A160756767.en> (2019).
- Lin, M. *et al.* Functional extinction of dugongs in China. *R. Soc. Open Sci.* **9**(8), 211994. <https://doi.org/10.1098/rsos.211994> (2022).
- Kayanne, H., Hara, T., Arai, N., Yamano, H. & Matsuda, H. Trajectory to local extinction of an isolated dugong population near Okinawa Island, Japan. *Sci. Rep.* **12**(1), 1–8 (2022).
- Preen, A. & Marsh, H. Response of dugongs to large-scale loss of seagrass from Hervey Bay, Queensland Australia. *Wildl. Res.* **22**(4), 507–519 (1995).
- 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. *Cont. Shelf Res.* **28**(16), 2152–2159 (2008).
- Brodie, J. & Waterhouse, J. A critical review of environmental management of the “not so great” barrier reef. *Estuar., Coast. Shelf Sci.* **104**, 1–22 (2012).
- Srinivas, Y. *et al.* Mitochondrial phylogeography reveals high haplotype diversity and unique genetic lineage in Indian dugongs (*Dugong dugon*). *Aquat. Conserv. Mar. Freshw. Ecosyst.* **31**(4), 818–829. <https://doi.org/10.1002/aqc.3490> (2021).
- Rabaoui, L. *et al.* Diversity, distribution, and density of marine mammals along the Saudi waters of the Arabian gulf: update from a multi-method approach. *Front. Mar. Sci.* **8**, 687445. <https://doi.org/10.3389/fmars.2021.687445> (2021).
- Khamis, A. *et al.* Identifying conservation priorities for a widespread dugong population in the Red Sea: Megaherbivore grazing patterns inform management planning. *Mar. Environ. Res.* **181**, 105762. <https://doi.org/10.1016/j.marenvres.2022.105762> (2022).
- 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).
- EIACP Programme Centre “Wildlife & Protected Areas Management”. Protected Areas of India; https://wiienviis.nic.in/Database/Protected_Area_854.aspx (2024).
- Convention on Biological Diversity. *Decision adopted by the Conference of the Parties to the Convention on Biological Diversity: 15/4. Kunming-Montreal Global Biodiversity Framework*; <https://www.cbd.int/doc/decisions/cop-15/cop-15-dec-04-en.pdf> (2022).
- Carroll, C. & Noss, R. F. How percentage-protected targets can support positive biodiversity outcomes. *Conserv. Biol.* **36**(4), e13869. <https://doi.org/10.1111/cobi.13869> (2022).
- Pompa, S., Ehrlich, P. R. & Ceballos, G. Global distribution and conservation of marine mammals. *Proc. Natl. Acad. Sci.* **108**(33), 13600–13605. <https://doi.org/10.1073/pnas.1101525108> (2011).
- Preen, A. R. Interactions between dugongs and seagrasses in a subtropical environment *Doctoral dissertation, James Cook University*; <https://researchonline.jcu.edu.au/10867/7/07Chapter6.pdf> (1992).
- Fuentes, M. M. *et al.* 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).
- 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. *J. Wildl. Manag.* **70**(1), 255–262 (2006).
- Marsh, H., Prince, R. I. T., Saafeld, W. K. & Shepherd, R. The distribution and abundance of the dugong in Shark Bay, Western Australia. *Wildl. Res.* **21**(2), 149–161 (1994).
- 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. <https://doi.org/10.1371/journal.pone.0076181> (2013).
- Ng, S. Z., Ow, Y. X. & Jaafar, Z. Dugongs (*Dugong dugon*) along hyper-urbanized coastlines. *Front. Mar. Sci.* **9**, 947700. <https://doi.org/10.3389/fmars.2022.947700> (2022).

24. FRAEED, CMFRI. Marine Fish Landings in India-2022. Technical Report, CMFRI Booklet Series No. 31/2023. ICAR-Central Marine Fisheries Research Institute, Kochi; http://eprints.cmfri.org.in/16883/1/Marine%20Fish%20Landings%20in%20India_2022.pdf (2023).
25. 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).
26. 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*). *Curr. Sci.* **123**(7), 919–924 (2022).
27. 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 Ecol. Evol.* **3**(3), 545–554. <https://doi.org/10.1111/j.2041-210X.2011.00182.x> (2012).
28. Kass, J. M. *et al.* ENMeval 2.0: Redesigned for customizable and reproducible modeling of species' niches and distributions. *Methods Ecol. Evol.* **12**(9), 1602–1608. <https://doi.org/10.1111/2041-210X.13628> (2021).
29. 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. *Ecol. Appl.* **31**(1), 2214. <https://doi.org/10.1002/eap.2214> (2021).
30. Pinto-Ledezma, J. N. & Cavender-Bares, J. Using remote sensing for modeling and monitoring species distributions. In *Remote Sensing of Plant Biodiversity* (eds Cavender-Bares, J. *et al.*) 199–223 (Springer International Publishing, Cham, 2020). https://doi.org/10.1007/978-3-030-33157-3_9.
31. Randin, C. F. *et al.* Monitoring biodiversity in the Anthropocene using remote sensing in species distribution models. *Remote Sens. Environ.* **239**, 111626. <https://doi.org/10.1016/j.rse.2019.111626> (2020).
32. Bonizzoni, S. *et al.* Modelling dolphin distribution within an important marine mammal area in Greece to support spatial management planning. *Aquat. Conserv. Mar. Freshw. Ecosyst.* **29**(10), 1665–1680 (2019).
33. Hashim, M. *et al.* Using fisher knowledge, mapping population, habitat suitability and risk for the conservation of dugongs in Johor Straits of Malaysia. *Mar. Policy* **78**, 18–25 (2017).
34. 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. *Sci. Rep.* **10**(1), 14366 (2020).
35. Derville, S., Cleguer, C. & Garrigue, C. Ecoregional and temporal dynamics of dugong habitat use in a complex coral reef lagoon ecosystem. *Sci. Rep.* **12**(1), 552 (2022).
36. Onial, M. *et al.* Updating India's national biodiversity action plan. *Curr. Sci.* **115**(3), 422–427 (2018).
37. 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).
38. 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. *Glob. Change Biol.* **27**(17), 4096–4109 (2021).
39. Hernawan, U. E. *et al.* The first nation-wide assessment identifies valuable blue-carbon seagrass habitat in Indonesia is in moderate condition. *Sci. Total Environ.* **782**, 146818 (2021).
40. Sheppard, J. K. *et al.* Movement heterogeneity of dugongs, *Dugong dugon* (Müller), over large spatial scales. *J. Exp. Mar. Biol. Ecol.* **334**(1), 64–83 (2006).
41. 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. <https://doi.org/10.1007/s00442-006-0477-1> (2006).
42. Frazier, J. G. & Mundkur, T. *Dugong dugon* Muller in the Gulf of Kutch, Gujarat. *J. Bombay Nat. Hist. Soc.* **87**(3), 368–379 (1990).
43. Pandey, N., Tatu, K. & Anand, Y. Status of Dugong (*Dugong dugon*) in India report, *Geer Foundation Report* (2010).
44. 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. <https://doi.org/10.1371/journal.pone.0141224> (2015).
45. Rajpurkar, S. *et al.* Lightweight unmanned aerial vehicle surveys detect dugongs and other globally threatened marine species from the Andaman and Nicobar Islands, India. *Curr. Sci.* **121**(2), 195 (2021).
46. Putra, M. I. H. & Mustika, P. L. K. Incorporating in situ prey distribution into foraging habitat modelling for marine megafauna in the solar waters of the Savu Sea, Indonesia. *Aquat. Conserv. Mar. Freshw. Ecosyst.* **30**(12), 2384–2401 (2020).
47. Boitani, L. *et al.* What spatial data do we need to develop global mammal conservation strategies?. *Philos. Trans. R. Soc. B: Biol. Sci.* **366**(1578), 2623–2632. <https://doi.org/10.1098/rstb.2011.0117> (2011).
48. Cleguer, C., Garrigue, C. & Marsh, H. Dugong (*Dugong dugon*) movements and habitat use in a coral reef lagoonal ecosystem. *Endanger. Species Res.* **43**, 167–181 (2022).
49. 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. <https://doi.org/10.1371/journal.pone.0237835> (2020).
50. 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). *Mar. Mamm. Sci.* **24**(3), 704–710 (2008).
51. Geevarghese, G. A. *et al.* A comprehensive geospatial assessment of seagrass distribution in India. *Ocean Coas. Manag.* **159**, 16–25 (2018).
52. Poommouang, A. *et al.* Genetic diversity in a unique population of dugong (*Dugong dugon*) along the seacoasts of Thailand. *Sc. Rep.* **11**(1), 11624 (2021).
53. Raoult, V. *et al.* Operational protocols for the use of drones in marine animal research. *Drones* **4**(4), 64 (2020).
54. Noviello, N. *et al.* Modelling Critically Endangered marine species: Bias-corrected citizen science data inform habitat suitability for the angel shark (*Squatina squatina*). *Aquat. Conserv. Mar. Freshw. Ecosyst.* **31**(12), 3451–3465. <https://doi.org/10.1002/aqc.3711> (2021).
55. 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. *J. Surv. Fish. Sci.* **10**, 62–77 (2023).
56. Sivakumar, K. Status and conservation of *Dugong dugon* in India: Strategies for species recovery. In *Ecology and Conservation of Tropical Marine Faunal Communities* (eds Venkataraman, K. *et al.*) 419–432 (Springer Berlin Heidelberg, Berlin, Heidelberg, 2013). https://doi.org/10.1007/978-3-642-38200-0_27.
57. 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. *Environ. Monit. Assess.* **193**(2), 1–16. <https://doi.org/10.1007/s10661-020-08820-2> (2021).
58. Thangaradjou, T., Sivakumar, K., Nobi, E. P. & Dilipan, E. Distribution of seagrasses along the Andaman and Nicobar Islands: A post tsunami survey. In *Recent Trends in Biodiversity of Andaman and Nicobar Islands* 157–160 (Zoological Survey of India, Kolkata, 2010).
59. EIACP Programme Centre "Wildlife & Protected Areas Management" *Andaman Nicobar Islands Protected Area Gazette Notification Database (Andaman Nicobar Islands)*. https://wiienviis.nic.in/Database/Andaman_Nicobar_Islands_7843.aspx (2021).
60. Bera, S., Majumdar, D. D. & Paul, A. K. Estimation of tourism carrying capacity for Neil Island, South Andaman, India. *J. Coas. Sci.* **2**(2), 46–53 (2015).
61. Velmurugan, A. *et al.* Climate of Andaman and Nicobar Islands: Long-term pattern analysis. *J. Andaman Sci. Assoc.* **23**(1), 1–7 (2018).

62. 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 Sci. J.* **48**, 173–181. <https://doi.org/10.1007/s12601-013-0014-1> (2013).
63. Gowthaman, R. *et al.* Waves in Gulf of Mannar and Palk Bay around Dhanushkodi, Tamil Nadu, India. *Curr. Sci.* **104**, 1431–1435 (2013).
64. 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, south-east coast of India. *Reg. Stud. Mar. Sci.* **41**, 101558 (2021).
65. 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*; <http://eprints.cmfri.org.in/6766/> (2006).
66. Jagadeesan, L. *et al.* Ocean currents structuring the mesozooplankton in the Gulf of Mannar and the Palk Bay, south-east coast of India. *Prog. Oceanogr.* **110**, 27–48 (2013).
67. Thangaradjou, T. & Bhatt, J. R. Status of seagrass ecosystems in India. *Ocean Coast. Manag.* **159**, 7–15 (2018).
68. 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. *J. Sea Res.* **76**, 39–49 (2013).
69. Anand, Y. A. A study on marine mammals of Gulf of Kachchh, Gujarat, India. [Doctoral thesis, Gujarat University] (2021).
70. McKenzie, L. J. *et al.* The global distribution of seagrass meadows. *Environ. Res. Lett.* **15**(7), 074041. <https://doi.org/10.1088/1748-9326/ab7d06/meta> (2020).
71. Bertelli, C. M., Bull, J. C., Cullen-Unsworth, L. C. & Unsworth, R. K. Unravelling the spatial and temporal plasticity of eelgrass meadows. *Front. Plant Sci.* **12**, 939. <https://doi.org/10.3389/fpls.2021.664523> (2021).
72. Jayatilake, D. R. & Costello, M. J. A modelled global distribution of the seagrass biome. *Biol. Conserv.* **226**, 120–126 (2018).
73. Johnson, J. A. *et al.* Annual Progress Report VI (2021–23) CAMPA-Recovery of dugongs and their habitats in India: An integrated participatory approach 234 (Wildlife Institute of India, (Ministry of Environment Forest Climate Change), Dehradun, 2023).
74. 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).
75. 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. *Peer J.* **5**, e4095 (2017).
76. 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).
77. Carter, A. B. *et al.* A spatial analysis of seagrass habitat and community diversity in the great barrier reef world heritage area. *Sci. Rep.* **11**(1), 22344 (2021).
78. Bayliss, P. *et al.* Modelling the spatial relationship between dugong (*Dugong dugon*) and their seagrass habitat in Shark Bay Marine park before and after the marine heatwave of 2010/11. *Dugongs Seagrass NESP Rep.* **2**, 1–55 (2019).
79. Warren, D. L. *et al.* ENMTools 1.0: An R package for comparative ecological biogeography. *Ecography* **44**(4), 504–511. <https://doi.org/10.1111/ecog.05485> (2021).
80. Wickham, H. reshape2: Flexibly reshape data: a reboot of the reshape package. *R package version*, **1**(2). (2012).
81. McKenzie, L. J., Campbell, S. J. & Roder, C. A. *Seagrass-watch: Manual for Mapping and Monitoring Seagrass Resources* 2nd edn, 100 (QFS NFC, Cairns, 2003).
82. Muscarella, R. *et al.* ENMeval: An R package for conducting spatially independent evaluations and estimating optimal model complexity for Maxent ecological niche models. *Methods Ecol. Evol.* **5**(11), 1198–1205. <https://doi.org/10.1111/2041-210X.12261> (2014).
83. Shcheglovitova, M. & Anderson, R. P. Estimating optimal complexity for ecological niche models: A jack-knife approach for species with small sample sizes. *Ecol. Model.* **269**, 9–17 (2013).
84. Vollerling, J., Halvorsen, R., Auestad, I. & Rydgren, K. Bunching up the background better bias in species distribution models. *Ecography* **42**(10), 1717–1727. <https://doi.org/10.1111/ecog.04503> (2019).
85. 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* <https://doi.org/10.22541/au.160551779.93380163/v1> (2020).
86. 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. <https://doi.org/10.1371/journal.pone.0097122> (2014).
87. Warren, D. L., Glor, R. E. & Turelli, M. Environmental niche equivalency versus conservatism: Quantitative approaches to niche evolution. *Evolution* **62**(11), 2868–2883 (2008).
88. Warren, D. L., Glor, R. E. & Turelli, M. ENMTools: a toolbox for comparative studies of environmental niche models. *Ecography* **33**(3), 607–611. <https://doi.org/10.1111/j.1600-0587.2009.06142.x> (2010).

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Author contributions

S.S. and S.B. compiled and analyzed the data, prepared the output maps, and wrote the entire manuscript. A.P. and K.S. conceived the study, reviewed, and supervised the manuscript writing. C.G., P.S.H., Sa.P., Sh.P., S.R., Su.P., S.G., S.I. and A.N. helped with 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 work and reviewed the manuscript. J.A.J. acquired the funds for the work. S.S. and S.B. share equal contributions in authorship.

Competing interests

The authors declare no competing interests.

Additional information

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(Advisor, BDCC-2023)

CERTIFICATE OF PARTICIPATION



This certificate is issued to

Sohom Seal

for attending the international Science Symposium - 'A CELEBRATION OF THE SCIENTIFIC LIFE OF TREVOR PLATT - Trends, Reflections, Evolution, and Visions in Ocean Research' organized by Trevor Platt Science Foundation and partners at Plymouth Marine Laboratory from 9th August to 11th August 2023. He presented a poster on the topic "Seagrass mapping using remote sensing for identification of critical dugong habitats in India" at the symposium.

A handwritten signature in blue ink, appearing to read 'Shubha Sathyendranath', written in a cursive style.

Dr. Shubha Sathyendranath
(Director, TPSF)

A handwritten signature in blue ink, appearing to read 'Nandini Menon N', written in a cursive style.

Dr. Nandini Menon N
(Director, TPSF)

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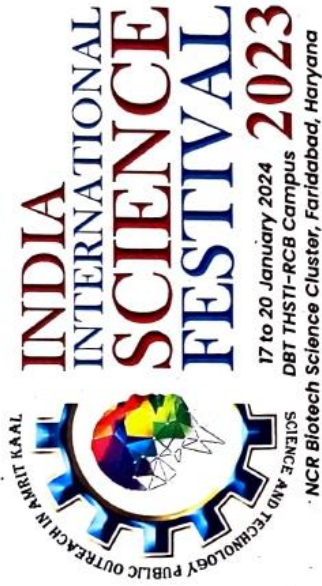


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This is to certify that Prof./Dr./Mr./Ms. Sohom Kal.....from
Wildlife Institute of India, Chandigarh..... has successfully
participated in..... Young Scientist Conference.....
conducted from 17.....to.....20.....January 2024 as a part of **9th India International Science Festival 2023** organised
by Government of India's Ministry of Science & Technology, Ministry of Earth Sciences, Department of Space, Department
of Atomic Energy and Government of Haryana in association with Vijnana Bharati (VIBHA). During this event he/she pre-
sented a oral presentation..... and secured..... best..... rank.

sewada

Dr. Shekhar C. Mande
President, Vijnana Bharati

Prof. Abhay Karandikar
Secretary, Department of Science & Technology

